APPENDIX 3

Broad Guidance for Natural Systems and Bay Trail Adaptation to Sea-Level Rise, ESA

Final

BAY TRAIL RISK ASSESSMENT AND ADAPTATION PRIORITIZATION PLAN

Broad Guidance for Natural Systems and Bay Trail Adaptation to Sea-Level Rise

Prepared for
East Bay Regional Park District,
Under Contract to Wallace Roberts & Todd, LLC

May 2021

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May 2021

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TABLE OF CONTENTS

Bay Trail RAAPP: Broad Guidance for Natural Systems and Bay Trail Adaptation to Sea-Level Rise

Page

Page

Appendices

List of Figures

Page

List of Tables

1 INTRODUCTION

The East Bay Regional Park District (District) operates over 200 miles of the San Francisco Bay Trail, as well as park lands, on the East Bay shore spanning from Fremont to the Benicia-Martinez Bridge north by the Carquinez Strait. The San Francisco Bay Trail provides public access to the Bay and shoreline for communities around the Bay Area; over 330 miles of trail have been completed and a total of 500 miles are planned as a complete and continuous loop around the Bay. Recent studies have identified that much of the San Francisco Bay shore is vulnerable to sea-level rise. Recent guidance from the Ocean Protection Council (OPC) provides projections of sea-level rise amounts that should be incorporated into project planning and design (OPC 2018). Generally, this guidance projects sea-level rise amounts of approximately three to ten feet by the end of the 21st century (OPC 2018). The range of potential consequences from elevated water levels (e.g. loss of trail connectivity, closures and repairs), as well as the temporal uncertainty around when these events are expected to occur, drives the need for thoughtful and robust adaptation planning for the Bay Trail in the present-day. Elevated water levels can also increase coastal erosion and the extent of wave runup which may damage trails even if placed above and inland of high Bay waters such as king tides. Shore armoring, the traditional approach to protect trails from erosion and wave action, can be expected to displace natural habitats progressively as sea-level rises. Consequently, trail design criteria are needed to account for anticipated sea-level rise.

In order to plan effectively for future sea-level rise, the District is currently conducting the Bay Trail Risk Assessment and Adaptation Prioritization plan (Bay Trail RAAPP) to prioritize adaptation planning for vulnerable segments, with a focus on nature-based solutions that are able to provide multiple benefits (e.g. ecological restoration, recreation, critical mobility, public education) for the region. Nature-based approaches to coastal adaptation present an opportunity to counter biodiversity loss, restore natural processes, and strengthen shoreline resilience against sea-level rise.

Although nature-based shoreline treatments are emerging as an alternative to traditional, engineered structures, nature-based or *living shorelines* remain a relatively young field. Coastal managers and planners need specific, place-based[1] guidance that factor in the range of environmental settings naturally found in that region and large-scale human modifications. Regional tools, such as the San Francisco Bay Shoreline Adaptation Atlas (Adaptation Atlas) developed by the San Francisco Estuary Institute (SFEI), have been developed to identify possible nature-based adaptation strategies around the Bay Area shoreline (SFEI 2019) for Operational Landscape Units (OLUs).

This document presents broad adaptation guidance for natural systems and the Bay Trail that builds upon the work conducted for the Adaptation Atlas and downscales the range of appropriate nature-based adaptation measures along the East Bay shore. This document introduces conceptual models of shore response to sea-level rise and adaptation strategies for the diverse shore types

1 *Place-based* refers to a scale that can be defined by specific or unique processes and conditions at the site level that are considered relevant in analysis and planning.

found along the East Bay. Ultimately, the information presented in this document is meant to support trail-specific adaptation approaches taken by the District in strengthening shoreline resilience along the Bay Trail.

This report is organized as follows:

- **Section 2 – Setting**
  This section provides a summary of the study area and describes existing and historic conditions, coastal hydrology and geomorphology and climate change and sea-level rise projections. Key documents and relevant studies are identified and briefly summarized.

- **Section 3 – Conceptual Models of Shore Response to Sea-Level Rise**
  This section presents a series of conceptual models of shore response to sea-level rise that are applied to the shore types introduced in Section 2. Major drivers, physical processes, structural response and functional response of the shore types are described. Specific adaptation measures for each shoreline type are introduced and discussed.

- **Section 4 – Adaptation Strategies for Consideration**
  This section presents major flood hazard and risk considerations relevant to sea-level rise adaptation and describes potential adaptation strategies that can be considered by the District along the Bay Trail study area. These adaptation strategies are discussed for potential application at the pilot sites identified in this study or implemented in the future at other sites as adaptive management strategies.

- **Section 5 – Conclusions & Recommendations**
  Based on the conceptual models of shore response to sea-level rise and nature-based adaptation strategies presented in Section 3 and 4, respectively, this section recommends potential next steps for the study area.

2 SETTING

This section describes the project setting and provides an overall context for this adaptation guidance along the East Bay shore. The following includes a discussion of the project study area, including its evolution from historical to existing conditions, a summary of the coastal hydrology and geomorphology, the Bay Trail, and a summary of relevant climate change and sea-level rise projections and policies.

2.1 Project Study Area

The District operates and maintains approximately 45 miles of the San Francisco Bay Trail[2] within approximately 200 miles of shoreline along the east shore of the San Francisco Bay. The following section summarizes existing shoreline conditions, an overview of historic conditions and delineation of sub-areas within the study area. Key documents and relevant studies are identified and briefly summarized.

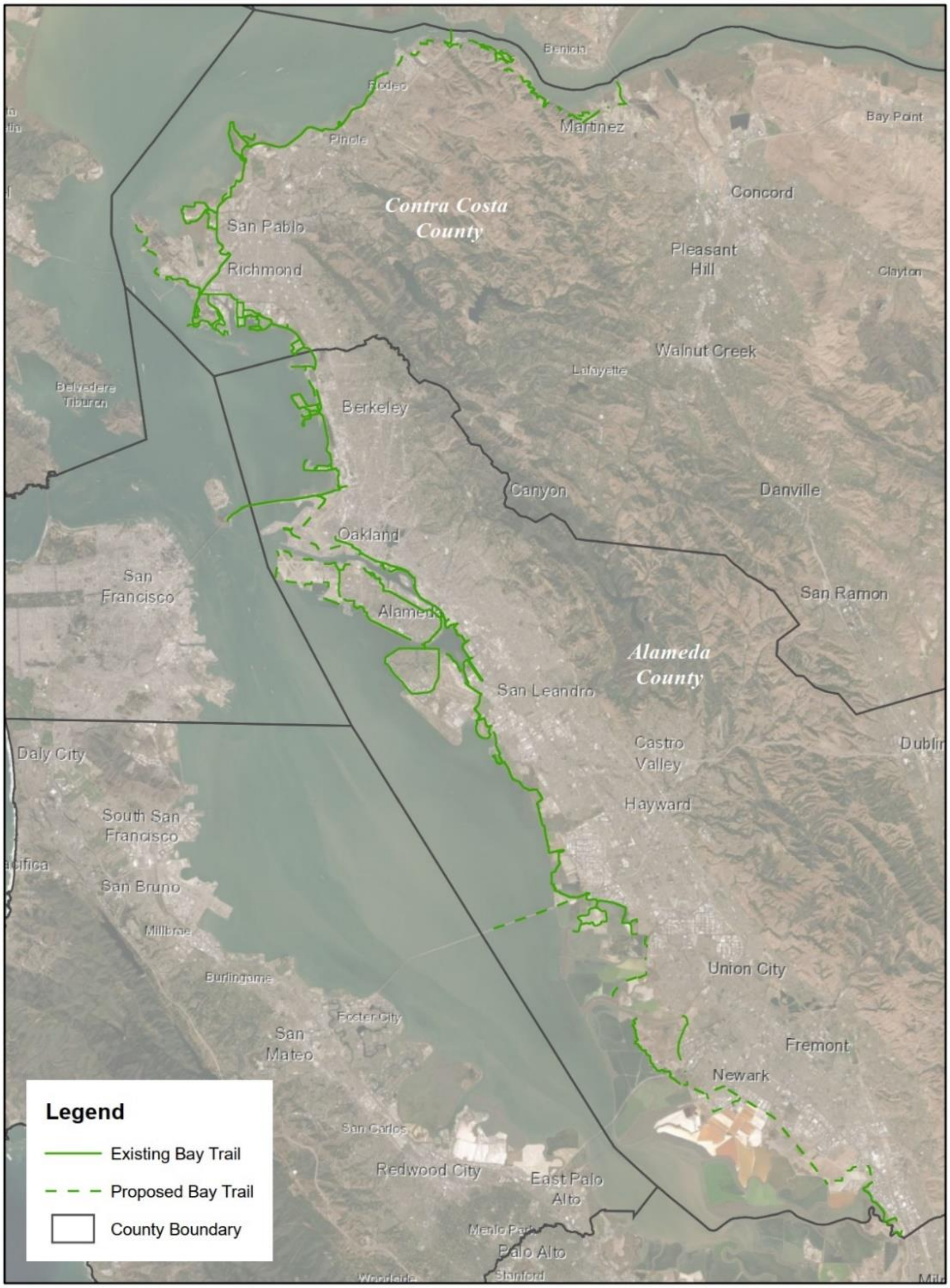
2.1.1 Existing Conditions

The study focuses on the segments of Bay Trail located within Contra Costa County and Alameda Counties. **Figure 1** shows the extents of the study area, which encompasses the East Bay shore from Benicia-Martinez Bridge in the north and Coyote Creek in the south.

Contra Costa County has over 80 miles of Bay Trail, which are adjacent to tidal marshes, protected wildlife areas and recreational areas, as well as industrial and residential areas. Railway infrastructure is located along parts of the shoreline. The Contra Costa County shoreline is connected to Marin County via the Richmond Bridge and the North Bay via the Carquinez and Benicia bridges. The Bay Trail is currently accessible on these transportation connections.

Due to the urban setting, shoreline use in Alameda County is wide-ranging. Generally, recreation, light industrial and commercial uses of the shoreline are common, with large swaths of residential housing located east/inland of the trail. The shoreline south of Oakland International Airport is comprised of recreational areas, salt and tidal ponds, wetlands and wastewater treatment facilities. Several pieces of major transportation infrastructure connect the Bay Trail segments in Alameda County to other parts of the Bay, including the Bay Bridge, San Mateo-Hayward Bridge and Dumbarton Bridge.

2 The San Francisco Bay Trail is a planned 500-mile transportation and recreation route for cyclists and pedestrians and will run through all nine Bay Area counties. More information on the San Francisco Bay Trail can be found here: https://baytrail.org/



SOURCE: San Francisco Bay Trail 2020

Bay Trail RAAPP / D201900102.00

Figure 1
Bay Trail Location in Study Area

Much of the existing study segment shoreline is developed and fortified with shoreline protection structures (SFEI 2016). In some segments, major transportation infrastructure, such as the Eastshore Freeway (part of I-80) is the first line of defense for flood protection. The Oakland International Airport and Martin Luther King Jr. Regional Shoreline are protected by an engineered levee. Small portions of the shoreline benefit from protection afforded by natural features; the majority of the shore is developed on filled areas through reclamation, where the natural shores and marshes were built up with fill, and is vulnerable to flooding. Crown Beach in Alameda is one of a few shoreline areas where the coast is fronted by a beach. Several pocket beaches have formed around engineered shorelines (e.g. Richmond) along the East Bay shore, where sands and gravels opportunistically deposited and are held in place by natural and man-made structures. Albany Beach and the small beaches to the south along McLaughlin Eastshore State Park are examples of pocket beaches, while to the north a series of wetlands front the shoreline between Albany Bulb and Marina Bay.

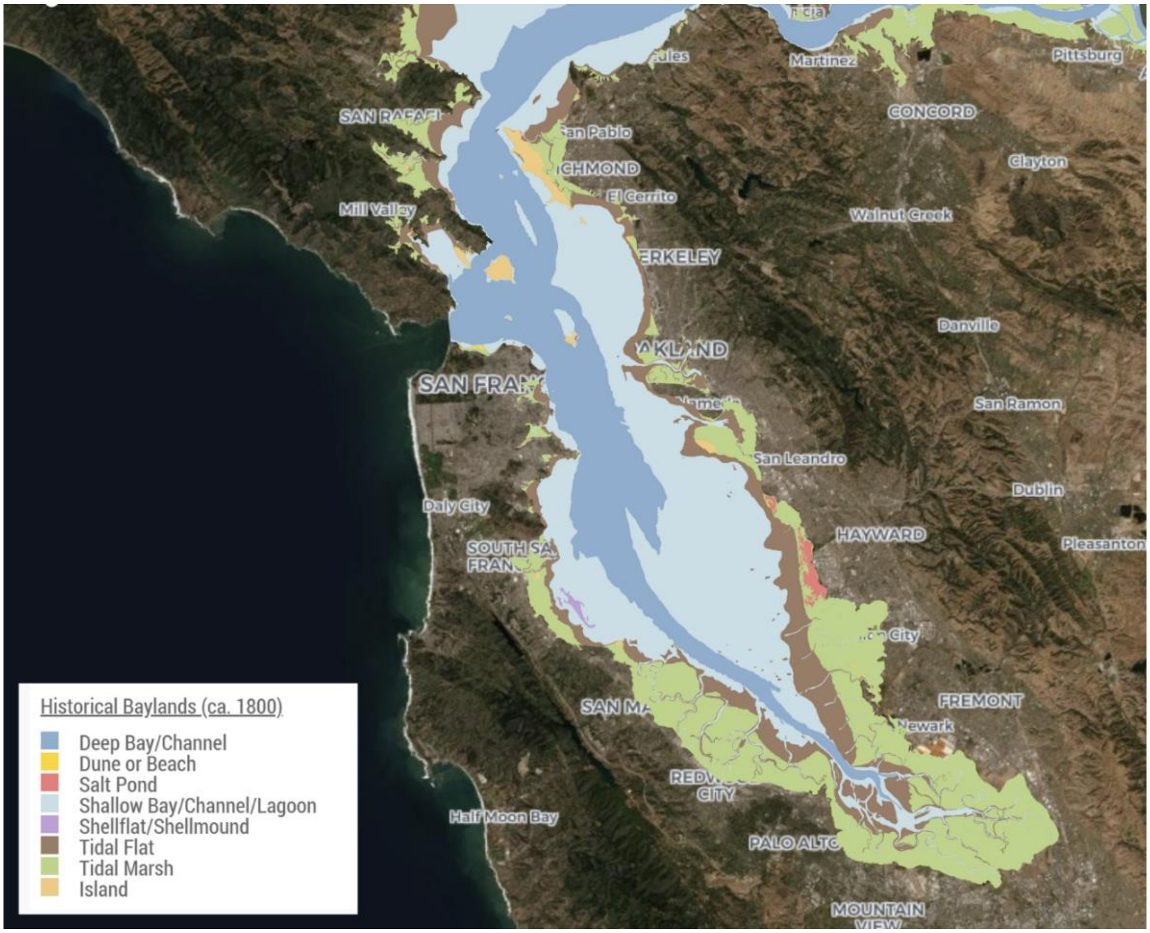
2.1.2 Historical Context

Prior to human development, the entirety of the Bay Trail study area and East Bay shoreline were predominantly shallow bay and tidal flat habitats backed by tidal marsh. Beaches found along the East Bay shoreline can be characterized as estuarine beaches with wind-waves limited by the fetches and swell exposure constrained by the local shoreline configuration within the embayment. The historic supply of sediment to these beaches, tidal flats and marshes came from the Sacramento-San Joaquin River watershed, although sand is also driven into San Francisco Bay from the coast by waves (Battalio 2014). Tidal marsh and beach habitats in the Bay expanded due to increased sediment supply from upstream hydraulic mining in the late 1800s. Concurrently, rapid development and industrialization of the region resulted in the conversion of low-lying wetlands to agricultural uses and artificial filling of the Bay. **Figure 2** shows the extent of historic wetlands from the 19th century.

Floodplain management and water supply developments during the mid-1900s led to the construction of dams throughout the Sierra Nevada, which drastically curtailed sediment supply to the Bay watershed.

2.1.3 Delineation of Sub-Areas

The diverse characteristics of the shoreline along the East Bay and associated alignment of the Bay Trail, in present land use and habitats, historical context and desired future by community stakeholders, emphasize the complex nature of multi-objective planning. Current management approaches by the District and regional climate change adaptation planning practices recommend the delineation of sub-areas along the shoreline, guided by the geomorphic setting and natural processes, in order to enable effective place-based planning. The boundaries of these sub-areas, more often than not, typically cross jurisdictional boundaries, since natural processes (e.g. waves, tides, etc.) affect all parts of the shoreline.



SOURCE: SFEI 2019

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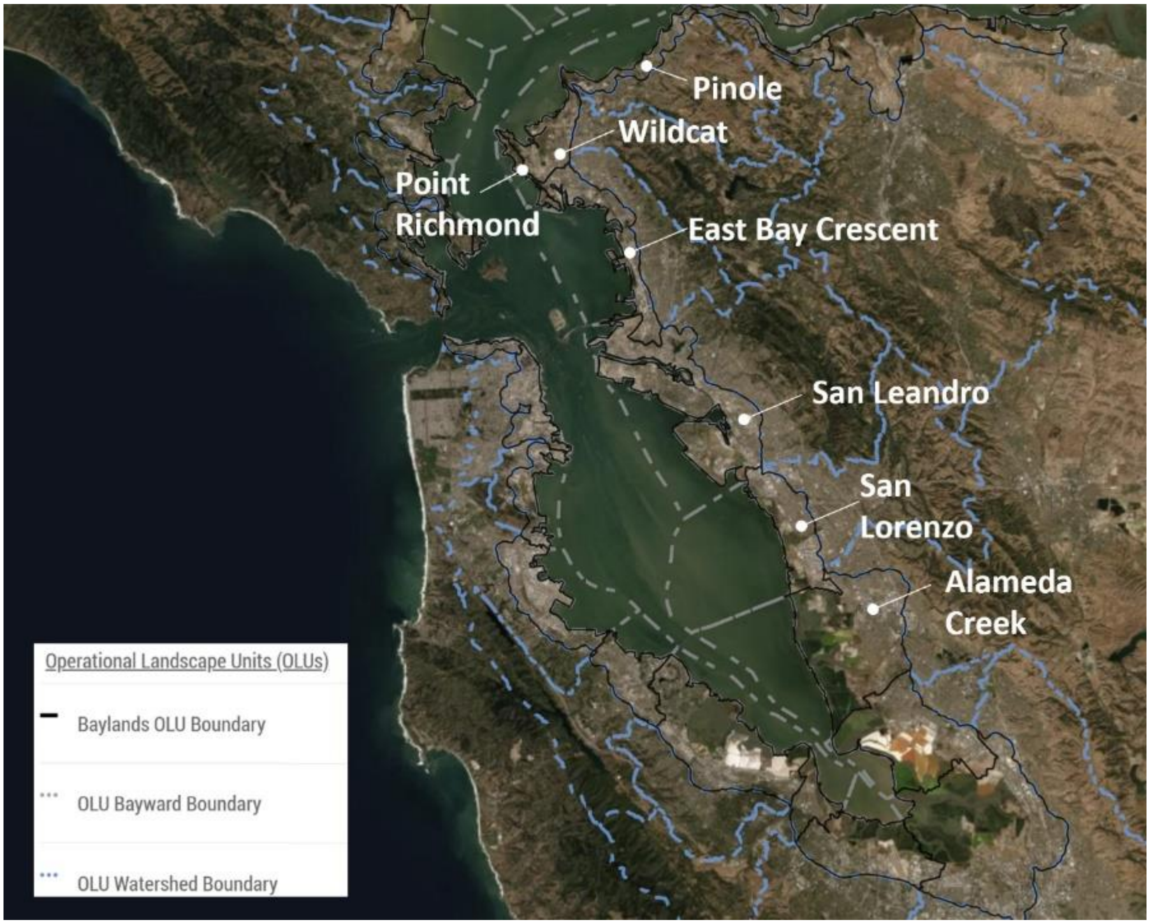
Figure 2
Historic Ecology of East Bay Shoreline

SFEI OLU Approach

The Adaptation Atlas (SFEI, 2019) introduces the concept of the Operational Landscape Unit (OLU), which are defined as "connected, geographic areas sharing physical characteristics that would benefit from being managed as a unit to provide particular desired ecosystem functions and services." This framework was applied to the Bay Area and a group of baylands OLUs were identified as recommended planning units for nature-based sea-level rise adaptation. bayland OLUs are connected by flow of water and sediment and consist of both landscape features and built environment. Datasets used to group the OLUs include geomorphic settings, baylands, shoreline and land use characteristics.

The SFEI Adaptation Atlas (2019) divides the East Bay shoreline into six distinct OLUs (north to south): Pinole, Wildcat, Point Richmond, East Bay Crescent, San Leandro and San Lorenzo. **Figure 3** shows the OLU extents along the study area.



SOURCE: SFEI 2019

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Figure 3
Baylands OLU Extent Along East Bay Shore

East Bay Regional Park District Management Approach

The District manages and operates segments of the Bay Trail in areas both owned by the District and others. Appendix A includes a map of the segments of Bay Trail that are operated by the District. Note that some portions of trail shown in the map of Appendix A are proposed, while others are active. The Bay Trail RAAPP team used these trail segments as a basis for conducting a detailed risk assessment that was used to prioritize different segments for adaptation planning.

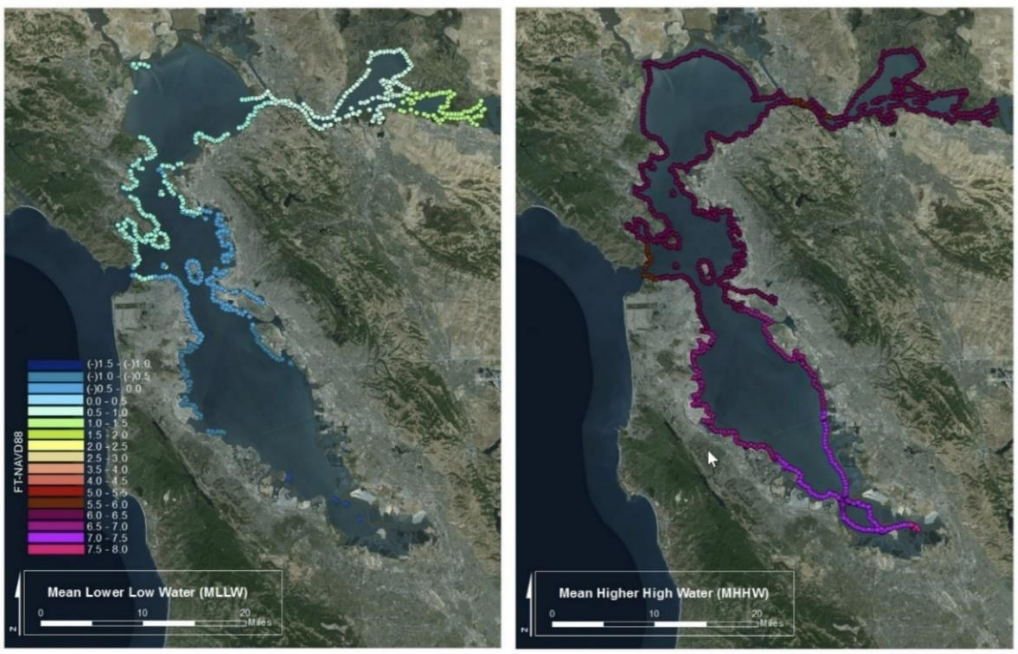
2.2 Coastal Hydrology and Geomorphology

This section provides a broad overview of primary physical processes that influence the coastal hydrology and geomorphology of the Bay Trail shoreline. The characteristics of existing natural coastal landforms, such as elevation ranges, berm crests or other, are readily linked to the interplay of these processes. In some areas, due to human activity and urbanization, the flow of water has been impeded, which has consequences for the types of future nature-based adaptation that can be pursued.

2.2.1 Water levels, Tides, and Datums

Tides within San Francisco Bay are controlled by water level fluctuations in the Pacific Ocean that travel through the Golden Gate and propagate throughout the Bay. The tides are characterized as mixed semi-diurnal, with two high tides and two low tides of unequal height occurring approximately daily. Along the Bay Trail, the tide range exhibits a latitudinal trend, varying from 5.5 feet at the Golden Gate Bridge to 8.5 feet in South San Francisco Bay. Amplification of the tide range is observed at locations further south in San Francisco Bay, due to its closed basin shape.

AECOM (2016) analyzed detailed hydrodynamic modeling for the entire Bay area (DHI 2011, DHI 2013), as part of the San Francisco Bay Conservation and Development Commission (BCDC) Adapting to Rising Tides[3] (ART) project. **Figure 4** shows elevations of the mean lower-low water[4] (MLLW) and mean higher-high water[5] (MHHW) tidal datums everywhere along the Bay shoreline relative to the North American Vertical Datum of 1988 (NAVD or NAVD88). Along the Bay Trail study segment, the elevation of MLLW ranges from -1 to +1 feet NAVD[6] and MHHW elevations range from approximately 6 to 8 feet NAVD.



SOURCE: AECOM 2016

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Figure 4
Elevations of Tidal Datums (MLLW & MHHW)
Along Shore of San Francisco Bay

3 The Adapting to Rising Tides datasets provide predicted flood extents in the Bay Area under future sea-level rise conditions. More information on ART is accessible here: https://www.adaptingtorisingtides.org/

4 MLLW refers to mean lower-low water, a tidal datum, computed as the average of the lower-low water height of each tidal day observed over the National Tidal Datum Epoch.

5 MHHW refers to mean higher-high water, a tidal datum, computed as the average of the higher-high water height of each tidal day observed over the National Tidal Datum Epoch.

6 NAVD or NAVD88 refers to the North American Vertical Datum of 1988, a fixed reference for elevations determined by geodetic leveling. The datum was derived from a general adjustment of the first-order terrestrial leveling nets of the United States, Canada, and Mexico.

Shoreline features around the Bay and their characteristics are influenced by tide elevations. For example, intertidal zones, which are the foundation of a number of estuarine habitats, exist between MLLW and MHHW. Mudflats generally form around low-tide elevations and salt marsh wetlands occur at high tide elevations. Transportation infrastructure, including major roadways and railways, are typically designed to have crests (high points) located several feet above high tide elevations to accommodate storm surge. Both natural and built landforms on the coast will be affected as water levels increase with sea-level rise.

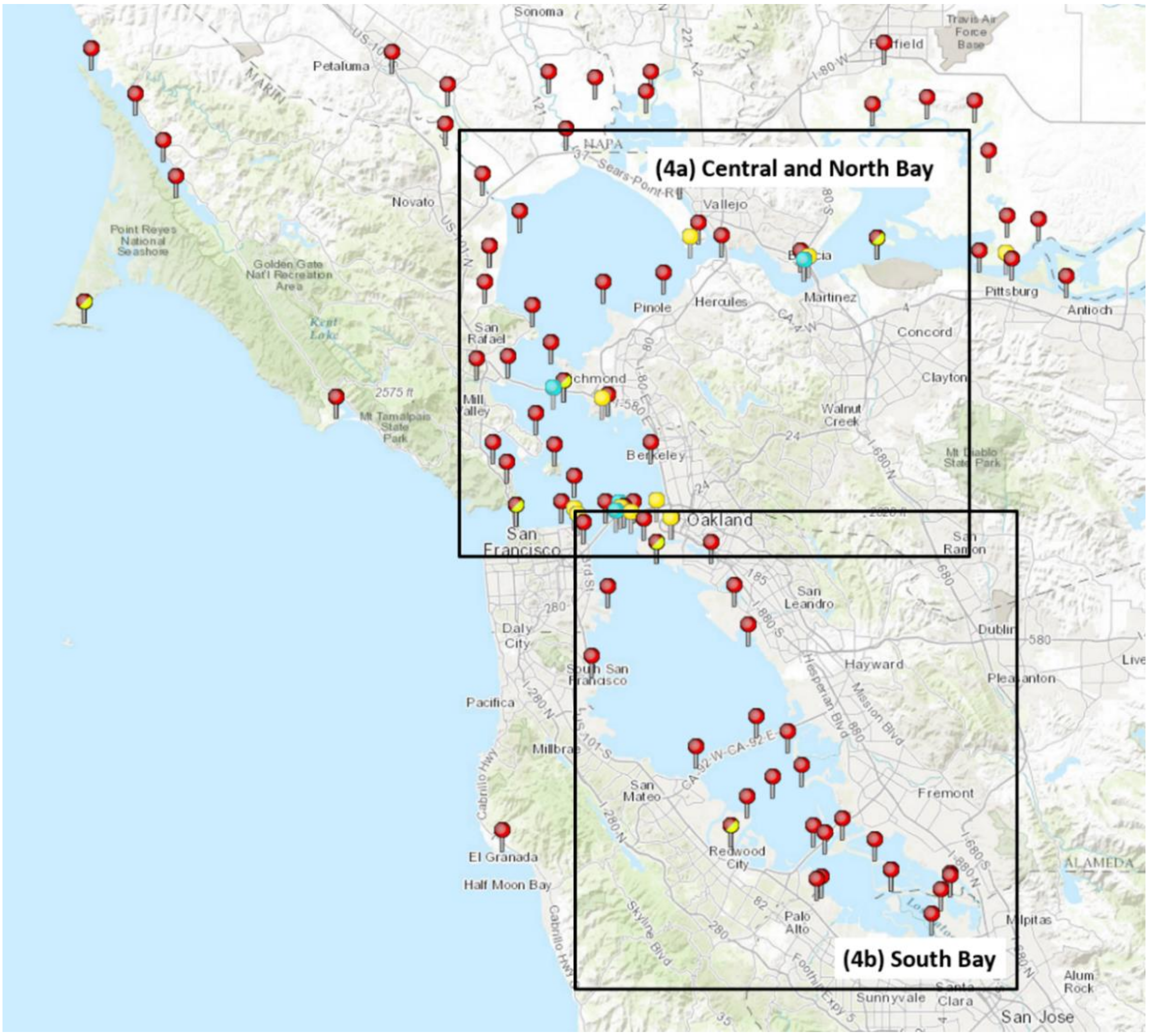
Since MLLW and MHHW vary around the Bay shoreline, and tidal range is a relevant design criterion for nature-based approaches, the Bay can further be subdivided by region. As part of the Natural Shoreline Infrastructure Guidance, ESA analyzed tidal range through the Bay based on tidal datum information provided by National Oceanic and Atmospheric Association (NOAA) gauges for the entire California coastline, which included the San Francisco Bay. The Highest Expected Tide is the 1-percent annual exceedance (100-year return period) water level computed by NOAA.[7] Note that these elevations do not include wind and wave effects and may be lower than those reported by FEMA, but are based on actual measurements which include climatic and other meteorological effects. This information is summarized in **Table 1**. **Figure 5** shows the subdivision of the Bay Area into the Central and North Bay and South Bay regions, based on observed North-South trends in tidal range.

TABLE 1
TIDE RANGE THROUGH SAN FRANCISCO BAY

Tide Gauge	Tide Range (feet)	Highest Expected Tide (feet NAVD)
Richmond	6.1	8.7
San Francisco	5.8	8.7
Redwood City	8.2	10.8

SOURCE: NOAA Tides and Currents

[7] For San Francisco, the 2018 value is obtained from this website, and adjusted to NAVD datum. https://tidesandcurrents.noaa.gov/est/stickdiagram.shtml?stnid=9414290



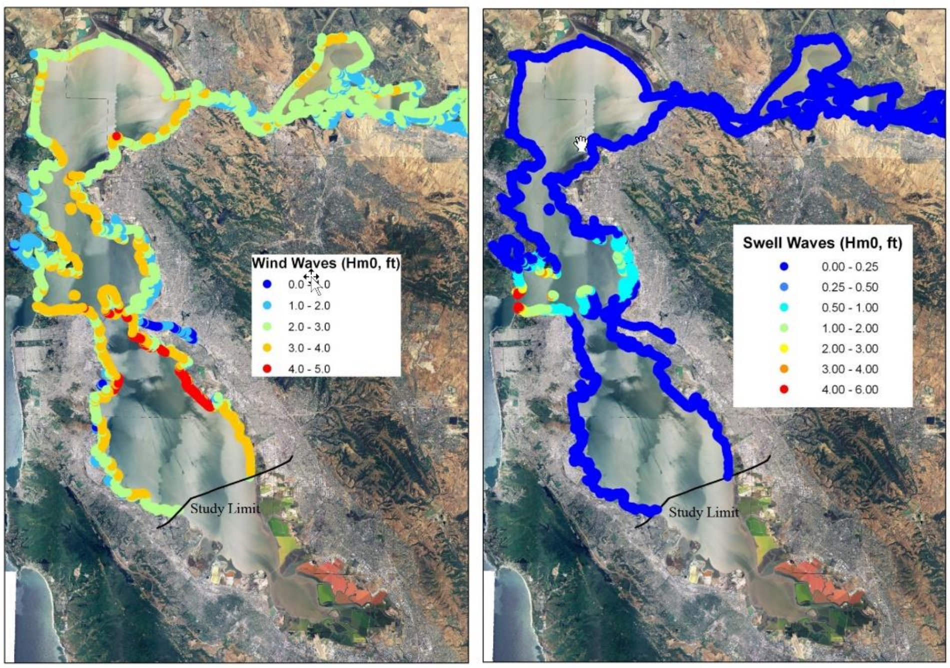
SOURCE: ESA 2018

Bay Trail RAAPP / D201900102.00

Figure 5
Tidal Range Subregions for San Francisco Bay

2.2.2 Wave Climate

Local wind action over the Bay generates short period, surface gravity waves generally known as wind waves. Wave heights are limited by the available fetch (e.g. distance across water surface wind can blow), duration and magnitude (i.e., speed) of the wind event, and water depth. The wind climate can vary significantly over the entire extent of the Bay; thus, variations in wind characteristics and shoreline orientation produce different local wave heights along the Bay shoreline and Bay Trail. Swell waves from deep ocean propagate through the Golden Gate (i.e., the entrance to San Francisco Bay) toward the East Bay shoreline by Berkeley and Emeryville. **Figure 6** presents extreme wave heights around the Bay, based on modeling by DHI evaluating wind-generated and swell wave heights for extreme conditions (1% and 0.2% recurrence interval events) as part of the coastal flood study for FEMA. In addition to wind-generated waves and swell, boat-generated wave wakes from ships and ferries traveling across the Bay impact local wave climates, spatially and temporally.



SOURCE: DHI 2011

Bay Trail RAAPP / D201900102.00

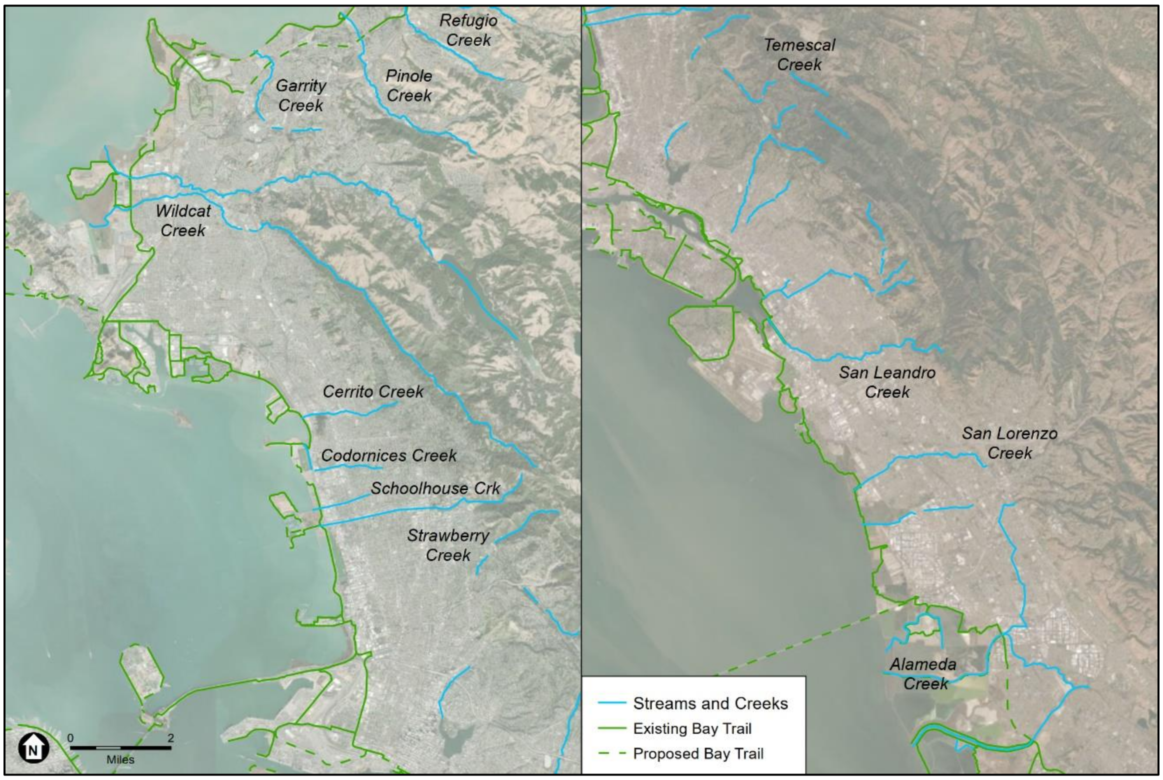
Figure 6
Wind Wave and Swell Wave Heights in San Francisco Bay for 100-year Event

Waves contribute to changes in shoreline geomorphology by driving sediment transport across littoral cells and causing erosion and potential flooding through wave runup and overtopping.

2.2.3 Watershed Discharges

The Bay Trail is located in the San Francisco Bay Delta watershed, which drains more than 75,000 square miles. The Sacramento and San Joaquin Rivers and their tributaries flow into the Bay Delta watershed via Suisun Bay and the Carquinez Strait. These flows merge with those from the Napa River and Petaluma River at San Pablo Bay which connects to San Francisco Bay and eventually to the Pacific Ocean. Developments in flood control and water supply during the mid-1900s drove dam construction throughout the Sierra Nevada, which drastically decreased water flow and sediment supply to the Bay.

Several creeks discharge directly into the Bay throughout the study area, including (north to south): Wildcat Creek, Cerrito Creek, Codornices Creek, Schoolhouse Creek, Strawberry Creek, Temescal Creek, Alameda Creek, San Leandro Creek and others (**Figure 7**). The watersheds range broadly in drainage area from less than 1 square mile (Schoolhouse Creek) to almost 50 square miles (San Leandro Creek).



SOURCE: USGS National Hydrography Dataset (2020); ESA (2020)

Bay Trail RAAPP / D201900102.00

Figure 7
East Bay Creeks

Historically, these creeks transported sediment from upstream watersheds into the Bay during the winter season. Human development and settlement drove major modifications to the natural hydrology of these creeks for water supply, land reclamation and flood risk management. Before historic tidal habitats by the East Bay shore were filled in, these creeks also exhibited a range of fluvial-tidal interface types (SFEI-ASC 2017). Some were connected directly to the Bay, others drained into tidal marsh and tidal marsh channels with natural levees. Other creeks ended in freshwater wetlands or upstream alluvial plains before reaching bayland habitats.

In their present day condition, large upstream portions of creeks have been culverted, channelized or confined via flood control levees, which has resulted in lower sediment yields to the estuarine and bayland environments and in-channel sedimentation. In many cases, channelized or culverted outlets at the bay shore constrain the extents and functional values of transitional estuarine conditions between tidal and fluvial systems. Historically, the interfaces of many creek, wetland and bayland systems created and maintained a broad mosaic of diverse and resilient shoreline habitat conditions. Dredging of channels in select watersheds to maintain flow capacity is a significant part of maintaining these flood infrastructure systems. The 2015 Goals Project identified sediments that have been trapped in these channels as a potential sediment source for bayland restoration in the 21st century. Some historical creeks along the East Bay shoreline have disappeared completely from being filled in; others flow through Bay fill to tidal channels.

Sediment re-use and creek reconnection to the baylands are potential enhancement measures that can be applied at the tidal-fluvial interface. Creek reconnection can reduce the risk of flooding and feed sediment to downstream estuarine habitats. Previous studies have identified suitable potential baylands enhancement measure for East Bay creeks, based on watershed analyses of sediment yields from 2000-2013 (SFEI-ASC, 2017). For example, Wildcat Creek in Contra Costa County generates over 900 tons/mi^2/yr of sediment. Wildcat Creek has been identified as a creek where re-connection to the Bay would result in lower flooding potential and sediment supply for tidal channel and tidal marsh habitat. San Leandro Creek in Alameda County has comparatively lower sediment yields (<300 tons/mi^2/yr); sediment generated from this system could potentially be re-used at neighboring existing and restored bayland habitats.

2.2.4 Groundwater

Shallow groundwater can be found along the coastal environments of the Bay Area, the depth of which is controlled by Bay water levels and rainfall. Plane et al. (2019) estimate that the minimum depth-to-water along the Bay Trail ranges between 0 and 6 feet. Along the shoreline, the proximity of groundwater can directly influence potential flood risks to greater or lesser extents in low-lying areas. Groundwater flooding during storm events may be an issue in low-lying areas with high groundwater tables and may be worsened with sea-level rise. A rising groundwater table can result in damage to buried infrastructure and foundations as well as flooding below residential and commercial properties. In areas where there are contaminated soils, groundwater can mobilize pollutants and endanger adjacent communities. Recent advances have resulted in the ability to approximate the response of ground water levels to sea-level rise (Befus et al. 2020).

2.2.5 Shore Morphology and Sediment Transport

Shore morphology refers to the shaping of the coastal zone over time by an array of natural morphodynamic processes (e.g., wind, tides, currents, waves, soil and sea-level changes). Sediment transport is defined as the movement of sediment by those same processes. Flowing water shapes the landscape when hydraulic forces are exerted on the coastal areas, eroding some areas, moving sediment, and building other areas through deposition.

Natural sediment activity driven by physical processes are relevant to the East Bay shoreline and its future condition. For example, the exposure of the historic Berkeley and Emeryville shoreline to swell waves generated from afar and propagating through the Golden Gate formed the shape of the coastline there, which was characterized by sand beaches fronting back-barrier marsh systems, prior to industrialization. Since then, the majority of the East Bay shoreline has been modified by human activity and is presently armored with both engineered structures and ad-hoc rubble and fill. The present-day eroding edge (and propensity of residential, commercial and mixed land use behind it) is now protected by armoring. The physical processes that inform shore morphology and sediment transport trends for the East Bay shore now interact with the hardened edge and generate different structural responses (e.g. formation of small pocket beaches, erosion), depending on the shoreline location.

2.3 Bay Trail

The Bay Trail (Trail) is a planned 500-mile regional hiking and bicycling trail around the perimeter of San Francisco and San Pablo Bay, connecting all nine counties of the Bay Area. To date, over 350 miles have been completed. The Trail is intended to create connections amongst existing parks and publicly accessible open space areas around the Bay Area, to “water trails” and to local and regional transit (e.g. BART, Caltrain). The Association of Bay Area Governments (ABAG) developed the Bay Trail Plan as part of Senate Bill 100, and oversees coordination between local stakeholders.

The Trail comprises the main alignment (referred to as the spine), with spur and connector trails that connect to points of natural, historic and cultural interest along or inland of the shoreline. Generally, trail policies strive to create a trail that is accessible to a diverse range of trail users and balancing opportunities to recreate by the Bay shoreline with protection of sensitive coastal habitats.

According to the San Francisco Bay Trail Plan, the Bay Trail is to be “locate[d], where feasible, close to the shoreline” (ABAG 1989). The proximity of the trail to the shoreline contributes to its flood risk. The location of the Trail alignment is often within BCDC’s jurisdictional band. As part of the McAteer-Petris Act, the BCDC exercises authority over the first 100 feet immediately landward of the edge of the Bay (BCDC 2005). The Act also calls for every proposed development to “provide maximum feasible public access, consistent with a proposed project.”

Neither the Plan nor BCDC public access guidelines define a set of criteria or thresholds for allowable amounts of flooding of the Bay Trail. Depending on the location, inundation of one location along the Trail may render larger segments inaccessible. While no accepted standards for trail design criteria related to coastal hazards and inundation currently exist, several examples of criteria have been developed for certain locations along the California coastline, as adaptation planning for a variety of coastal assets progresses. The following criteria were applied at the Humboldt Bay Trail South (ESA 2018):

- **Trail Damage from Wave Overtopping:** Damages to the trail are evaluated using the thresholds of wave overtopping rates published by EuroTop (2018)
  - Damage to lightly-protected surfaces resulting when wave overtopping rates exceed 0.5 cubic feet per second per linear foot of shore (cfs/lf)
  - Damage to trail pavement when wave overtopping rates exceed 2.2 cfs/lf

- **Trail Usability (Wave Overtopping):** Wave overtopping could inhibit trail usability by creating potentially unsafe conditions. Trail usability as a result of wave overtopping is evaluated using the threshold of wave overtopping rate of 0.22 cfs/lf, as published by EuroTop (2018)
- **Trail Usability (Still Water Flooding):** Nuisance flooding inhibits trail usability when tidal flooding results in at least 0.5 feet of inundation over the potential trail finished grade elevation

2.4 Climate Change and Sea-Level Rise

This section outlines how climate change is anticipated to affect regional and local coastal and fluvial processes that shape the environmental setting in the 21st century. Since this study focuses on the adaptation of shoreline assets and habitats, the information presented discusses impacts from sea-level rise and changes to hydrology. However, it is widely acknowledged that climate change will result in a range of other, additional environmental stressors: wildfire impacts, urban heat island effect and others.

2.4.1 Climate Change Hydrology

Climate change is driving impacts to major hydrologic parameters and processes which occur over a range of temporal and spatial scales on the West Coast. Changes in rainfall distribution and freshwater inputs, as well as the higher occurrence and intensity of extreme precipitation events will disproportionately impact the freshwater, sediment and nutrient inputs received by downstream coastal and estuarine habitats. Over 50% of annual streamflow in the western United States originates from snowmelt (Li et al. 2017). In general, warmer winter temperatures have decreased snowpack accumulation and shifted more watersheds towards rain-dominated flood regimes. Watersheds along the coastal ranges are expected to see the most immediate increases in flood extents under future temperatures (Davenport et al. 2020).

The Sacramento-San Joaquin River Delta is the primary source of freshwater and sediment supply to San Francisco Bay. Sediment eroded from upstream sources in these major watersheds contribute to marsh accretion and increased turbidity, which is beneficial for fish nurseries. Due to changes in land use and subsequent damming along the Sacramento River, sediment delivery to coastal wetland habitats in the Bay have drastically decreased. The projected increases in surface runoff and sediment transport through the 21st century could potentially boost the historically declining sediment supply to the Bay, which affects the ability of wetland and estuarine habitats to keep pace with sea level rise (Stern et al. 2020).

2.4.2 Sea-Level Rise

Coastal shorelines will primarily be exposed to climate change impacts via an increase in sea levels, due to thermal expansion of oceanic water and melting of the ice sheets. Estimates of sea-level rise vary by location over the California coastline. Sea-level rise projections for San Francisco tabulated in the *State of California Sea-Level Rise Guidance* (OPC 2018) were used to inform the inundation and flood hazard analysis for the Project site.

The 2018 OPC Guidance provides a science-based methodology for state and local governments to analyze and assess the risks associated with sea-level rise, and to incorporate sea-level rise into their planning, permitting, and investment decisions. The 2018 OPC Guidance draws from a probabilistic approach and provides ranges of likely sea-level rise estimates for future time horizons, compared to previous guidance that delineated future scenarios by specific greenhouse gas emission scenarios (e.g., NRC 2012, OPC 2013, etc.).

The Bay Trail is within the jurisdiction of the San Francisco Bay Conservation and Development Commission (BCDC), one of three coastal zone management agencies in California. BCDC follows the latest California guidance (2018 OPC) for planning and regulatory actions. The San Francisco Bay Plan (Bay Plan) was amended in 2011 to include Climate Change, affecting among other items Public Access and Shoreline Protection. The Draft San Francisco Bay Plan Climate Change Policy Guidance is in-progress in 2021 to clarify how climate change and associated sea-level rise is addressed by BCDC (BCDC 2021).

The selection of appropriate sea-level rise criteria to guide Bay Trail adaptation warrants consideration of the trail function (current and future function) and existing facilities that contribute to that function. The Bay Trail represents a significant, regional public access asset for communities around the Bay Area, supporting local economies, recreation and public education on shoreline ecosystems. Ultimately, a design that supports the Bay Trail *function* under high sea-level rise amounts is desirable. On a practical level, trail segments are maintained by an array of local and regional agencies and adaptation will require coordination between multiple stakeholders for each segment. Choosing more conservative sea-level rise criteria for adaptation of the existing *facility* may, in some locations, warrant elevating and relocating landward, which runs counter to the overall vision of the Bay Trail. It may be more appropriate to select design criteria that accommodates a lower level of sea-level rise in the near-term, while local and regional stakeholders work to secure necessary components for substantive, meaningful adaptation action (e.g., long-term funding streams, parcel acquisition) for higher levels of sea-level rise.

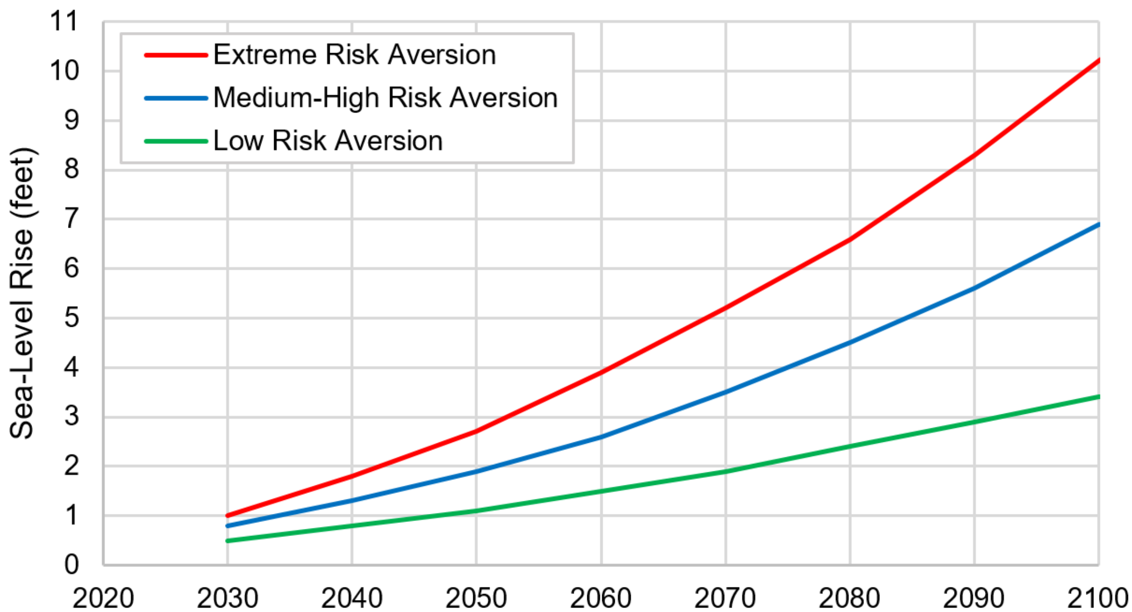
Table 2 summarizes sea-level rise projections from the 2018 OPC Guidance. **Figure 8** shows the envelope of sea-level rise estimates for the medium-high and extreme risk aversion scenarios from the 2018 OPC Guidance. For the purposes of this study, which represents a planning-level effort, based on the medium-high risk aversion projections for San Francisco, 3 feet and 6 feet were selected to represent mid- and late-century sea-level rise conditions along the East Bay shore. For the purposes of this analysis, the mid-century time frame is defined as 2050 through 2060 and late-century as 2080 through 2100. These sea-level rise values have a probability of exceedance of 0.005, or 1-in-200 chance.

TABLE 2
SEA-LEVEL RISE PROJECTIONS FOR SAN FRANCISCO BAY, CA

Scenario	2030	2050	2070	2100
Low Risk Aversion	0.5 feet	1.1 feet	1.9 feet	3.4 feet
Medium-High Risk Aversion	0.8 feet	1.9 feet	3.5 feet	6.9 feet
Extreme Risk Aversion	1.0 feet	2.7 feet	5.2 feet	10.2 feet

NOTES:
a Sea level rise projections assume high emissions (RCP 8.5).

SOURCE: Ocean Protection Council (2018)



SOURCE: San Francisco Bay Trail 2020

Bay Trail RAAPP / D201900102.00

Figure 8
Sea-Level Rise Projections for San Francisco, CA

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3 CONCEPTUAL MODEL OF SHORE RESPONSE TO SEA-LEVEL RISE

The coastal geomorphology of the East Bay shoreline is directly influenced by major drivers of change (e.g. sea-level rise, human intervention) that affect the rate and patterns of physical processes along the shore. These spatial and/or temporal shifts in physical processes can be related to the structural (and functional) response of a shoreline unit. This section presents:

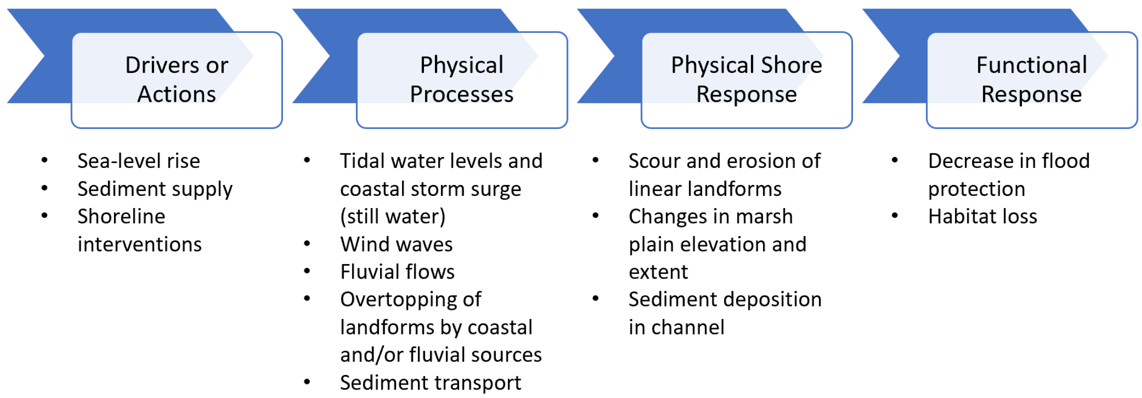
- A conceptual model of shore response to sea-level rise, and
- Application of the conceptual model framework to the range of shore types found along the East Bay to assess future geomorphic change.

This conceptual model is considered a planning-level tool to help understand how physical changes in the landscape could accelerate the potential flooding and erosion impacts that are often computed on a static landscape. The approach can also inform expectations for different types of potential adaptation strategies and measures that rely on natural infrastructure or nature-based adaptation.

3.1 Overview of Conceptual Model

This section describes a conceptual framework for assessing the shoreline response to sea-level rise over time. The conceptual model relates the functional response, or the system output, to major drivers or actions through changes in the physical processes and shore response. The model is a simple way to illustrate how drivers, such as sea-level rise, can potentially affect the physical landscape as well as the functions of the system, such as habitat or recreation (for example). This type of conceptual model is based on similar approaches which relate changes in physical conditions to changes in ecological value (e.g., Adolfson et al. 2009).

Figure 9 presents a diagram of the conceptual model of shore response and includes examples of primary drivers, physical processes, physical shore responses and changes in shore function. As shown by this example, the degree to which the functions of a site are affected by a driver can be assessed. Furthermore, actions or interventions, including specific adaptation measures, can be tested to evaluate how effective they are at changing the functional response. Applying simple equations and standard methods of computing the physical and shore responses can yield a quantitative tool that can help inform planning and management of coastal systems (e.g. see Behrens et al. 2016, where a quantified conceptual model was developed for coastal lagoons).



SOURCE: San Francisco Bay Trail 2020

Bay Trail RAAPP / D201900102.00

Figure 9
Conceptual Model of Shore Response Diagram

3.1.1 Drivers or Actions

Drivers describe conditions (e.g. sea-level rise) that affect or interact with physical processes and result in *changes to the typical, observed patterns of shoreline geomorphic change* (e.g. erosion or deposition) at a site. Actions refer to interventions, typically man-made, that interact with physical processes and change local geomorphology. Major drivers/actions for the Bay Trail shoreline include:

- Sea-level rise
- Sediment supply
- Shoreline interventions or adaptation

3.1.2 Physical Processes

Physical processes constitute the second component of the conceptual model of shoreline change to sea-level rise. Physical processes (e.g. tides and waves) occurring under typical (i.e., calm) conditions and those corresponding to extreme weather events (e.g. coastal storm surge, wave action) affect the geomorphology and flood risk of natural and developed shorelines in the vicinity of the Bay Trail. Extreme coastal and fluvial storms generally result in the overtopping of landforms through wave runup and flooding and can cause the greatest rates of geomorphic change. The primary physical processes to be considered along the Bay Trail shoreline include:

- Tides and coastal storm surge
- Wind waves
- Fluvial flows
- Overtopping of landforms by coastal and/or fluvial inputs
- Sediment transport

Sea-level rise will drive the increase in flood frequency in the future. Typical high tides in future conditions may result in or exacerbate flooding in low-lying areas.

3.1.3 Physical Response

The physical response of a shoreline unit, whether comprised of built structure or natural coastal landform, is defined as the response to change in physical processes. For example, heightened wave exposure at a beach increases the rate of alongshore transport for the littoral cell, causing the long-term physical response at the beach to be erosion (assuming no intervention). The physical response of armored shores is related to the structure’s capacity to provide continued flood protection. Damage to the structure via overtopping and/or erosion constitutes a failure response.

3.1.4 Functional Response

The functional response of a shoreline unit is defined as the change in use or function of the coast, as a consequence of its physical response to changes in physical processes. For example, beach erosion driven by greater exposure to wave attack (physical response) under future sea-level rise conditions (driver) will result in the loss of public access and recreation (functional response). Similarly, erosion of a sandy beach or the conversion of a tidal wetland to mudflat would result in the loss of specific habitat functions.

3.2 Identification of Shore Types

The following introduces shore types that are found on the East Bay shoreline and applies the conceptual model of shore response to sea level rise to each category.

3.2.1 Tidal Marshes

Tidal marshes are coastal wetlands exposed to tidal action and/or freshwater inputs and include a range of estuarine habitats such as salt marsh, freshwater marsh, mudflats and others. This estuarine habitat is typically found adjacent to tidal flats and mudflats, where sediment in offshore flats are suspended by wind waves and subsequently deposited in the marshes. **Figure 10** presents a photo showing an example of a tidal marsh and channel on the Albany shore.

Depending on local sediment supply, tidal marsh response to sea-level rise will vary. Marshes receive sediment from fluvial/creek discharge and other sources (e.g. sediment eroded from seaward edge or offshore flats). Without a sufficient sediment supply, marsh vegetation will effectively drown under higher water levels and eventually the tidal marsh will convert into a mudflat without vegetation. The disappearance of marsh habitat results in the loss of a buffer against wave action and tidal currents. This may accelerate sediment transport processes and potential erosion at the shoreline landward of the marsh.

SOURCE: ESA

Bay Trail RAAPP / D201900102.00

Figure 10
Tidal Marsh and Channels Along Albany Shore

3.2.2 Coarse Sand and Gravel Beaches

Coarse-grained beaches are dynamic coastal landforms comprised of sand, gravel and/or cobble. Beaches include a supratidal beach berm, formed by wave deposition, and a beach face. Due to the sediment size, beaches with coarse sand and gravel tend to have steeper slopes. The berm crest elevation is controlled by the maximum wave runup and sediment availability. **Figure 11** shows an example of a beach at Point Pinole Regional Shoreline.

Beaches are not static and are expected to migrate inland under future sea-level rise conditions. As water levels increase, waves will break closer to the shore and the landward extent of wave deposition (which influences the berm location) will shift landward. If there is sufficient volume of beach sediment and space landward, the beach crest will increase in height. Features such as large boulders or other natural groins found around coarse-grained beaches help to limit alongshore drift and support sediment retention.

SOURCE: ESA

Bay Trail RAAPP / D201900102.00

Figure 11
Coarse-Grained Beach at Point Pinole Regional Shoreline

3.2.3 Sand Dunes

Coastal sand dunes are found along the entirety of the California coastline. While commonly found in open coast shorelines, where beaches are exposed to stronger onshore winds, sand dunes can also be situated along estuarine shorelines with seasonally strong winds and sand supply. San Francisco Bay has some sandy beaches and dunes, and historically more existed (SFEI and Baye 2020). There is sufficient sand supply in some locations of the Bay resulting in beach and dune formation around filled and armored shore (Figure BEACH). There is increasing interest in using coarse sediments (sand, gravel, cobble) to adapt to sea-level rise, including the use of dunes (Newkirk et al. 2018, SFEI and SPUR 2019).

Sand dune habitat morphology is influenced by wave action, tides, wind and local human or wildlife-related movement (e.g. trampling). Local, naturally occurring sand sources (e.g. eroding bluff) are critical to dune formation and longevity. Examples of dunes within San Francisco Bay include those at Crissy Field in San Francisco and Albany Beach in Eastshore State Park (see **Figure 12**). Native coastal plant species play a vital role in sand dune formation; vegetation root systems and foliage assist in trapping sand particles and anchoring the dune profile. The sand dune then gradually captures more windblown sand as it increases in height. With sufficient sand supply and landward space, wave runup will build up the dune crest.

SOURCE: Bob Battalio, 3/20/13 (left)

Bay Trail RAAPP / D201900102.00

Figure 12
(Left) Beach in Richmond, CA, formed since 1930s construction of coastal structures. Note backshore vegetation on beach berm and wetlands behind the berm.; (Right)Sand Dunes at Albany Beach

3.2.4 Armored Shorelines

Armored shorelines refer to shorelines modified with man-made, typically erosion-resistant materials with a steep aspect ratio (height/width) for shoreline and flood protection purposes and minimal space footprint and material volume. Types of armored shorelines include engineered examples, such as a rock revetment, reinforced concrete seawall, or compacted earth levee, or arrangements having an armoring effect in addition to its primary function (e.g. railway elevated on fill embankment). The East Bay shoreline is predominantly fortified with various types of shoreline protection structures (SFEI 2016). **Figure 13** shows an example of an armored shore at Albany Beach, where a rock revetment was constructed along the Albany "Neck" as an urban overlay in which concrete rubble and debris was removed and reconfigured to accommodate an engineered shore protection utilizing imported rock.

SOURCE: ESA

Bay Trail RAAPP / D201900102.00

Figure 13
Armored Rock Revetment at Albany Shore

The following describe major characteristics and impacts of armored shorelines:

- *Footprint*: Engineered coastal structures replace the natural area within its footprint, thus resulting in a loss of habitat (e.g. beach, wetland).

- *Dissipation*: Engineered structures change local sediment transport patterns by increasing wave reflection, scour and turbulence. Changes in these processes actively modify the nearshore geometry. Compared to natural shorelines, engineered structures do not allow shore migration and concentrate wave energy dissipation on and in front of the structure, in order to provide protection for landward assets. Natural shorelines allow wave energy to be expended on the formation of a new shore (e.g. erosion) and turbulent processes over the full extent of the shoreline. Because of the concentration of wave energy at the armored structure, the adjacent bayward profile is subject to greater risk of erosion (e.g. scour), which affects the long-term function of the structure.

- *Loss of Habitat*: Local scour induced by engineered structures affects sediment supply to marshes and beaches. The loss of sediment changes nearshore elevations, potentially resulting in subtidal or lower intertidal depths.

- *Increased Loads*: Scour at the toe of an engineered structure creates greater depths immediately in front of the structure. The structure is more easily exposed to wave loads greater than what it may have been designed for, due to larger breaking wave heights and faster currents impinging upon the structure. This can result in failure or increased maintenance.

Sea-level rise will increase water depths in front of armored shorelines, increasing their susceptibility to wave overtopping and subsequent structural failure. Wave loads increase non-linearly with wave height, which means that even a small increase in sea-level rise and resultant depth increase could disproportionately impact the magnitude of wave loading experienced by the structure. Additionally, sea-level rise can contribute to overtopping through elevated wave runup and total water level (TWL). Total water levels scale nonlinearly with the increase in sea-level rise, due to larger incident waves at the structure.

The risk of catastrophic failure, flooding, and erosion of the backshore, and the loss of nearshore habitat, are likely to increase with greater wave loading and overtopping associated with sea-level rise. Where possible, the State of California recommends the use of nature-based approaches in lieu of traditional armoring, to provide relative co-benefits to ecology, access and overall resilience.

3.2.5 Filled Reclaimed Areas

Filled reclaimed areas refer to lands that were previously low-lying tidal flats and marshlands that were drained, diked and filled for human use. These areas are prone to experiencing groundwater emergence as sea-levels rise, which will impact land-use. It is possible, in some areas, that flooding from elevated groundwater will occur before flooding from coastal sources. This phenomenon has the potential to change – and potentially worsen – overland flooding patterns during extreme events. **Figure 14** shows an example of a filled and reclaimed shoreline at the North Basin Strip on the Berkeley shore.

The segments of East Bay shoreline that are filled reclaimed areas can be further characterized by the presence of contaminants. Previously, a number of industries, including shipping, construction, military operations, pesticide, and pharmaceuticals, disposed of toxic chemicals into Bay waters. Human-driven inputs of contaminants into filled reclaimed areas are a significant consideration in adaptation planning for sea-level rise, since a rising groundwater table could potentially exacerbate leaking of toxic chemicals into the Bay, adjacent habitats, low-lying areas, and stormwater infrastructure. Traditional approaches to containing the contaminated material via capping would likely keep the existing shoreline edge where it is and preclude adaptation measures which typically require a more expansive footprint. Excavation and removal of the contaminated fill is costly but would ultimately allow for a wider range of adaptation actions. Recent changes in regulatory policies to allow bay fill for restoration and sea-level rise adaptation projects may be an option for pursuing innovative shore enhancement and adaptation approaches in areas where excavating contaminated materials is difficult or not feasible.

SOURCE: ESA

Bay Trail RAAPP / D201900102.00

Figure 14
Filled Reclaimed Areas with Rubble at North Basin Strip, McLaughlin Eastshore State Park

3.2.6 Earthen Levees and Dikes

Earthen levees and dikes are earth fill embankments designed to obstruct surface flows and provide flood protection (USACE 2000). The terms levee and dike are often used interchangeably. Levees may or may not be formally designed by professional engineers but are often considered more substantial than dikes. In this study, levee refers to a flood control structure constructed to protect people and property very intolerant to flooding, and a dike refers to a similar structure that does not prevent flooding or has a lower flood protection performance. An engineered earthen levee currently protects the Martin Luther King Jr. Regional Shoreline and the Oakland International Airport. **Figure 15** shows a levee embankment with trail at the Point Isabel Shoreline.

SOURCE: ESA

Bay Trail RAAPP / D201900102.00

Figure 15
Levee Embankment with Trail at Point Isabel Shoreline

Sea-level rise increases the probability of triggering the failure modes of constructed earthen levees and dikes, as described below:

- *Overtopping* – Rising water levels can exceed the earthen levee and dike crest and result in flooding of the interior. Flooding from overtopping can lead to erosion of the levee crest and interior slope, which further reduce the protective capacity of the levee and contribute potentially to localized failure of the structure.

- *Erosion* – Regular, repeated exposure to typical and extreme waves, wave runup and high water levels, and tidal currents contribute to erosion on the outboard side of a levee.

- *Rapid drawdown* – When water levels are drawn down too quickly after a high water event (which saturates the levee soil), this may trigger structural shear failure of earth dikes and levees. The saturated soil weight may result in soil shear stresses that exceed soil shear strength, resulting in failure and mass sloughing of the section. Typically, the levee section fails "outwards" towards the flood source. This type of failure mode can occur during a tidal signal and/or the falling limb of a flood hydrograph.

- *Seepage and groundwater piping* – Elevated outboard water levels can cause flooding inboard of the levee due to increased water pressure in the soil beneath and on the "dry" side of the embankment. If the pressure is high enough, soil can be entrained resulting in soil "boils" indicating that foundation and full structural failure may occur. Seepage can also daylight on the face of the levee. CGI (2016) describes these processes as *underseepage* and *through-seepage*, respectively.

- *Penetration* – Drainage pipes and other infrastructure penetrate earthen fill embankments and result in increased permeability of surrounding soils. A rising groundwater table and saltwater intrusion from sea-level rise may contribute to failure of local soils.

3.2.7 Tidal Flats and Mudflats

Tidal flats and mudflats are non-vegetated, soft-sediment areas that are alternately submerged and exposed depending on the tide level. Sediment is typically deposited by tidal action or nearby fluvial sources. They are typically found between the mean high water and mean low water tidal datums. These habitats act as buffers from elevated water levels and waves from extreme events and are valuable wildlife habitat for migratory birds and fish species. **Figure 16** shows tidal flat habitat where Codornices Creek flows out to the Bay along the Albany shoreline.

Elevated water levels from sea-level rise will convert existing tidal and mudflats from intertidal into subtidal habitats. Due to greater water depths, these habitats will no longer be able to act as a "sponge" during high tide events or wave action.

SOURCE: ESA

Bay Trail RAAPP / D201900102.00

Figure 16
Tidal Flats at Codornices Creek, Albany, CA

3.2.8 Estuaries and Baylands

Estuaries and surrounding baylands are generally characterized by the confluence of tidal waters and stream discharges. The mixing of salt and freshwater is influenced by the rate at which fresh water from fluvial sources and tidal waters (salty) from the ocean enter the estuary. The resulting gradient of fresh to brackish to salty waters supports a diversity of aquatic vegetation and fauna that provide a number of ecosystem services. **Figure 17** shows the estuarine transition at the outlet of Strawberry Creek within the Eastshore State Park.

Sea-level rise will impact estuaries and their creek connections, by shifting the salt-fresh mixing zone farther inland. Saltwater intrusion will affect the types of vegetation present at the estuary-creek interface; specifically, saline water will act as a stressor for tidal freshwater wetland plants and may trigger a conversion of local vegetation palettes to be salt-tolerant. Elevated water levels in downstream creek channels may correspond with higher tidal velocities, which may have implications for bank stability.

SOURCE: ESA

Bay Trail RAAPP / D201900102.00

Figure 17
Estuary-Creek Connection at Strawberry Creek, West Berkeley, CA

3.3 Adaptation Measures by Shore Type

Adaptation measures, in the context of the conceptual model of shore response to sea-level rise, are actions taken to change the structural and functional response of a shoreline unit. The design of adaptation measures should address the structural response triggered by changes in physical processes.

A range of nature-based solutions are possible as potential adaptation measures to be applied at a shoreline unit. Design guidance around nature-based approaches typically require knowledge of available space at different tidal elevation bands through a shoreline profile as well as available space landward of the high tide line (HTL). In the absence of accommodation space in the backshore, adaptation actions may necessitate placing fill into the Bay, which could be costly and have a higher degree of regulatory considerations.

3.3.1 Nature-Based Adaptation Measures

This section defines six types of natural shoreline infrastructure that could be used as adaptation measures for shore types along the Bay Trail and East Bay shoreline.

Dunes

Coastal sand dunes act as buffers against high water levels and wave runup, providing landward assets and habitat protection from storm damage, erosion and flooding. Dunes are naturally dynamic and self-sustaining systems, assuming a local, regenerative source of sand is available. Wind and waves act to carry sand away during storm events to build up nearshore sand bars, which dissipate incoming waves. The sand is transported back to the dune system via waves and the dunes are re-built via aeolian (i.e., wind-blown) transport of the sediment landward.

While dunes are typically found in open coast environments in California, they can be found in some estuary environments with seasonally strong winds. Examples of dunes within San Francisco Bay include those at Crissy Field and Albany Beach in Eastshore State Park. Constructed dunes require a sandy backshore setting which can serve as long-term sediment supply. Native vegetation and other erosion control measures are particularly important in providing both adequate sediment retention and flexibility for sands to shift, as dunes move naturally landward in response to rising seas.

Coarse-Grained (Cobble/Gravel) Berm

Coarse-grained berms are mounds of rounded rock (cobble or gravel) that ocean waves have sorted and shaped into embankments. These features can typically be found close to river mouths and can be constructed around tidal-fluvial environments. Coarse-grained berms dissipate wave energy and can act as backstop that limits erosion. Sediment size scales with wave exposure; larger sediment sizes correspond to open coast environments, while gravel berms occur in areas sheltered from high wave energy (e.g. embayments, estuaries).

Coarse-grained berms are simpler and more cost-effective to construct, compared to traditional riprap revetments. Additionally, the substrate provides potential habitat for marine invertebrates and in some cases, supports salt grass or other vegetation to establish. Cobble and gravel are also suitable for recreational access, if added to a beach environment.

Marsh Sill

Marsh sills are low-profile stone structures with vegetated slopes, typically constructed in the shallow flats of estuarine, sheltered waters. A marsh sill protects against erosion by dissipating wave energy on its hard surface, acting as a buffer o the softer, more easily erodible natural shoreline. Marsh sills have the additional benefit of providing space for sand and sediment to collect between the rocks, which can lead to marsh growth (more habitat and more shoreline protection) over time.

Marsh sill projects need to be undertaken with care, and often require permitting to limit or mitigate damage to existing marsh and mudflats during construction. The electiveness the sill may diminish with rising sea levels, so the rate at which local water elevations will rise in the coming decades should be considered when calculating the project's long-term performance. Monitoring of a marsh sill constructed 25 years ago at the Greenbrae Boardwalk in Marin County shows that the sill continues to provide adequate shoreline protection and has withstood the pressures of locally generated wind waves, as well as the daily impact of ferry boat wakes, while the marsh has thrived.

Tidal Bench

A tidal bench is a gently sloping bench that is then vegetated with native plants, similar to a horizontal levee. Tidal benches extend from mean tide level (MTL) to the backshore, and act as wind and wave breaks, reducing the force of waves on upland areas during storms. These features are appropriate for estuarine, sheltered waters.

The gradual slope of the bench encourages sediment deposition and accretion, which improves shoreline stabilization and marsh growth. Tidal marshes are effective at cleaning nutrients and pollutants out of the water and offer one of the highest per acre rates of carbon sequestration. In contrast to rock armoring, tidal benches provide a range of habitat for a diversity of plants and animals including the potential for critical nesting areas, resting and feeding grounds for migratory birds traveling along the Pacific Flyway. Tidal benches are also amenable to hiking, bird watching, fishing, and canoe or kayaking.

Construction typically entails the use of heavy machinery for excavation and grading and requires areas for staging and stockpiling. Tidal marsh vegetation also may require maintenance, which should be factored into construction and monitoring costs. The Hamilton/Bel Marin Keys Wetland Restoration in Novato, and Warm Springs Marsh, in the south San Francisco Bay in Fremont, are prime examples of successful implementation of tidal benches as part of broader shoreline protection projects. Tidal benches are a narrow version of the horizontal levee concept (ESA PWA 2013, Judge et al. 2017, Newkirk et al. 2018).

Native Oyster Reefs

Oyster reefs are large aggregations of living oysters and oyster shells and occur or can be constructed in the intertidal or subtidal zones, in bays and estuarine waters. West coast native oyster (*Ostrea lurida*) reefs are increasingly being constructed or restored as a method for reducing erosion from waves and currents, especially at low tides. Oyster reefs benefit a range of fauna, by providing foraging opportunities and habitat diversity. Reefs also filter suspended particles, and this decreased turbidity encourages the growth of aquatic vegetation, creating more coastal protection as well as better habitat for crustaceans and fish. Oysters survive and thrive within a narrow tidal elevation range and require saline waters; reefs built outside of oysters' preferred range will not be as productive nor as effective.

Successful reef placement requires sediment with sufficient strength to support the unit. Both natural (recycled shell, gravel) and manmade (aggregates, special concrete mixtures) materials are appropriate for oyster reef substrates and for constructing reef elements. In California, native oyster reefs have been successfully installed as a form of Natural Shoreline Infrastructure in several locales, including projects in San Rafael, at Eden Landing Ecological Reserve in Hayward, Point Pinole in Richmond, and at the Berkeley Marina.

Eelgrass Beds

Eelgrass beds form when clusters of the marine plant *Zostera marina* (Pacific eelgrass) grow, or are planted, along the seafloor or near the shoreline. The aquatic vegetation increases drag and slows tidal currents and can dissipate wave energy at low tide. As eelgrass beds offer little protection at high tide, it is recommended to utilize this measure in tandem with other protection measures, such as coarse-grained berms and marsh sills, in a "layered" approach. Eelgrass beds may also accrete sediment and move upslope in response to rising seas, thereby enhancing shoreline resilience. Similar to oyster reefs, eelgrass beds also provide improved water clarity and increased rearing and foraging opportunities for a range of aquatic species including commercially important fishes. Pacific eelgrass has successfully been installed to provide low-level coastal defense in bays and estuaries at several project sites including at Eden Landing Ecological Reserve in Hayward, Marin Rod and Gun Club Restoration Site in San Rafael, in Morro Bay, and in San Diego Bay.

3.3.2 Scales of Adaptation

Nature-based adaptation measures can vary in spatial footprint required for implementation and scale of impact. A larger footprint may or may not be directly linked to the complexity of designing and constructing a living shoreline feature; the setting of a shoreline unit and its specific history are major factors in determining the scope and scale of a given project. For example, a shoreline unit may have adequate landward space to accommodate future sea level rise and may be a potentially ideal site for a vegetated tidal bench. However, the presence of contaminated soils and rubble in any part of the spatial footprint would warrant removal and regulatory oversight that require greater time, funding and consideration.

The following summarize distinct scales that a single or multiple nature-based adaptation measure(s) can operate on:

- Standalone feature in coastal shoreline unit (e.g., local eelgrass bed plantings)
- Coastal shoreline unit / littoral cell (e.g. local eelgrass bed plantings and coarse-grained beach restoration)
- Operational Landscape Unit - ecological connectivity across habitats (e.g. large-scale marsh restoration and enhancements)

3.3.3 Suitability by Shore Type

The nature-based adaptation measures described in Section 3.3.2 have varying suitability at each shoreline type. The suitability of a measure is related to 1) if these geomorphic features could realistically be found in these environmental settings and 2) if these features are self-sustaining and able to function reliably for the designated design life within a dynamic physical context. **Table 3** shows the suitability of the nature-based adaptation measures by shore types found along the East Bay shoreline. The assigned rankings are meant to guide preliminary planning and are not intended to be prescriptive. Site-specific evaluations will be necessary in order to confirm suitability for analysis and design.

TABLE 3
SUITABILITY MATRIX OF NATURE-BASED ADAPTATION MEASURES FOR EAST BAY SHORE TYPES

	Shore Type / Nature-Based Adaptation Measure	*Dune*	*Coarse-Grained Berm*	*Marsh Sill*	*Tidal Bench*	*Oyster Reef*	*Eelgrass Bed*
Sheltered Water (Wind-Waves)	*Tidal Marshes*	Low	**Low**	**High**	**High**	**High**	**High**
	Coarse-Grained Beaches	**Medium**	**High**	**High**	**High**	**High**	**High**
	Armored Shorelines	**Low**	**Medium**	**Low**	**Low**	**Medium**	**Medium**
	Filled Reclaimed Areas	**Low**	**High**	**Medium**	**Medium**	**Medium**	**Medium**
	*Earthen Levees and Dikes**	**Low**	**Medium**	**Medium**	**High**	**Medium**	**Medium**
	Tidal Flats and Mudflats	**Low**	**Low**	**High**	**High**	**High**	**High**
	Estuaries and Baylands	**Low**	**High**	**High**	**High**	**High**	**High**

The suitability of nature-based adaptation measures for shorelines that have been heavily modified by human action and land use, such as armored or leveed shorelines will depend on the larger desired vision for that shoreline. Pre-existing armoring may have been placed to offer flood protection up to a certain (often static) design water level that will be exceeded with future sea-level rise. If landward assets, such as the trail or other development, are relocated landward, then there is potential to naturalize the shore by removing the armoring (i.e., no need to provide the same degree of flood protection). Armored shorelines are linked to poor ecological outcomes and have a higher risk of structural failure; assuming that a shoreline unit remains armored, any potential nature-based adaptation measures implemented would have to be bayward, which may be limited spatially in the appropriate elevation range (e.g., eelgrass and oyster reefs will recruit only in specific elevation bands).

4 ADAPTATION STRATEGIES

This section describes a methodology for developing adaptation strategies for sea-level rise and major factors considered: flood and wave runup hazards, available migration space and future adaptive capacity. The guidance identifies opportunities and constraints for the Bay Trail and East Bay shoreline based off of the OLU framework introduced by SFEI and presents potential adaptation strategies, comprised of adaptation measures (Section 3.3), for distinct shore types.

4.1 Overview of Potential Adaptation Strategies

Adaptation strategies to sea-level rise will require coordination, action and implementation across all scales of jurisdictional stakeholders: local and regional. Depending on the shore type, an adaptation strategy can be composed of multiple *adaptation measures* (Section 3.3), which may vary in spatial-temporal footprint, design and benefits provided.

The Bay Trail is a significant regional asset to communities around San Francisco Bay, providing public recreation and access alongside vibrant Bay ecosystems and local points of interest. By definition, as the Bay Trail, it is assumed that it is more desirable to have the trail alignment located close to the shore for continual visual experience of the Bay by users. Future sea-level rise, however, will elevate Bay water levels and result in landward shifts of the shoreline. The proximity of the Trail to the Bay provides value to its users, yet it also elevates the overall risk of damage to the Trail by flooding, erosion and overtopping under future conditions. Recognizing the unique nature of this shoreline asset, it is clear that a successful adaptation strategy for the Trail must determine the appropriate balance of locating the alignment close to the (shifting) shoreline and designing for future sea-level rise. This guidance document presents a preliminary methodology for doing so and how nature-based/living shorelines approaches can be integrated into a holistic and practical solution.

Planning and adaptation to sea-level rise is complex due to the long-term uncertainty that accompanies scientific projections of increased water levels. The concept of *adaptive pathways* is becoming widely adopted within climate change adaptation planning because it proposes a decision-making framework for determining actions taken in the short-term and actions taken with consideration of future sea-level rise. Adapting to six to seven feet of sea-level rise by the end of the century will likely be accomplished in intentional increments of change, which support and preserve adaptive capacity of the system for the next magnitude of stressor. It is difficult to design and implement a trail alignment in present-day for end-of-century estimated sea-level rise levels that would provide the desired trail experience and remain in the same location for perpetuity (end of century).

To date, the consideration of adaptive capacity has not existed in traditional engineering approaches towards coastal systems. For example, traditional approaches to extending the useful life of a shoreline trail (e.g., preserve trail use for recreation by protecting it from being flooded) have typically been limited to armored structures. Armoring and "hardened" shorelines prevent shore migration inland and preclude the creation of accommodation/migration space for sea-level rise and shore transgression. Particularly, in urban areas, hardened shorelines are more often than not backed immediately by development. Thus, filling and armoring shorelines "removes" the possibility of a trail alignment being located further inland, since in practice, development has been located up to the landward edge of the shoreline protection.

This document considers the goal of the study to be the following: *to maintain the Bay Trail along the Bay under existing and future conditions, by supporting overall adaptive capacity with trail design.* Key place-based parameters that will ultimately influence design include the setting and shore type (summarized as an OLU). The coastal geomorphology for a specific setting and shore type determines the response to sea-level rise, as described in Section 3.

To develop a design that meets the stated goal above, we recommend:

1. Examining the setting and shore type of the identified trail segment
2. Evaluate the landward location and elevation required to meet trail criteria (Section 2.3) for existing and a range of future sea-level rise conditions (e.g. +2 feet, +3 feet, +6 feet)
3. Decide how many feet of sea-level rise can feasibly be accommodated in the present
4. Design and implement appropriate nature-based solutions, to the maximum extent possible, for the shoreline
5. Identify avenues to preserve future adaptive capacity of trail segment

In contrast to historic perspectives regarding coastal land use, where adjacent land use in the future was assumed to remain the same, this guidance recommends considering the baseline for both existing and future scenarios.

4.1.1 General Adaptation Categories

Adaptation strategies can be categorized into the following themes:

- **Hold the Line:** Maintains and defends existing shoreline configuration by upgrading flood protection infrastructure and limited use of natural and nature-based adaptation approaches.
- **Buffer with Public Open Space:** Moving the existing first line of shoreline defense landward by creating a buffer of public open space where additional habitat can be restored. Requires minimal reconfiguration of existing vulnerable infrastructure. Use of nature-based adaptation measures as necessary for identified vulnerabilities.

  Table 4 presents a summary of spatial requirements along the shore profile for different adaptation features. Technical guidance for the use of nature-based approaches were developed by ESA for the CA 4th Climate Assessment (ESA 2018, Newkirk et al. 2018) and provides estimates for the alongshore and cross-shore geometry and appropriate placement within the tidal profile for each nature-based adaptation measure. These guidance documents were used to inform development of the information in Table 4. Note that these spatial requirements are approximate and are considered minimums to achieve some degree of ecological function: these elements can be installed within smaller spaces but will likely require increased maintenance and limited ecological benefit. Alternatively, landward realignment of built of proposed infrastructure, such as a Bay Trail, can provide the minimum or greater space to achieve multiple objectives.

- **Maximize Habitat and Realignment:** Realignment of vulnerable shoreline infrastructure as necessary in order to maximize opportunities for nature-based approaches, with an emphasis on restoring/enhancing connectivity of natural processes.

TABLE 4
SPATIAL REQUIREMENTS AND LOCATION WITHIN TIDAL PROFILE BY ADAPTATION MEASURE

Nature-Based Adaptation Measure	Slope Range	Min. Alongshore Dimension (ft)	Min. Cross-shore Dimension (ft)	Location within tidal profile
Dunes	-	100 ft	100-200 ft for dune footprint, +50 ft behind dune footprint	Backshore
Coarse-Grained Berm	5H:1V to 10H:1V on bayward side, 3H:1V or flatter on landward side	10 ft	45 ft	Foreshore – 0.8 x TWL (crest elev.)
Marsh Sill	8H:1V to 10H:1V	30 ft	10 ft	
Tidal Bench	Minimum 7H:1V slope or gentler		30 ft	MLLW to 10-yr TWL
Native Oyster Reefs	-	-	-	+/- 2 ft of MLLW
Eelgrass Beds	-	-	-	Low intertidal (+1 ft MLW) to subtidal (< MLLW)

SOURCE: ESA, 2018; Newkirk et al., 2018

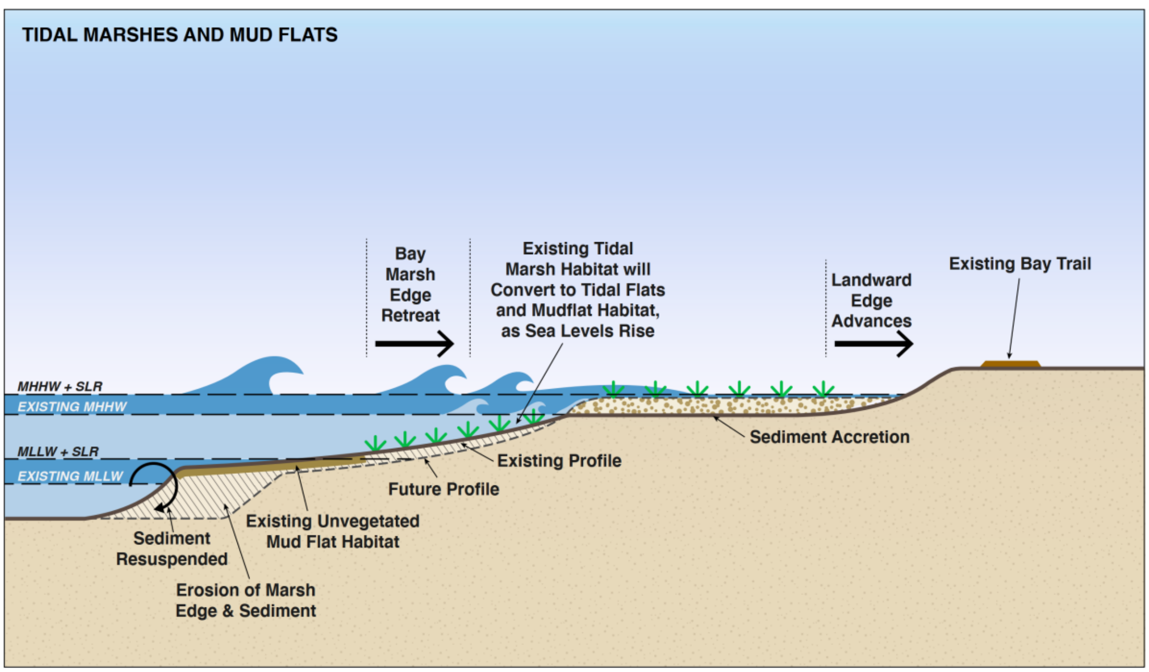
Taking an adaptive pathways approach to devising an adaptation strategy could look like maintaining proximity to the Bay over the near-term until a trigger point (e.g. higher amounts of sea-level rise) and aggregating resources and institutional capacity to pursue longer-term, large-scale adaptation actions (e.g., realignment, restoration). This approach requires building consensus around the long-term vision of the future Bay shoreline and surrounding land uses and identifying obstacles to achieving that vision.

4.2 Example Adaptation Actions for Shoreline Types

Based on the suitability and spatial requirements of different nature-based adaptation measures to the range of shoreline types found along the East Bay, ESA developed example adaptation cross-sections to show how specific measures might be implemented alongside trail elevation/re-alignment for a more resilient future condition. For comparison, profiles for the shore types under a no-action scenario are shown as well, in order to illustrate the intended benefit (e.g. flood protection, wave attenuation, enhanced ecology or other) that nature-based adaptation measures can provide. The adaptation action figures in this section are meant to represent an initial sketch of potential approaches that may be used at a certain shore segment; site-specific studies and analyses should and will inform engineering design.

4.2.1 Tidal Marsh and Mudflats

Tidal marsh and mudflat response to sea-level rise is dependent on local sediment supply. Fluvial/creek discharge and sediment eroded from the seaward edge are primary sources of sediment for marshes. Lack of adequate sediment supply under rising sea levels will result in conversion of existing tidal marsh habitat to tidal flats and mudflats and marsh edge retreat. Existing unvegetated mudflat habitat will convert to subtidal habitat. As the landward edge of tidal marsh advances, the existing Bay Trail alignment may be impacted; the loss of a marsh buffer may result in exposure of the trail to inundation (**Figure 18**).

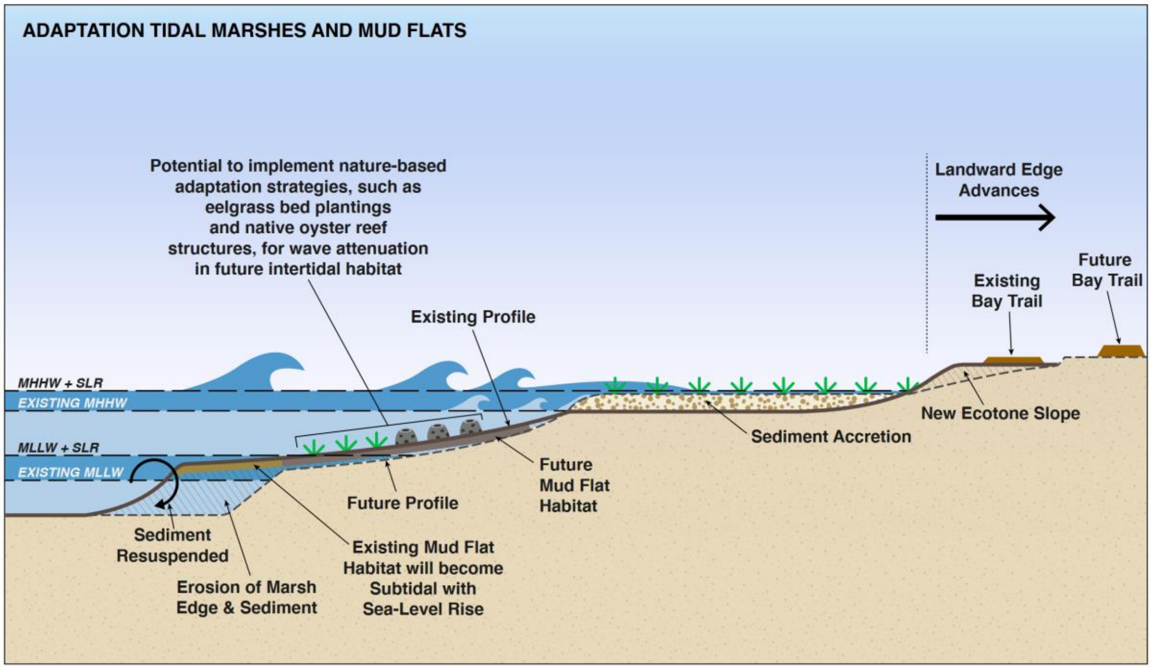


SOURCE: ESA

Bay Trail RAAPP / D201900102.00

Figure 18
No-Action Scenario for Tidal Marsh and Mudflat Habitats

Nature-based adaptation measures for tidal marsh and mudflat environments could include use of eelgrass plantings and oyster reef structures at the appropriate tidal elevation bands to provide wave attenuation and encourage sediment retention for tidal marsh (**Figure 19**). Where possible, landward assets (like the Trail) can be set back to create a wider buffer of future marsh habitat and decrease risk of being in the future flood zone. Transitions from wetlands to uplands elevations can incorporate horizontal levees, which are gently sloping, vegetated, ecotone slopes, that dissipate wave energy and provide room for habitats to transgress with sea-level rise.



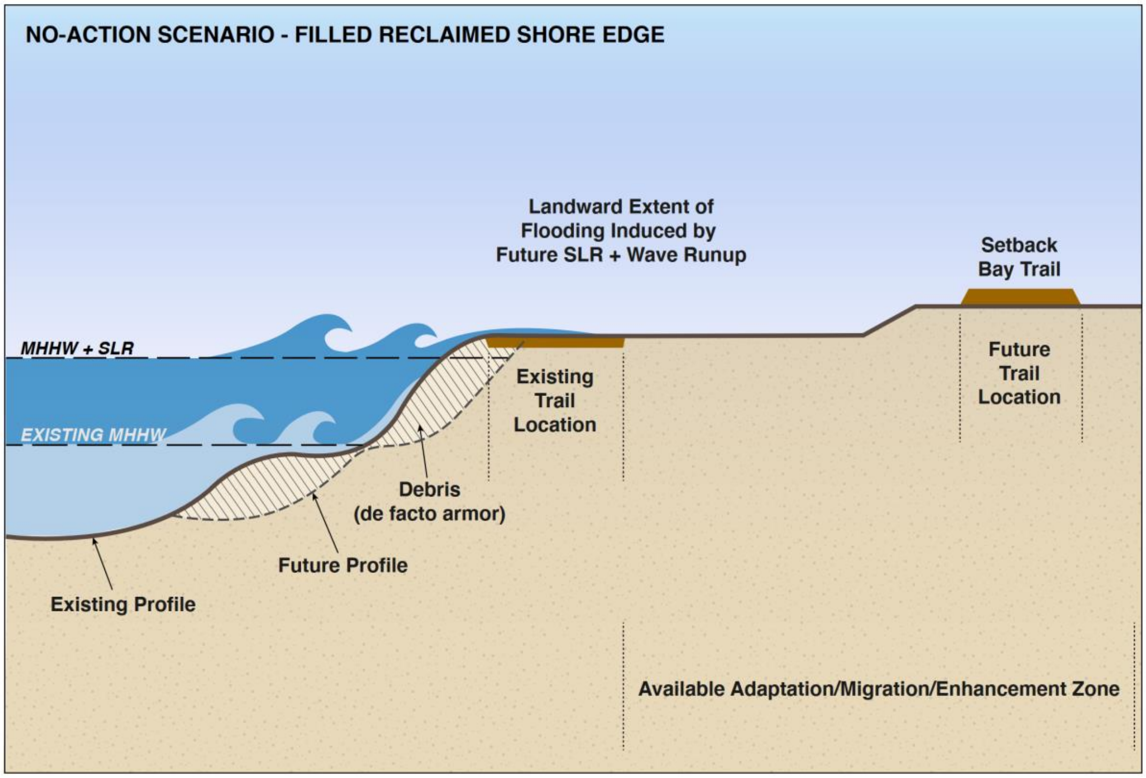
SOURCE: ESA

Bay Trail RAAPP / D201900102.00

Figure 19
Adaptation Measures for Tidal Marsh and Mudflat Habitats

4.2.2 Filled Reclaimed Shore Edge

Under a no-action scenario, filled reclaimed shore edges are vulnerable to inundation from future sea-level rise and wave runup. The existing Bay Trail, which may be located at the shore edge, would likely be impacted by this flooding. With no protection, the shore edge is predicted to erode away due to exposure to higher water levels and wave attack. The Bay Trail would likely have to be set back farther than the landward extent of flooding and elevated to avoid future impacts to accessibility.

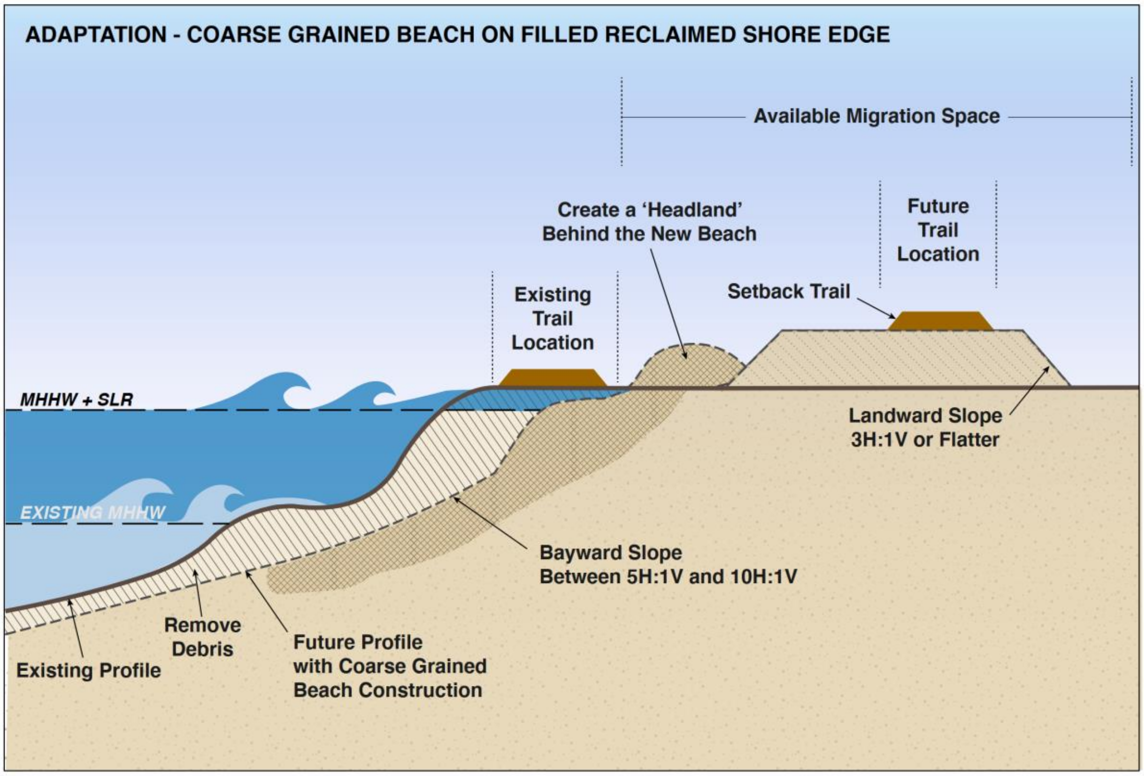


SOURCE: ESA

Bay Trail RAAPP / D201900102.00

Figure 20
No-Action Scenario for Filled Reclaimed Shore Edge

Potential adaptation actions for filled reclaimed shorelines could include construction of a new coarse-grained beach face at the water/land interface, which would minimize further erosion of the shore edge materials (e.g. fill, debris) into the Bay and provide flood protection for landward assets. The trail could be elevated by the new beach crest, allowing for closer access to the Bay. In a no-action scenario, the trail location would likely have to be set back in order to avoid flooding impacts.



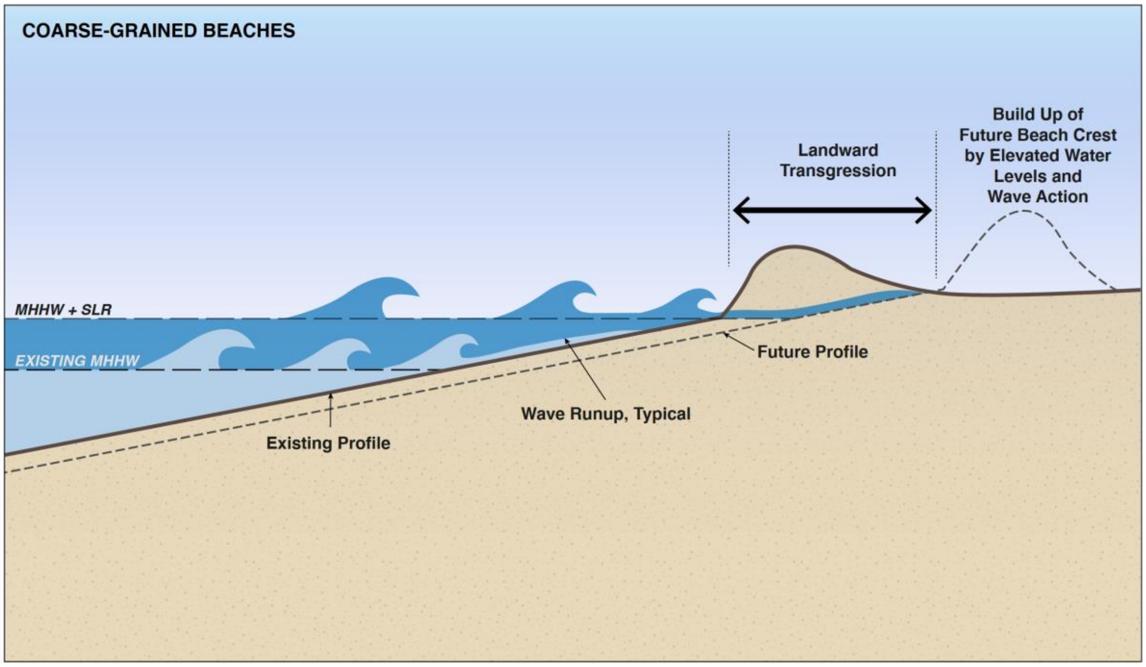
SOURCE: ESA

Bay Trail RAAPP / D201900102.00

Figure 21
Coarse-Grained Beach Adaptation on Filled Reclaimed Shore Edge

4.2.3 Coarse-Grained Beaches

Coarse-grained beaches are dynamic coastal landforms comprised of sand, gravel and/or cobble. Beaches include a supratidal beach berm, formed by wave deposition, and a beach face. As water levels increase, waves will break closer to the shore and the landward extent of wave deposition (which influences the berm location) will shift landward. Under a no-action scenario, if there is sufficient volume of beach sediment and space landward, the beach crest will increase in height (**Figure 22**).

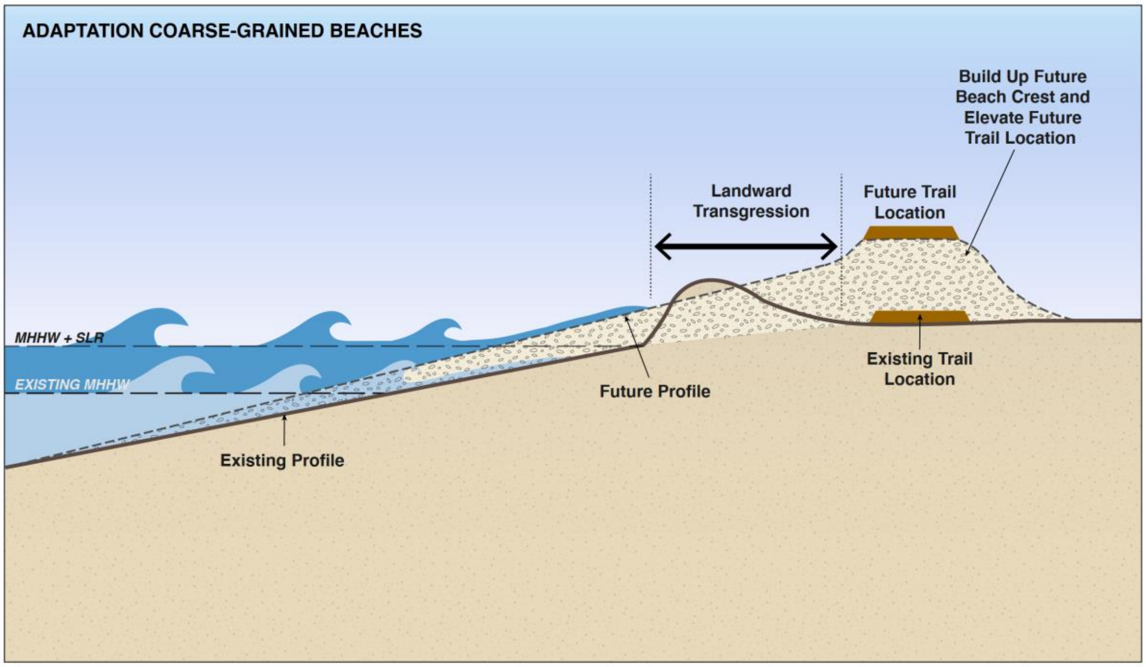


SOURCE: ESA

Bay Trail RAAPP / D201900102.00

Figure 22
No-Action Scenario for Existing Coarse-Grained Beach

Adaptation actions for an existing coarse-grained beach can include setting back to the trail to allow for landward transgression of the beach edge and nourishing the coarse grained sediment supply of the beach and elevating the trail on top of the future beach crest (**Figure 23**). Features such as large boulders or other natural groins found around coarse-grained beaches can help to limit alongshore drift and support sediment retention.



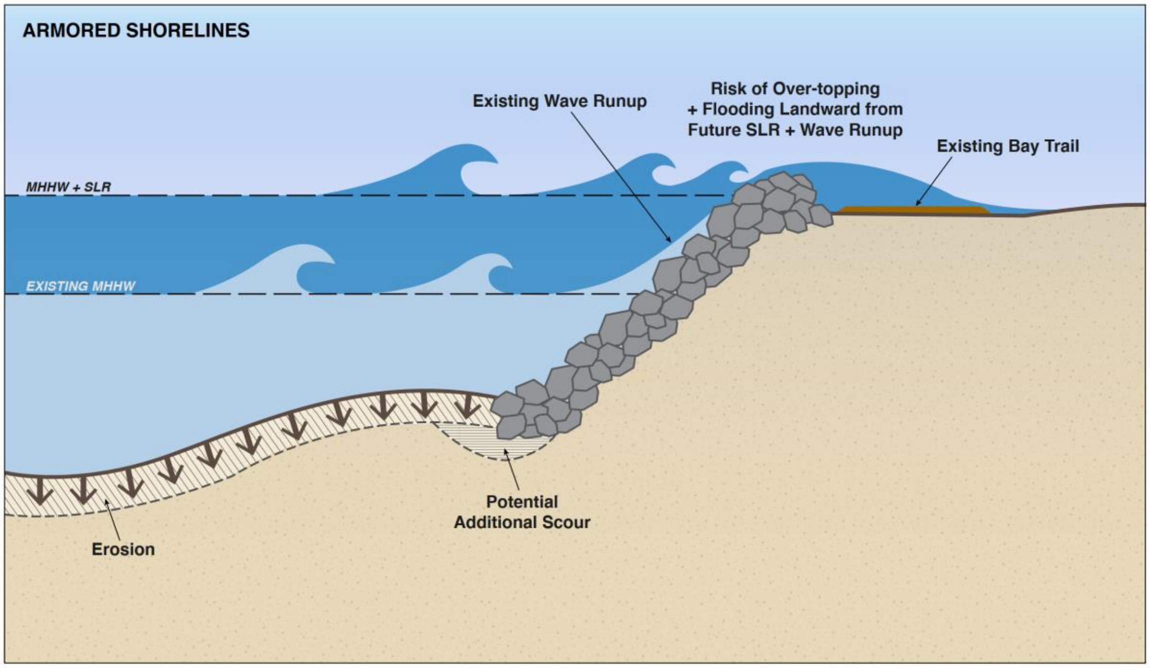
SOURCE: ESA

Bay Trail RAAPP / D201900102.00

Figure 23
Coarse-Grained Beach Adaptation on Filled Reclaimed Shore Edge

4.2.4 Armored Shorelines

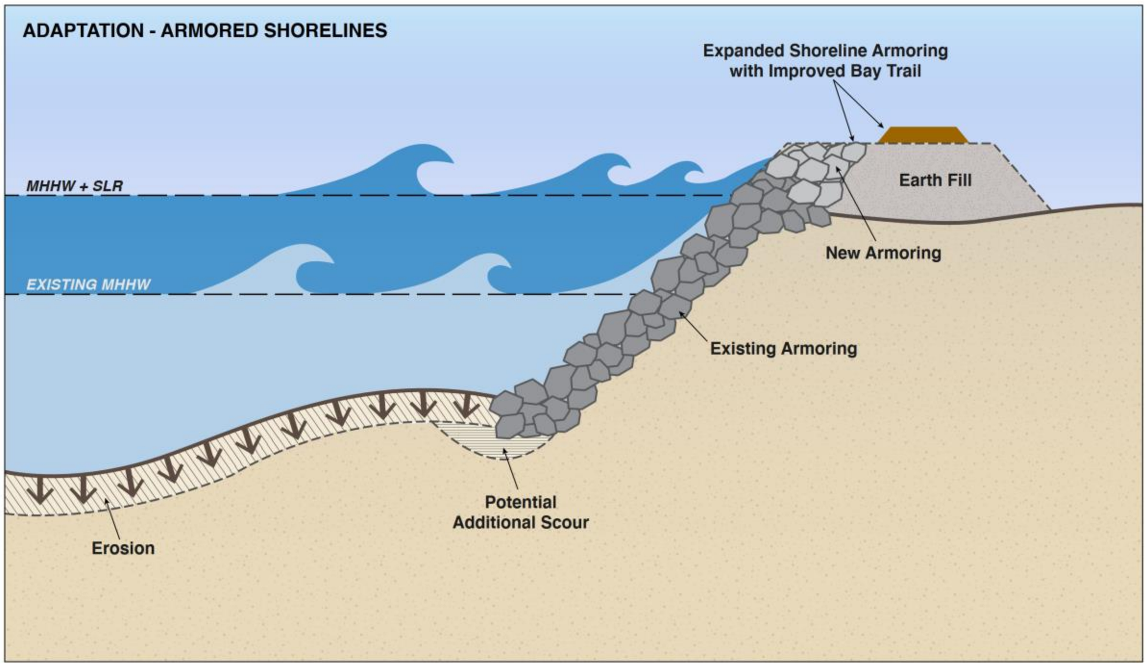
Armored shorelines are susceptible to failure (e.g. flooding of landward assets) via risk of overtopping of the structure crest from sea level rise and wave runup (**Figure 24**). Potential adaptation actions in the short-term may include constructing new armoring on top of the existing structure to keep pace with sea level rise (**Figure 25**). However, as the rate of sea levels increases in the latter part of the century, this may ultimately be a costlier and less effective solution.



SOURCE: ESA

Bay Trail RAAPP / D201900102.00

Figure 24
No-Action Scenario for Armored Shorelines



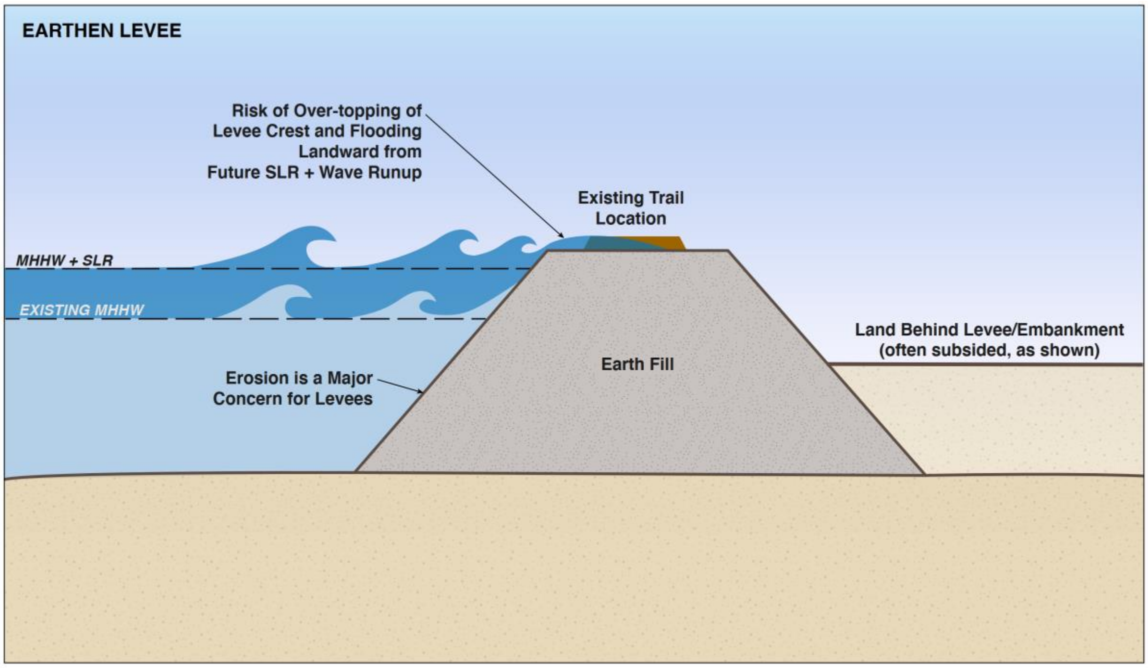
SOURCE: ESA

Bay Trail RAAPP / D201900102.00

Figure 25
Adaptation for Armored Shorelines

4.2.5 Earthen Levee/Embankment

Earthen levee/embankments typically protect subsided, lower-elevation land behind the structure. In parts of the East Bay shoreline where this shore type is present, the existing trail alignment is located on the crest of the levee/embankment. As sea levels rise, the levee may potentially be overtopped by elevated water levels and wave runup and assets located landward may be damaged by flooding. Additionally, erosion of the outboard side of the levee due to wave action is a concern (**Figure 26**).

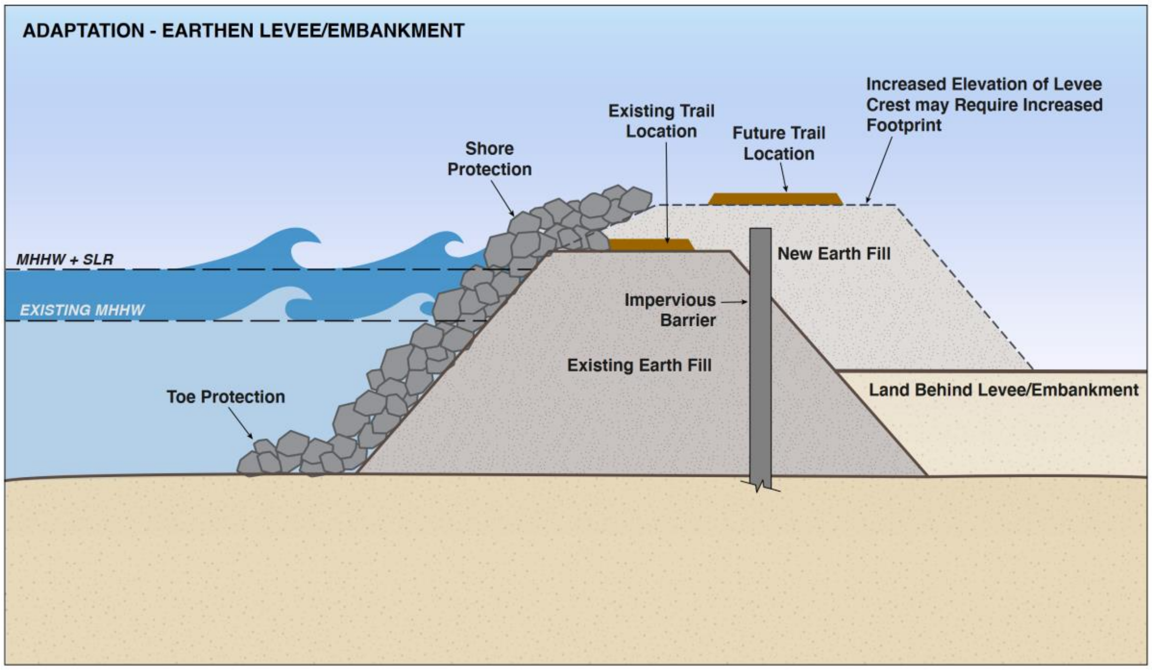


SOURCE: ESA

Bay Trail RAAPP / D201900102.00

Figure 26
No-Action Scenario for Earthen Levee/Embankment

Potential adaptation actions to preserve the trail and maintain protection for land/assets behind the levee may include adapting/retrofitting the existing structure by placing new earth fill with an increased crest elevation and footprint, with the trail location on top (**Figure 26**). If there is adequate space landward, the construction of a new earthen levee inland may be feasible. A horizontal levee approach, which entails the construction of a shallow slope on the bayward side of the existing embankment, is also another potential adaptation approach.



SOURCE: ESA

Bay Trail RAAPP / D201900102.00

Figure 27
Adaptation for Earthen Levee/Embankment

4.3 Setting

The built and natural setting for a shoreline unit heavily influences the characteristics, extent and scope of adaptation actions that can and should be taken. As described in Section 4.1, land use within the existing and future floodplain are factors in how flexibly the trail alignment can be shifted landward. Like physical and environmental processes (e.g. hydrology), the implications of a particular adaptation action are better understood when these characteristics are examined as part of a meaningful planning unit. Six distinct OLUs along the East Bay Shoreline are defined in the Adaptation Atlas (north to south): Pinole, Wildcat, Point Richmond, East Bay Crescent, San Lorenzo and San Leandro (see **Figure 3**). Some OLUs share similar characteristics due to geography, such as having naturally occurring bluffs, which may support opportunities to implement certain nature-based adaptation measures at a larger scale.

The following summarize the opportunities and constraints identified for each OLU:

Point Pinole OLU:

Opportunities

- Characterized by steep bluffs, narrow baylands, pocket marshes and beaches by shallow water with limited space
- Naturally occurring bluffs could provide a natural source of coarse material to support pocket beach sediment supply; coarse-grained beaches could be appropriate here
- Tidal and mudflat augmentation and nearshore reefs are potential opportunities in parallel with other adaptation measures
- Use of ecotone levees to provide high-tide refuge and transition zones behind pocket marshes

Constraints

- Existing railroad tracks front the majority of the Pinole shoreline, which provide flood protection. Under future sea-level rise conditions, re-location or elevating these tracks will be necessary.

Point Richmond OLU:

Opportunities

- Characterized by steep bluffs and pocket beaches
- Coarse-grained beaches could be used to front existing pocket marshes and railroad berms
- Nearshore oyster reefs and eelgrass beds are appropriate to implement in the vicinity of rocky intertidal habitat

Constraints

- Steep and narrow footprint constrains spatial extent of adaptation measures taken

Wildcat OLU:

Opportunities

- Characterized as wide baylands, urban centers with more available space

- Opportunity to use marshes as flood protection. Space available to implement other nature-based approaches.
- Coarse-grained beaches as well as creek connection to tidal baylands are appropriate nature-based adaptation measures here
- Ecotone levees can be used to create high-tide refugia and transition zones in locations where marshes are adjacent to development

Constraints

- This OLU has a high percentage of industrial and infrastructure land use, which may entail additional consideration around environmental contamination and removal.

East Bay Crescent OLU:

Opportunities

- Characterized as narrow baylands, urban centers with limited space
- Perimeter protection with grey or hybrid green/grey infrastructure
- Opening up floodable areas for water retention and reduce combined flooding
- Highways I-580/I-80 could be redesigned/elevated to a levee to provide upland flood protection
- Creeks draining in this OLU have been modified by culverting/channelizing; connections could be enhanced to direct sediment loads to support mudflats or beaches
- Coarse or composite beaches as alternative to riprap with use of natural, artificial headlands
- Existing marsh areas could be enhanced with ecotone or horizontal levees

Constraints

- Limited opportunities for migration space preparation due to urban density
- Constrained present-day marshes due to presence of existing highway corridors (not going to move)
- Opportunity to enhance isolated marsh habitat along MLK Jr. Regional Shoreline – critical habitat for endangered species.

San Lorenzo OLU:

Opportunities

- High potential for marsh restoration and use of levee ecotones (tidal benches) in between development and the Bay by Roberts Landing, Oro Loma and Cogswell Marshes.
- Some limited areas for potential marsh migration space and connectivity; could be acquired or protected to secure space.
- Coarse beaches and eelgrass beds identified as suitable along the shoreline and in the northern part of the OLU

Constraints

- Significant amount of housing and workplaces in this OLU; may be costly to protect-in-place.

San Leandro OLU:

Opportunities

- Coarse grained beaches can buffer wave energy and soften shorelines for habitat and recreation. Could be combined with groins and beach nourishment.
- Opportunities for nature-based areas mostly concentrated at shoreline or in subtidal areas (eelgrass beds or other SAV approaches suitable)

Constraints

- Limited open space, so retreat/migration space preparation is not as feasible
- Limited space for ecotone levees.
- Long-term SLR will result in risk everywhere for this OLU; industrial and residential land use over fill and rising groundwater table.

The above summary of opportunities and constraints by OLU show that the existing trail alignment is located along diverse shore types and backed by a panoply of land use, the evolution of which will heavily influence what adaptation actions can feasibly be taken. In their present condition, urban, developed areas (East Bay Crescent, San Lorenzo and San Leandro OLUs) have minimal space landward of the Bay Trail to accommodate a wider array of adaptation measures in the long-term. Assuming that the edge of developed areas will not shift in the future, any adaptation action taken would need to occur bayward of the trail. This effectively precludes a number of nature-based adaptation measures which may have greater lateral space requirements and may inadvertently increase the use of traditional engineered structures as a short-term solution. As described previously in the document, the latter are linked with higher potential for catastrophic failure and poor ecological outcomes. Sea-level rise is anticipated to increase exponentially in the late century, making adaptation via grey infrastructure much costlier to re-design and difficult to recover from, if structural failure to occur.

4.4 Methodology for Developing Adaptation Strategy

In the context of this study, an adaptation strategy for the Bay Trail is composed of multiple nature-based adaptation measures, the design and placement of which are informed by the setting, shore type and available space. The methodology presented in this section is meant to guide preliminary planning-level processes. Ultimately, site-specific information is necessary and critical to refine design and develop a clear picture of anticipated project opportunities and constraints.

Coastal Floodplain: A major component in developing an adaptation strategy for the Bay Trail is determining the trail location laterally and vertically for the existing and future shorelines. This entails:

1. Evaluating the future location of the shoreline for a range of sea-level rise scenarios and accounting for the processes of wave runup and erosion, and

2. Determining the lateral and vertical placement of the trail, relative to that future shoreline and water levels, such that the trail criteria (Section 2.3) are satisfied.

As sea levels rise and the existing conditions of the shoreline change, the definition of coastal hazard zones will shift as well.

The coastal floodplain is defined by the landward extent of tidal inundation and wave runup / overtopping for a particular risk level. The Federal Emergency Management Agency (FEMA) uses the 1% annual exceedance level event, also known as the 100-year event. Hence, FEMA coastal flood maps provide a panning-level estimate of the coastal flood plain. It should be noted, however, that FEMA does not include coastal erosion or sea-level rise, both of which result in a landward movement of the coastal flood plain with time (Battalio et al. 2016). Another source is the Adapting to Rising Tides (ART) Bay Shoreline Flood Explorer, which provides maps of future flooding with sea-level rise. Please note that these ART maps do not include wave runup and hence can under-predict the existing flood plain extents. Also, these maps do not include erosion but rather a static landscape. Therefore, additional effort is required to identified the existing coastal floodplain.

To determine a rough approximation of the future floodplain, the District or other project sponsors could start with the FEMA flood map information for the distinct East Bay shoreline segments and apply guidance outlined in the Technical Methods Manual (TMM) for select sea-level rise amounts (Battalio et al., 2016). The TMM documents methods for adjusting FEMA coastal flood maps to account for increased sea levels associated with climate change. Users can evaluate future total water levels and landward extents of wave runup. Flooding induced by wave runup is assumed to be a rough proxy for the minimum lateral space needed for adaptation. As additional planning tools become available, it would also be appropriate to use future coastal hazard planning resources which account for the processes of wave runup and erosion.

Having established the spatial extents at risk from future flooding from wave runup and erosion, appropriate nature-based adaptation measures for that shoreline unit can be assessed on 1) the relative capacity to mitigate those hazards, so that the space requirement to move inland is reduced and 2) the space requirement of the adaptation measure itself (e.g. the “footprint”). The design process should evaluate the extent and effectiveness of each nature-based adaptation measure to provide direct blockage of inundation and/or wave energy dissipation, which can decrease flooding via wave runup and reduce erosion by shifting the location of breaking waves farther from shore. Previous studies have shown that one hundred feet of tidal marsh can dissipate most waves, except at high tides (Bay Institute 2013). Additionally, the adaptive capacity of nature-based approaches to sea-level rise should be considered in its design lifetime and how this relates to the larger adaptation strategy. Compared to a traditional engineered structure, natural shoreline infrastructure has inherent vertical capacity to accommodate higher water levels. For example, a coarse-grained beach implemented in the appropriate setting could provide protective function for future conditions with 2 to 3 feet of sea-level rise, if there were space behind the beach to move upwards and inwards.

Where to locate the Bay Trail can also be informed by considering the levels and frequency of inundation and velocity water movement that can be accommodated. For example, it may be acceptable for the trail to be inundated occasionally, perhaps no more than once per year. With consideration of future sea-levels, siting the trail above and landward of the 100-year coastal floodplain will provide the capacity to accommodate some future sea-level rise before the trail is subject to the more frequent inundation (e.g., annual inundation). The threshold can be used to estimate the functional “life” of the trail, at which time additional adaptive actions are likely to be necessary to maintain trail functions. This concept of functional life can be also thought of as the trail’s adaptive capacity, and can be expressed in terms of “vertical capacity”, which is the amount of sea-level rise that can be accommodated.

There are guidance documents that indicate the water depth and water movement velocity for pedestrian safety. A higher threshold of trail damage can also be established. This is still an approximate and developing area of practice, likely because public safety is a sensitive issue for design professionals, government agencies and their insurance providers. Still, informed judgments are likely better than implicit judgments or uninformed, unclear decisions. An example of application of available guidance can be found in an analysis for the Humboldt Bay South Trail (ESA 2018).

As outlined in Section 4.1, the alongshore and cross-shore geometry of a nature-based adaptation measure can be related to the local water levels and physical processes. For example, the crest elevation of a coarse-grained berm can be approximated as a percentage of the total water level (TWL). The total water level can be calculated based on site-specific tidal, wave and planform information. It should be noted that tides and waves are variable throughout the Bay (see Section 2); the Blueprint, which was developed as part of the ESA and The Nature Conservancy’s Natural Shoreline Infrastructure Technical Guidance, can be used as a resource for applying these parameters to estimating space requirements for natural infrastructure (Newkirk et al., 2018).

The Bay Trail spans a diverse range of shore types along the East Bay. What may work for one segment of the Trail may not be applicable elsewhere or may shift as we approach mid-century. Buffering with public open space with minimal realignment may be viable for certain stretches of the trail up to a particular trigger point (e.g. water elevation), after which a larger degree of realignment will be necessary due to greater extents of inland flooding. The location of the shoreline and coastal hazards will be different with the increment of sea-level rise (e.g. +3 feet, +6 feet). The process outlined for developing an adaptation strategy will likely be iterative, given the unique nature of the Bay Trail as an asset that derives its value from (and is at risk because of) its proximity to the shore.

4.5 Lessons Learned from Case Studies

The RAAPP team (Team) investigated the exposure of the Bay Trail, and identified vulnerable sections. The Team has also selected several sections for early planning “Case Studies”. Lessons learned pertinent to coastal hazards and Bay Trail siting are used and discussed to further develop adaptation guidance.

- Sea-level rise planning and adaptation is a relatively new aspect of land use planning – tested and successful institutional frameworks and capacity to tackle issues and address range of implications are still being developed.

- Multiple physical, spatial, jurisdictional and stakeholder considerations inform existing and future use of the shore

- How should public access, ecology and habitat evolution, aesthetics and current and future site constraints be prioritized with coastal hazard mitigation?
  - Should we focus our attention on “here and now” issues (e.g. use benefitting community members or limiting habitat impacts today) or evaluate and forecast future scenarios to drive a configuration that would benefit multiple functions (flood, community, habitat, etc.) in the long-term, given the uncertainty around what the future may look like?
  - Consideration of opportunity costs in planning and decision-making: costs now vs costs later
  - How should we factor in uncertainty around the effectiveness of solutions, nature-based or otherwise, into the future?
- Closer examination of pilot sites at Alameda Point, Doolittle Drive and Schoolhouse Creek – Eastshore State Park demonstrate that there can be a range of factors such as unanticipated and unresolved stakeholder priorities and/or constraints including projected habitat transgression/evolution along the shoreline that highlight the need for proactive and collaborative processes. Develop planning frameworks to outline shared and well defined goals and objectives, consistent planning criteria and data, study methods and analyses including sea level rise projections, wave runup and total water level estimates.

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5 CONCLUSIONS & RECOMMENDATIONS

This broad adaptation guidance document is a first step towards establishing a synoptic and integrated perspective towards adapting the Bay Trail along the East Bay shore to future sea-level rise conditions. This report describes the environmental setting and relevant physical processes that shape the coastal and hydrologic climate by the East Bay shore (Section 2) and introduces a conceptual model of shore response to sea-level rise for the range of existing shore types (Section 3). Applying a framework towards understanding the structural and functional response of shore environments to major drivers, such as sea-level rise, allows us to better define site-specific issues and identify opportunities for adaptation actions. Nature-based adaptation measures are correlated with positive ecological outcomes and can offer a range of co-benefits (e.g. flood protection, aesthetics, recreation) that are compatible with the Bay Trail adaptation effort. Specific adaptation measures for each shore type are introduced and discussed within the report and the reader is referred to other relevant technical guidance and considerations related to their design and implementation.

The focus of this document has been on landscape-based features and processes and how these factor into appropriate adaptation measures and strategy. Section 4 discusses types of adaptation strategies and presents a framework for relating local, physical parameters related to tides and wave climate to the design of nature-based measures that are implemented as part of a larger scheme. Due to the urbanized nature of the study area, it should be noted that these are but a single category of considerations when applying these methodologies. Other major considerations that have not been discussed at length in this report include non-structural (policy) strategies and perspectives on adaptation from adjacent land users and owners that may impact the overall adaptation strategy. The issue of creating available adaptation space under future conditions is particularly pertinent for the East Bay shoreline, as 1) historical development has encouraged the human footprint to expand up to the existing shore edge on the landward side which limits the space for the trail and setback of built assets and property, and 2) building into the Bay also entails a number of design challenges, as well as environmental and regulatory considerations.

A regional approach to shoreline adaptation entails coordination, planning and meaningful action by a number of stakeholders, who may historically have competed for the same space, access and resources. This guidance document examines and proposes a methodology that applies best available science and planning perspectives to adapting the Bay Trail along the East Bay shoreline using nature-based adaptation measures. When applied in appropriate settings, nature-based solutions can shift the structural and functional response of the shoreline to sea-level rise and offer a number of co-benefits (e.g. flood protection, enhanced habitat, access, aesthetics). While the space requirements and initial implementation cost of living shorelines may be greater than that of traditional engineered approaches, studies have shown that in the long-term, they outperform the latter, exhibit higher resilience, and are cost-efficient.

The creation of space for the Bay Trail under existing and future conditions should be viewed as a pre-requisite for a cohesive and robust regional adaptation strategy to sea-level rise. If landward space for adaptation is to be created, the edge of future developed areas should be located away from the future floodplain; otherwise, competing short-term land use objectives reduce the opportunity for regional adaptation. The design and implementation of nature-based solutions are inherently place-based, which contribute to the complexity of devising a large-scale approach, but we can quantify the space requirements to inform planning. Where space is limited due to overwhelming constraints, hybrid approaches that blend nature-based adaptation measures with traditional engineered approaches may be functional and provide a reasonable balance of multiple objectives, including coastal resources. Building upon these landscape-based and regional adaptation tools for the Bay Area and technical understanding of flooding and wave hazards, this document represents one of the first steps in the process of re-envisioning the future Bay Trail and East Bay shoreline.

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Appendix A
Map of District Bay Trail Segments

Appendix A: Map of EBRPD Bay Trail Segments