SAN FRANCISCO BAY SHORELINE Adaptation Atlas

Working with Nature to Plan for Sea Level Rise Using Operational Landscape Units

SFEI San Francisco Estuary Institute

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SAN FRANCISCO BAY SHORELINE Adaptation Atlas

Working with Nature to Plan for Sea Level Rise

USING OPERATIONAL LANDSCAPE UNITS

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San Mateo County shoreline near Foster City (courtesy of Google Earth)

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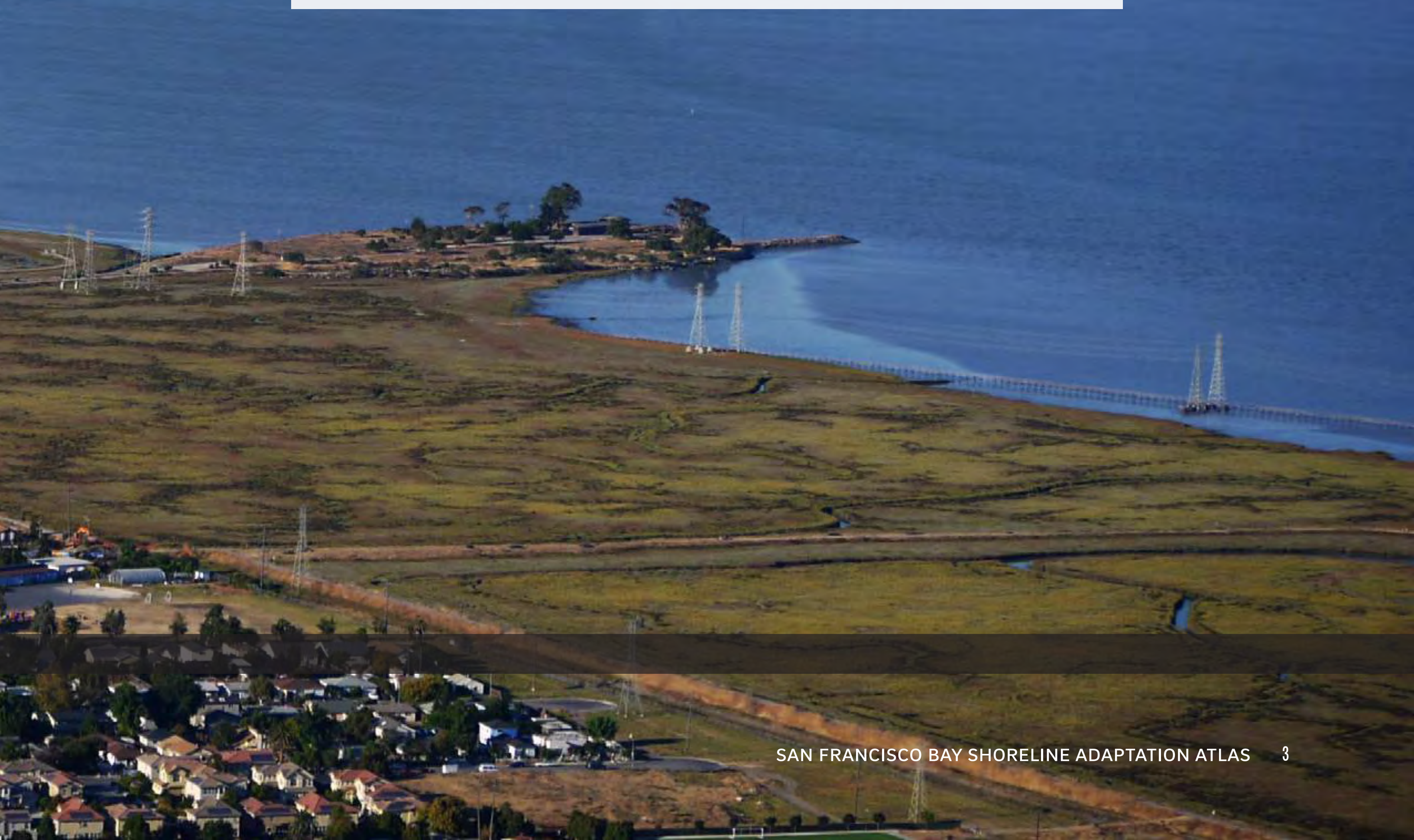
CONTENTS

AERIAL VIEW OF EAST PALO ALTO AND COOLEY LANDING LOOKING TOWARDS DUMBARTON BRIDGE • PHOTO BY CRAIG HOWELL (CC BY 2.0)

EXECUTIVE SUMMARY

As the climate continues to change, San Francisco Bay shoreline communities will need to adapt in order to build social and ecological resilience to rising sea levels. Given the complex and varied nature of the Bay shore, a science-based framework is essential to identify effective adaptation strategies that are appropriate for their particular settings and that take advantage of natural processes. This report proposes such a framework—*Operational Landscape Units* for San Francisco Bay.



Operational Landscape Units (OLUs) are a practical way to manage the physical and jurisdictional complexity of the Bay shoreline. Home to airports, landfills, marinas, wetlands, beaches, ports, residential neighborhoods, and more, San Francisco Bay's 650 km (400 mi) shoreline is diverse, which means there is no one-size-fits-all solution to rising sea levels. The framework provided in this report divides the Bay shoreline into 30 OLUs—connected geographic areas that share common physical characteristics and that would accordingly benefit from being managed as individual units. OLUs cross traditional jurisdictional boundaries of cities and counties, but adhere to the boundaries of natural processes like tides, waves, and sediment movement. Taken as a whole, OLUs span the entire Bay shoreline, cover that portion of the region's land area potentially vulnerable to future sea level rise (SLR), and encompass areas along and adjacent to the shore for which geographically specific and science-based sea level rise adaptation strategies can be developed.

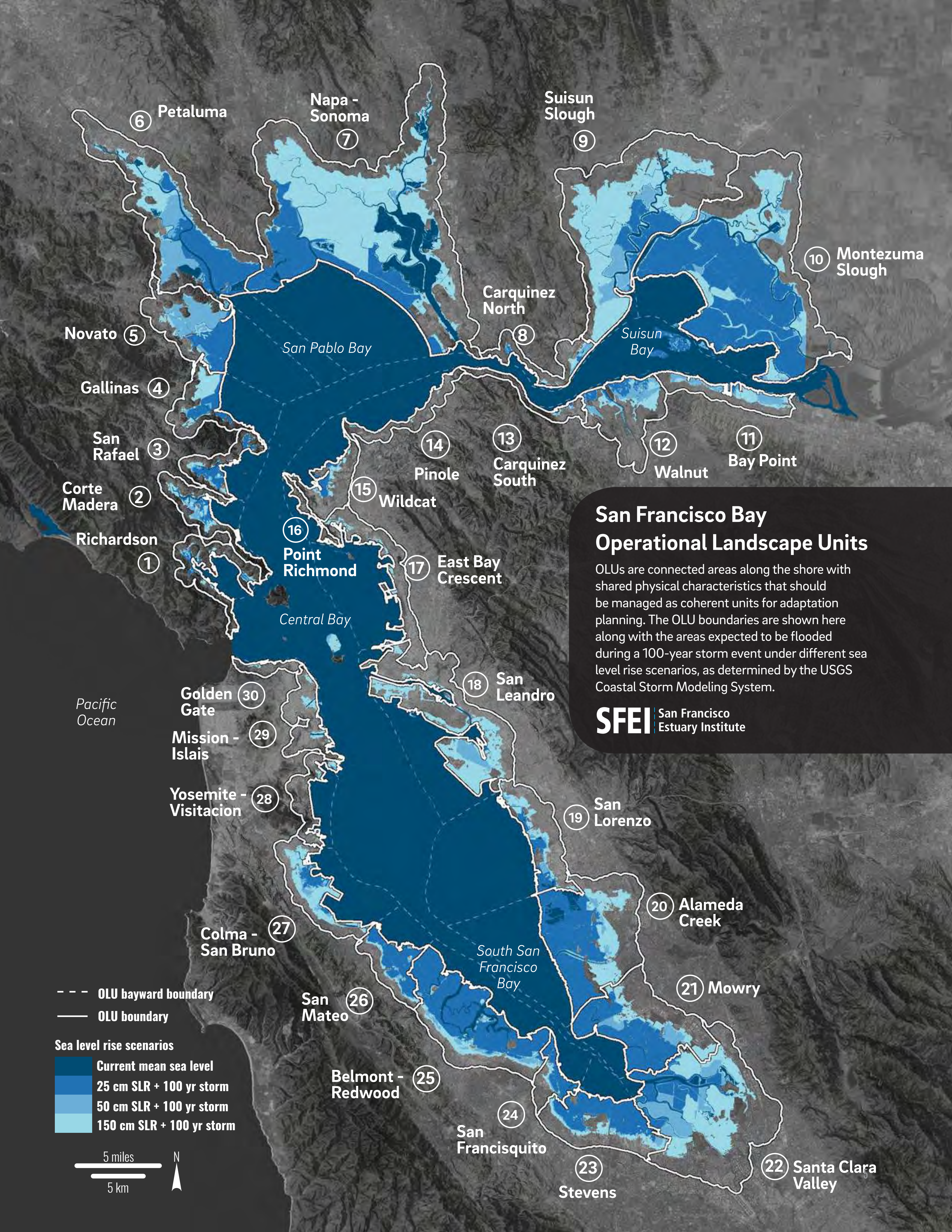
There are many activities currently underway to modify the Bay shore in ways that improve flood resilience, restore ecological systems, increase recreational access, and provide other ecosystem services. Many of these efforts have been, and continue to be, crucially important to establishing safer and stronger communities, and to restoring the Bay's health. This report supports these endeavors by locating them within the landscape areas they benefit and by providing information about key processes (like sea level rise) that could impact their resilience over the long term.

A key purpose of the OLU framework is to identify where nature-based approaches, such as beaches, marshes, and subtidal reefs, can help create a resilient shoreline with multiple benefits. Nature-based approaches, and hybrid measures that integrate nature with engineered structural approaches, may perform better than traditional engineered infrastructure alone. They can also cost less over time and provide important co-benefits like new recreational opportunities and habitat for native species. Adaptation in each OLU will most likely require a combination of nature-based measures, traditional engineering, and non-structural or policy strategies.

In the past, different locales have generally pursued shoreline planning separately, yet this approach does not confer the greatest value or benefits. Those involved in these planning processes must remember that the Bay is an interconnected physical system. Though it is locally diverse, it is fundamentally linked: the way all parts of the Bay collectively respond to the threat of sea level rise will determine the Bay's long-term health and fate. OLUs provide a critical planning framework for prioritizing appropriate nature-based solutions that work together in synergy, which can help to avoid unintended impacts in neighboring locales. This framework can help ensure that future adaptation actions are sustainable and confer the most benefits per dollar spent.

This report presents information about how OLUs were developed and how they might be applied. The following pages summarize this content, chapter by chapter. These summaries begin with Chapter 2 (Chapter 1 is an introduction to the overall concept of OLUs).


KING TIDE AT FORT POINT • PHOTO BY SHIRA BEZALEL, SFEI



San Francisco Bay Operational Landscape Units

OLUs are connected areas along the shore with shared physical characteristics that should be managed as coherent units for adaptation planning. The OLU boundaries are shown here along with the areas expected to be flooded during a 100-year storm event under different sea level rise scenarios, as determined by the USGS Coastal Storm Modeling System.

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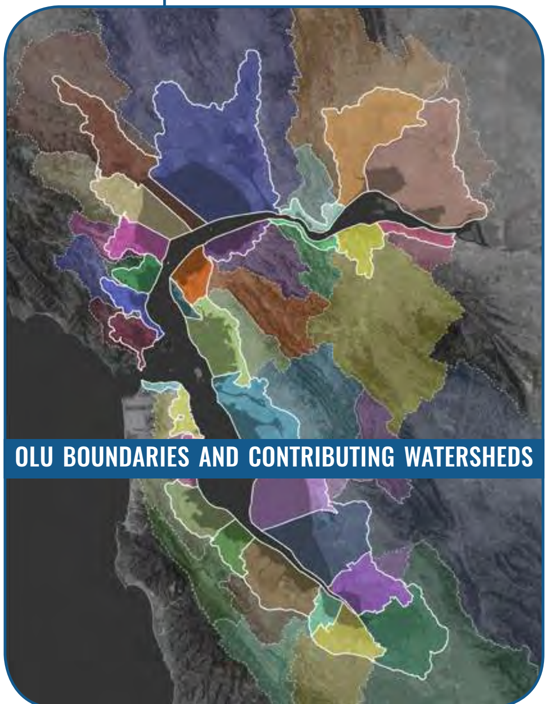
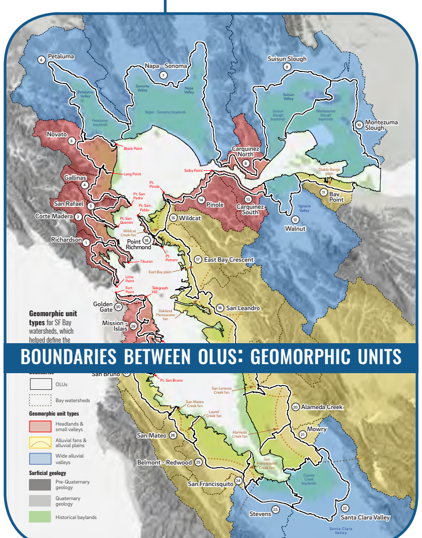
Chapter 2

Delineating OLU boundaries

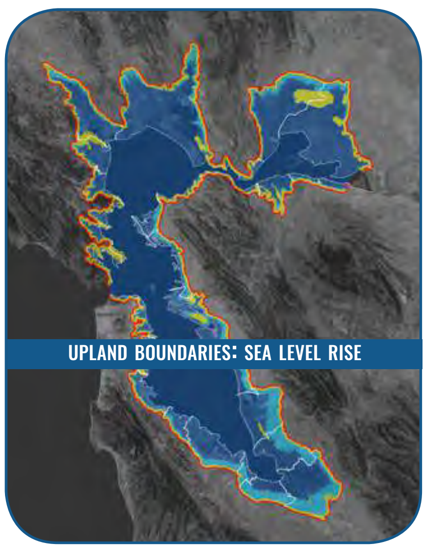


OLU BOUNDARIES AND CONTRIBUTING WATERSHEDS

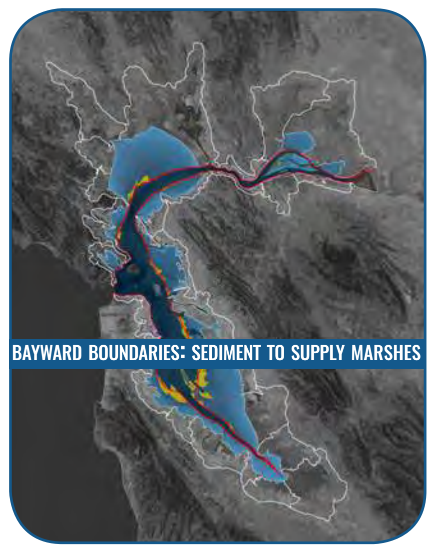
Physical landscape conditions set the boundaries around each of the 30 San Francisco Baylands OLUs—on the upland side, the bay side, and between OLUs. The area established for each OLU is meant to include most areas potentially subject to the geomorphic, hydrologic, and ecological effects of sea level rise over a relatively long horizon (100–150 years), while also including watershed and Bay processes to the extent possible. Each unit is large enough to encompass the major physical and ecological processes that determine adaptation possibilities along the shoreline, yet small enough for people to organize around and effectively manage.



BOUNDARIES BETWEEN OLUS: GEOMORPHIC UNITS



UPLAND BOUNDARIES: SEA LEVEL RISE



BAYWARD BOUNDARIES: SEDIMENT TO SUPPLY MARSHES

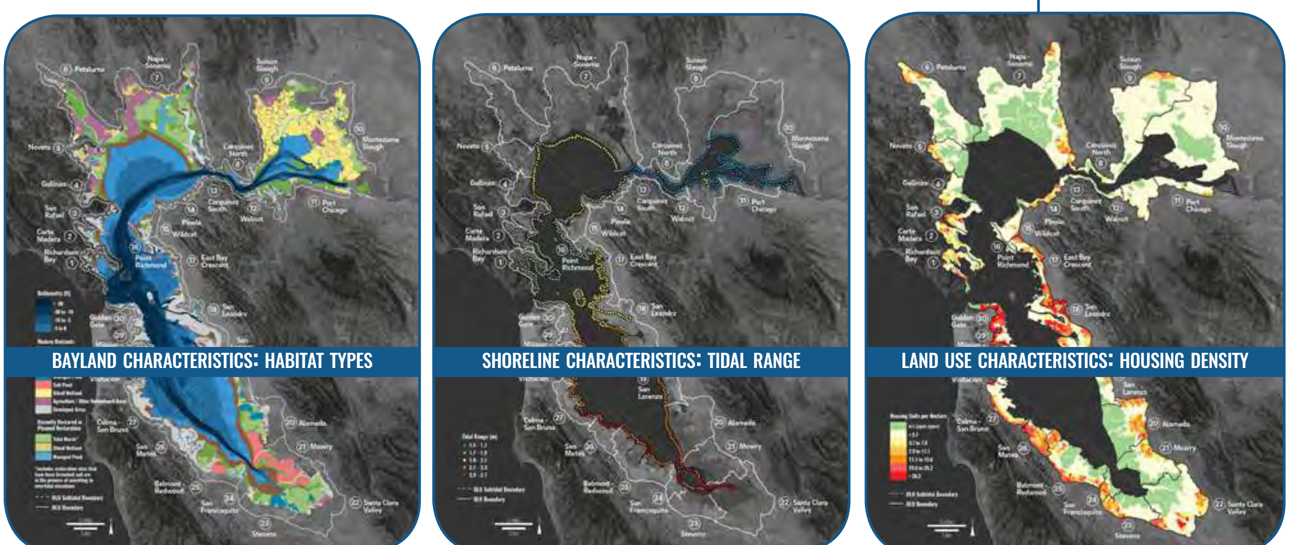
OLU boundaries around the Bay. The boundaries between OLUs are based on **geomorphic units** (i.e., the basic characteristics of the physical landscape and watershed boundaries); the **upland boundaries** of the OLUs are based on an extreme sea level rise scenario; and the **bayward boundaries** of the OLUs are based on where wind-driven waves are capable of resuspending fine sediment that can then supply sediment to marshes and mudflats in intertidal parts of the OLUs.

Chapter 3

Characterizing the OLUs

Each OLU is characterized by numerous factors that range from natural physical and ecological gradients to patterns within the built environment. In this chapter we present many types of spatial data, from elevation and the orientation of contributing watersheds, to habitat types and infrastructure—capturing the impacts of modifications, land uses, and impending vulnerabilities from climate change. The maps shown in this chapter lay the data-driven foundation that supports subsequent qualitative and quantitative analyses. We also discuss the limitations of existing data and identify notable data gaps.

The OLU Typology (Appendix 4) identifies fundamental similarities and differences between OLUs on a regional level. The typology aids an understanding of how stretches of shoreline in different parts of the Bay are similar in character, may have similar problems, and thus might support similar types of sea level rise adaptation measures.



Three examples of layers used to characterize the OLUs. The many types of data used to characterize the OLUs were grouped into broad categories: geomorphic setting, bayland characteristics, shoreline characteristics, land use characteristics, and exposure to sea level rise.

Chapter 4

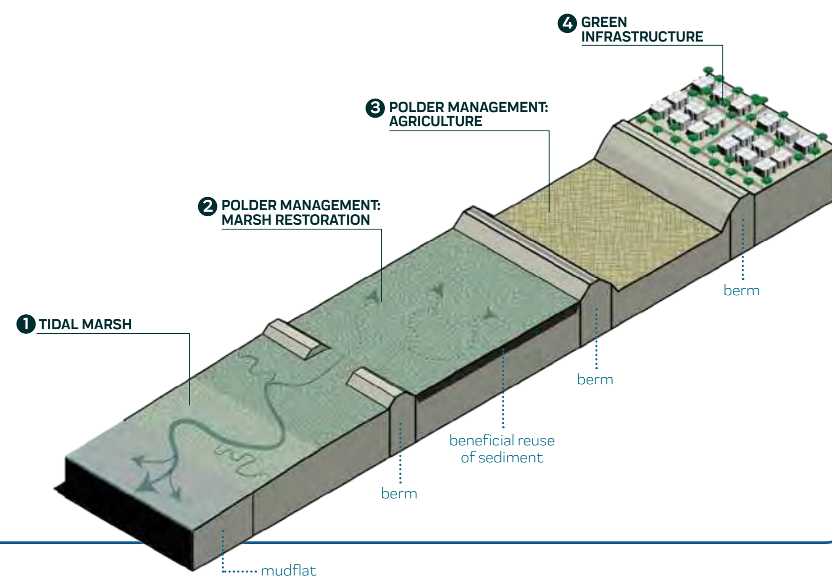
Adaptation measures

Adaptation measures are specific interventions or ways to manage the shoreline, flooding, and sea level rise. They can be combined and implemented over time in a planned sequence (or "pathway") that is appropriate to the landscape setting and, over time, helps to manage and reduce various coastal risks, including erosion, fluvial flooding, sea level rise, and combined (fluvial and tidal) flooding. This chapter defines and describes more than two dozen adaptation measures that are potentially appropriate to the Bay's OLUs (when combined strategically and implemented over time). Four categories of adaptation measures are explored:

- **Nature-based measures:** physical landscape features that are created and evolve over time through the actions of environmental processes operating in nature (or features that mimic characteristics of natural features but are created by human design, engineering, and construction in concert with natural processes) to provide coastal protection and other ecosystem services
- **Grey infrastructure:** physical conventional infrastructure (such as levees and seawalls) built by humans for coastal protection with minimal concern for the provision of other ecosystem services
- **Policy and regulatory measures:** non-physical ways of influencing future land use and the built environment to manage risk
- **Financial measures:** non-physical ways of creating incentives and disincentives to enable implementation of other structural and policy measures

The list of measures is not exhaustive, but it is meant to describe many of our region's options and to explore their suitability under different land use, shoreline, and offshore conditions. This chapter also includes detailed maps of where several nature-based adaptation measures are suitable within the region.

Conceptual diagram of integrated adaptation measures. In this conceptual example, a tidal marsh fronts a breached polder (diked historical tidal wetlands in this case), which is in the process of accreting to marsh elevation through both beneficial reuse of sediment and increased tidal action. The polder landward of the accreting polder remains in agricultural production. Behind the flood risk levee, green infrastructure is helpful for spreading, sinking, and slowing runoff.

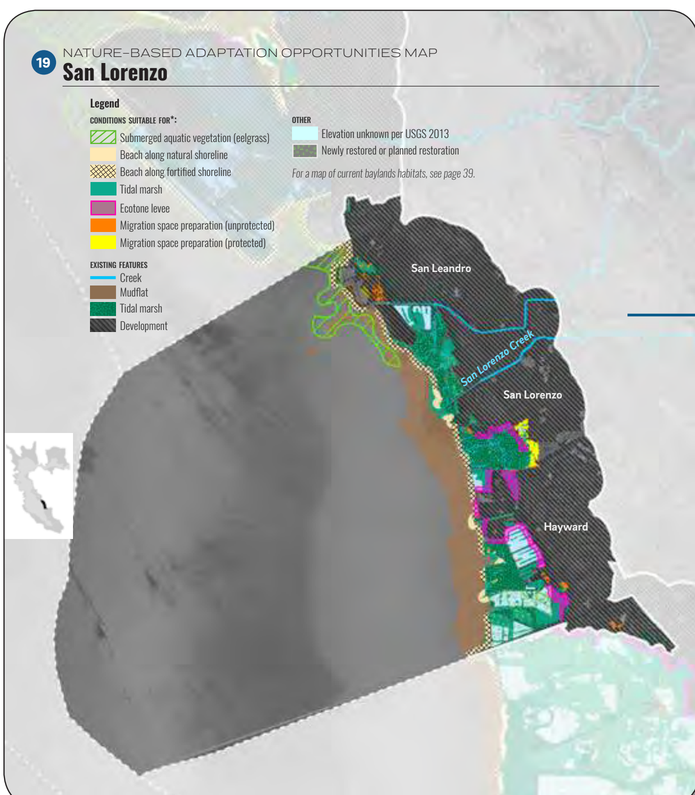


Adaptation opportunities by OLU

This chapter synthesizes information described in the preceding chapters and discusses the findings OLU by OLU. For each of the 30 OLUs, this chapter presents:

- An opportunity map, displaying the results of the nature-based adaptation measure suitability analyses
- A discussion of the suitability of each measure in the context of ongoing adaptation and restoration progress and regional ecological goals
- A discussion of policy, regulatory, and financial adaptation approaches that may be suitable based on an analysis of land use place types.

The opportunity maps do not constitute an adaptation plan, and should not be interpreted as such. The maps and accompanying materials should instead be considered tools to use during adaptation planning processes; they provide background on the suitability of nature-based measures and policy and regulatory tools under current conditions. The suitability of different combinations of measures will need to be tested, monitored, and reevaluated as new information is gained and conditions on the ground continue to evolve. In the OLU opportunity maps, strategies discussed for a specific OLU are those that our analyses suggest might be especially well-suited to the OLU given its landscape conditions.



Suitability of natural and nature-based measures in the San Lorenzo OLU. (Left) Example OLU opportunity map highlighting locations with conditions suitable for many nature-based measures. (Below) Suitability ratings accompany each opportunity map.

	Selected Measures	Suitability
NATURE-BASED	Nearshore reefs	Limited suitability
	Submerged aquatic vegetation	High suitability
	Beaches	High suitability
	Tidal marshes	High suitability
	Polder management	Some suitability
	Ecotone levees	High suitability
	Migration space preparation	Some suitability

Limited suitability · Some suitability · High suitability

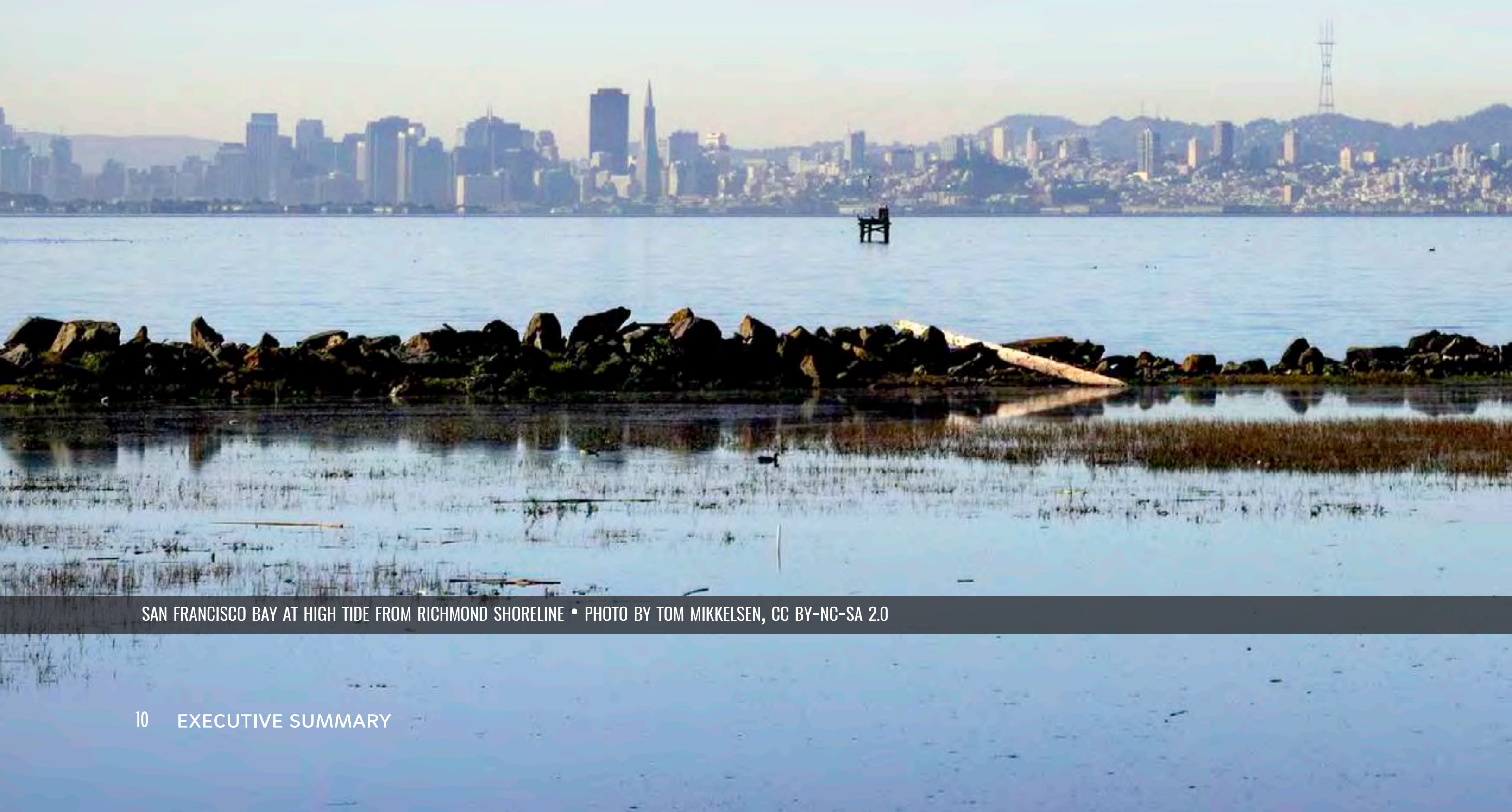
RESOURCES IN THE REPORT

This report is designed as an input for planning processes that affect places near the shoreline, including those related to flood control, transportation, parks, land use, and ecosystem restoration. Adaptation planning will involve pairing the information here with vulnerability assessments, public/stakeholder engagement to help identify favorable options, and ultimately site-specific engineering and feasibility analyses to identify the viability and costs of adaptation options. Information included in this report may also be useful in creating vulnerability and feasibility studies, but is not a substitute for them.

We hope this work can further local and regional discussions around sea level rise adaptation and climate change in several ways:

The OLU framework encourages communities to work together on long-term shoreline adaptation strategies. OLUs cut across traditional jurisdictional boundaries, allowing stakeholders who experience similar hazards and share similar physical and ecological settings to come together to develop effective adaptation solutions.

This report offers a first cut at determining the suitability of nature-based measures for different parts of the San Francisco Bay shoreline. The simple and robust criteria can



SAN FRANCISCO BAY AT HIGH TIDE FROM RICHMOND SHORELINE • PHOTO BY TOM MIKKELSEN, CC BY-NC-SA 2.0

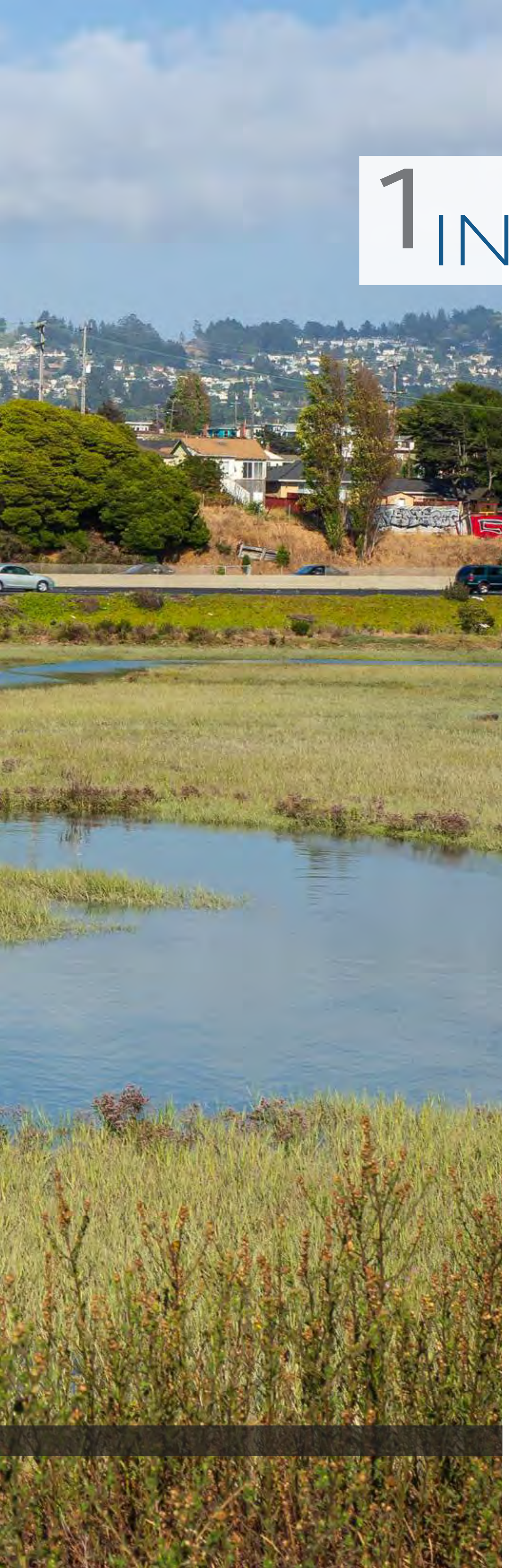
be used to help site and size several nature-based shoreline protection features within different physical and ecological settings. Detailed maps show which adaptation measures can work together in a particular place.

OLUs integrate across the land-water divide to connect bayside and landside adaptation strategies. Combining measures suitable for shallow parts of the Bay, the wetlands along the Bay shore, and the land above the shoreline will help create synergistic and locally appropriate strategies. Local and regional priorities will guide the selection and integration of these strategies into a pathway or vision for a particular area over time.

Climate adaptation action is urgently needed now, and will only become more pressing as sea level rise impacts accelerate in the coming decades. The intent of this report and the OLU framework is to foster and inform a collaborative, data-driven vision for resilience to sea level rise that can be implemented at multiple scales. Building on and supporting the many progressive projects already underway, this report intends to provide guidance for the regulatory community, regional governments, planners, and members of local communities on how to proactively integrate nature-based adaptation measures into adaptation plans.

This report, and future updates to these datasets, maps, and OLU-based projects around the region, will be available online at ***adaptationatlas.sfei.org.***

RICHMOND SHORELINE AT KING TIDE • PHOTO BY SHIRA BEZALEL (SFEI)



1 INTRODUCTION

In the coming decades the San Francisco Bay shoreline will face increasing threats from rising sea levels. To address this challenge proactively, communities will need to work with scientists, planners, and other decision makers to re-envision and adapt the complex nearly 650-kilometer (400-mile) shoreline to provide greater ecological, social, and economic resilience. A critical but missing tool for this process is a science-based framework for developing climate adaptation strategies that are appropriate to our diverse shoreline settings and that take advantage of natural processes in the Bay. This report proposes such a framework: Operational Landscape Units for San Francisco Bay, or OLUs.

The primary focus of this framework is to work with nature to identify where natural and nature-based approaches can be used to create a resilient shoreline with multiple benefits. Nature-based approaches, and hybrid measures that integrate nature with engineered structural approaches, can often perform better than traditional engineered infrastructure while costing less and providing co-benefits like new recreational opportunities and habitat for native species (Bridges et al. 2015). Despite the advantages of natural and nature-based approaches, they are often not as familiar or well understood as traditional engineering. This report provides a practical synthesis of scientific information on how and where to use natural and hybrid shoreline measures in San Francisco Bay.

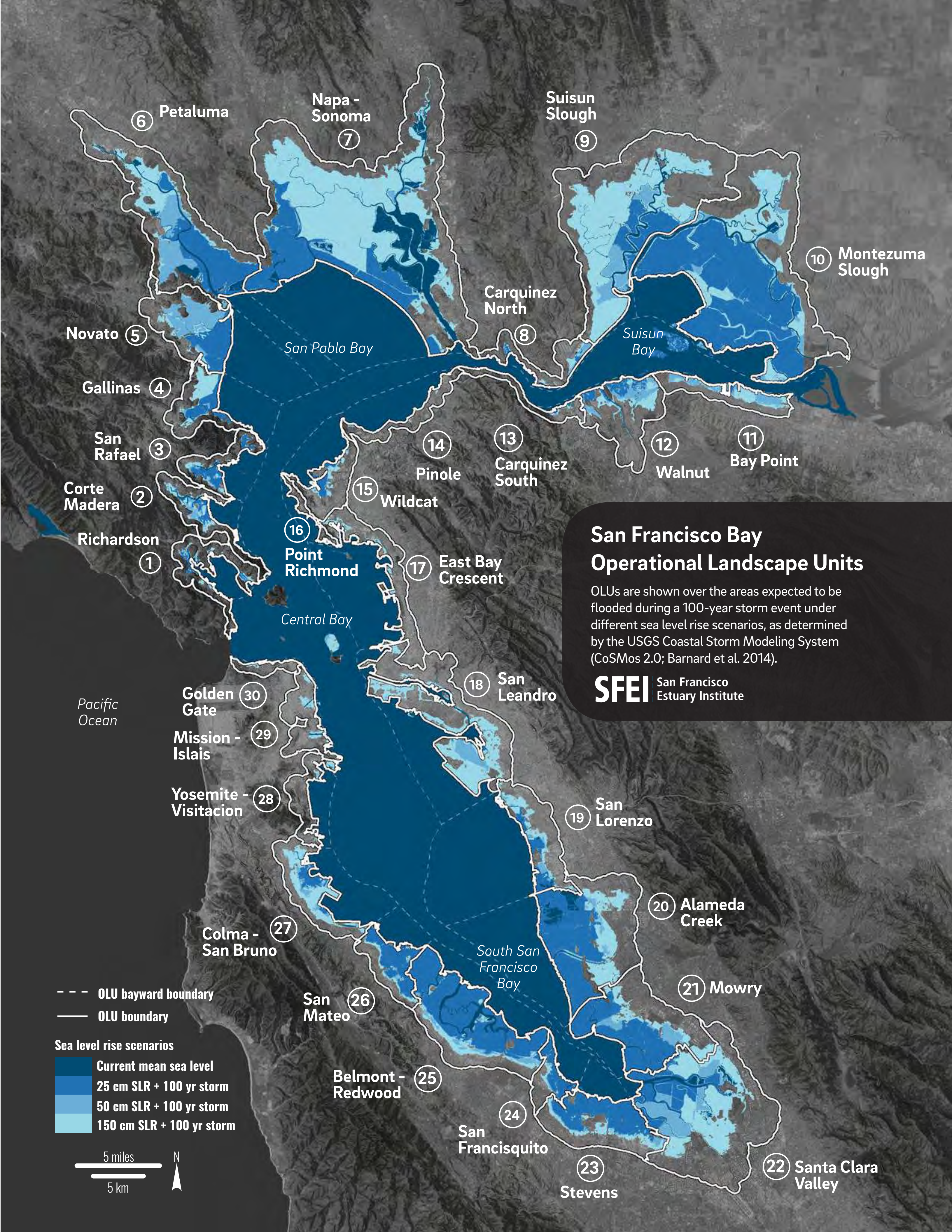
Of course physical solutions alone—be they natural, nature-based, grey infrastructure, or hybrid—will not solve all of the challenges posed by sea level rise (SLR). Non-structural policy, regulatory, and financial approaches will also be critical to phase adaptation in a way that balances the needs of communities, businesses, infrastructure, and nature while reducing flood risk over time. This report also discusses these measures and where they might be used to adjust land use and protect people as sea levels continue to rise.

Our framework: Operational Landscape Units

The San Francisco Bay shoreline is both regionally interconnected and locally diverse. The varying geology, hydrology, micro-climates, land use, and demographics around the Bay shore make different areas vulnerable to sea level rise in different ways. The region has 101 cities, nine counties, and hundreds of special districts and local government agencies, many of which are responsible for actions and permitting activities along the shoreline (Appendix 1). These many jurisdictions form a complex governance structure with no overarching regional governing body. Adapting to sea level rise will be challenging, with limited resources that will need to be deployed as effectively and as efficiently as possible. Given the natural variety and scale of the Bay, adaptation will ultimately require a coordinated, place-based, cross-jurisdictional, and landscape-scale approach.

Our framework addresses these needs by dividing the Bay shore into 30 practical, science-based planning units called Operational Landscape Units, or OLUs. This approach provides communities with a way to develop coherent, geographically-appropriate adaptation strategies. The proposed OLUs are a first attempt to subdivide the Bay shore into segments based on common kinds and conditions of controlling processes, such as the flow of sediment and water. The OLUs may be adjusted in the future as new understanding is gained about the controlling processes, their effects on adaptation measures, and interactions between measures within and among OLUs.

This report also identifies a host of different types of adaptation measures, from nature-based options to policy tools, and describes their suitability within each OLU. For example, tidal marshes can provide shoreline protection, as well as many other co-benefits, but they are only sustainable in areas with the right elevations and wave environments, and with sufficient supplies of sediment. Due to the diverse nature of the shoreline and shoreline-adjacent land uses, neighboring OLUs may have completely different settings with different suites of appropriate adaptation measures. This framework can also be used to reduce adverse and unintended consequences—certain actions might have a short-term resilience benefit for some but worsen outcomes for others or over the long-term. For example, seawalls built in certain areas can worsen erosion on neighboring shorelines by reflecting wave energy and interrupting sediment supply.



San Francisco Bay
Operational Landscape Units
OLUs are shown over the areas expected to be flooded during a 100-year storm event under different sea level rise scenarios, as determined by the USGS Coastal Storm Modeling System (CoSMos 2.0; Barnard et al. 2014).
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1 Richardson
2 Corte Madera
3 San Rafael
4 Gallinas
5 Novato
6 Petaluma
7 Napa - Sonoma
8 Carquinez North
9 Suisun Slough
10 Montezuma Slough
11 Bay Point
12 Walnut
13 Carquinez South
14 Pinole
15 Wildcat
16 Point Richmond
17 East Bay Crescent
18 San Leandro
19 San Lorenzo
20 Alameda Creek
21 Mowry
22 Santa Clara Valley
23 Stevens
24 San Francisquito
25 Belmont - Redwood
26 San Mateo
27 Colma - San Bruno
28 Yosemite - Visitacion
29 Mission - Islais
30 Golden Gate
San Pablo Bay
Suisun Bay
Central Bay
South San Francisco Bay
Pacific Ocean
OLU bayward boundary
OLU boundary
Sea level rise scenarios
Current mean sea level
25 cm SLR + 100 yr storm
50 cm SLR + 100 yr storm
150 cm SLR + 100 yr storm
5 miles
5 km
N

What is an Operational Landscape Unit

Operational Landscape Units (OLUs) are connected geographic areas sharing certain physical characteristics that would benefit from being managed as a unit to provide particular desired ecosystem functions and services. OLUs can be identified anywhere across the earth's surface, with their size and composition depending upon the landscape in question and the ecosystem functions and services of interest. For example, Verhoeven et al. (2008), who originated the OLU concept, identify OLUs for regional wetland restoration initiatives that consider areas connected by the flow of water and movement of particular plants and animals. In this report, we identify Baylands OLUs, which we define as connected areas along the shoreline of San Francisco Bay with particular physical characteristics that should be managed as coherent units for nature-based sea-level rise adaptation.

Specifically, each Bayland OLU is connected by the flow of water and sediment, as governed by topography, bathymetry, tidal and wave energy, and the sources of the water and sediment. OLUs each have particular combinations of environmental variables (including topography, bathymetry, elevation, wave climate, shoreline characteristics, sediment supply, and adjacent land use) that influence their vulnerability and adaptability. Watersheds form fairly clear hydrologic boundaries for the flow of water and sediment in the uplands; however, in the marshes and mudflats of the baylands the flatter topography and fine sediment processes tend to blur the boundaries between the Baylands OLUs. In some places the boundaries may be easily identifiable headlands, and in other places the boundary may be a less distinct location representative of a fuzzy zone between adjacent creeks or tidal sloughs.

Baylands OLUs consist of landscape features such as rivers, floodplains, and wetlands, as well as elements of the built environment such as parking lots, landfills, and residential neighborhoods. The connections between the features of the Baylands OLUs are important: altering the movement of sediment or water in one part of an OLU is likely to have an impact elsewhere in the OLU. For example, within a single OLU, detaining water and sediment behind dams in a watershed will likely have an effect on the wetland accretion downstream; leveeing fluvial channels will reduce the width of the riparian corridor and reduce salinity gradients in the baylands; opening a diked area to tidal action could affect the sediment supply to other parcels along the same tidal channel. Because of these close connections, effective management of one feature within the OLU should require the consideration and management of the other connected features within the OLU.

For more information on how OLUs were delineated for San Francisco Bay, see Chapter 2 (page 21).

How to use this report

This report aims to establish a shared understanding of which measures used in which places could provide effective, multi-benefit, sustainable sea level rise adaptation for the Bay shore. The intent of this report and the OLU framework is to help foster and inform a collaborative, data-driven, long-term vision for regional resilience. Building on many progressive projects already underway, it can also provide guidance for the regulatory community, landscape designers, planners, developers, engineers, and members of local communities who are grappling with the challenges of how to adapt to climate change. The report is designed as an input to permitting and planning processes that affect places near the shoreline, including processes related to flood control, transportation, parks, land uses, and ecosystem restoration.

Chapter 5, Adaptation opportunities by OLUs (page 115) discusses measures for specific OLUs that might be especially well suited given an OLU's landscape and land uses. However, this report does not constitute a vulnerability assessment, and it describes vulnerabilities and adaptation strategies at a broad, landscape scale. The maps and supporting information are not meant to be applied at a site- or parcel-specific level and should not be used as the basis for design. Adaptation planning will involve pairing the information in this report with a vulnerability assessment, a public engagement and stakeholder planning process, and site-specific engineering design, feasibility, and cost estimates to identify the viability and costs of adaptation options. New types of measures will need to be piloted, monitored, and re-thought as knowledge increases and the rate and impacts of sea level rise are observed.

The OLU framework can be applied to adaptation planning at several levels, including by users with a regional view who are interested in understanding the places in the Bay where specific nature-based adaptation measures are suitable. This group may include federal and state government permit analysts and project applicants, non-governmental organizations, regional planners and agencies, and local government staff and officials who want to understand the range of suitable nature-based and other policy-based adaptation opportunities when evaluating project permits, investing in shoreline changes, and developing climate change policies and regulations. This report can also help these users identify opportunities for habitat restoration and endangered species recovery. In addition, the OLU concept can serve as a spatial framework for monitoring the health of wetlands over time, or as an organizing framework for governance and decision making for adaptation in general.

Paired with vulnerability information developed by counties and other government agencies, the OLU framework is being used in the Bay Area as an input to both regional and county-wide adaptation planning processes. This framework could continue to provide support to users focused on a specific community or local area who are engaged in or interested in launching a planning process for sea level rise adaptation. This group may include communities or local government planners. This report could support these users in developing OLU-based strategies and visions, considering trade-offs among adaptation strategies, and creating local climate action plans, flood risk management plans, and general and local plans.

Data from this report, as well as other additional resources, are available at *adaptationatlas.sfei.org*.

Precedents and inspiration

This report was inspired and builds on earlier work in the Bay Area and beyond:

- **Baylands Ecosystem Habitat Goals Update (Goals Project 2015),** published by the Coastal Conservancy, in partnership with many scientists and managers, updated the landmark 1999 Baylands Ecosystem Habitat Goals to address the threat of climate change. (The 1999 publication was the first-ever set of comprehensive regional restoration goals for the San Francisco Bay Estuary.) The 2015 update synthesized the latest science, focused particularly on advances in the understanding of climate change and sediment supply, and incorporated projected changes through 2100 to generate new recommendations for achieving healthy baylands ecosystems. The OLU project builds on this work and was highlighted in the report as a needed next step for regional ecosystem planning.

- **Urban Waterfront Adaptive Strategies (NYC DCP 2013),** published by the New York City Planning Department, identified coastal area typologies, catalogued a range of grey and green adaptive strategies that could be used in the city's diverse shoreline settings, and described the applicability of various strategies within these settings.
- **Louisiana's Coastal Master Plan (CPRA 2017),** updated every five years by the Louisiana Coastal Protection and Restoration Authority, identifies ways to reduce coastal land loss by modeling suitability of different adaptation strategies (sediment diversion, marsh creation, oyster barrier reefs, levee improvements, and more) for specific kinds of places along the coast and creates a plan for rapid implementation.
- **The Puget Sound Nearshore Ecosystem Restoration Project (e.g., Cereghino et al. 2012)** identifies ways to improve the health of the Sound and people's access to the water by restoring depleted and poorly modified reaches through nature-based strategies.
- **CoastAdapt (e.g., Brussen et al. 2017),** a resource developed by the Australian government, identifies sea level rise risks on Australia's coast and ways to manage these risks. It provides a decision-support tool and significant guidance on the process of conducting coastal adaptation planning.

AERIAL VIEW OF O'NEILL SLOUGH IN BELMONT-REDWOOD OLU • PHOTO BY MICHA SALOMON (SFEI)

MARSH VEGETATION ALONG POINT PINOLE REGIONAL SHORELINE • PHOTO BY KATIE MCKNIGHT (SFEI)

Why natural and nature-based adaptation?

Natural and nature-based adaptation measures work with natural processes and landforms to provide protection for both ecosystems and the built environment and to support coastal resilience and risk reduction (Bridges et al. 2013). Along our highly modified shorelines, natural and nature-based measures are also inherently hybrid approaches—engineered to mimic natural processes and also provide specific services such as coastal risk reduction and critical habitat. Estuarine wetlands, for example, can reduce flooding by attenuating waves and spreading out and slowing down high water, enhance water quality by filtering out and breaking down contaminants, provide nurseries for fish and shellfish, sequester carbon, and provide important recreational opportunities (Goals Project 2015).

Natural and nature-based approaches may have lower whole-life costs, provide more benefits to people, plants, and wildlife, and be more adaptable over time than conventional alternatives (Gittman et al. 2014, Currin et al. 2016, Hirschfield and Hill 2017). However, knowledge about and confidence in the performance of natural and nature-based measures varies (Bridges et al. 2015). Because nature-based measures have so much promise, they should continue to be piloted and monitored around the Bay, and their performance analyzed to inform continuous improvement in their design and implementation.

CORTE MADERA MARSH • DRONE IMAGERY BY PETE KAUHANEN (SFEI)

2 DELINEATING OLU BOUNDARIES

This chapter describes the methods we used to define the boundaries of the San Francisco Baylands OLUs. The goal of this process was to create units that are each large enough to encompass the physical and ecological processes that drive the vulnerabilities and adaptation possibilities of the shoreline, but small enough for people to organize around and effectively manage.

As described on page 30, OLUs are a refinement of the Baylands Goals segments which have been used for almost 20 years to identify restoration priorities and opportunities for the baylands. OLUs build upon these segments by applying a sea level rise (SLR) planning framework that emphasizes nature-based adaptation strategies. Specifically, the area covered by the OLUs is meant to capture places potentially subject to the geomorphic, hydrologic, and ecological effects of sea level rise over a relatively long planning horizon (100–150 years). To capture the importance of watershed processes for adaptation potential, we also identified each OLU's contributing watershed.

The process for generating the OLU boundaries involved three steps, which are described in more detail below:

1. Defining boundaries between OLUs based on geomorphic units, (i.e., the basic characteristics of the physical landscape and watershed boundaries.)
2. Defining the upland boundaries of the OLUs based on an extreme sea level rise scenario.
3. Defining the bayward boundaries of the OLUs based on where wind-driven waves are capable of resuspending fine sediment that can then supply marshes and mudflats in higher parts of the OLUs.

Whenever possible, OLUs were named after their dominant creek or creeks (e.g., the "Corte Madera" OLU is named after Corte Madera Creek). Conveniently, these creek names also relate to familiar cultural features (e.g.,the Town of Corte Madera). OLUs without major creeks were instead named after another major physical landform (e.g., the "Richardson" OLU, which was named after Richardson Bay). See Appendix 2 for a list of the OLU names and how they were determined.

It should be noted that this effort is only a first attempt at identifying OLUs. Their boundaries should not be considered overly-precise and may be adjusted in the future as conditions change, as new information is developed, or as the use of OLUs in actual adaptation planning efforts matures.

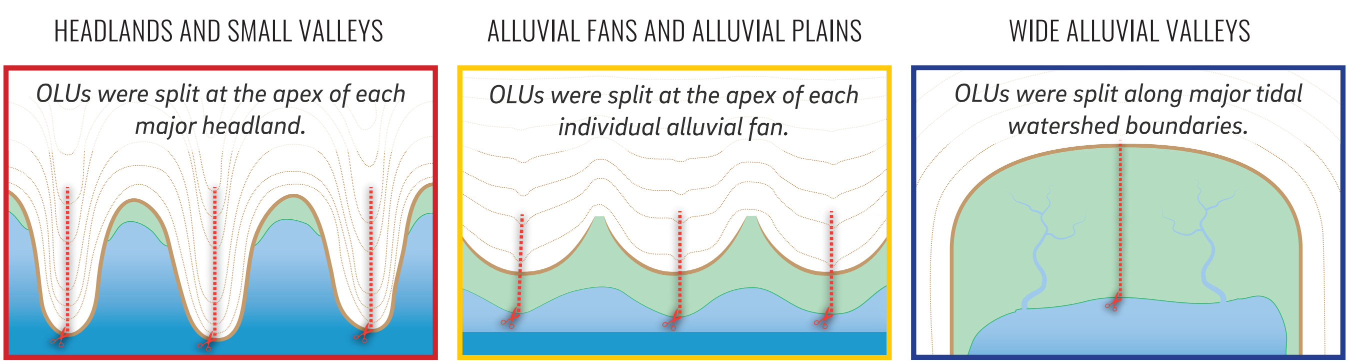
Identifying boundaries between OLUs

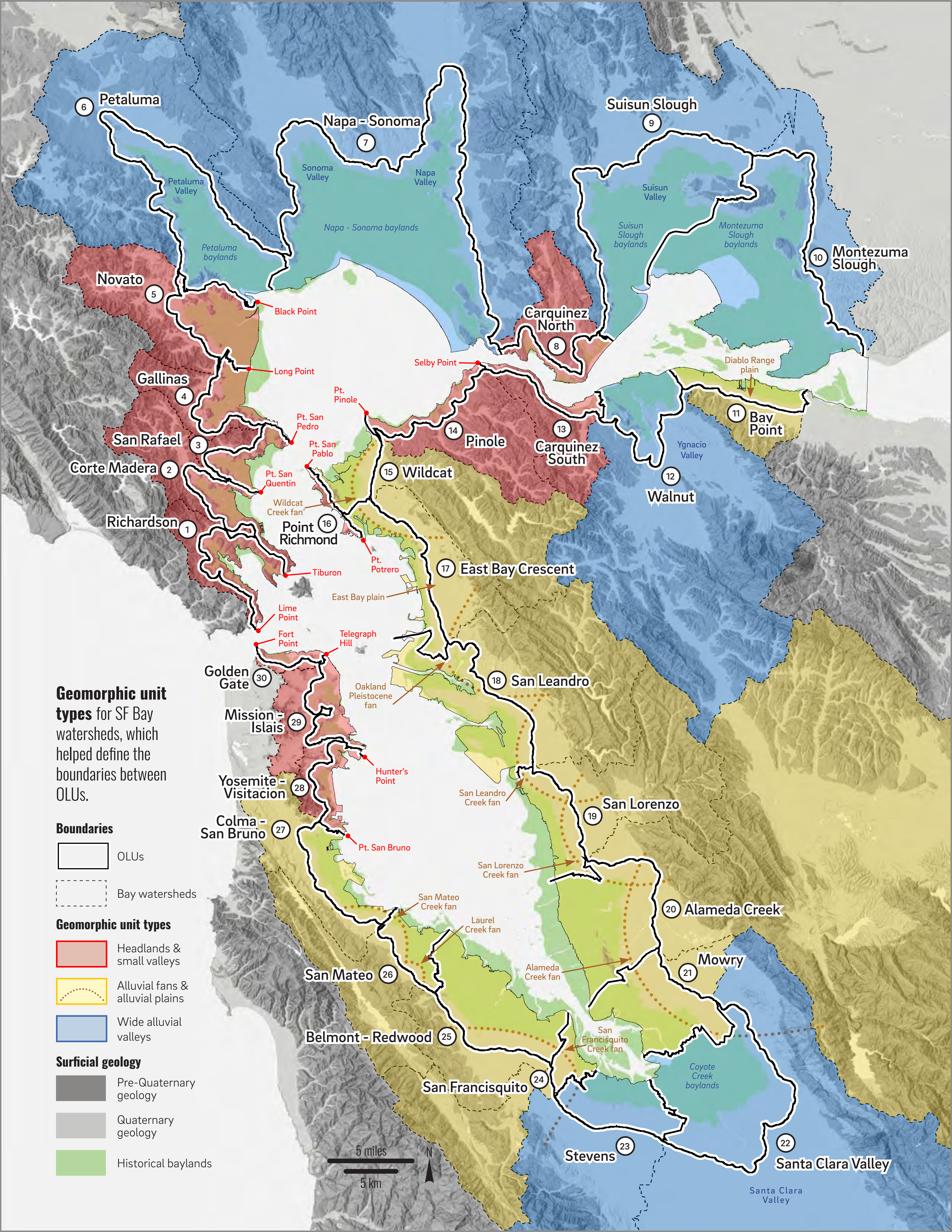
To delineate individual OLUs, we first identified three major geomorphic unit types along the shore: (1) headlands and small valleys, (2) alluvial fans and alluvial plains, and (3) wide alluvial valleys. These distinct units are distinguished by different underlying geology and resulting landscape morphometrics, such as slope of the shoreline, the width of the baylands, and watershed size. More information about each of these geomorphic unit types is available on page 24.

Geomorphic unit type was determined on a watershed by watershed basis based on conditions at the shoreline (watershed boundaries were derived from USGS 2014). The headlands and small valleys geomorphic unit type was assigned to watersheds where old (pre-Quaternary) rock formations intersect the shoreline, as shown on regional geologic maps (e.g., Wentworth 1997). In the watersheds where the shoreline is composed of younger (Quaternary) alluvium we examined maps of surficial geology (Knudsen et al. 2000, Witter et al. 2006) to identify the locations of major alluvial fans. Watersheds where alluvial fan deposits lie adjacent to the baylands (and have clearly influenced the extent/shape of the baylands as a result) were classified as alluvial fans and alluvial plains. Watersheds associated with large valleys without major alluvial fans or in which the alluvial fans are set farther back from the baylands were classified as wide alluvial valleys. The flow direction of each watershed's major creek was also helpful for distinguishing these two types of geomorphic units (creeks generally flow perpendicular to the ridges of the Coast Range hills and associated fault lines in units classified as alluvial fans and alluvial plains, but parallel to the ridges and associated fault lines in units classified as wide alluvial valleys). These general rules were used for approximating contiguous areas with major differences in geology, slope, and associated shoreline characteristics, including shoreline orientation, baylands width, and incident wave height. It is important to note, however, that these boundaries are not absolute and that some watersheds have qualities associated with more than one geomorphic unit type.

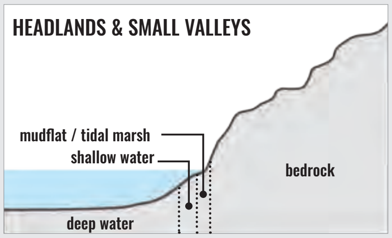
Once determined, geomorphic units were further divided into individual Baylands OLUs. Within geomorphic units classified as headlands and small valleys, OLU boundaries were located along the shoreline at the apex of major points or promontories, using the distance from the shoreline to deep water as a guide. This split adjacent embayments or coves into separate OLUs. Within geomorphic units classified as alluvial fans and alluvial plains, OLU boundaries were located along the shoreline at the apex of each individual alluvial fan. This had the effect of separating OLUs at locations where the baylands are relatively narrow and grouping wider baylands that occupy the space between adjacent alluvial fans. Since the creeks that formed the alluvial fans do not currently meet the baylands at the apex of the fan, this method also prevented us from splitting individual creeks into multiple OLUs. Finally, for wide alluvial valley geomorphic units, we relied on major tidal watershed boundaries to determine the boundaries between individual OLUs along the shoreline (see page 26).

(Below) Different methods used to define OLU boundaries along the shoreline for each geomorphic unit type.

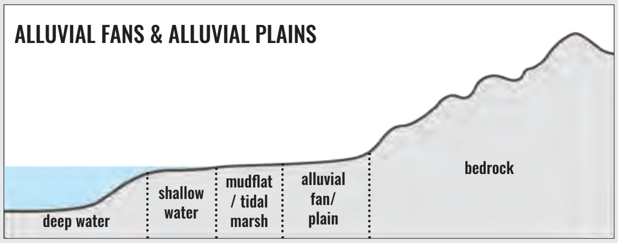



Geomorphic unit types for SF Bay watersheds, which helped define the boundaries between OLUs.
Boundaries
OLUs
Bay watersheds
Geomorphic unit types
Headlands & small valleys
Alluvial fans & alluvial plains
Wide alluvial valleys
Surficial geology
Pre-Quaternary geology
Quaternary geology
Historical baylands
6 Petaluma
Napa - Sonoma 7
Suisun Slough 9
10 Montezuma Slough
Petaluma Valley
Sonoma Valley
Napa Valley
Suisun Valley
Napa - Sonoma baylands
Petaluma baylands
Suisun Slough baylands
Montezuma Slough baylands
Novato 5
Black Point
Carquinez North 8
Long Point
Selby Point
Diablo Range plain
Gallinas 4
Pt. Pinole
11 Bay Point
Pt. San Pedro
14 Pinole
13 Carquinez South
Ygnacio Valley
San Rafael 3
Pt. San Pablo
Corte Madera 2
15 Wildcat
12 Walnut
Pt. San Quentin
Wildcat Creek fan
Richardson 1
Point Richmond 16
Pt. Potrero
17 East Bay Crescent
Tiburon
East Bay plain
Lime Point
Fort Point
Telegraph Hill
Golden Gate 30
Oakland Pleistocene fan
18 San Leandro
Mission - Islais 29
Hunter's Point
Yosemite - Visitacion 28
San Leandro Creek fan
San Lorenzo
19
Colma - San Bruno 27
Pt. San Bruno
San Lorenzo Creek fan
San Mateo Creek fan
20 Alameda Creek
Laurel Creek fan
Alameda Creek fan
Mowry
21
San Mateo 26
Belmont - Redwood 25
San Francisquito Creek fan
Coyote Creek baylands
San Francisquito 24
Stevens 23
22
Santa Clara Valley
Santa Clara Valley
5 miles
5 km
N

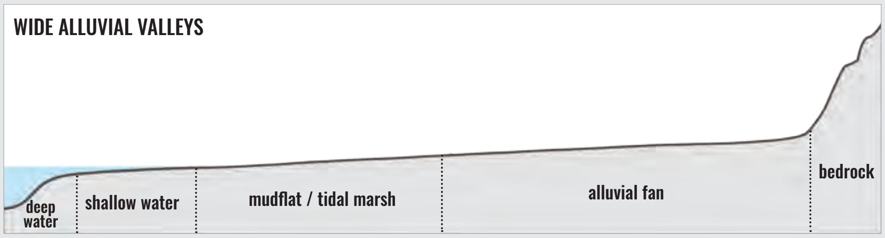
DEFINING GEOMORPHIC UNIT TYPES



Headlands and small valleys are generally located where older, uplifted pre-Quaternary rock formations lie directly adjacent to the Bay. These large resistant blocks of rock include: serpentinite at Fort Point, Potrero Hill, and Hunter's Point that once formed steep shorelines along San Francisco's Bay shore; the belt of Great Valley Sequence rocks at Carquinez Strait; Franciscan Complex formations that punctuate the Central Bay's northern shoreline at the Marin Headlands, Tiburon Peninsula, Point San Pedro, Telegraph Hill, Rincon Hill, Point San Pablo, and Point Richmond; and the Upper Tertiary sedimentary rocks that form the southeast boundary of San Pablo Bay (Sloan 2006). These headlands often alternate with small valleys filled with younger, Quaternary alluvium. Relative to the other geomorphic unit types, headlands and small valleys are typically characterized by small watersheds, steep slopes, narrow baylands, and a short distance from the shoreline to deep water.



Alluvial fans and alluvial plains are the areas built up over the last million years with silts, sand, and gravel eroded from the Coast Range hills and deposited on the floor of the valley that currently contains San Francisco Bay. These areas include the distinct fans formed by San Mateo, San Francisquito, Alameda, San Lorenzo, San Leandro, and Wildcat creeks, as well as less pronounced plains formed by many smaller creeks, such as the East Bay flats between Oakland and El Cerrito and the flats northeast of the Diablo Range between Port Chicago and Oakley (Knudsen et al. 2000, Sloan 2006). The location and shape of the fans and plains influence the shape of the baylands, which generally have filled in the spaces between and at the feet of the fans. Note that the creeks that formed the alluvial fans and alluvial plains flow (or once flowed) down from the hills of the Coast Range in a direction perpendicular to the dominant axis of the hills and associated fault lines (compare with wide alluvial valleys below). Relative to the other geomorphic unit types, alluvial fans and alluvial plains are typically characterized by watersheds of intermediate size, moderate slopes, baylands of intermediate width, and an intermediate distance from the shoreline to deep water.

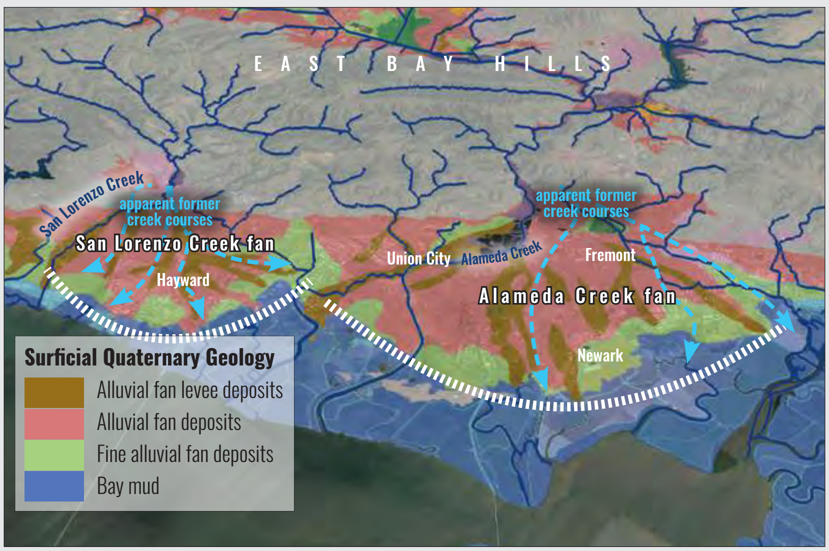


Wide alluvial valleys are down-dropped tectonic valleys that have formed between parallel fault lines and ridges of the Coast Range (Sloan 2006). Wide alluvial valleys include Santa Clara, Petaluma, Sonoma, Napa, Green, Suisun, and Ygnacio valleys. Unlike the creeks that formed the alluvial fans and alluvial plains (see above), the creeks that filled the wide alluvial valleys with sediment flow parallel to the axis of the Coast Range hills and the associated fault lines. Relative to the other geomorphic unit types, wide alluvial valleys are typically characterized by large watersheds, very gradual slopes, wide baylands, and a great distance from the shoreline to deep water.

(Photo by Michael Estigoy, CC BY-NC 2.0)

Examples of headlands and small valleys. Left is a photo of Point San Pedro, with San Rafael creek and valley in the background. Point San Pedro marks the north end of the San Rafael OLU; Point San Quentin in the distance marks the south end. Below is a photo of Lime Point (the northern landing of the Golden Gate Bridge), which defines the southern limit of the Richardson OLU. In both photos the land is seen rising steeply from the Bay.

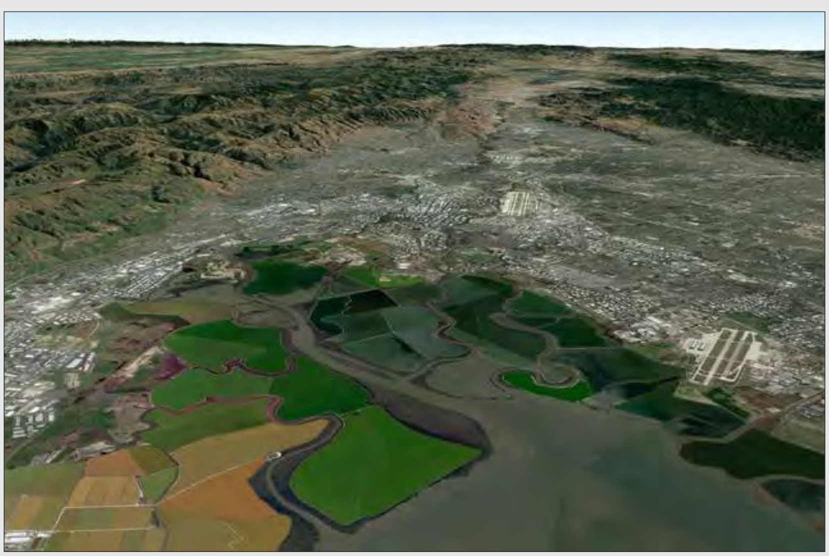

(Photo by Glenn Beltz, CC BY 2.0)



(Image courtesy Google Earth)

Examples of alluvial fans and alluvial plains. Left is an image of the Alameda and San Lorenzo creek drainages, with a surficial geology layer overlaid to show the alluvial fans (Knudsen et al. 2000). The apexes of these fans define the north and south boundaries of the Alameda Creek OLU. Below is a photo of Bair Island, which formed between the alluvial fans of San Mateo and San Francisquito creeks. It is part of the Belmont-Redwood OLU. The ridges of the Coast Range are visible in the background.


(Photo by Dicklyon, CC BY-SA 4.0)


(Image courtesy Google Earth)

Examples of wide alluvial valleys. Left is an image looking south up Santa Clara Valley. The tidal drainage divide between Coyote Creek and the baylands to the west forms the boundary between the Santa Clara Valley and Stevens OLUs. Below is a photo looking east across the Napa-Sonoma OLU. The Petaluma OLU (another wide alluvial valley) is visible in the distance, separated from Napa-Sonoma by the drainage divide below Sears Point.


(Photo by Dicklyon, CC BY-SA 4.0)

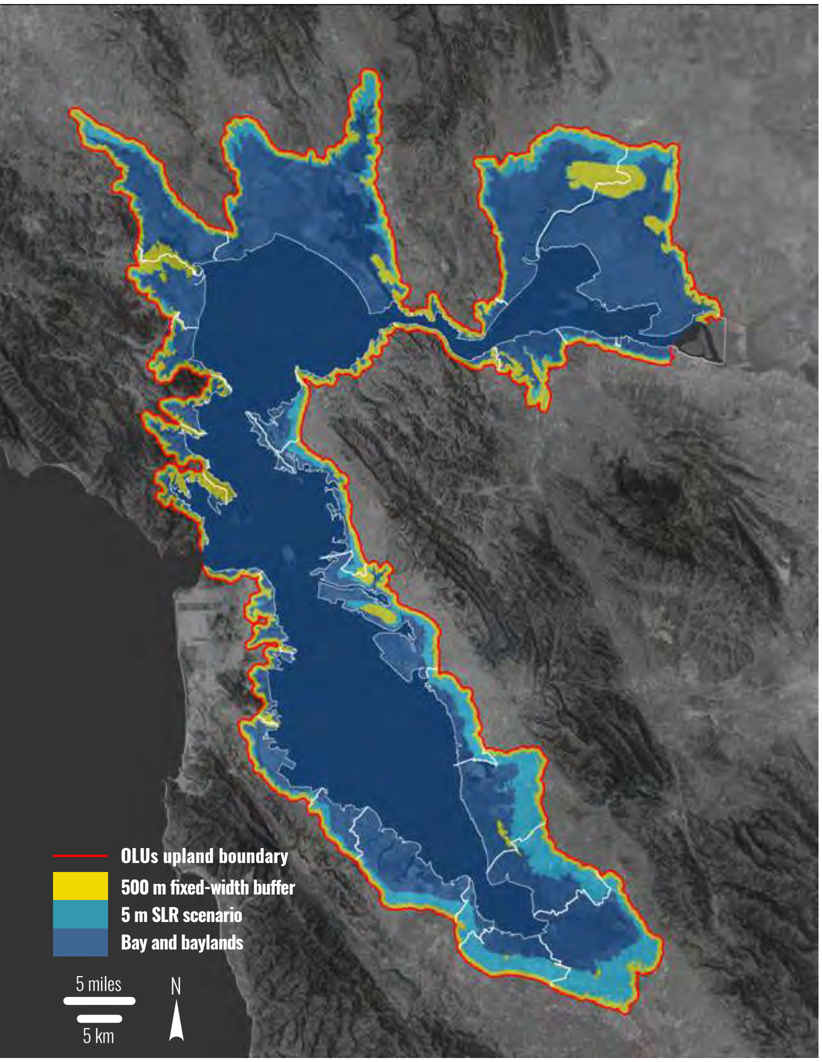
Once boundaries between OLUs along the shoreline were identified, we used the National Hydrography Dataset (USGS 2014), local watershed/sewershed maps (Sowers et al. 2003, 2005, 2007a, 2007b, 2010), and other datasets (e.g., slope and channel maps) to identify each OLU's drainage area and side boundaries. The most challenging part of this process was identifying tidal watershed boundaries within the baylands. Whenever possible, we used contemporary maps of tidal channels (BAARI version 2.1; SFEI-ASC 2017a) to elucidate these tidal watershed boundaries, but in areas where the baylands have been diked and extensively modified we sometimes relied on maps of historical tidal channel networks (e.g., SFEI 1998). Some minor exceptions to the guidelines described above and other details associated with identifying boundaries between OLUs are described in Appendix 2.

Identifying upland OLU boundaries

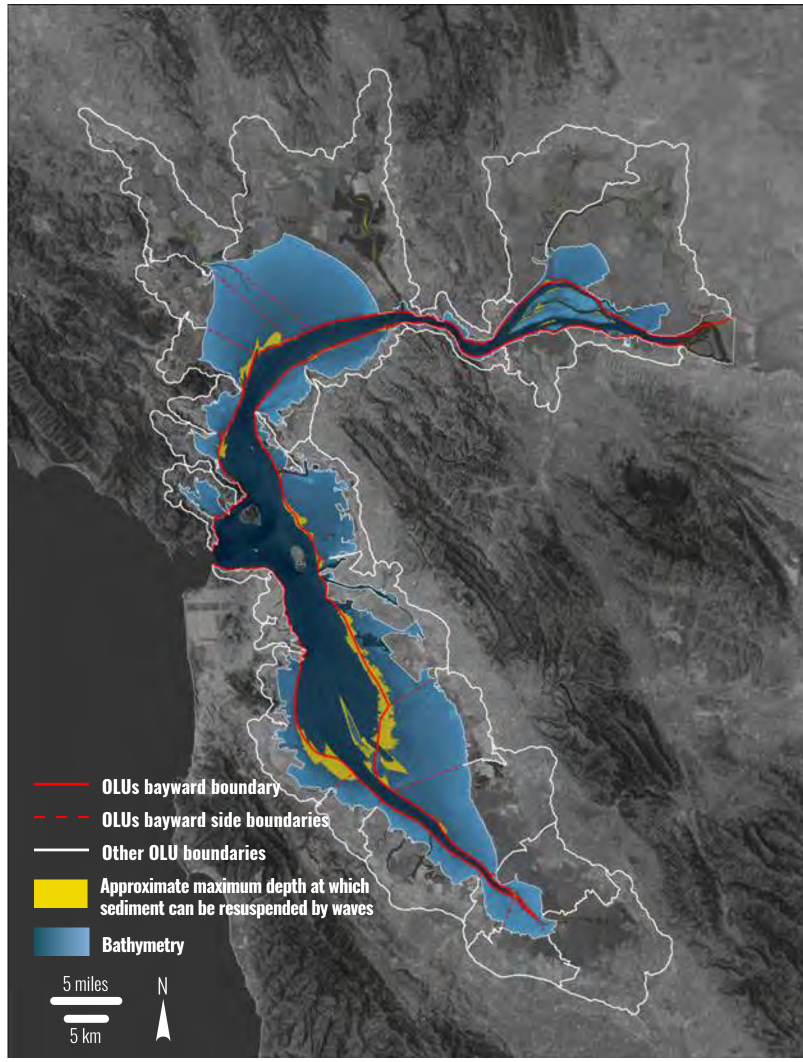
The upland OLU boundaries have been drawn to include most areas potentially subject to the geomorphic, hydrologic, and ecological effects of sea level rise over a relatively long time horizon (100–150 years). To accomplish this, we began with the current extent of the Bay and baylands, which are the areas upstream of the Golden Gate and downstream of the Sacramento-San Joaquin Delta below maximum tide elevations, including the areas that would be flooded by the tides if not for human-made water-control structures (Goals Project 2015). Next, we added the additional areas that will potentially be inundated during average daily conditions following 5 m of sea level rise, as modeled and mapped by the USGS Coastal Storm Modeling System (CoSMos 2.0; Barnard et al. 2014). Though 5 m of sea level rise is the most extreme scenario modeled as part of the CoSMos effort, it is possible before the year 2140 under the "H++" scenario modeled by Griggs et al. (2017), which "represents a world-consistent rapid Antarctic ice sheet mass loss." Finally, to this combined area (the Bay/baylands plus the SLR scenario) we added a fixed-width buffer of 500 m to capture transitional areas upslope of the SLR zone and the associated ecological functions and services of the future marsh-upland transition zone. The 500 m buffer width was based on SFEI-ASC's T-zone Project, which identified this width space over which over which most key physical and biological transition-zone processes occur (Robinson et al. 2017). Isolated high points within the buffered area immediately adjacent to the baylands (e.g., Coyote Hills in Alameda County and the Potrero Hills in Solano County) were combined with the buffered area to create a contiguous area of analysis. The outer edge of this area served the upland boundary for the OLUs.

Identifying bayward OLU boundaries

The bayward OLU boundaries have been drawn to include parts of the Bay that could be a source of suspended fine sediment to marshes and mudflats the OLUs. In the shallow subtidal parts of the Bay, the suspended sediment concentration depends mostly on the resuspension of sediments by wind-driven waves, which is triggered when the force of the wave moving over of the bottom of the Bay (wave shear stress) exceeds a critical threshold (Schoellhamer 1996). Wave shear stress, in turn, is a function of water depth, wave height, and the roughness of the surface over which the wave is moving (Lacy et al. 1996, Brand et al. 2010). By using known relationships between wave height and the maximum water depth at which sediment resuspension occurs in the Bay (Brand et al. 2010) and by assuming a constant bed surface roughness typical of mudflats (also from Brand et al. 2010), we were able to calculate the maximum depth of sediment resuspension associated with the 100-year wave height in each OLU (derived from DHI 2011 & 2013). By subtracting this depth from the elevation of the water surface at MLLW (derived from AECOM 2016), we were then able to calculate the minimum elevation at which sediment resuspension is likely to occur in each OLU (ranging from -3.19 to -4.37 m NAVD88 [-10.5 to -14.3 ft NAVD88]). Finally, we calculated the average minimum elevation across all OLUs (-3.70 m NAVD88 [-12.1 ft NAVD88]) and used bathymetric data to trace the approximate location of this contour, which serves as the lower boundary of the OLUs. Boundaries between OLUs in the subtidal zone were drawn simply by connecting the boundary of the OLU at the shoreline to the lower boundary contour with a straight line. These bayward "side boundaries" are only illustrative and do not meaningfully distinguish which portions of the subtidal zone are potential sources of resuspended sediment to individual OLUs.



Upland boundaries for the OLUs were identified by starting with the current extent of the Bay and baylands, adding a 5 m SLR scenario, and then buffering this combined area by 500 m to account for the future transition zone.



Bayward boundaries for the OLUs were identified by tracing a contour at the approximate maximum depth where sediment can be resuspended from the bottom of the Bay by waves, which bounds the approximate areas that could be a source of suspended fine sediment to marshes and mudflats within higher parts of the OLUs. The maximum depth of sediment resuspension is highlighted in yellow on the map. We drew the bayward boundary (solid red line) at approximately the average minimum elevation at which sediment can be resuspended across all OLUs. The side boundaries between OLUs in the subtidal zone (dotted red lines) are simply straight lines connecting the shoreline to the bayward OLU boundary.

SAN FRANCISCO BAYLANDS OPERATIONAL LANDSCAPE UNITS (OLUs)
& THEIR CONTRIBUTING WATERSHEDS

This map shows the 30 OLUs that were created using the methods described in this chapter. The upland boundaries of the OLUs encompass the areas potentially subject to the geomorphic, hydrologic, and ecological effects of sea level rise over a relatively long planning horizon (100–150 years), while the bayward boundaries of the OLUs encompass the areas that could be sources of fine re-suspended sediment to the baylands. We also show each OLU’s contributing watershed. Although the OLUs are constrained to the areas potentially impacted by sea level rise, their contributing watersheds are important to consider because they provide sediment and freshwater to the baylands and ultimately influence both the vulnerability and adaptation potential of each OLU.

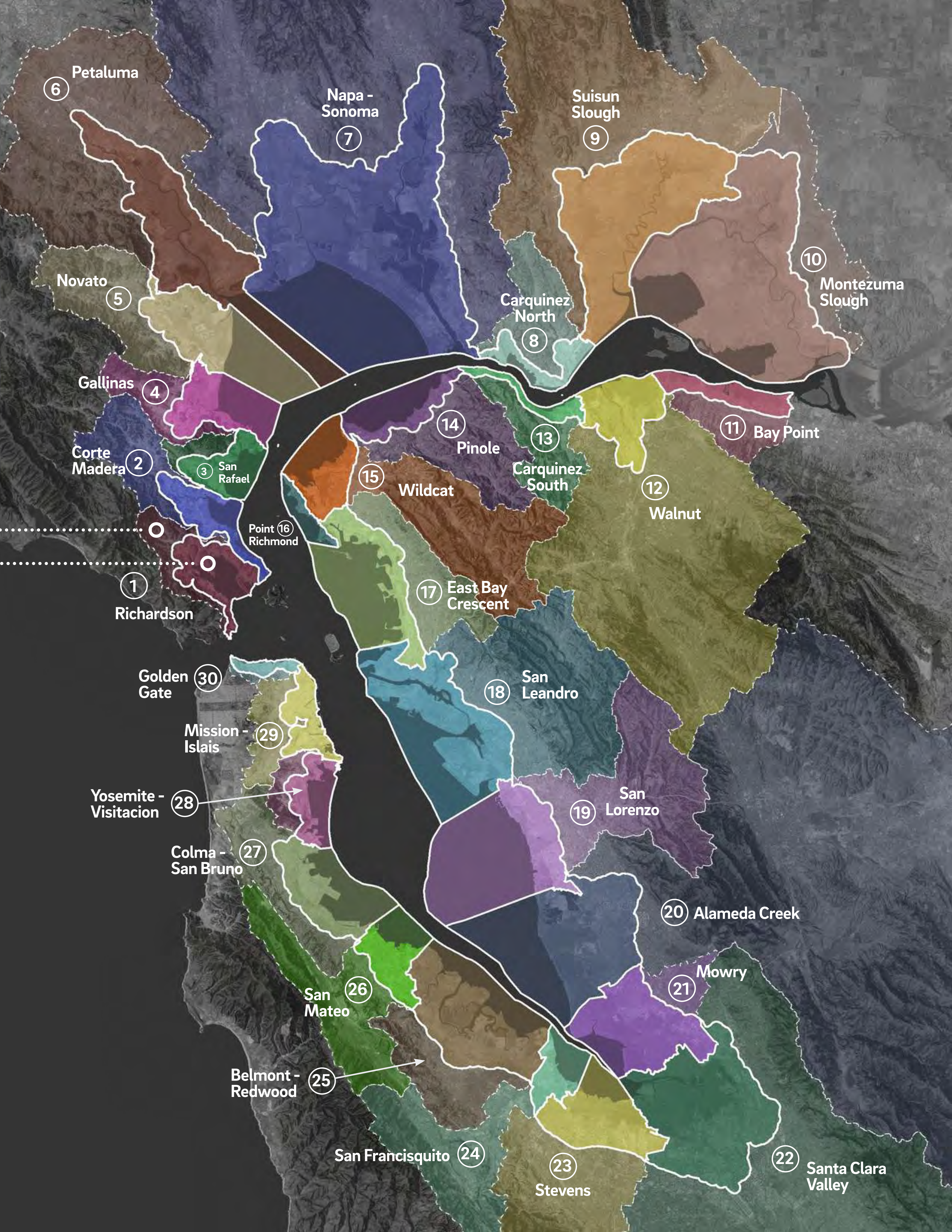
OLU boundaries

Contributing watersheds

5 miles

5 km

N

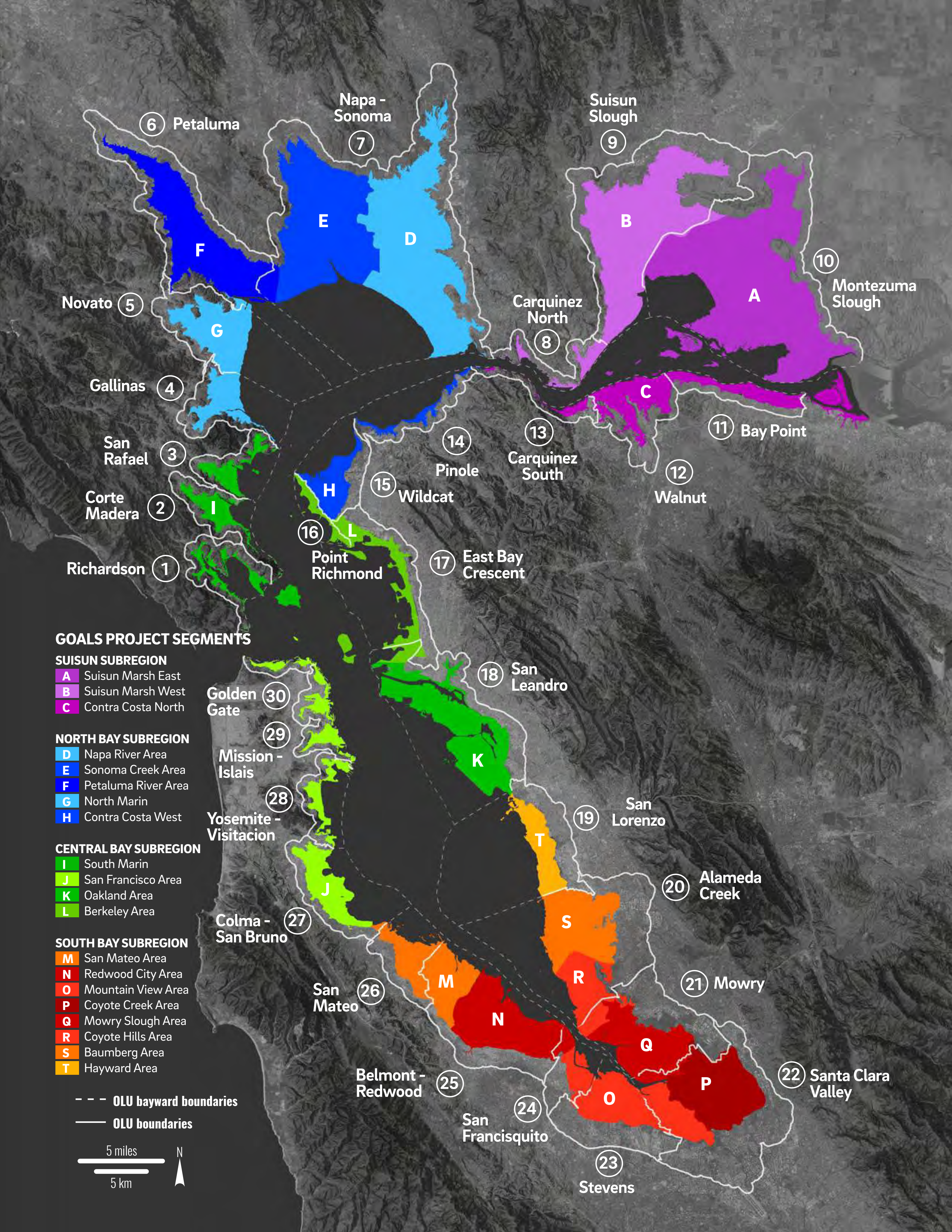


6 Petaluma
Napa - Sonoma 7
Suisun Slough 9
10 Montezuma Slough
5 Novato
Carquinez North 8
Gallinas 4
Corte Madera 2
3 San Rafael
14 Pinole
13 Carquinez South
11 Bay Point
15 Wildcat
12 Walnut
Point 16 Richmond
1 Richardson
17 East Bay Crescent
Golden Gate 30
18 San Leandro
Mission - Islais 29
Yosemite - Visitacion 28
19 San Lorenzo
Colma - San Bruno 27
20 Alameda Creek
Mowry 21
San Mateo 26
Belmont - Redwood 25
San Francisquito 24
23 Stevens
22 Santa Clara Valley

HOW ARE OLUs DIFFERENT FROM BAYLANDS GOALS SEGMENTS?

The creation of OLUs is a recommendation of the *Baylands Ecosystem Habitat Goals Science Update* (Goals Project 2015), and builds directly from the regional science and collaboration of the Goals Project. Twenty baylands "segments" were developed by SFEI in the late 1990s for the original *Baylands Ecosystem Habitat Goals* (Goals Project 1999). The segments were intended to capture the basic ecological and geomorphic units of the baylands (tidal watersheds, marsh complexes, creeks, and headlands) as a spatial framework to facilitate baylands restoration (Goals Project 1999, 2015), drawing primarily on the historical ecology mapping of the baylands as they appeared in the early 1800s. The OLUs are also based on geomorphic and ecological processes, but with the added intention of creating a spatial framework to facilitate baylands climate adaptation. Nature-based adaptation usually needs more space, sediment, and water to function as compared to engineered shorelines, so fluvial inputs, sediment transport, and the availability of transition zone to allow habitats to migrate and expand become important. The OLUs therefore also consider watershed inputs, wetland-upland transition zones, subtidal environments, and shoreline processes. Below we summarize some of the most important points of comparison between OLUs and Baylands Goals segments:

- **The scale of the OLUs can facilitate development of coherent adaptation strategies** and reflect the natural variability of the Bay—e.g., Baylands Goals Segment L spans the East Bay shoreline (wide mudflat, shallow water, a cove-like setting, beaches) and the hills between Point San Pablo and Point Potrero (steep shoreline adjacent to the deep water channel). This segment is now divided two OLUs to reflect the different opportunities and constraints for adaptation strategies.
- **There are 50% more OLUs than segments, which provides greater spatial resolution,** particularly along the more urbanized shoreline of the Central Bay where there are considerable nature-based adaptation opportunities—e.g., the San Francisco shoreline, which is one segment but four OLUs, reflecting different wave environments and other physical conditions.
- **Natural headlands, shoreline orientation, or tidal watersheds are used as boundaries for OLUs**—e.g., Point Pinole, which is crossed by Segment H but divides the Wildcat and Pinole OLUs.
- **OLUs consist of one or more watersheds;** no watershed is shared between two or more OLUs.
- **No tidal watershed is shared between two or more OLUs**—e.g., the Napa-Sonoma marshes are one OLU when previously they were two segments (Segments D & E).
- **No creek or slough is split by an OLU boundary**—e.g., Steinberger Slough between Redwood Shores and Bair Island is wholly contained within the Belmont-Redwood OLU instead of serving as the boundary between two segments.
- **Unlike Baylands Goals segments, the upland boundary of an OLU is not the historical mapped extent of baylands.** The OLU boundaries extend further inland to capture the marsh-upland transition zone (the importance of which is highlighted by the Goals Project [2015]) and most areas potentially subject to the geomorphic, hydrologic, and ecological effects of sea level rise over a relatively long time horizon (100–150 years).
- **Similarly, the bayward boundary of an OLU reflects the importance of the shallow subtidal parts of the Bay** (Subtidal Goals 2010) and is defined as the maximum depth at which fine sediment can be resuspended by wind-generated waves.


6 Petaluma
Napa - Sonoma
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Suisun Slough
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Montezuma Slough
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Novato 5
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Carquinez North
8
Gallinas 4
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11 Bay Point
San Rafael 3
14
13
Pinole
Carquinez South
12
Walnut
H
15 Wildcat
Corte Madera 2
I
16
L
Point Richmond
Richardson 1
17 East Bay Crescent
GOALS PROJECT SEGMENTS
SUISUN SUBREGION
A Suisun Marsh East
B Suisun Marsh West
C Contra Costa North
NORTH BAY SUBREGION
D Napa River Area
E Sonoma Creek Area
F Petaluma River Area
G North Marin
H Contra Costa West
CENTRAL BAY SUBREGION
I South Marin
J San Francisco Area
K Oakland Area
L Berkeley Area
SOUTH BAY SUBREGION
M San Mateo Area
N Redwood City Area
O Mountain View Area
P Coyote Creek Area
Q Mowry Slough Area
R Coyote Hills Area
S Baumberg Area
T Hayward Area
OLU bayward boundaries
OLU boundaries
5 miles
5 km
N
18 San Leandro
Golden Gate 30
29
Mission - Islais
K
28
Yosemite - Visitacion
19 San Lorenzo
T
20 Alameda Creek
J
Colma - San Bruno 27
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M
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San Mateo 26
21 Mowry
N
Q
22 Santa Clara Valley
P
Belmont - Redwood 25
O
24
San Francisquito
23
Stevens

AERIAL VIEW OF REDWOOD SHORES ALONG BELMONT SLOUGH LOOKING NORTHEAST TOWARDS HAYWARD • PHOTO BY CRAIG HOWELL, CC BY 2.0

3 CHARACTERIZING THE OLUs

Each OLU can be characterized by numerous spatial factors across the landscape that range from natural physical and ecological gradients to human-made patterns within the built environment. In this chapter we present many layers of spatial data,from elevation and the orientation of contributing watersheds, to habitat types and infrastructure—capturing the impacts of modifications, land uses, and impending vulnerabilities from climate change. These factors vary temporally and can help describe how the landscape functioned in the past, how it has changed over time, and how it may respond to future flooding. While each meter of the shoreline is different, we attempt to synthesize broadly across the estuary, to test the concept that different segments of the shoreline may be best suited to a particular suite of nature-based adaptation measures, and that lessons can be shared across similar settings. Throughout the chapter, we discuss the limitations of existing data and identify important data gaps.

Inputs to characterizing OLUs

We obtained or created many layers of spatial data to begin to characterize the shoreline, baylands, and contributing watersheds, in order to differentiate one OLU from another. As part of this process, we identified five groups of variables key to characterizing OLUs and pairing them with adaptation measures. These are: geomorphic setting (such as land surface slope and geology), baylands characteristics (such as historical and current extent of wetlands), shoreline characteristics (including mudflat width, tidal range, and degree of shoreline modification), land use patterns, and selected information about exposure to sea level rise (SLR). When combined, these factors begin to form a narrative that can be used at various scales to differentiate OLUs from one another, and determine and acknowledge variability within OLUs themselves.

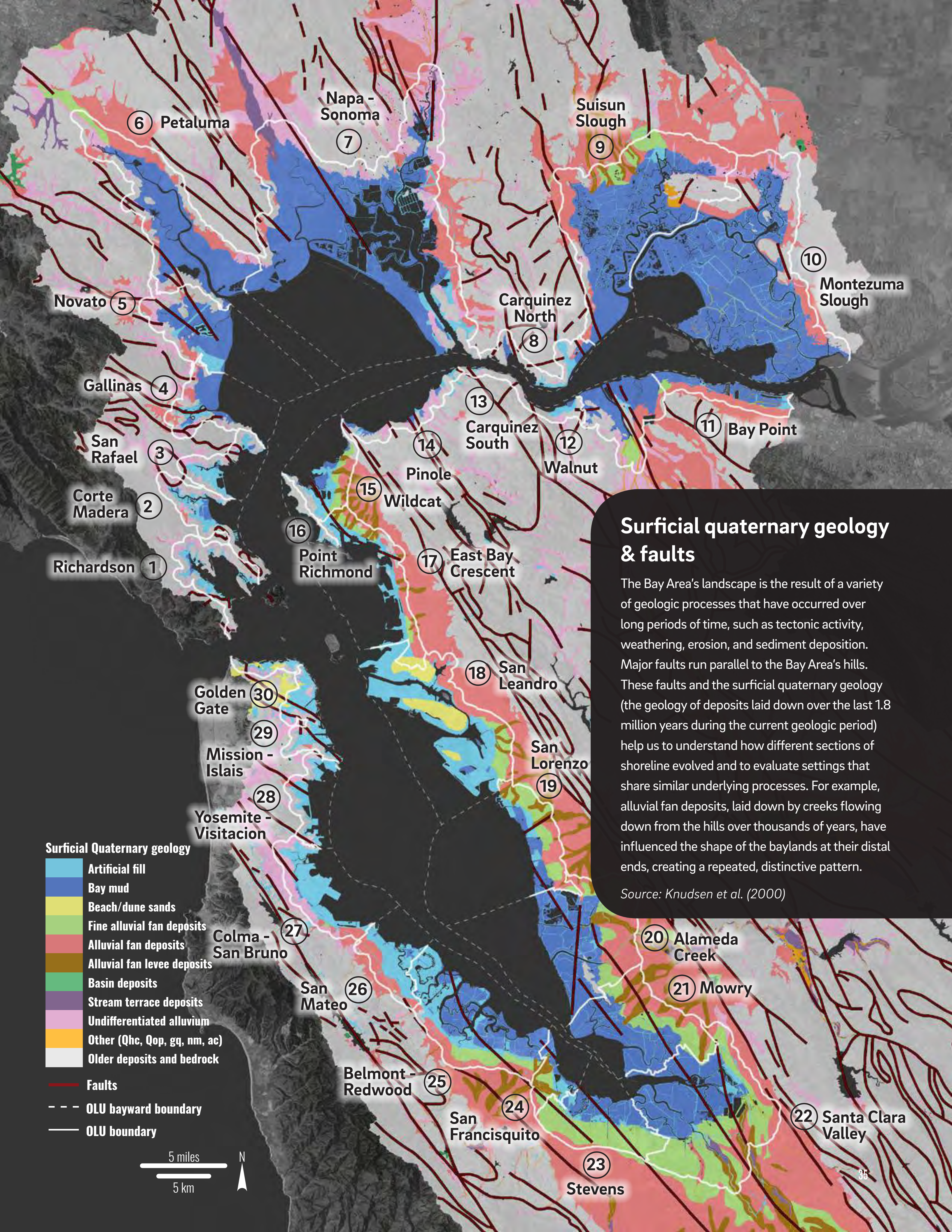
The series of maps and variable groups shown in this chapter lay the data-driven foundation that supports the qualitative and quantitative analyses which determine suitability of adaptation measures presented in Chapter 4. Most of these datasets were existing (created by SFEI and others), and are simply displayed in this context to answer key questions related to OLUs, and demonstrate where OLUs fit in the larger context of the Bay Area and its watersheds (see the table below). However, some datasets were created specifically for this effort, and are described in more detail in the following pages. In particular, we 1) created a map of tidally referenced elevations to characterize the elevation potential in each OLU (page 40), and 2) synthesized different land use characteristics such as job and housing density and other parameters to develop a "Place Types" map of OLUs (see page 48). These two new datasets form much of the basis for determining suitability of adaptation strategies as described in Chapter 4.

The Bay is dynamic and changing constantly, so these data will need updating as the Bay evolves. These maps represent snapshots of active processes which vary over time and space. There are also many data gaps and the following maps provide only a subset of the types of information critical to siting adaptation strategies. Key data gaps include lack of information about mudflat shape and orientation, erosional and depositional patterns of mudflats and the shoreline, sediment supply to the Bay under different climate change conditions, as well as a number of variables related to exposure and vulnerability.

The guiding questions and variables used to create each variable group are described in the table below. Maps, with data sources cited, are shown on pages 35-55.

Datasets used to characterize the OLUs, grouped by theme and the kinds of questions they can help answer.

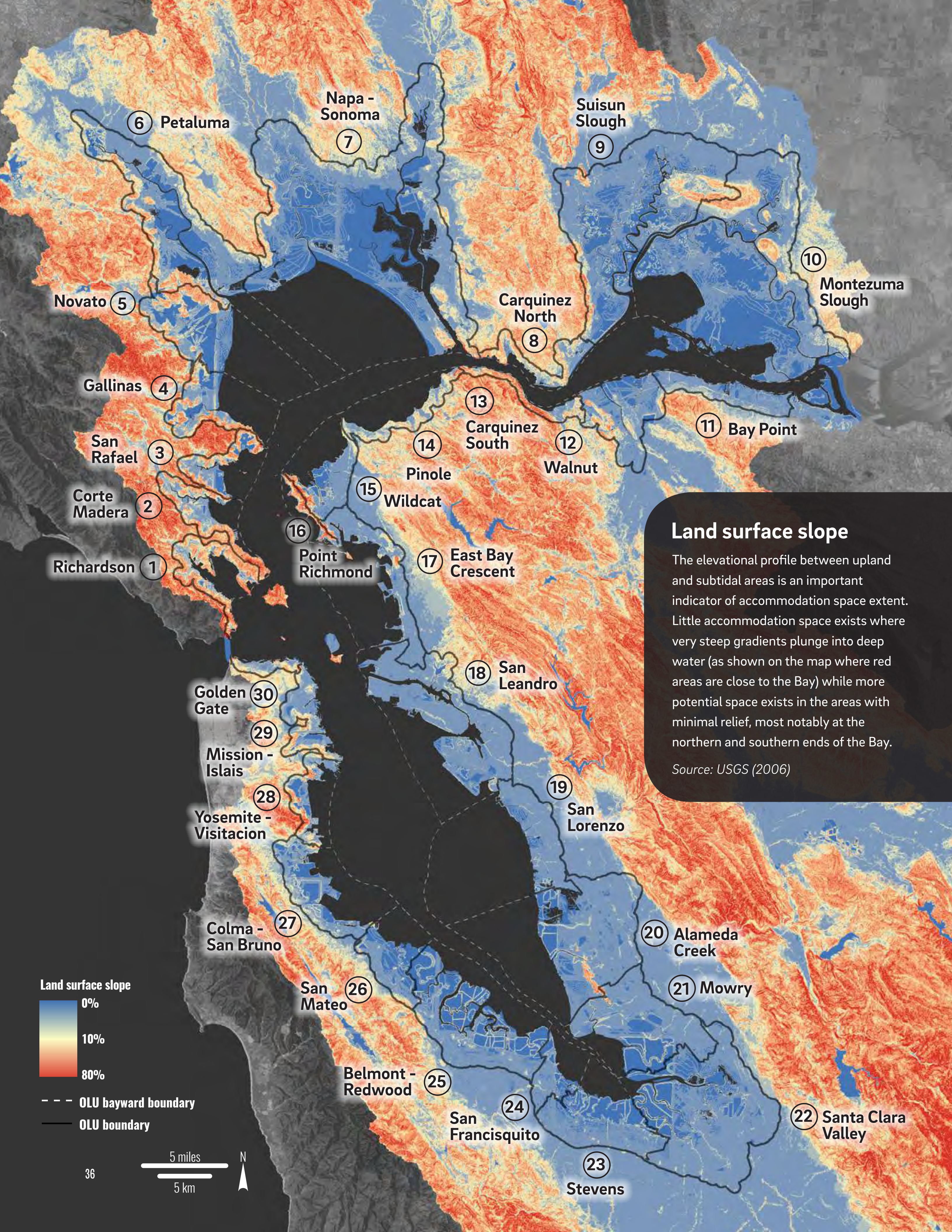
Variable group	Example variables	Guiding questions
Geomorphic setting	Surficial geology, land surface slope, watershed size, sediment load	How does the geomorphic setting influence baylands and shoreline size and shape? How do watershed size and sediment supply vary between geomorphic unit types?
Baylands characteristics	Mudflat and marsh width (historical and modern baylands; bathymetry), tidally referenced elevation of baylands	Which shorelines were artificially filled past their historical mudflat boundary? How much space exists for future marsh migration and transition space based on current elevations relative to the tides?
Shoreline characteristics	Tidal range, wind-wave heights, shoreline inventory	What are the dominant physical processes that shape the Bay shoreline, and what types of shoreline protections exist? Is the shoreline eroding or prograding?
Land use characteristics	Permeability and land cover, housing density, job density, infrastructure, place types	How have the baylands and surrounding upland areas been developed? Where are the major housing and job centers? Where does critical infrastructure exist in low-lying areas? What are the major place types within OLUs?
Selected exposure related to SLR	Depth to groundwater, sea level rise projections, FEMA 100-year flood zone, subsidence, shoreline elevations	Where is major near-term combined flooding risk (i.e., resulting from fluvial, groundwater, and sea level rise)? How high are existing levees, berms, and shoreline protection infrastructure?



Surficial quaternary geology & faults

The Bay Area's landscape is the result of a variety of geologic processes that have occurred over long periods of time, such as tectonic activity, weathering, erosion, and sediment deposition. Major faults run parallel to the Bay Area's hills. These faults and the surficial quaternary geology (the geology of deposits laid down over the last 1.8 million years during the current geologic period) help us to understand how different sections of shoreline evolved and to evaluate settings that share similar underlying processes. For example, alluvial fan deposits, laid down by creeks flowing down from the hills over thousands of years, have influenced the shape of the baylands at their distal ends, creating a repeated, distinctive pattern.

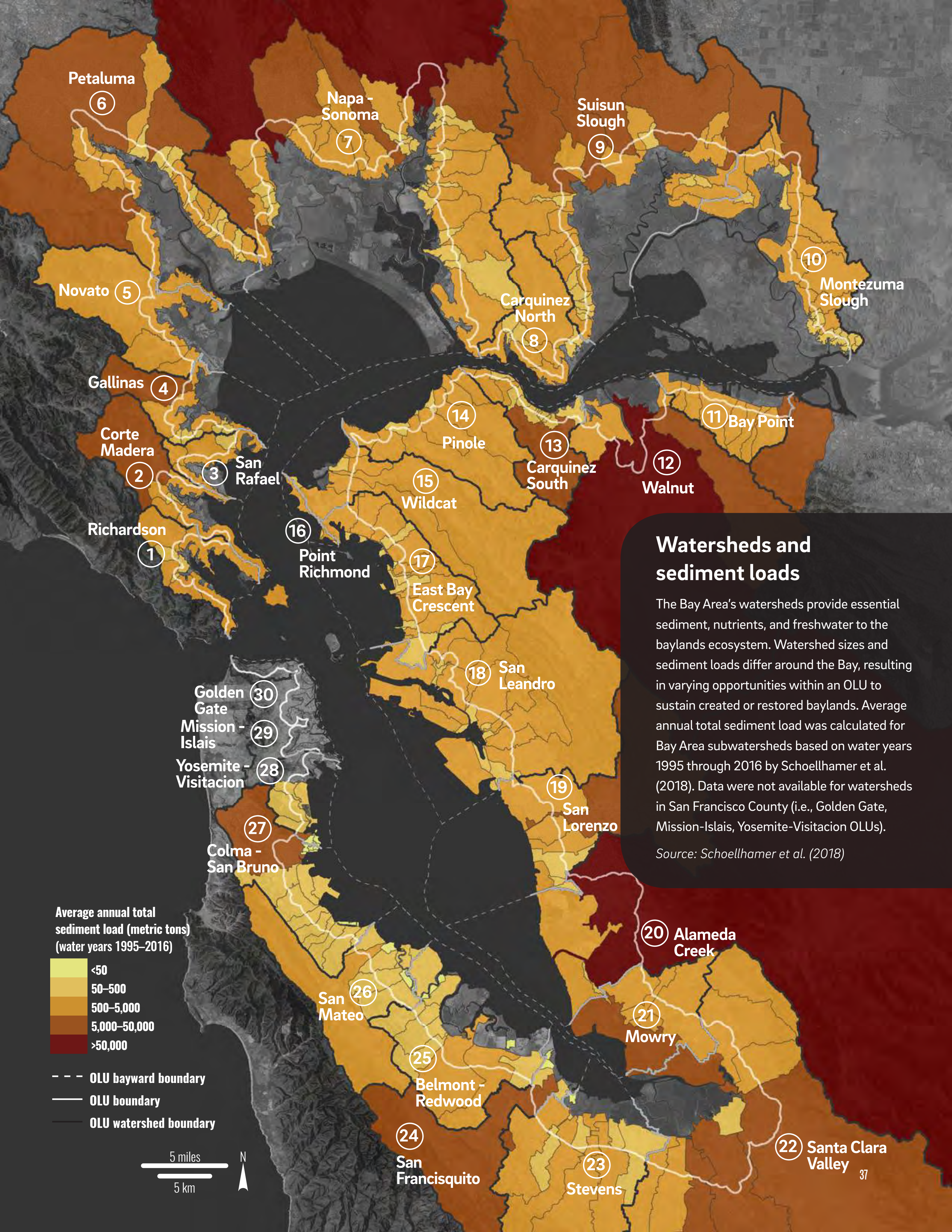
Source: Knudsen et al. (2000)



Land surface slope

The elevational profile between upland and subtidal areas is an important indicator of accommodation space extent. Little accommodation space exists where very steep gradients plunge into deep water (as shown on the map where red areas are close to the Bay) while more potential space exists in the areas with minimal relief, most notably at the northern and southern ends of the Bay.

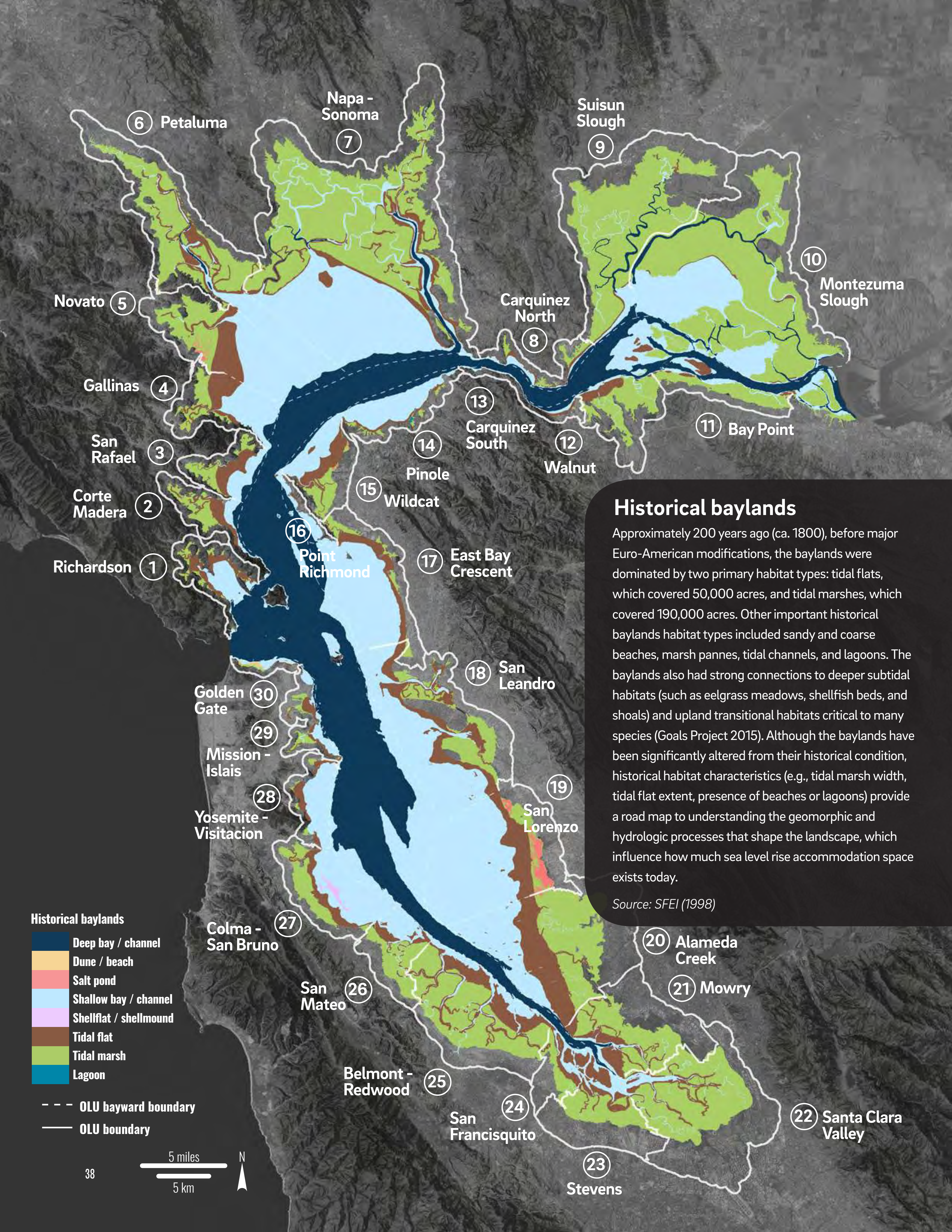
Source: USGS (2006)



Watersheds and sediment loads

The Bay Area's watersheds provide essential sediment, nutrients, and freshwater to the baylands ecosystem. Watershed sizes and sediment loads differ around the Bay, resulting in varying opportunities within an OLU to sustain created or restored baylands. Average annual total sediment load was calculated for Bay Area subwatersheds based on water years 1995 through 2016 by Schoellhamer et al. (2018). Data were not available for watersheds in San Francisco County (i.e., Golden Gate, Mission-Islais, Yosemite-Visitacion OLUs).

Source: Schoellhamer et al. (2018)



Historical baylands

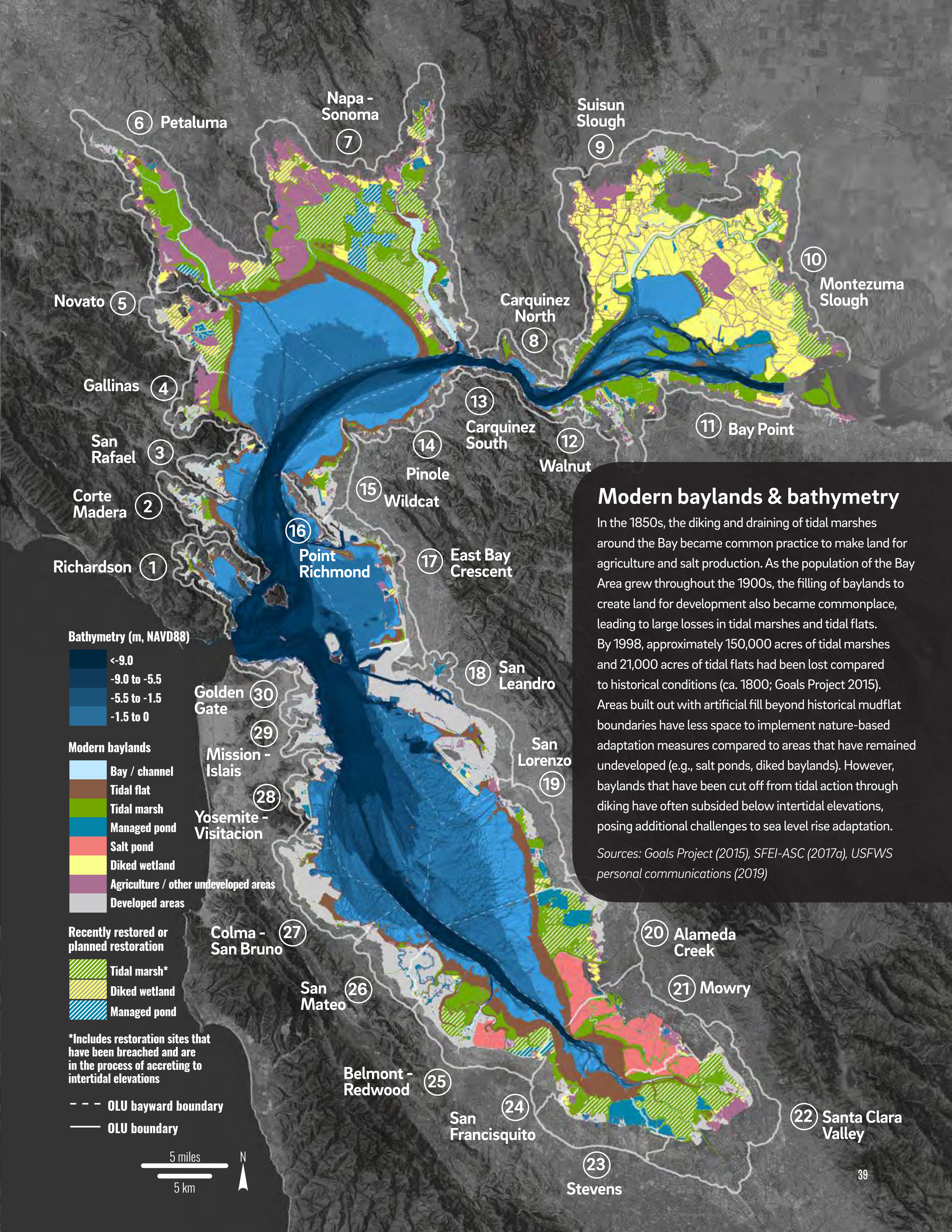
Approximately 200 years ago (ca. 1800), before major Euro-American modifications, the baylands were dominated by two primary habitat types: tidal flats, which covered 50,000 acres, and tidal marshes, which covered 190,000 acres. Other important historical baylands habitat types included sandy and coarse beaches, marsh pannes, tidal channels, and lagoons. The baylands also had strong connections to deeper subtidal habitats (such as eelgrass meadows, shellfish beds, and shoals) and upland transitional habitats critical to many species (Goals Project 2015). Although the baylands have been significantly altered from their historical condition, historical habitat characteristics (e.g., tidal marsh width, tidal flat extent, presence of beaches or lagoons) provide a road map to understanding the geomorphic and hydrologic processes that shape the landscape, which influence how much sea level rise accommodation space exists today.

Source: SFEI (1998)

Modern baylands & bathymetry

In the 1850s, the diking and draining of tidal marshes around the Bay became common practice to make land for agriculture and salt production. As the population of the Bay Area grew throughout the 1900s, the filling of baylands to create land for development also became commonplace, leading to large losses in tidal marshes and tidal flats. By 1998, approximately 150,000 acres of tidal marshes and 21,000 acres of tidal flats had been lost compared to historical conditions (ca. 1800; Goals Project 2015). Areas built out with artificial fill beyond historical mudflat boundaries have less space to implement nature-based adaptation measures compared to areas that have remained undeveloped (e.g., salt ponds, diked baylands). However, baylands that have been cut off from tidal action through diking have often subsided below intertidal elevations, posing additional challenges to sea level rise adaptation.

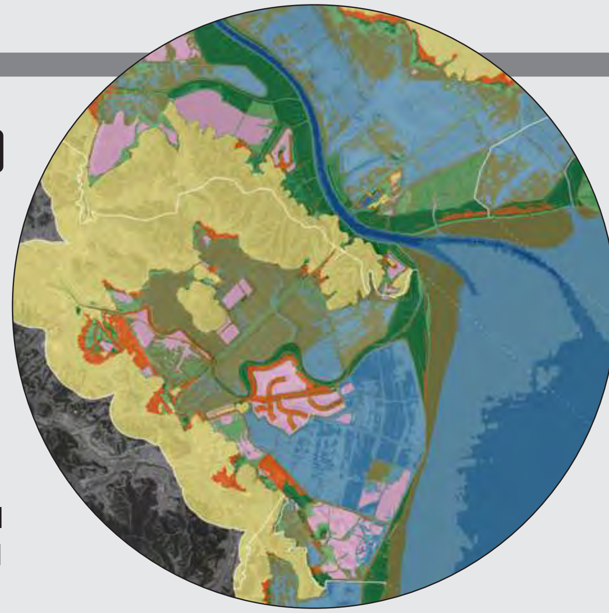
Sources: Goals Project (2015), SFEI-ASC (2017a), USFWS personal communications (2019)

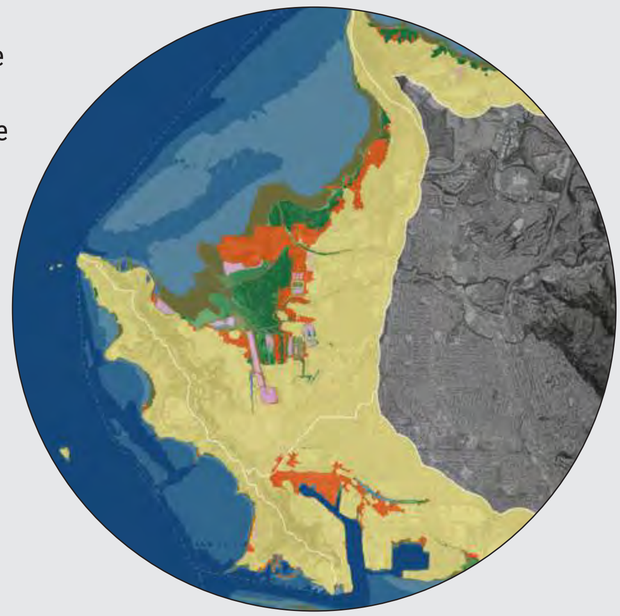


ELEVATION RELATIVE TO THE TIDES (z*)

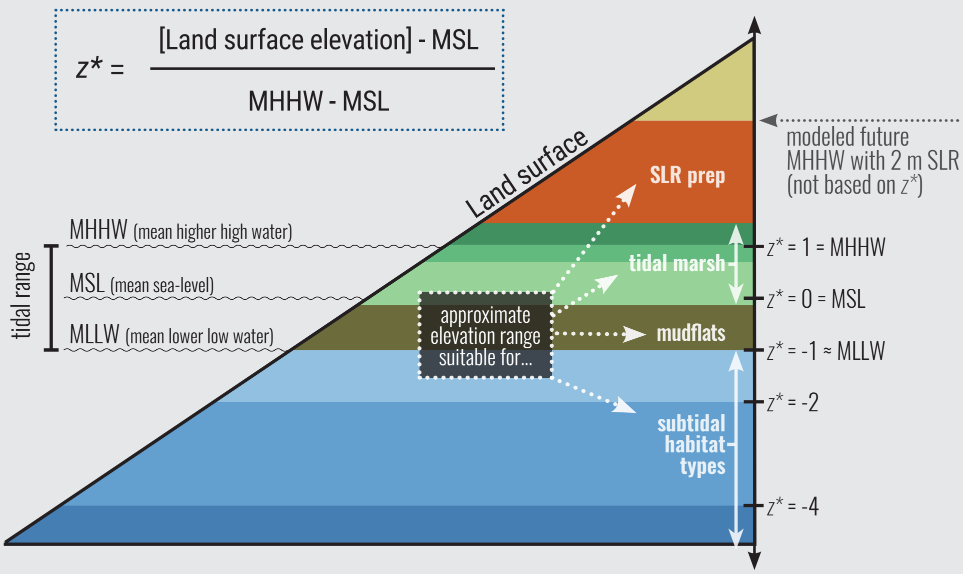
Elevation is a critical driver of which adaptation measures are appropriate in a given area. Particularly important is a site's elevation relative to the tides: whether an area is situated within, above, or below the tidal zone (and by how much) influences what types of natural communities can be supported and how vulnerable the area is to sea level rise. We determined the relative elevation within the tidal frame using a dimensionless metric referred to as *z**, calculated by dividing a location's height above or below mean sea level (MSL) by the local difference in height between mean higher high water (MHHW) and MSL (Swanson et al. 2014). By definition, *z** is equal to 0 when the land surface elevation is equal to the local elevation of MSL and *z** is equal to 1 when the land surface elevation is equal to the local elevation of MHHW. A *z** value of -1 would be approximately equal to mean lower low water (MLLW). See Appendix 5 for a more detailed discussion of how *z** was calculated and mapped.

Measuring elevation relative to the tides makes it possible to compare the elevation capital of marshes in different parts of the Bay with different tidal regimes (Cahoon and Gutenspergen 2010). Beyond helping to understand marsh resilience, knowing the relative elevation allows us to identify areas of the baylands that have subsided below MLLW and would be permanently inundated if opened to the tides (known as "polders"). Indeed, in Chapter 4, we use *z** to identify areas potentially appropriate for polder management, as well as for tidal marshes, ecotone levees, and migration space preparation.

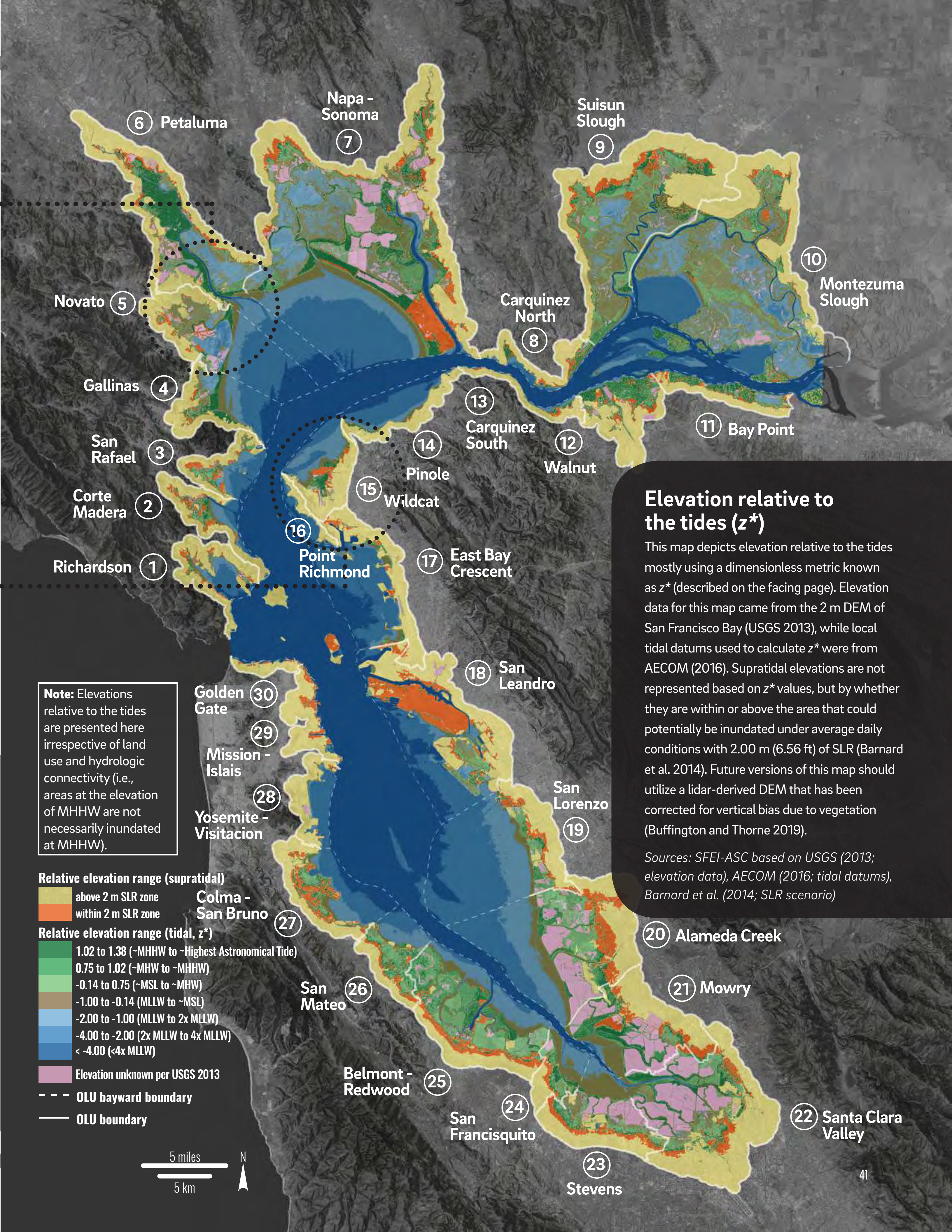




$$z^* = \frac{\text{[Land surface elevation] - MSL}}{\text{MHHW - MSL}}$$



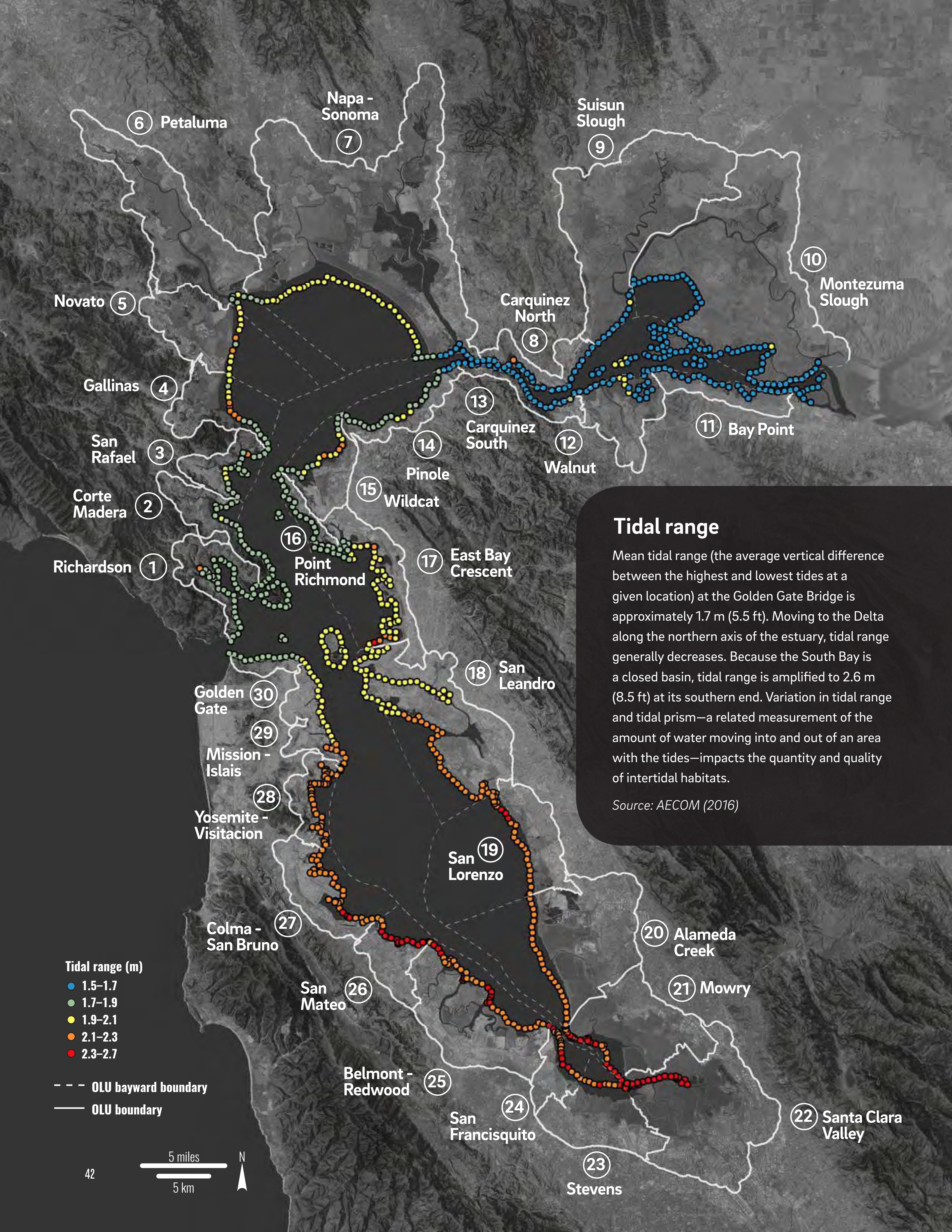
(Left) Schematic illustrating how tidal datums relate to relative elevation (z*) values. It also shows how different relative elevation ranges are suitable for different habitat types and management actions. Note that relative elevation is only one component of whether or not an area is actually suitable for a particular habitat type or management action (e.g., developed areas—even if at the right elevation for tidal marsh—are not good opportunities for tidal marsh restoration). The relative elevation ranges suitable for mudflats and tidal marshes were derived from Thorne et al. (2018).



Elevation relative to the tides (*z**)

This map depicts elevation relative to the tides mostly using a dimensionless metric known as *z** (described on the facing page). Elevation data for this map came from the 2 m DEM of San Francisco Bay (USGS 2013), while local tidal datums used to calculate *z** were from AECOM (2016). Supratidal elevations are not represented based on *z** values, but by whether they are within or above the area that could potentially be inundated under average daily conditions with 2.00 m (6.56 ft) of SLR (Barnard et al. 2014). Future versions of this map should utilize a lidar-derived DEM that has been corrected for vertical bias due to vegetation (Buffington and Thorne 2019).

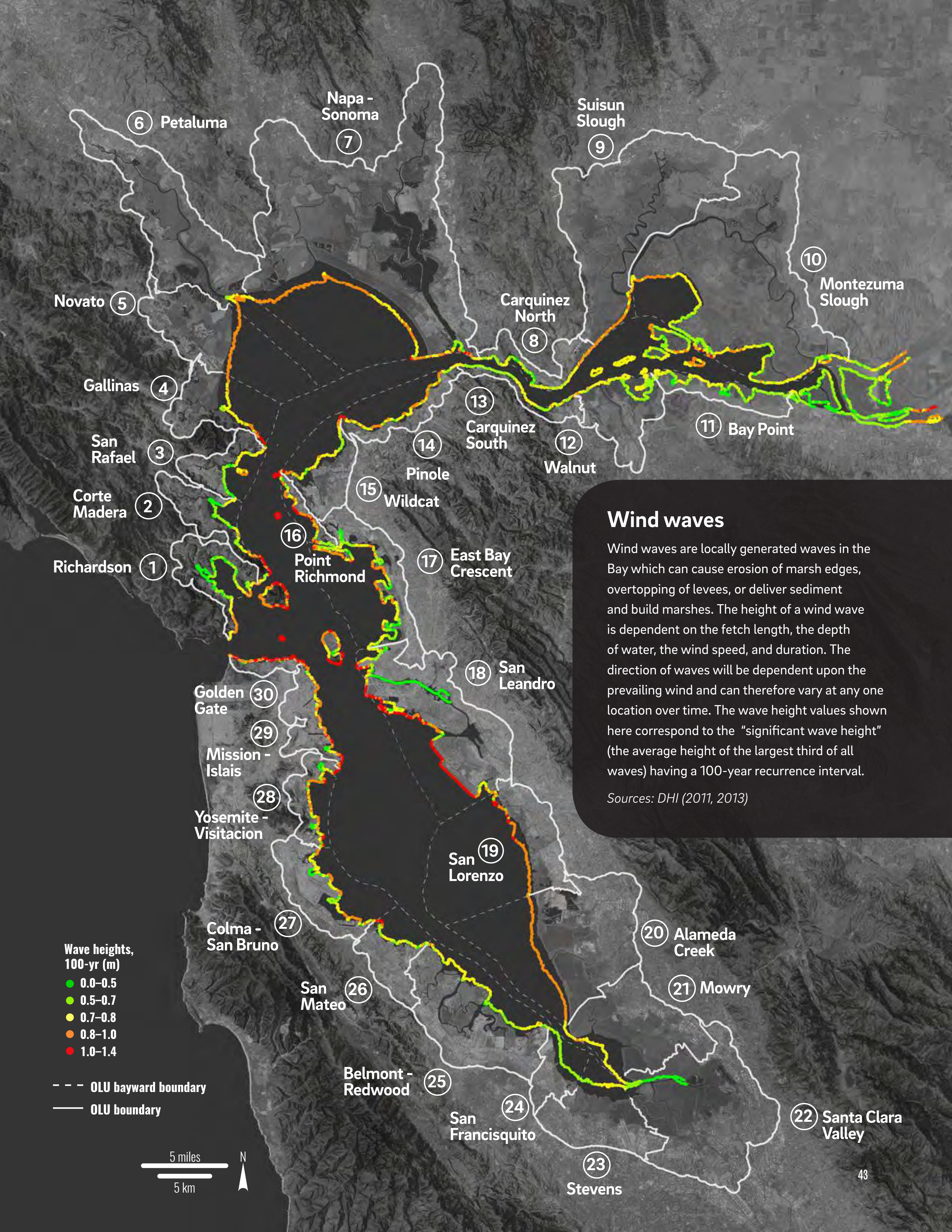
Sources: SFEI-ASC based on USGS (2013; elevation data), AECOM (2016; tidal datums), Barnard et al. (2014; SLR scenario)



Tidal range

Mean tidal range (the average vertical difference between the highest and lowest tides at a given location) at the Golden Gate Bridge is approximately 1.7 m (5.5 ft). Moving to the Delta along the northern axis of the estuary, tidal range generally decreases. Because the South Bay is a closed basin, tidal range is amplified to 2.6 m (8.5 ft) at its southern end. Variation in tidal range and tidal prism—a related measurement of the amount of water moving into and out of an area with the tides—impacts the quantity and quality of intertidal habitats.

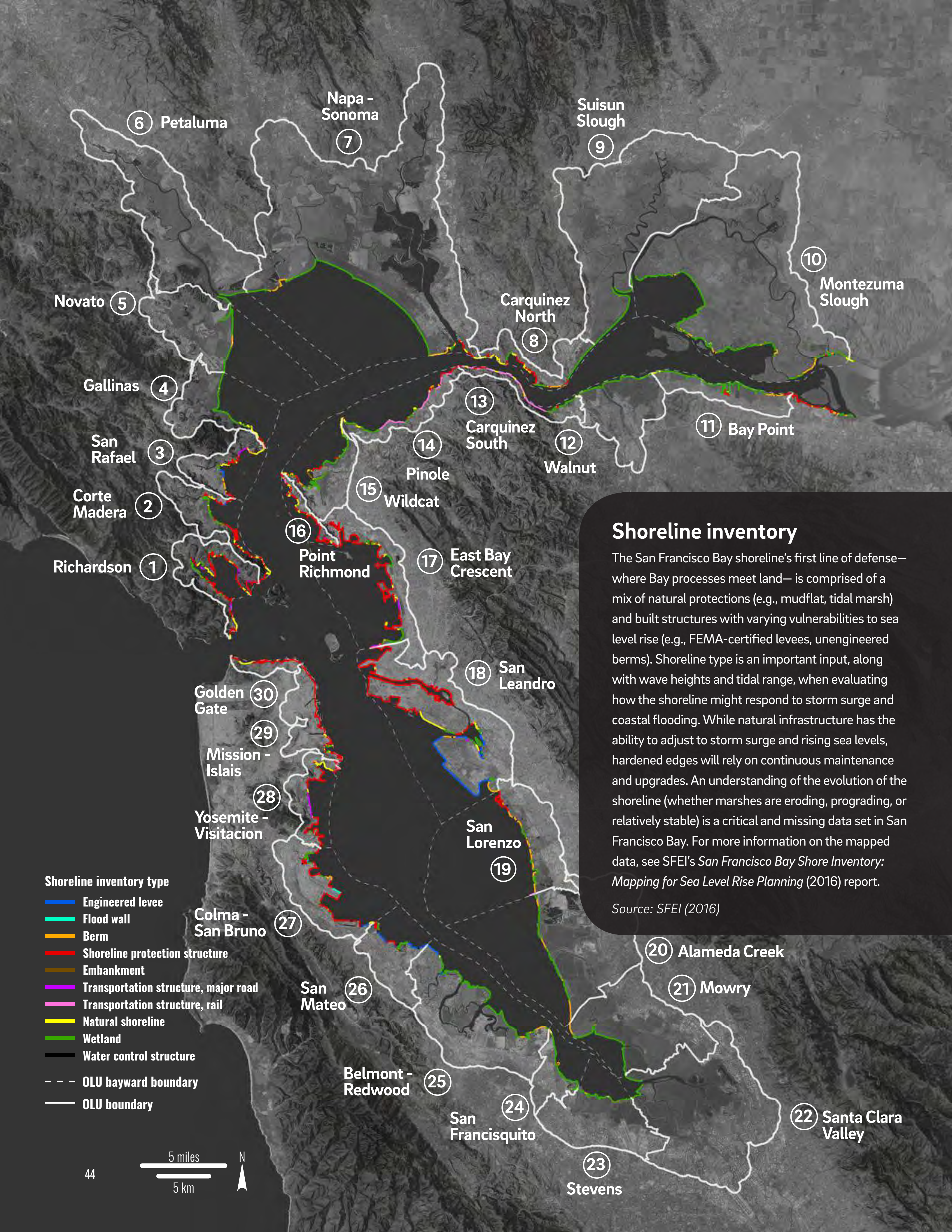
Source: AECOM (2016)



Wind waves

Wind waves are locally generated waves in the Bay which can cause erosion of marsh edges, overtopping of levees, or deliver sediment and build marshes. The height of a wind wave is dependent on the fetch length, the depth of water, the wind speed, and duration. The direction of waves will be dependent upon the prevailing wind and can therefore vary at any one location over time. The wave height values shown here correspond to the "significant wave height" (the average height of the largest third of all waves) having a 100-year recurrence interval.

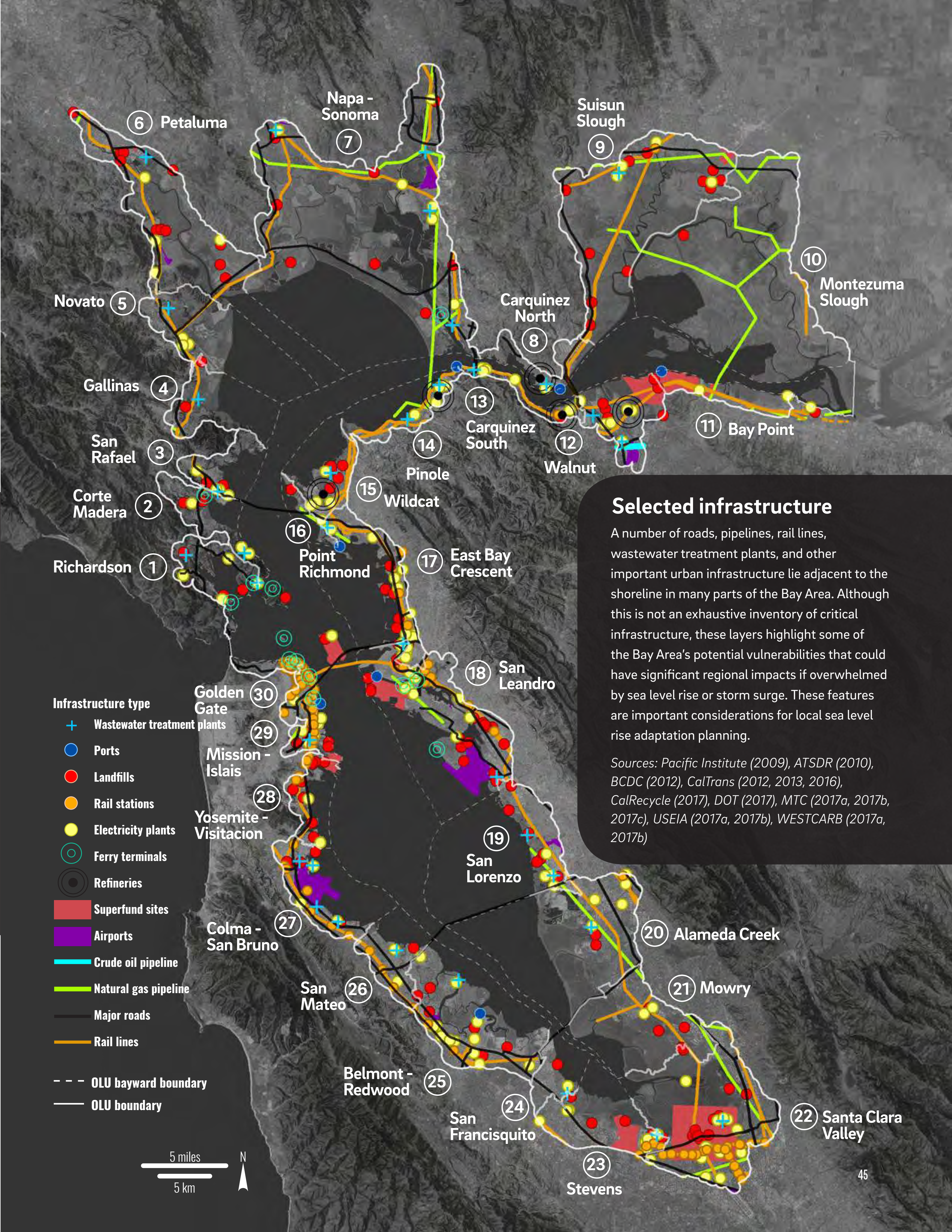
Sources: DHI (2011, 2013)



Shoreline inventory

The San Francisco Bay shoreline's first line of defense—where Bay processes meet land— is comprised of a mix of natural protections (e.g., mudflat, tidal marsh) and built structures with varying vulnerabilities to sea level rise (e.g., FEMA-certified levees, unengineered berms). Shoreline type is an important input, along with wave heights and tidal range, when evaluating how the shoreline might respond to storm surge and coastal flooding. While natural infrastructure has the ability to adjust to storm surge and rising sea levels, hardened edges will rely on continuous maintenance and upgrades. An understanding of the evolution of the shoreline (whether marshes are eroding, prograding, or relatively stable) is a critical and missing data set in San Francisco Bay. For more information on the mapped data, see SFEI's *San Francisco Bay Shore Inventory: Mapping for Sea Level Rise Planning* (2016) report.

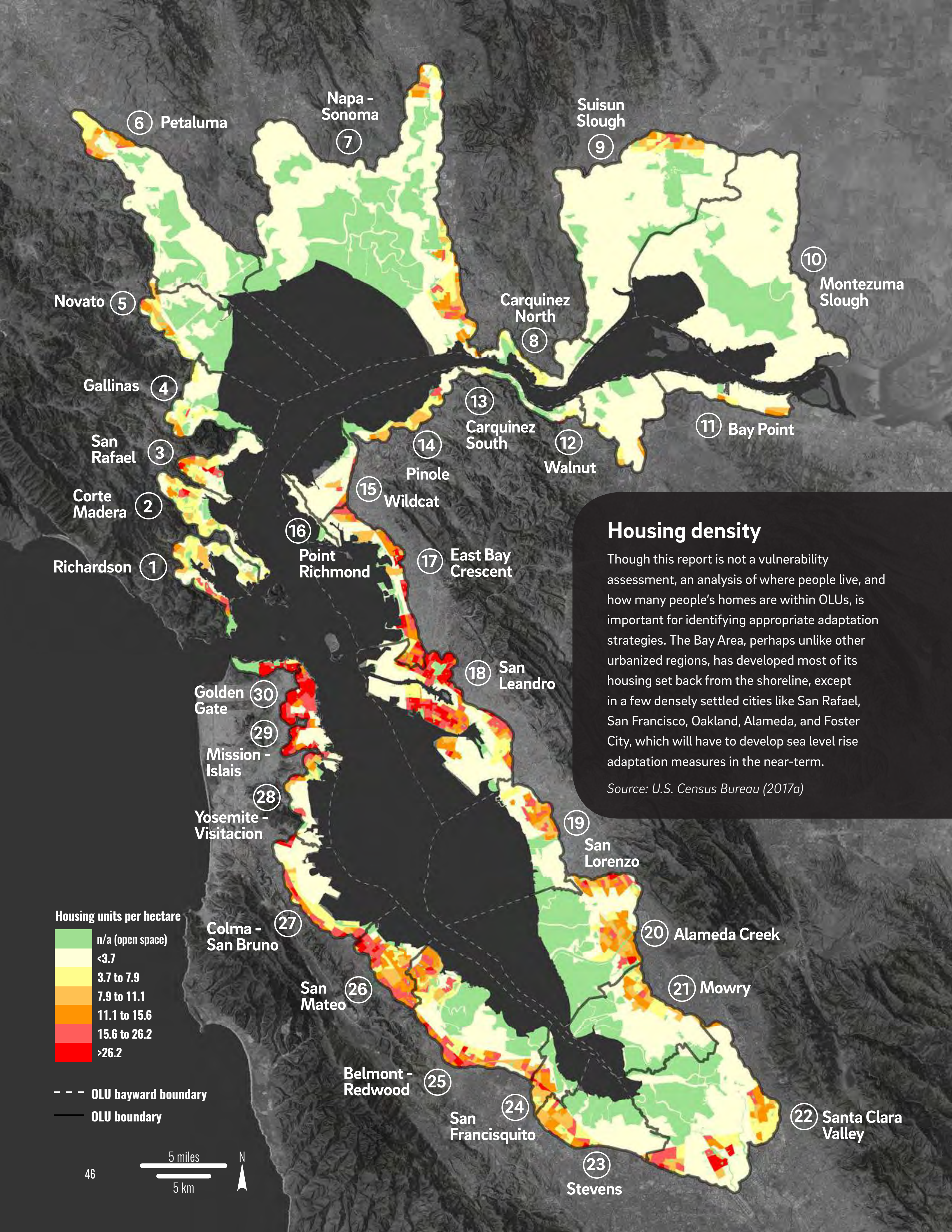
Source: SFEI (2016)



Selected infrastructure

A number of roads, pipelines, rail lines, wastewater treatment plants, and other important urban infrastructure lie adjacent to the shoreline in many parts of the Bay Area. Although this is not an exhaustive inventory of critical infrastructure, these layers highlight some of the Bay Area's potential vulnerabilities that could have significant regional impacts if overwhelmed by sea level rise or storm surge. These features are important considerations for local sea level rise adaptation planning.

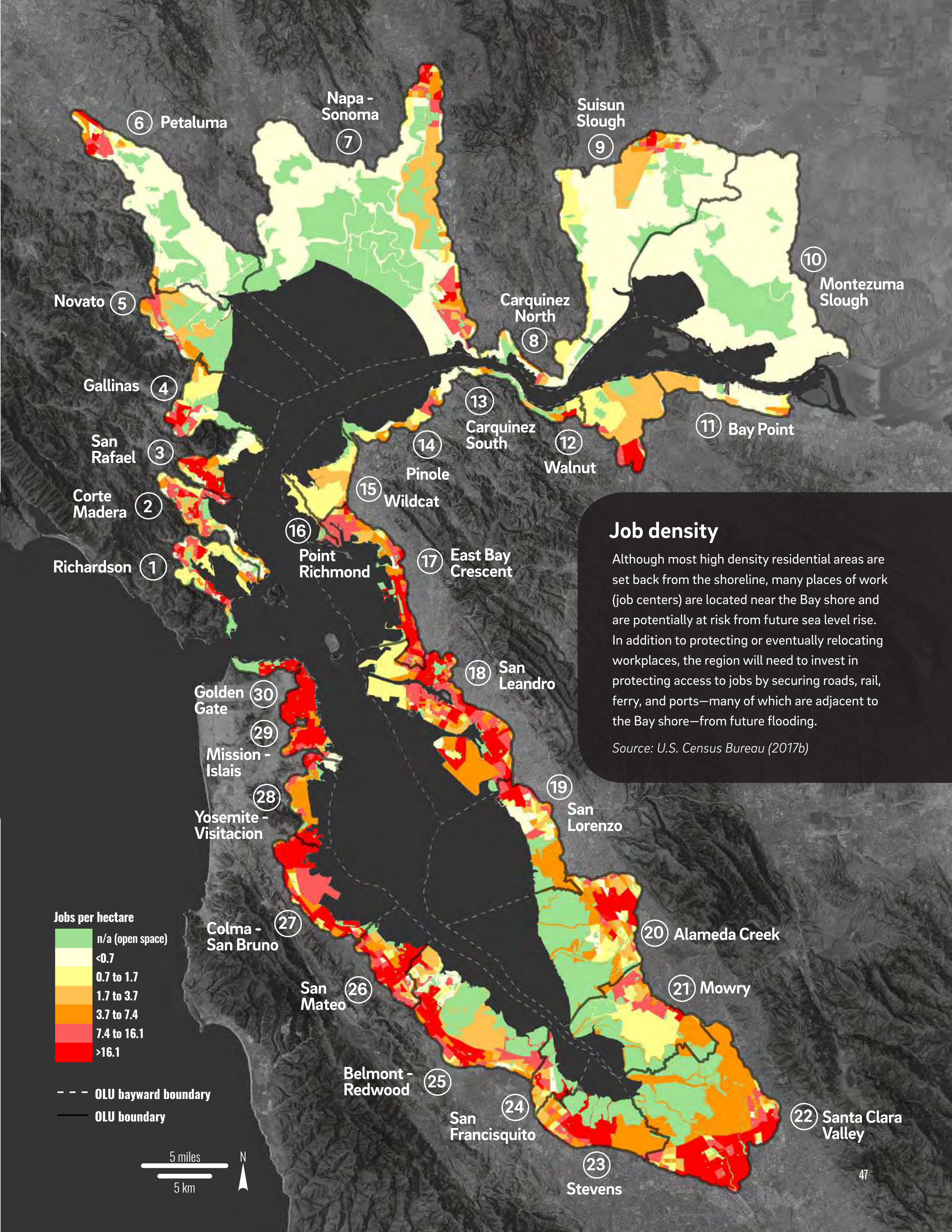
Sources: Pacific Institute (2009), ATSDR (2010), BCDC (2012), CalTrans (2012, 2013, 2016), CalRecycle (2017), DOT (2017), MTC (2017a, 2017b, 2017c), USEIA (2017a, 2017b), WESTCARB (2017a, 2017b)



Housing density

Though this report is not a vulnerability assessment, an analysis of where people live, and how many people's homes are within OLUs, is important for identifying appropriate adaptation strategies. The Bay Area, perhaps unlike other urbanized regions, has developed most of its housing set back from the shoreline, except in a few densely settled cities like San Rafael, San Francisco, Oakland, Alameda, and Foster City, which will have to develop sea level rise adaptation measures in the near-term.

Source: U.S. Census Bureau (2017a)



Job density

Although most high density residential areas are set back from the shoreline, many places of work (job centers) are located near the Bay shore and are potentially at risk from future sea level rise. In addition to protecting or eventually relocating workplaces, the region will need to invest in protecting access to jobs by securing roads, rail, ferry, and ports—many of which are adjacent to the Bay shore—from future flooding.

Source: U.S. Census Bureau (2017b)

PLACE TYPES

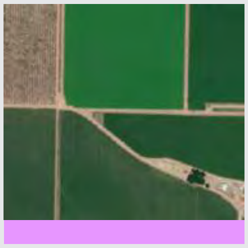
The San Francisco Bay Area Planning and Urban Research Association (SPUR) developed place types to classify every quarter-square-mile of the Bay Area into major categories of land use and physical form. SPUR defined 14 distinct place types in four different categories: rural and open space, primarily residential, primarily job centers, and densely mixed uses.

Place types were generated from five variables: housing density, job density, road intersection density, pavement permeability, and how mixed the land use is. While many variables can be used to describe or illustrate land use, including zoning, population density, and others, these five variables best help classify how densely and intensely developed different areas are in terms of both housing and economic activity. This provides a proxy for how flexible areas may be to a range of potential sea level rise adaptation strategies, particularly policy, financial, and regulatory measures.

For more details on the methods used to create the place types, see Appendix 3.

RURAL AND OPEN SPACE

Parks and protected areas: Span the region and include federal, state, regional, and city parks and more.



Cultivated land: croplands and wineries.

Rural and open space: Spread over half the region and include working lands, sparse housing and more.

PRIMARILY RESIDENTIAL

Suburban edge: Very low density housing; single family homes at the edge of open space.

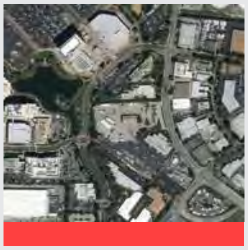
Cul-de-sac suburbs: Low density housing; rings the center of almost every city of the region.

Small lot and streetcar suburbs: Medium density housing; found mostly in older San Francisco, East Bay, and Peninsula neighborhoods.

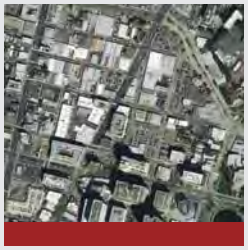
PRIMARILY JOB CENTERS

Industrial and infrastructure: Very low density jobs; large, low buildings with few intersections.

Office parks: Low density jobs; couple-story buildings for office, retail, and other jobs.

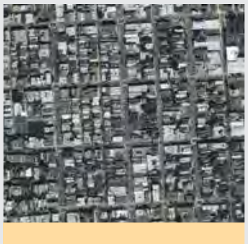


Job centers: Medium density jobs; multi-story commercial buildings in many cities.



Urban job centers: High density jobs; ten-plus story offices in job centers and large cities.

DENSELY MIXED USES (FOUND ONLY IN SAN FRANCISCO AND OAKLAND)

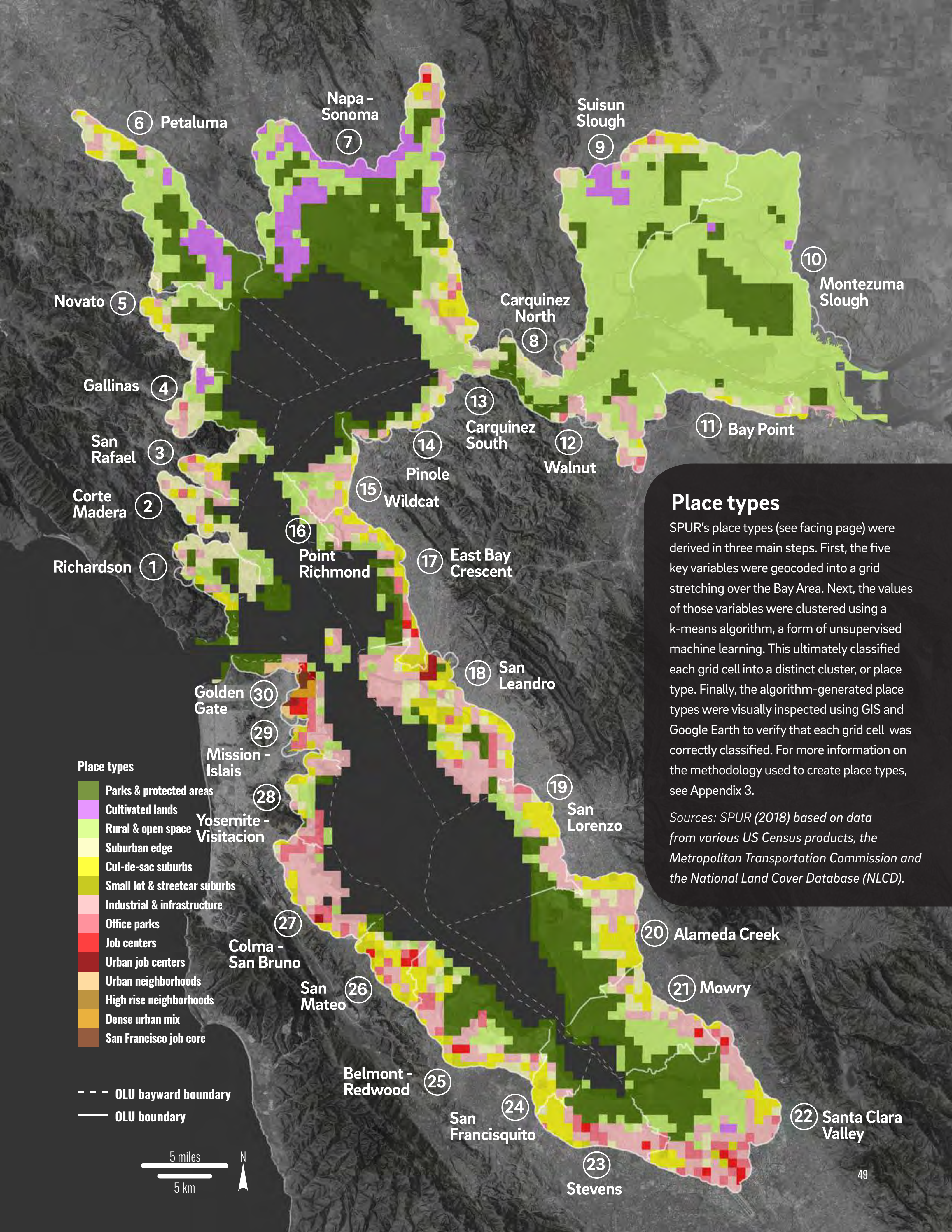


Urban neighborhoods: Multifamily housing, retail and jobs (San Francisco and Oakland only).

High rise neighborhoods: Multistory housing and jobs on small blocks (San Francisco only).

Dense urban mix: Residential and job towers (San Francisco and Oakland only).

San Francisco job core: Highest job density in the region (downtown San Francisco only).



Place types

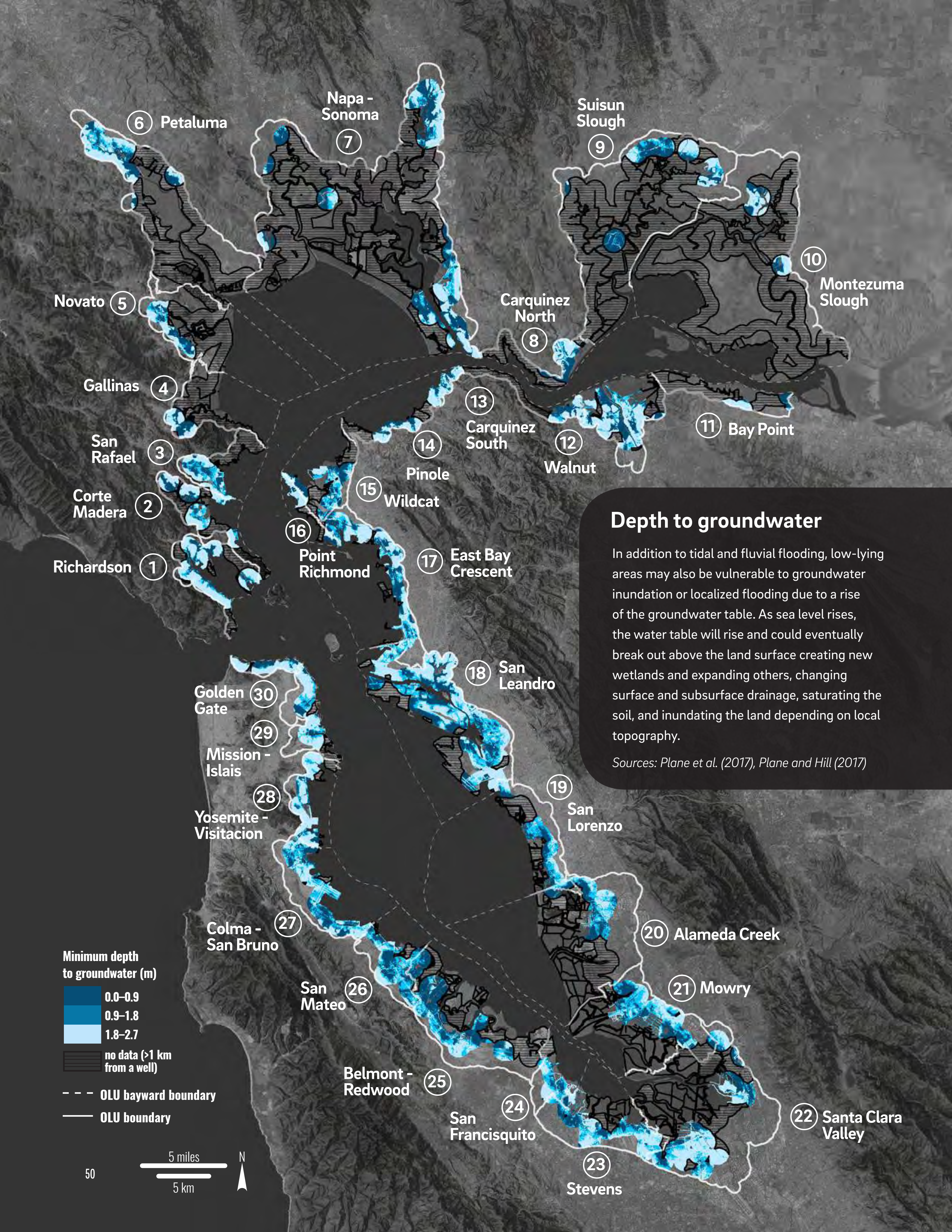
SPUR's place types (see facing page) were derived in three main steps. First, the five key variables were geocoded into a grid stretching over the Bay Area. Next, the values of those variables were clustered using a k-means algorithm, a form of unsupervised machine learning. This ultimately classified each grid cell into a distinct cluster, or place type. Finally, the algorithm-generated place types were visually inspected using GIS and Google Earth to verify that each grid cell was correctly classified. For more information on the methodology used to create place types, see Appendix 3.

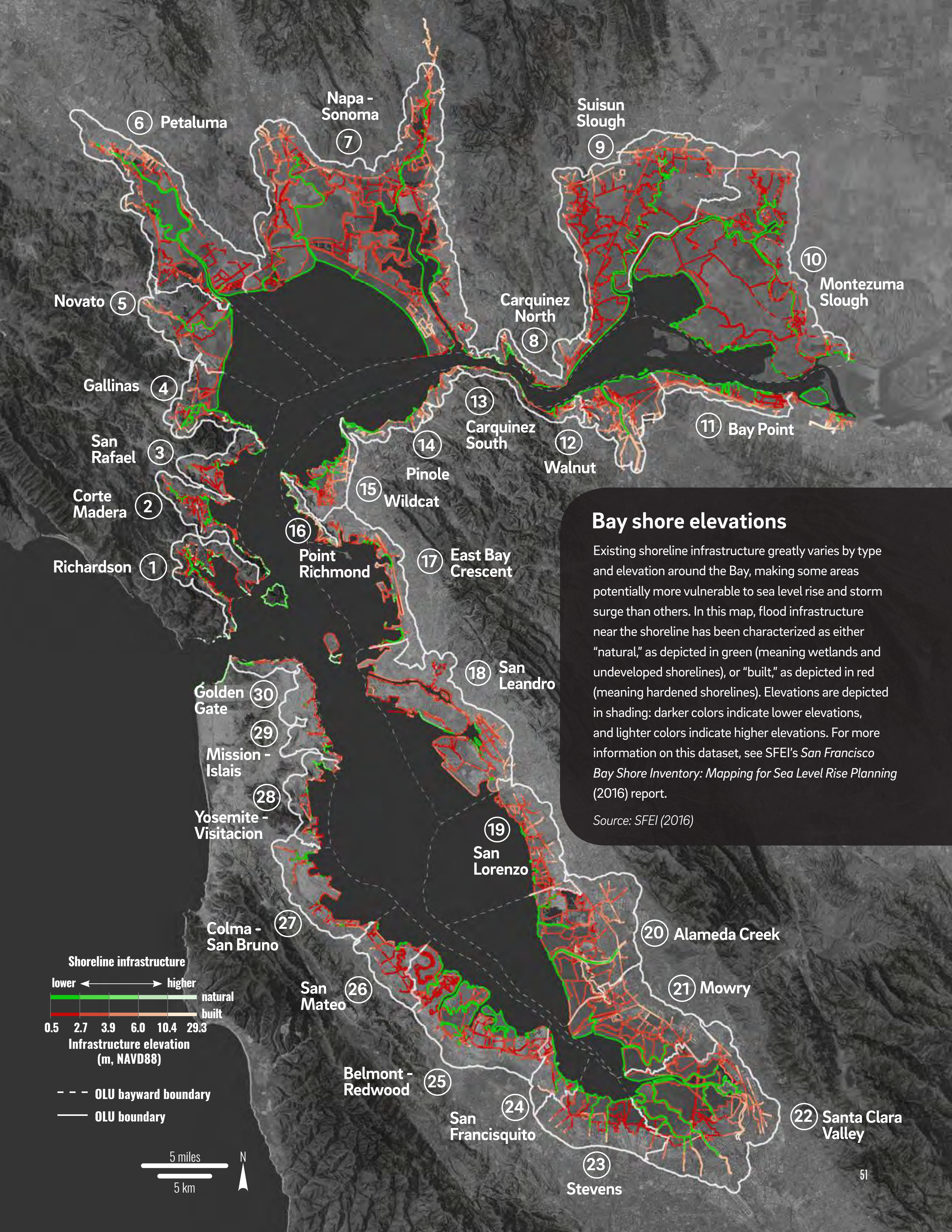
Sources: SPUR (2018) based on data from various US Census products, the Metropolitan Transportation Commission and the National Land Cover Database (NLCD).

Depth to groundwater

In addition to tidal and fluvial flooding, low-lying areas may also be vulnerable to groundwater inundation or localized flooding due to a rise of the groundwater table. As sea level rises, the water table will rise and could eventually break out above the land surface creating new wetlands and expanding others, changing surface and subsurface drainage, saturating the soil, and inundating the land depending on local topography.

Sources: Plane et al. (2017), Plane and Hill (2017)





Bay shore elevations

Existing shoreline infrastructure greatly varies by type and elevation around the Bay, making some areas potentially more vulnerable to sea level rise and storm surge than others. In this map, flood infrastructure near the shoreline has been characterized as either "natural," as depicted in green (meaning wetlands and undeveloped shorelines), or "built," as depicted in red (meaning hardened shorelines). Elevations are depicted in shading: darker colors indicate lower elevations, and lighter colors indicate higher elevations. For more information on this dataset, see SFEI's *San Francisco Bay Shore Inventory: Mapping for Sea Level Rise Planning* (2016) report.

Source: SFEI (2016)

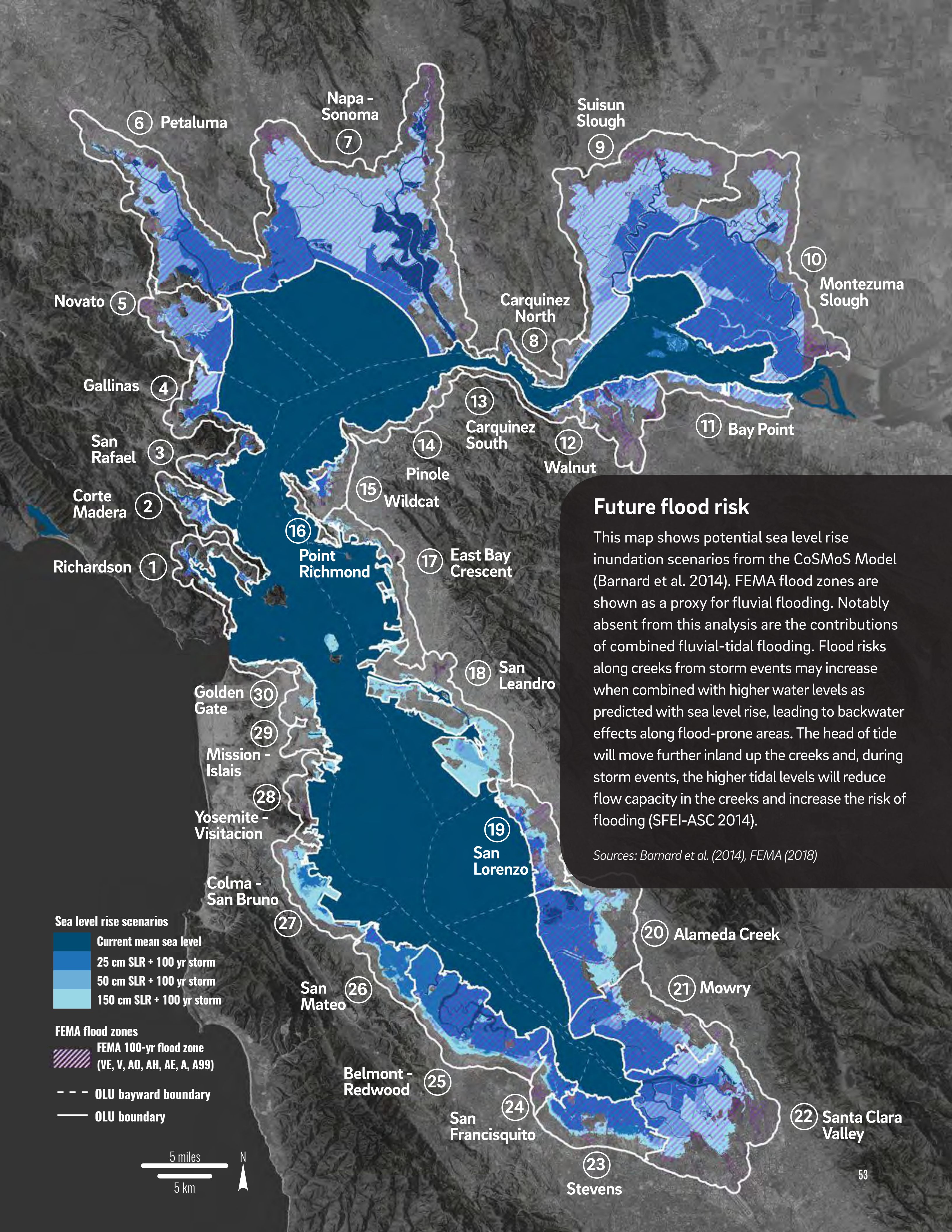
Summarizing estimated flood risk by OLU

This table and the accompanying map summarize the areal extent of coastal flooding during a 100-year storm event in each OLU under three different sea level rise (SLR) scenarios as modeled and mapped by the USGS Coastal Storm Modeling System (CoSMos 2.0; Barnard et al. 2014). The maps of inundation are based on current topography and do constitute a vulnerability analysis. Instead, this analysis shows the extent of low-lying ground as a first-cut approximation of exposure by OLU over time. Some OLUs, such as Pinole and Yosemite-Visitacion, may have a smaller percentage of land area inundated over time, likely due to their steeper shorelines. Other OLUs, such as Montezuma Slough and Belmont-Redwood, have extensive areas situated at low elevations that are within the sea level rise inundation projections if no actions are taken. Finally, OLUs such as Colma-San Bruno and Bay Point have lower percentages of their land at risk of inundation under lower sea level rise scenarios, but as seas rise their flood risk may increase. The levels and timing of possible risk tend to align with the slope, elevations, and orientation of the baylands and shoreline.

ESTIMATED FUTURE FLOOD RISK

OLU	Extent of OLU inundated with 25 cm SLR & 100-yr storm surge (%)	Extent of OLU inundated with 50 cm SLR & 100-yr storm surge (%)	Extent of OLU inundated with 150 cm SLR & 100-yr storm surge (%)
1. Richardson	7%	9%	16%
2. Corte Madera	11%	17%	30%
3. San Rafael	22%	26%	35%
4. Gallinas	21%	23%	44%
5. Novato	27%	51%	58%
6. Petaluma	28%	42%	55%
7. Napa - Sonoma	27%	29%	68%
8. Carquinez North	5%	12%	21%
9. Suisun Slough	12%	19%	60%
10. Montezuma Slough	52%	56%	73%
11. Bay Point	3%	26%	46%
12. Walnut	11%	23%	36%
13. Carquinez South	5%	6%	9%
14. Pinole	2%	2%	5%
15. Wildcat	13%	15%	24%
16. Point Richmond	0%	0%	2%
17. East Bay Crescent	2%	3%	12%
18. San Leandro	1%	7%	41%
19. San Lorenzo	17%	23%	42%
20. Alameda Creek	47%	49%	67%
21. Mowry	45%	52%	65%
22. Santa Clara Valley	17%	27%	54%
23. Stevens	44%	49%	61%
24. San Francisquito	49%	53%	62%
25. Belmont - Redwood	66%	71%	80%
26. San Mateo	51%	56%	64%
27. Colma - San Bruno	12%	20%	54%
28. Yosemite - Visitacion	1%	3%	11%
29. Mission - Islais	2%	2%	15%
30. Golden Gate	0%	0%	12%

Sea level rise projections based on Barnard et al. (2014)



Future flood risk

This map shows potential sea level rise inundation scenarios from the CoSMoS Model (Barnard et al. 2014). FEMA flood zones are shown as a proxy for fluvial flooding. Notably absent from this analysis are the contributions of combined fluvial-tidal flooding. Flood risks along creeks from storm events may increase when combined with higher water levels as predicted with sea level rise, leading to backwater effects along flood-prone areas. The head of tide will move further inland up the creeks and, during storm events, the higher tidal levels will reduce flow capacity in the creeks and increase the risk of flooding (SFEI-ASC 2014).

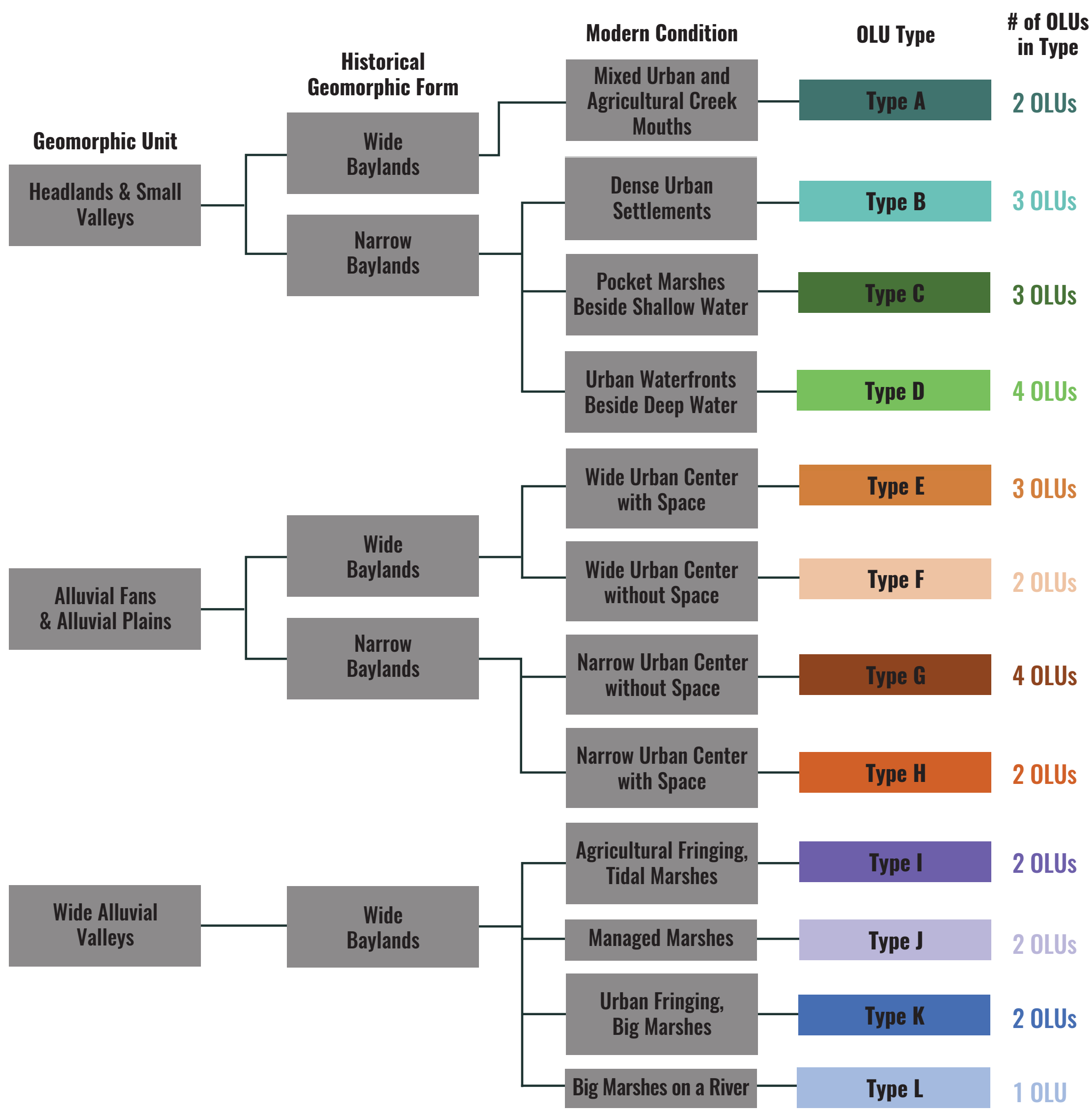
Sources: Barnard et al. (2014), FEMA (2018)

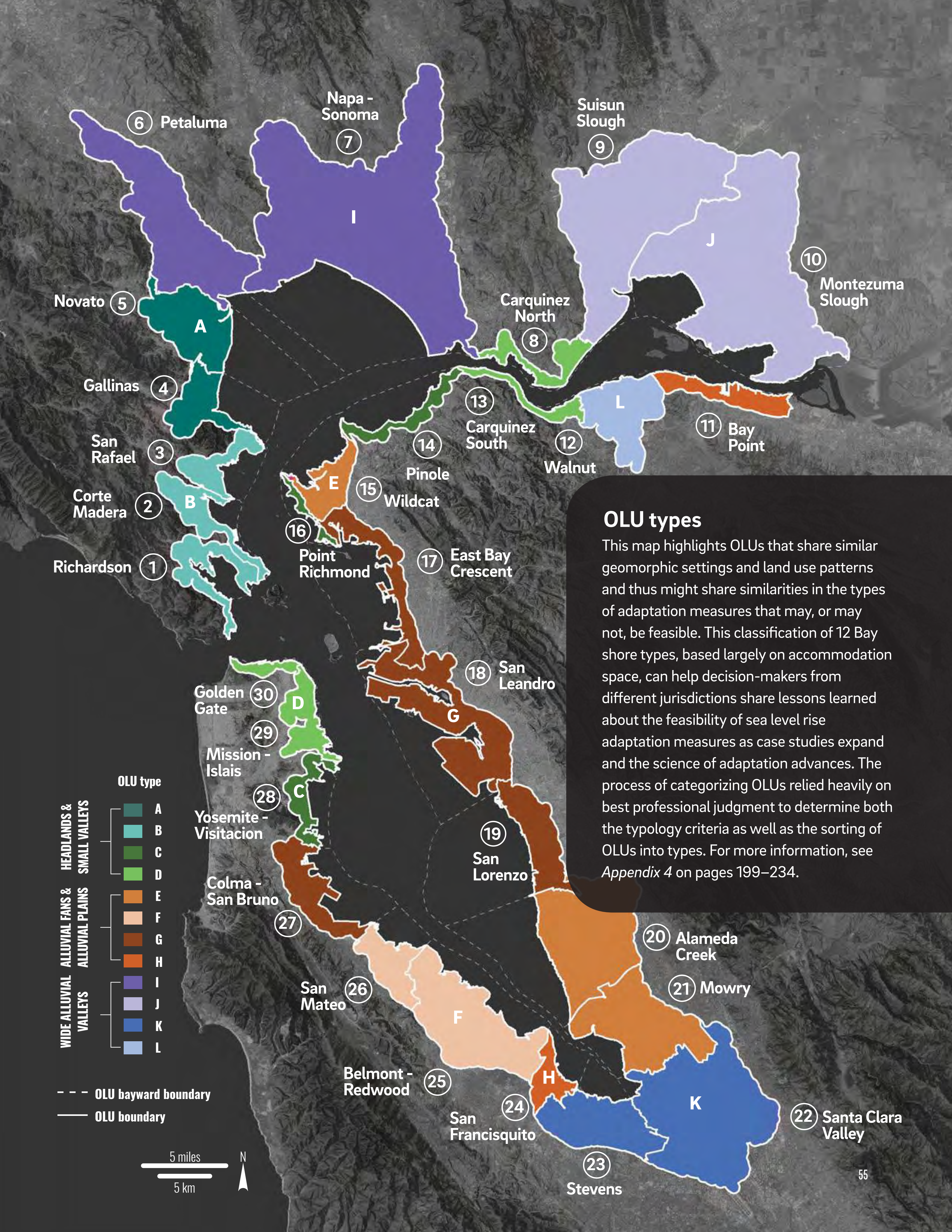
An OLU typology

The data layers described in this chapter reflect the unique vulnerabilities, opportunities, and features within each Baylands OLU that helps determine the appropriateness and feasibility of different adaptation measures. We created a typology—a classification of general Bay shore types—to describe fundamental similarities and differences between OLUs on a regional level to help guide successful and sustainable adaptation planning efforts. Using a combination of data analysis and best professional judgment, we categorized the 30 OLUs into 12 types to understand how stretches of shoreline in different parts of the Bay may be similar in character and may have similar challenges. The types are based on differing historical and current landscape setting of each OLU, and incorporate a broad characterization of the modern place types. The resulting OLU Types, while perhaps overly simplifying the vast complexity within and between OLUs, complement the information in *Chapter 5: Adaptation opportunities by OLU*.

Regulators, policy-makers, planners, and engineers can use the OLU typology to apply lessons learned from existing and future sea level rise adaptation case studies in one OLU to other OLUs in diverse geographic regions throughout the Bay that share some similar characteristics. Since municipalities, counties, and regulatory agencies rarely operate within natural boundaries, OLU Types could help catalyze collaborations beyond traditional jurisdictions. For more detailed information on OLU Types, including maps, methods, and visual tools, see pages 199–234 of Appendix 4.

The process used to classify the 30 OLUs into 12 types. Accommodation space—where sufficient room exists to implement a nature-based adaptation measure along a stretch of shoreline—was a key variable used to map each nature-based adaptation measure and became the main variable guiding typology classification. This process relied heavily on best professional judgment to determine both the typology criteria as well as the sorting of OLUs into types.





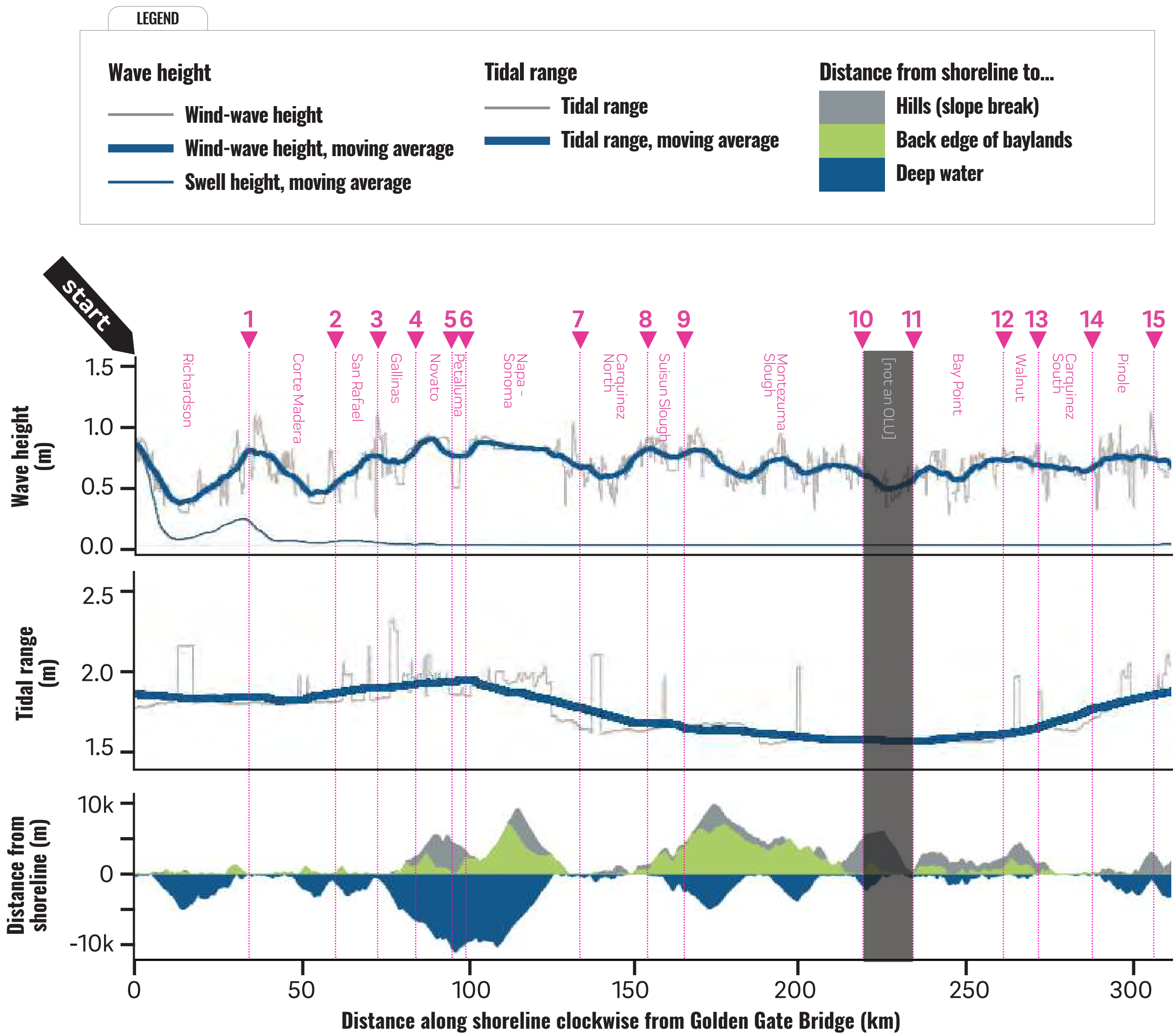
OLU types

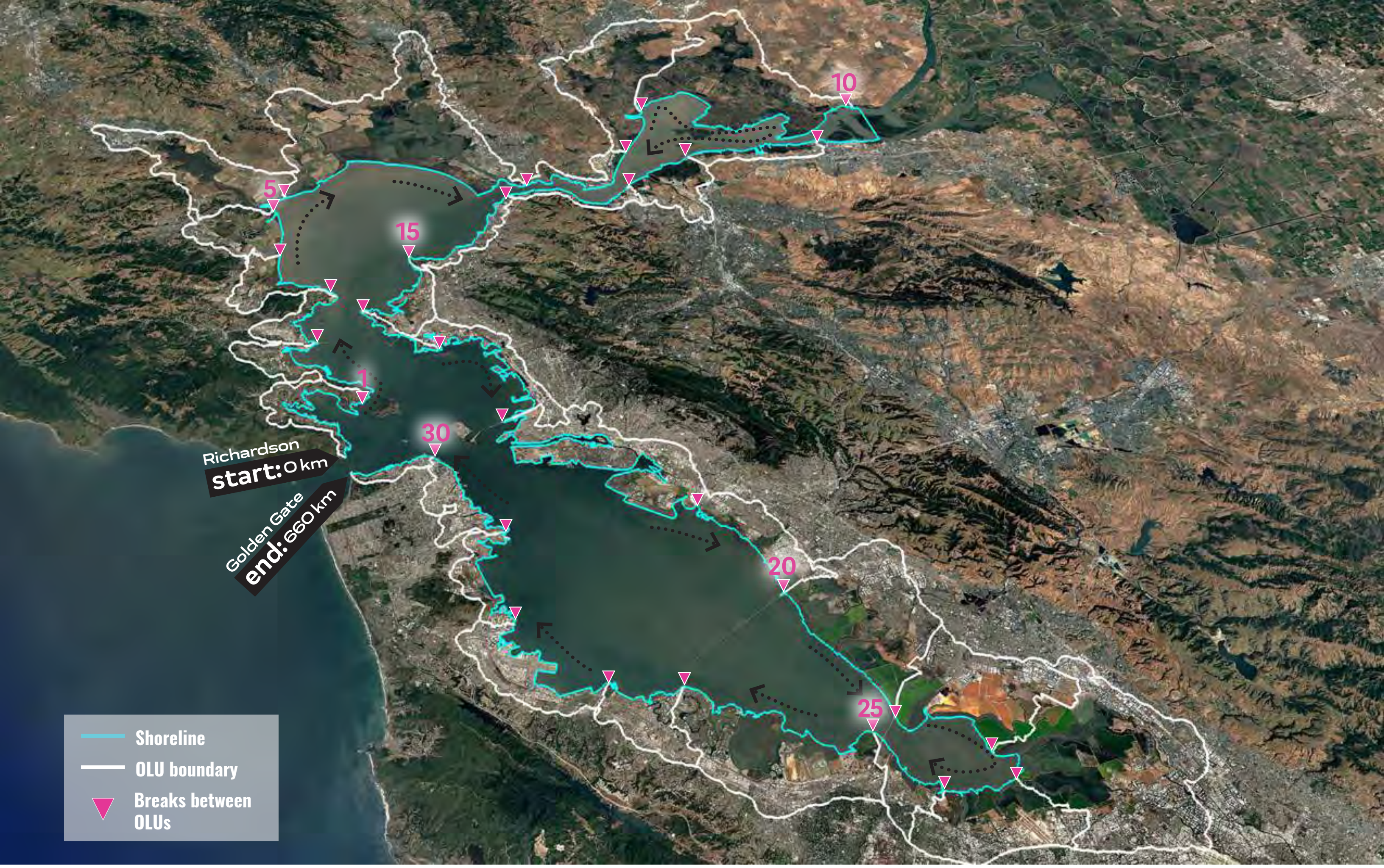
This map highlights OLUs that share similar geomorphic settings and land use patterns and thus might share similarities in the types of adaptation measures that may, or may not, be feasible. This classification of 12 Bay shore types, based largely on accommodation space, can help decision-makers from different jurisdictions share lessons learned about the feasibility of sea level rise adaptation measures as case studies expand and the science of adaptation advances. The process of categorizing OLUs relied heavily on best professional judgment to determine both the typology criteria as well as the sorting of OLUs into types. For more information, see *Appendix 4* on pages 199–234.

The Bay unraveled

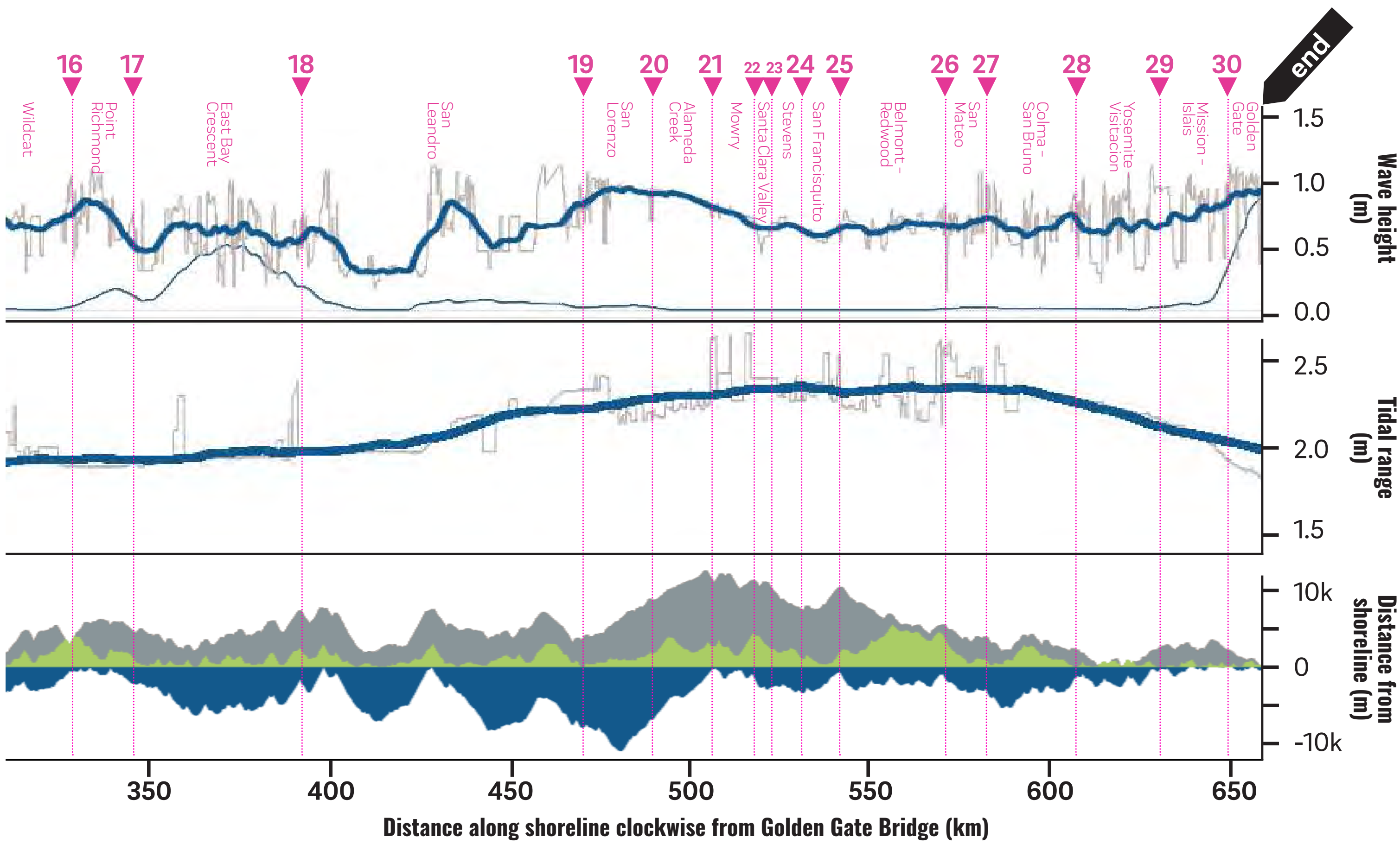
(Below and facing page) **Key physical variables plotted along the unraveled Bay shoreline**, moving clockwise from the Richardson OLU (0 km mark) to the Golden Gate OLU (660 km mark). The aerial image on the facing page illustrates the locations marked on the chart. (Imagery courtesy Google Earth)

Here we snip the Bay shore at the Golden Gate, and unravel it, graphing a few example variables analyzed every 100 m (328 ft) along the entire shoreline. The x-axis demarcates shoreline position by moving clockwise from the Golden Gate bridge in Marin (0 km) along the entire Bay shoreline and ending at the Golden Gate bridge in San Francisco (660 km [410 mi]). The y-axis displays three spatial variables at different scales to compare across OLUs: 1) wave heights, 2) tidal range, and 3) distances from the shoreline to the deep water channel, the back edge of the historical baylands, and the first major slope break at the base of the hills. This way of visualizing data can help see breaks in the landscape that characterize different OLUs. For example, around kilometer 130, Carquinez Strait is associated with a decrease in tidal range and very narrow topography. The wide Napa-Sonoma baylands are apparent in the large distance from the shoreline to the edge of the baylands values between kilometers 100 and 130.





Richardson
start: 0 km
Golden Gate
end: 660 km
1
5
10
15
20
25
30
Shoreline
OLU boundary
Breaks between OLUs



end
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
Wildcat
Point Richmond
East Bay Crescent
San Leandro
San Lorenzo
Alameda Creek
Mowry
Santa Clara Valley
Stevens
San Francisquito
Belmont - Redwood
San Mateo
Colma - San Bruno
Yosemite Visitacion
Mission - Islais
Golden Gate
Wave height (m)
1.5
1.0
0.5
0.0
Tidal range (m)
2.5
2.0
1.5
Distance from shoreline (m)
10k
0
-10k
350
400
450
500
550
600
650
Distance along shoreline clockwise from Golden Gate Bridge (km)

RICHMOND SHORELINE NORTH OF POINT ISABEL • PHOTO BY SHIRA BEZALEL, SFEI

4 ADAPTATION MEASURES

The natural shoreline of the Bay Area has been significantly modified over time through diking, ditching, draining, dredging, development, and other changes. Today's shoreline needs regular maintenance to keep people safe from flooding, does not always integrate well with the Bay's natural habitats, and is not designed to accommodate rapid sea level rise (SLR). There are significant opportunities to develop adaptation strategies and modify our shorelines to incorporate natural and nature-based measures which may help address these shortcomings and provide both flood risk and ecological benefits as sea levels rise. The primary goal of this chapter, and the ultimate goal of this project, is to help identify what types of natural and nature-based adaptation measures, as well as policy, financial, and regulatory measures are suited for particular places, in order to inform adaptation planning processes that might not otherwise consider alternative and potentially more resilient approaches.

Adaptation measures are specific interventions or actions that can help address the threats of flooding as well as realize ecological benefits. The U.S. Army Corps of Engineers uses the terms "natural," "nature-based," "structural," and "non-structural" to describe the "full array of measures that can be employed to support coastal resilience and risk reduction" (Bridges et al. 2015). For instance, the restoration of a marsh, the construction of an ecotone levee, or the placement of a beach are all adaptation measures. Individual measures are appropriate in certain places, or landscape settings, around the Bay. They are also appropriate in certain combinations with other measures. In many cases these combinations will be hybrid, including nature-based measures together with conventional grey infrastructure measures (such as a tidal marsh that helps protect a flood risk management levee). In this way, individual measures can be combined and phased to create place-based adaptation strategies. In our approach, the OLU defines the landscape setting and physical environment within which a number of appropriate measures, together with a robust vulnerability assessment, can be combined into adaptation strategies through a combination of science, engineering, and stakeholder planning. Adaptation strategies would consist of a combination of adaptation measures that would be implemented over time in specific places (perhaps prompted by specific triggers). OLUs that have similar characteristics would likely benefit from sharing monitoring data and lessons learned on adaptation strategies.

Describing adaptation measures

In this chapter, we define and describe 27 adaptation measures that could potentially be appropriate and suited to OLUs in the Bay (see table below). The four categories of adaptation measures explored are:

- **Structural, natural and nature-based measures:** physical landscape features that are created and evolve over time through the actions of environmental processes, or features that mimic characteristics of natural features but are created by engineering and construction (in concert with natural processes) to provide coastal protection and other ecosystem services (Bridges et al. 2015).
- **Structural, conventional physical (grey) infrastructure:** physical features constructed by humans to provide coastal protection. Usually constructed with relatively hard materials such as concrete, rock, and steel, and without incorporation of biological components.
- **Non-structural, policy and regulatory measures:** utilizing laws, policies, and regulations such as permits, zoning, and general plans to influence future land use and the built environment to manage risk.
- **Non-structural, financial measures:** non-physical ways of creating financial incentives and disincentives to enable implementation of other structural and policy measures.

Class	Category	Adaptation measures
Structural	Natural and nature-based measures	Nearshore reefs Submerged aquatic vegetation Mudflat augmentation Beaches Tidal marshes Polder management Ecotone levees Migration space preparation Creek-to-baylands reconnection Green stormwater infrastructure
	Conventional physical (grey) infrastructure	Super levees Elevate land Flood walls and berms Elevate or realign transportation Seawalls Bulkheads Revetments and riprap Levees and dikes
Non-structural	Policy and regulatory measures	Zoning and overlay zones Setbacks, buffers, and clustering Building codes and building retrofits Rebuilding and redevelopment restrictions
	Financial measures	Conservation easements Tax incentives and special assessments Geologic Hazard Abatement Districts (GHAD) Transfer of Development Rights (TDR) Buyouts

Natural and nature-based and non-structural measures are increasingly viewed as a critical parts of an overall adaptation strategy to help shoreline communities to adapt to the adverse effects of climate change (e.g., Grannis 2011, Center for Ocean Solutions 2018). This understanding has been codified in a variety of official plans, guidelines, and regulations, including the California Ocean Protection Council Sea-Level Rise guidance (OPC 2018), the California Coastal Commission's Residential Adaptation Policy guidance, the California Natural Resources Agency's Safeguarding California Plan, and Executive Order B-30-15, which all promote and prioritize natural and nature-based measures for sea level rise adaptation.

The available literature suggests that natural and nature-based measures may be less expensive, more effective, and more flexible over time (Gittman et al. 2014, Currin et al. 2016, Hirschfield and Hill 2017). Borsje et al. (2011) highlight a few of the qualities of natural and nature-based features that make them desirable for flood protection, including the ability of natural features such as oyster beds and marsh vegetation to modify the local physical environment–trapping and stabilizing sediment so that elevation of mudflats and marshes increases and subsequently attenuate waves (Jones et al. 1997); their ability to respond to sea level rise by natural accretion of organic material and mineral sediments as a more sustainable and cost-effective approach to flood management (Temmerman et al. 2004); and their ability to reduce physical stress on other organisms by creating a more hospitable habitat (Crain and Bertness 2006). As noted above, natural and nature-based measures may be used as a replacement for conventional physical infrastructure such as levees, or more likely, used in combination as a hybrid solution. A hybrid approach can mitigate some of the negative ecological impacts of constructing levees, facilitate permitting, and engender community support.

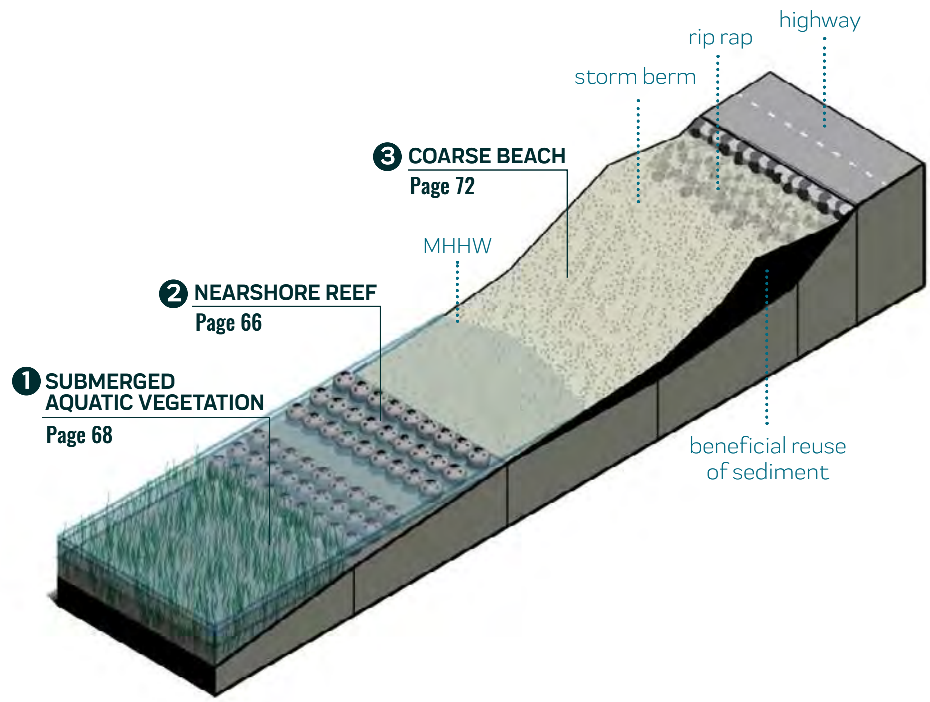
However, there are some important differences between traditional engineering approaches and ecological approaches to sea level rise adaptation and flood control that should be noted (Thom 1997). Ecological thresholds complicate the performance of natural and nature-based measures and increase uncertainty. A sudden change in salinity, for instance, can change the vegetation composition of a marsh and alter its ability to dampen waves. In general, natural and nature-based measures also need more space to provide the same level of flood-control function as conventional physical infrastructure measures. However, unlike many natural and nature-based measures, conventional physical structures are static and generally need to be "over-designed" (i.e., levees need to be built with freeboard to anticipated future flood stages). Natural and nature-based measures are dynamic and (if they have the space and sediment to do so) can adapt in response to changing environmental conditions like sea level rise, often with minimal human intervention.

In this chapter on measures, we have devoted more space to discussing natural and nature-based measures than to discussing conventional physical infrastructure. Conventional structural measures are already commonly used, well-understood, and have extensive engineering guidelines for their siting, construction, and maintenance. Without guidance for alternative approaches, conventional infrastructure will continue to be the default approach, at least until more hybrid approaches can be shown to be more ecologically resilient and provide more benefits with the same level of service. Ultimately, our understanding of the relative benefits of natural and nature-based measures will increase as more pilot projects are constructed and monitored over time (Parker and Boyer 2017).

Combining measures into strategies

Though measures are mapped individually in this chapter, they are rarely intended to be implemented independently. Rather, to meet multiple adaptation objectives at the landscape scale, natural and nature-based measures will be combined with grey, hybrid, and non-structural measures to create a "strategy" which can be adapted over time as conditions change. Throughout this chapter we provide several conceptual examples of how measures might be combined. For instance, in the diagram below, submerged aquatic vegetation is combined with nearshore reefs to provide intertidal and subtidal habitat and wave attenuation for a coarse beach, which in turn helps protect the road berm. Other examples of combined measures can be found on pages 83, 87, and 91.

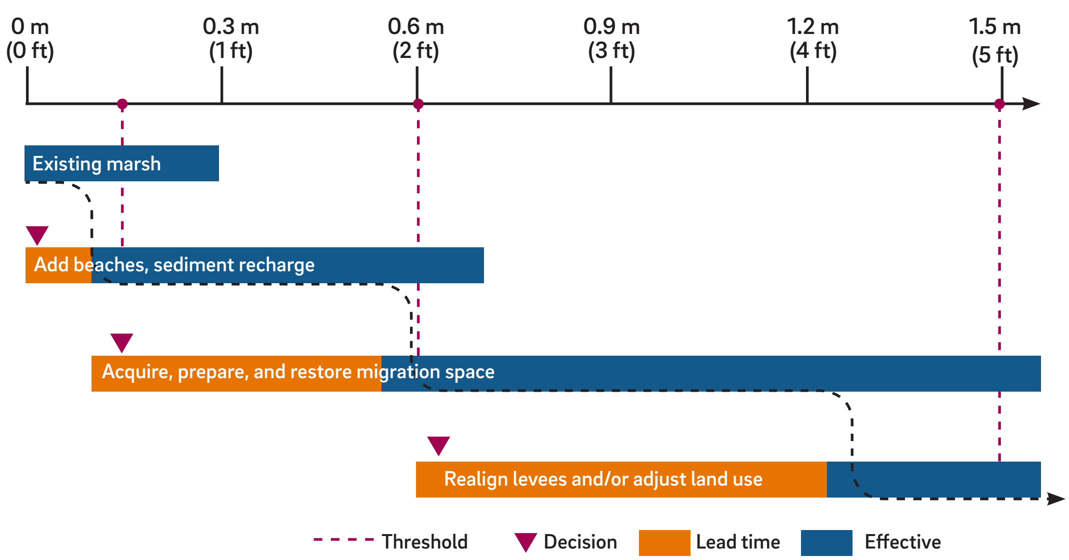
Combining multiple measures into a cohesive strategy. In this conceptual example, submerged aquatic vegetation, a nearshore reef, and coarse beach provide protection to each-other and a highway.



Adaptation pathways

Implementing strategies using a series of planned phases that identify "what to do and when" based on particular environmental thresholds, is a useful framework for adaptation work (Reeder and Ranger 2011, Haasnoot et al. 2013). These "adaptation pathways" are a way to address uncertainty in future projections of climate change and allow for flexibility and adjustment over time (Reeder and Ranger 2011). For example, an adaptation pathway for an OLU would include measures to pursue immediately to reduce present flood risk and to improve present habitat quality, measures to pursue later as sea level rises and flood risk increases, and measures to pursue into the future when flood levels may become intolerable and threaten human health and property. The pathway would take into account existing and projected future vulnerabilities faced in that OLU. However, the pathway would not specify when exactly to implement each measure: it would propose a phased implementation with each phase triggered once predetermined thresholds are reached (e.g., amount of sea level rise or frequency of flooding).

Because many of the measures have fairly long lead times for planning, permitting, and construction, decisions about how and when to implement them will have to be made well in advance of when they are needed to be implemented and effective. Many large-scale restoration projects in the Bay have taken more than a decade to plan, permit, fund, and implement. Building consensus around new, innovative, and impactful concepts, or around controversial actions such as managed realignment, could need multiple decades of planning. Finally, many nature-based measures are not presently allowable under existing permit conditions of regulatory agencies, though many policies are currently being evaluated for necessary adaptation to the changing environmental conditions. These long time frames all point to the need to develop thoughtful adaptation pathways. The figure below shows a hypothetical adaptation pathway derived from the Baylands Goals (Goals Project 2015). In this examples, decisions are triggered at certain SLR thresholds (e.g., deciding to acquire, prepare, and restore migration space once sea levels have risen 0.15 m [0.5 ft] so that it's in place and ready to accommodate marshes before sea level rise exceeds 0.6 m [2 ft]).



Conceptual phasing of measures triggered by sea level rise, rather than a chronological timeline (adapted from Goals Project 2015)

Resources for each adaptation measure

Across the following pages, we characterize each measure in terms of a number of different factors:

- **Definition:** a short description of the measure as it is used in San Francisco Bay.
- **Landscape configuration, design, and process guidelines:** a description of the landscape setting where the measure is appropriate, as well as design parameters to help the measure function as intended and persist over time (e.g., how wide a marsh must be to attenuate waves down to a manageable height). This section also describes the landscape settings where it would be difficult for the measure to succeed.
- **Ecosystem functions:** a high-level description of the functions provided by the measure for wildlife (e.g., the provision of breeding habitat or food resources).
- **Policy and funding considerations:** a description of legal, policy, and economic barriers to implementation, as well as potential socioeconomic impacts and trade-offs.
- **Coastal risks managed:** a qualitative assessment of which coastal risks each measure can help to mitigate, including storm surge, erosion, short-term sea level rise, long-term sea level rise, fluvial flooding, and combined flooding.
- **Other ecosystem services:** a list of other ecosystem services (in addition to coastal risk management) that are potentially provided by the measure. Our list of ecosystem services was derived from the United Nation's assessment of the services provided by wetlands and was extended to non-wetland nature-based measures (MEA 2005; see Appendix 5, p. 245).
- **Impact on the shoreline:** whether the measure serves to "protect" from, "accommodate," or "retreat" from coastal hazards (a categorization introduced by Gilbert and Vellinga [1990]). "Protect" entails continuing to use vulnerable areas by employing defensive measures. "Accommodate" entails continuing to occupy and use vulnerable areas by adjusting structures and habits. "Retreat" entails withdrawing from vulnerable areas (Gilbert and Vellinga 1990, Fletcher 2013).
- **Location along tidal transect:** a schematic showing where in the tidal frame a measure is appropriate (i.e., is the measure appropriate in subtidal areas, below mean sea level [MSL], above MSL, or above the reach of the tides entirely?). The transect runs from the deep Bay to the upland edge of the OLU.
- **Examples:** where possible, we identify locations where the measure has been implemented, either within or outside the Bay Area.

Additionally, for the nature-based measures, we provide maps indicating suitable locations for each measure across all of the OLUs. These maps provide a first-cut at guidance for what types of nature-based measures are suited to which natural settings, and which parts of the Bay and baylands are the best places for these measures in our current landscape. Summaries of the methods used to map the suitable areas are provided with each map. More detailed descriptions of the methods are available in Appendix 5.

Assumptions

When mapping suitable areas for each nature-based measure and determining how extensive measures should be to provide coastal flood control and shoreline protection (e.g., how wide marshes should be), we worked with a standard set of planning assumptions:

- **Sea level rise:** when required for mapping and calculations, we assumed 2.1 m of sea level rise, which is the amount estimated to have a 0.5% probability (a 1-in-200 chance) of occurring by 2100 for a high emission scenario, based on an assessment of the observational, modeling and theoretical evidence (OPC 2018, based on Kopp et al. 2014). This is the projection recommended by the state for use when making decisions requiring a medium to high level of risk aversion (OPC 2018). Although this is a good starting place, in cases where measures are serving to protect critical infrastructure with low tolerance for risk, such as large power plants, major airports and roads, wastewater treatment plants, and hazardous waste and toxic storage sites, it would be prudent to plan for even higher levels of sea level rise consistent with extreme risk aversion (the "maximum physically plausible" sea level rise scenario, or H++, is 3.1 m by 2100; OPC 2018).
- **Storm surge:** our calculations account for a storm surge having a 100-year recurrence interval based on the historical frequency of occurrence (a surge event of that magnitude has a 1% chance of occurring in any given year). These values were derived from modeled water surface elevations generated by AECOM (2016) for FEMA mapping studies.
- **Wind wave heights:** our calculations account for significant wave heights having a 100-year recurrence interval based on the historical frequency of occurrence (waves of that magnitude have a 1% chance of occurring in any year). These values were derived from modeled wave heights generated by DHI (2011 & 2013) for FEMA mapping studies.

Data gaps, uncertainties, and next steps:

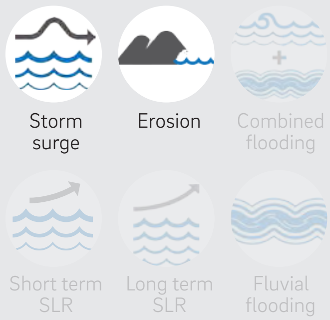
There are several caveats, data gaps, and uncertainties that apply to this chapter and are important to acknowledge. First, this is only a first cut at characterizing the suitability of different natural and nature-based measures around the Bay. The suitability analysis will need to be tested with projects that are carefully monitored. Experience with permitting, constructing, and maintaining natural and nature-based measures in San Francisco Bay is limited. As more experience with the measures is gained, the suitability analyses will need to be updated based on new information. Similarly, the suitability of the measures is based on current environmental conditions (e.g., current wave heights, current water depth, and current elevation relative to the tides); the suitability will change in the future as environmental conditions change and as our understanding and data about current conditions improves.

Second, the list of adaptation measures is not comprehensive. There are many other natural and nature-based measures, including various measure appropriate in the subtidal zone (e.g., rocky nearshore islands) that are not addressed in this report. There are also many kinds of conventional physical infrastructure, policy, and financial measures that are not addressed in this version of the report, including the use of storm-surge barriers. Future versions will address a wider range of measures, but will continue to focus on natural and nature-based approaches.

Finally, the relationship between the measures and major infrastructure projects has not been fully developed. For example, opportunities to link ecotone levees with wastewater treatment facilities were not addressed, nor were opportunities to integrate natural and nature-based measures as part of highway design. This will be important, since many opportunities to implement nature-based measures will be associated with major projects to repair and improve existing infrastructure and efforts to improve water quality in the Bay.

Nearshore reefs

COASTAL RISKS MANAGED



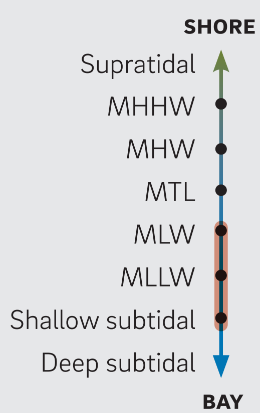
OTHER ECOSYSTEM SERVICES

• Biodiversity • Food supply •
• Climate regulation •
• Water quality improvement •
• Recreation •
• Other cultural services •

IMPACT ON SHORELINE

Protect • Accommodate • Retreat

LOCATION
WITHIN TIDAL TRANSECT



EXAMPLES

The San Francisco Bay Living Shoreline Project (State Coastal Conservancy)

DEFINITION

Nearshore (lower intertidal/subtidal) reefs made of materials such as oyster shell and baycrete (a cement mixture composed mostly of Bay sand and shells) that provide hard substrate for shellfish including native Olympia oysters *(Ostrea lurida)* and other aquatic plants and animals. Nearshore reefs can also reduce wave transmission at lower tidal elevations and stabilize areas in their lee (Latta and Boyer 2015).

LANDSCAPE CONFIGURATION, DESIGN, & PROCESS GUIDELINES

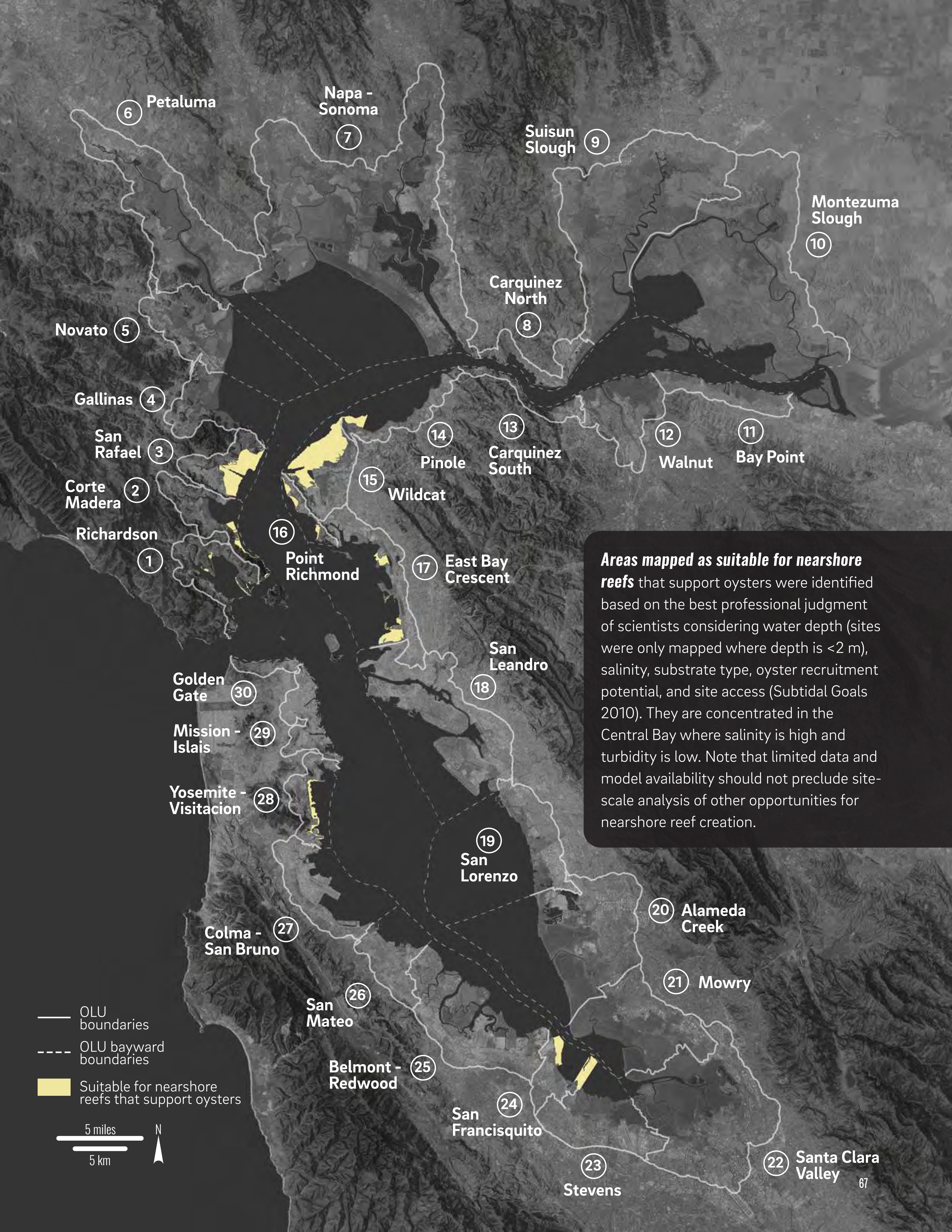
Because oyster reefs do not occur naturally in San Francisco Bay, artificial reefs are created from bags of oyster shells or structures such as reef balls. These nearshore reefs are best suited to shallow water in areas of low wave action, near mudflats. They have the ability to reduce wave transmission both directly and indirectly by trapping sediment and stabilizing the substrate so that bed elevation increases, and subsequently, attenuates waves (Subtidal Goals 2010, Boyer et al. 2017). The reduction in wave transmission associated with a reef will depend the height and width of the reef's crest in relation to wave height and period, local tidal amplitude, and water depth. In this way, reefs perform in a similar manner to low-crested breakwaters and guidance for the sizing and positioning of low-crested breakwaters should be followed. Reefs are generally located relatively close to shore in order to create a wave shadow in their lee, trapping sediment and reducing marsh scarp erosion. Reefs work especially well in several rows or paired with another measure such as eelgrass beds to maximize habitat value (Boyer et al. 2017). Oysters are usually found below mean sea level, and therefore reefs built as habitat to support them may be less effective than marshes (which occur higher up in the intertidal zone) in attenuating waves at high tide or during storm surges (Boyer et al. 2017). Areas with relatively low salinity and relatively high turbidity are less suitable for supporting native oysters than areas with higher salinity and lower turbidity (Subtidal Goals 2010). Native oysters are also subject to predation by invasive species such as the Atlantic oyster drill (*Urosalpinx cinerea*).

ECOSYSTEM FUNCTIONS

Nearshore reefs provide habitat for native Olympia oysters, as well as a diverse range of other species including mussels, shrimp, crabs, shorebirds, diving ducks, salmon, sturgeon, marine mammals, and vegetation. The reefs alter the environment around them by adding physical heterogeneity, reducing water current speeds, and trapping sediment. This can increase the diversity of other marine invertebrates in the area. These invertebrates provide additional food and resources for fish, crabs, and birds. Nearshore reefs may potentially provide spawning sites for Pacific herring (*Culpea pallasii*).

POLICY CONSIDERATIONS

Submerged features in the Bay are fill, and require permits from the U.S. Army Corps of Engineers (USACE), San Francisco Bay Conservation and Development Commission (BCDC), the San Francisco Bay Regional Water Quality Control Board (the Water Board), California Department of Fish and Wildlife (CDFW), and State Lands Commission (SLC). Submerged, constructed materials may also be considered a navigational hazard by the U.S. Coast Guard, and must be reported and marked.

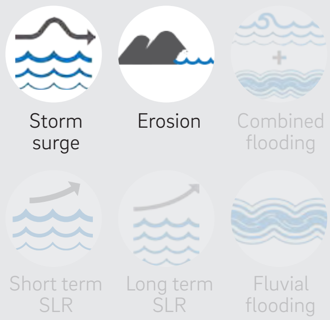


Areas mapped as suitable for nearshore reefs that support oysters were identified based on the best professional judgment of scientists considering water depth (sites were only mapped where depth is <2 m), salinity, substrate type, oyster recruitment potential, and site access (Subtidal Goals 2010). They are concentrated in the Central Bay where salinity is high and turbidity is low. Note that limited data and model availability should not preclude site-scale analysis of other opportunities for nearshore reef creation.

NATURAL AND NATURE-BASED MEASURES

Submerged aquatic vegetation

COASTAL RISKS MANAGED



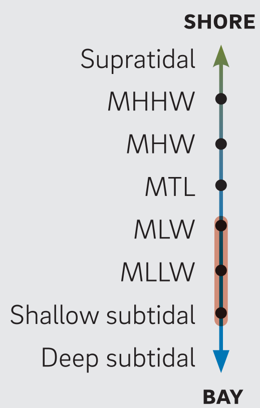
OTHER ECOSYSTEM SERVICES

• Biodiversity • Food supply • • Climate regulation • • Water quality improvement • • Recreation • • Other cultural services •

IMPACT ON SHORELINE

Protect • Accommodate • Retreat

LOCATION WITHIN TIDAL TRANSECT



EXAMPLES

Point San Pablo, Richardson Bay, Keller Beach, Alameda Beach

DEFINITION

"Submerged aquatic vegetation" (SAV) refers to all underwater flowering plants, and can contribute to trapping sediment and slowing shoreline erosion. Eelgrass (*Zostera marina*) is the main species in the lower parts of the San Francisco Estuary, but other submerged vegetation species include sago pondweed (*Stuckenia pectinata*) in Suisun Bay, the surfgrasses (*Phyllospadix torreyi* and *P. scouleri*) at the entrance to San Francisco Bay, and widgeongrass (*Ruppia maritima*) in protected brackish areas.

LANDSCAPE CONFIGURATION, DESIGN, & PROCESS GUIDELINES

Suitable habitat for SAV depends upon a number of factors, including depth of water and light, current speed, exposure to wind waves, water temperature, and salinity (Subtidal Goals 2010). A habitat suitability model developed for the Bay (Merkel 2005) shows the potential to establish eelgrass beds at depths less than about 2 m in broad swaths along the shores of San Pablo Bay, the Central Bay, and the South Bay. Salinity is a limiting factor for eelgrass beds, and the Carquinez Strait marks their inland limit, except in periods of drought when eelgrass can move into Suisun Bay. Another limiting factor is light, which limits suitable sites in the more turbid South Bay. Factors contributing to the future success of eelgrass in the Bay will be the continued decrease in suspended sediment concentrations, the long-term improvement of water quality, and the maintenance of freshwater flows from the Delta and tributaries (Subtidal Goals 2010).

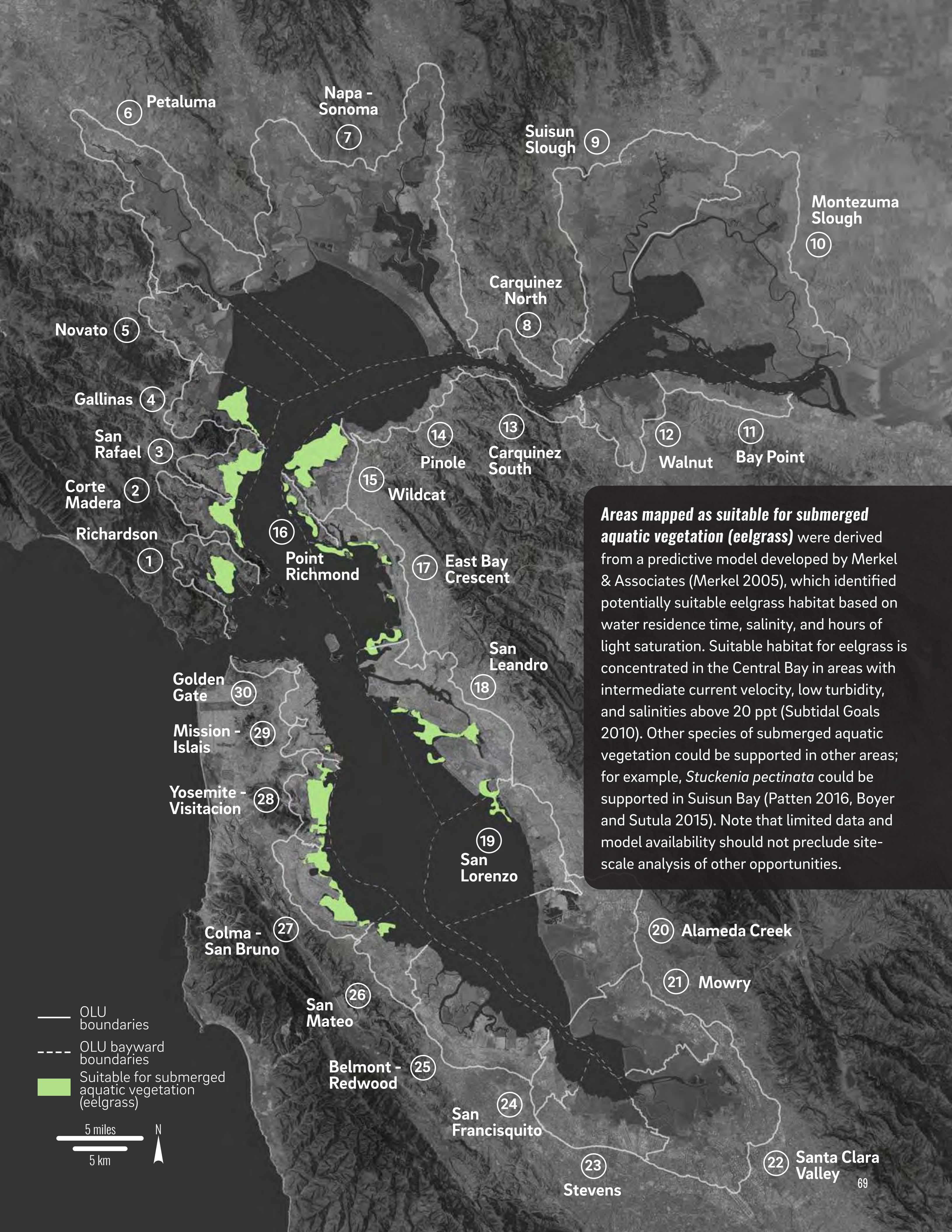
There are a number of design criteria for eelgrass beds. The substrate can be sand, silt, or clays, where current speeds and wave energy are not excessive. Eelgrass depends on light penetrating the water column: the more turbid the water, the shallower the maximum depth at which eelgrass beds can grow. A nearby supply of seeds or seed-bearing, flowering shoots from adjacent beds is important in establishing and maintaining beds. Seeds are heavier than water, and thus transport across deep water is limited; however, if flowering shoots break off they can raft considerable distances before rooting or dropping seeds. Once established, eelgrass beds alter the substrate by extending a network of rhizomes horizontally under the sediment, and producing new shoots. The beds trap mostly fine sediment and thereby further reduce turbidity. However, eelgrass can be ephemeral and are sensitive to changes in salinity and other stressors. Rising sea levels may enhance growth at the shallow end of the bed and reduce it at the deep end, resulting in an landward migration of the bed (Subtidal Goals 2010).

ECOSYSTEM FUNCTIONS

Submerged aquatic vegetation beds reduce currents, trapping and stabilizing fine sediments. SAV beds provide structure and food for a variety of organisms. Amphipods, geese, and ducks graze on the eelgrass directly, while fish feed on the algae and invertebrates that the eelgrass supports. Some fish use the eelgrass as nursery habitat while others, such as pipefish, stay there throughout their life cycle.

POLICY CONSIDERATIONS

Modifying substrate for SAV to flourish at the right depth may involve fill material, which requires permits from USACE, BCDC and the Water Board. If fish or wildlife species may be affected by these alterations, consultations with state and federal wildlife managers, and appropriate mitigations, may be needed.

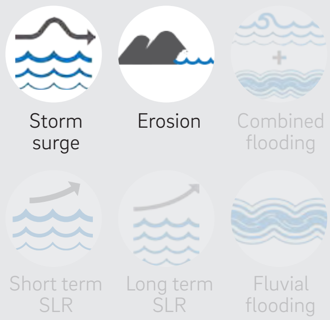


Areas mapped as suitable for submerged aquatic vegetation (eelgrass) were derived from a predictive model developed by Merkel & Associates (Merkel 2005), which identified potentially suitable eelgrass habitat based on water residence time, salinity, and hours of light saturation. Suitable habitat for eelgrass is concentrated in the Central Bay in areas with intermediate current velocity, low turbidity, and salinities above 20 ppt (Subtidal Goals 2010). Other species of submerged aquatic vegetation could be supported in other areas; for example, *Stuckenia pectinata* could be supported in Suisun Bay (Patten 2016, Boyer and Sutula 2015). Note that limited data and model availability should not preclude site-scale analysis of other opportunities.

NATURAL AND NATURE-BASED MEASURES

Mudflat augmentation

COASTAL RISKS MANAGED



OTHER ECOSYSTEM SERVICES

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• Water quality improvement •
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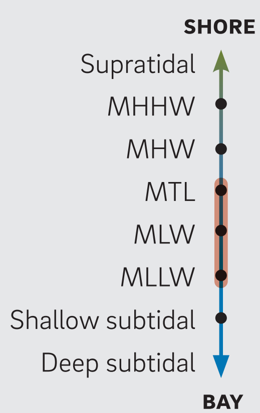
• Other cultural services •

IMPACT ON SHORELINE

Protect • Accommodate • Retreat

LOCATION WITHIN TIDAL TRANSECT



EXAMPLES

Seal Beach (Southern California)

DEFINITION

Intertidal mudflats and shallow water shoals are the most common substrate in San Francisco Bay. They are composed of fine silts, clays, and sands from the Delta and local watersheds. Mudflat augmentation refers to the direct or indirect placement of fine sediment to increase mudflat elevation relative to the tides, which can help protect adjacent marshes or other shoreline types.

LANDSCAPE CONFIGURATION, DESIGN, & PROCESS GUIDELINES

Mudflats dissipate wave energy through shoaling processes in shallow water and limit the size of waves reaching the marsh edge, which can limit marsh erosion. The degree of shoaling depends upon the width, depth, and surface roughness of the mudflat. The cohesive properties of fine sediment, together with biological activity such as burrowing organisms, microalgae, and biofilm, also increase the resistance of the mudflat to erosion.

Mudflats and shoals act as a sediment reservoir, storing fine silt, clay, and sand sediments from winter floods. The continued resupply of fine sediment to mudflats is therefore essential to maintaining their present form and allowing them to respond to sea level rise. They are also intimately linked to the adjacent tidal marshes since they act as a reservoir of erodible sediment to supply the marshes and limit the amount of wave energy reaching the marsh scarp. Recently deposited fine sediment is suspended by strong tidal currents and wind waves and is gradually winnowed out through the dry, windy summer and fall and redeposited in tidal marshes.

Direct placement of fine dredged sediment on lower mudflats and shallow subtidal areas could be effective at supplying local mudflats (and marshes) with sediment. A small-scale pilot project to look at the impacts of such placement on the shallow water benthic community and the water column is planned by USACE under the Water Infrastructure Improvements for the Nation Act. This pilot study will also develop numerical models to identify locations in the shallow subtidal and on the mudflats to place sediment to supply particular areas of mudflats and marshes, building on previous numerical studies of sediment dispersion from in-bay disposal sites (Bever et al. 2014).

ECOSYSTEM FUNCTIONS

Mudflats provide important foraging habitat for shorebirds, wading birds, and dabbling ducks. These areas are particularly important for overwintering shorebirds, who rely on these areas for sufficient food. In certain areas mudflats can also provide important haul-out locations for harbor seals.

POLICY CONSIDERATIONS

Placing sediment on mudflats and in shallow water is considered fill material. This action will also generally increase local water turbidity. This will require permits from USACE, BCDC, the Water Board, and potentially other resource management agencies, especially if the fill placement will result in the burial of fish or wildlife species including benthic organisms.

The current extent of mudflats in San Francisco Bay, as shown here, is a useful starting place for determining where mudflat augmentation might be appropriate. However, future work should identify which mudflats are actually eroding or are otherwise most at risk of loss with sea level rise. Data were derived from the Bay Area Aquatic Resource Inventory (SFEI-ASC 2017a).

Beaches

COASTAL RISKS MANAGED

Storm surge · Erosion · Combined flooding

Short term SLR · Long term SLR · Fluvial flooding

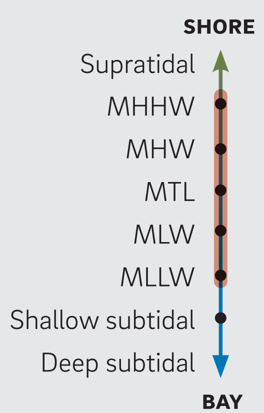
OTHER ECOSYSTEM SERVICES

• Biodiversity • Food supply •
• Climate regulation •
• Water quality improvement •
• Recreation •
• Other cultural services •

IMPACT ON SHORELINE

Protect • Accommodate • Retreat

LOCATION
WITHIN TIDAL TRANSECT



EXAMPLES

Aramburu Beach

DEFINITION

Coarse or composite estuarine beaches are dynamic features that can consist of a mixture of sand, shell, gravel, or cobble. Beaches include a supratidal beach berm and a beach face. The lowest portion of the beach is often characterized by a low tide terrace and transition to tidal flat. The low tide terrace limits the duration that the beach is exposed to waves and also limits the size of the waves. The focus here is on coarser gravel and cobble beaches which can dissipate wave energy over shorter distances and therefore are generally more suitable within the urbanized and constrained estuary.

LANDSCAPE CONFIGURATION, DESIGN, & PROCESS GUIDELINES

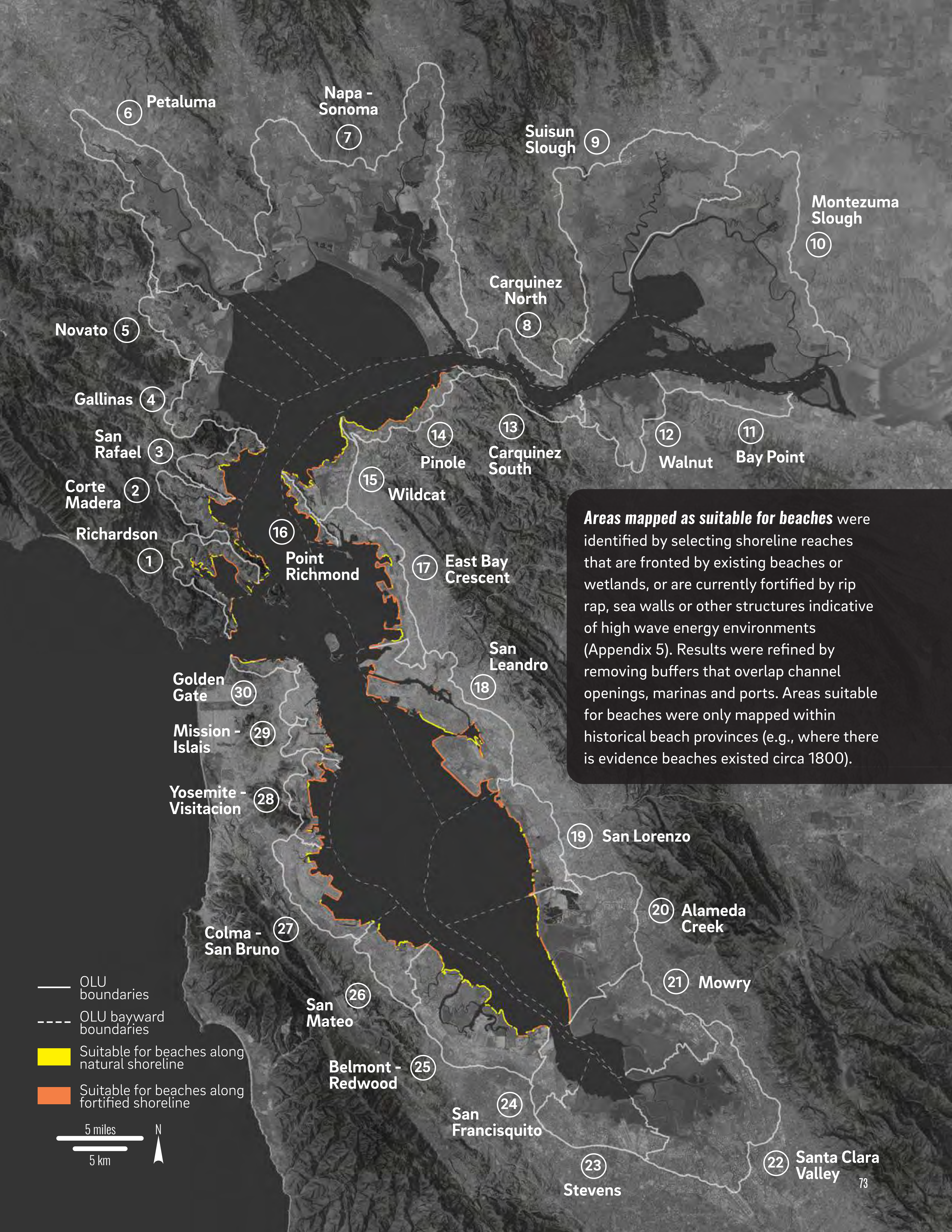
Beaches can be created in many places in the Bay to attenuate waves. They can, for instance, be placed in front of levees, roads or other infrastructure vulnerable to wave overtopping, or in front of marshes vulnerable to erosion. Ultimately, there will be significant differences in beach function and form depending on the problem a beach is meant to address, the type of beach material used, and the incident wave energy. A predominantly coarse beach is highly permeable, needs less space compared to a composite or fine beach, and can form a steep profile in response to storm events. The surf zone on a coarse beach is often narrow or even absent and the beach face is dominated by swash and backwash processes. A specific feature of a coarse beach is the wave-deposited beach ridge or crest. The elevation of the crest depends primarily upon the maximum run-up and sediment availability. During storms the movement of particles on a coarse beach is predominantly landward and the beach crest will increase in height and roll landward if there is sufficient volume of beach sediment and space landward. The sand and shell materials that comprise the beach face may be intermittently lost to longshore drift but also naturally redeposited by the tides and waves. Groins or other retention structures (e.g., woody debris, microgroins, buried rough on-site material) should be considered for beaches implemented along high-drift shorelines, but are not necessary for naturally constrained pocket beaches. Historical and artificial beach types and existing reference sites to inform beach designs are described on pages 74 and 75.

ECOSYSTEM FUNCTIONS

Coarse and composite beaches can provide breeding or foraging habitat for birds such as Forster's terns (*Sterna forsteri*), black-necked stilts (*Himantopus mexicanus*), American avocets (*Recurvirostra americana*), black oystercatchers (*Haematopus bachmani*), and other shorebirds. They can also provide unvegetated, high tide roosts for shorebirds and high-tide refuge for marsh wildlife. Beaches provide spawning habitat for grunion (*Leuresthes tenuis*) and haul out spaces for harbor seals (*Phoca vitulina*; Goals Project 1999).

POLICY CONSIDERATIONS

Modifying the shoreline, including the slope, of any stream channel or floodplain requires a permit from the Water Board. Grading or modifying land within 100 ft (30.5 m) of the shoreline requires a permit from BCDC and consultation with USACE. Environmental impact statements and consultations with state and federal wildlife managers are additionally required for locations supporting threatened or endangered species.



Areas mapped as suitable for beaches were identified by selecting shoreline reaches that are fronted by existing beaches or wetlands, or are currently fortified by rip rap, sea walls or other structures indicative of high wave energy environments (Appendix 5). Results were refined by removing buffers that overlap channel openings, marinas and ports. Areas suitable for beaches were only mapped within historical beach provinces (e.g., where there is evidence beaches existed circa 1800).

BEACH CREATION

Sand, shell hash, gravel, and cobble beaches were part of the historical ecology of San Francisco Bay, fronting approximately 27 miles of shoreline in the 1800s before major modifications such as filling and diking (Goals Project 2015). Some of these natural beach types, along with additional hybrid types exist along the modern shoreline and can act as reference sites to guide beach design for sea level rise adaptation. Composite beaches (i.e., mixed profiles) are a commonly employed engineered solution that provide ecological and recreational value while dissipating wave energy, reducing erosion, and protecting infrastructure. Because they have a wider availability of sediment with mixed grain sizes, and can to respond to water levels and wind-wave conditions during large storm events, beaches with composite profiles may be most effective for sea level rise adaptation.

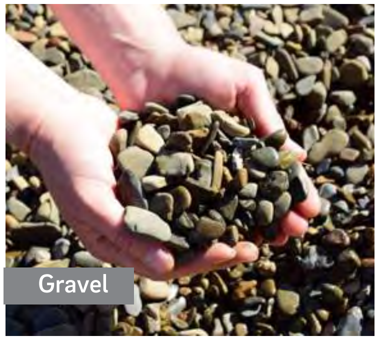
Historical beach types:

- **Medium sand beaches** *(Modern example: Radio Beach):* Sand beaches were historically found in areas where wind and waves deposited coarser sediments and sand along the shoreline, namely in the Central Bay and eastern shore of the North Bay. In areas with coves between headlands, particularly along the Marin and San Francisco shorelines, some beaches prevented runoff from flowing into the Bay (i.e., barrier beaches) resulting in the formation of natural tidal lagoons. Elsewhere in the Bay, sandy beaches were found fringing tidal marsh and tidal flats, such as in the Oakland estuary (Goals Project 1999).
- **Shell hash beaches** *(Modern example: Beaches fronting Foster City):* Shell hash beaches naturally formed from shell fragments of native oysters present in San Francisco Bay. Some shell beaches are found on the outboard side of marshes in the South Bay.
- **Coarse gravel and coarse sand beaches** *(Modern examples: Point Pinole beaches, China Camp beaches):* This beach type is found near sandstone and shale bedrock headlands, common to the shorelines of Marin and Richmond.
- **Cobble beaches** *(Modern example: western shore of Point Pinole, Red Rock Island):* Cobble beaches in the Bay are formed through erosion of headlands containing coarse-grained sedimentary rocks with rounded gravel deposits (i.e., conglomerate).

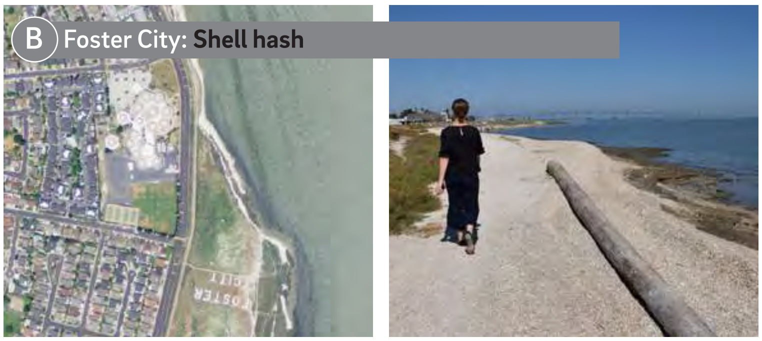
Example of constructed beaches:

- **Gravel and mixed sand beaches** *(Modern example: Aramburu Island):* This beach type is comprised of a sand beach face, sand berm, and gravel storm berm. During accretion phases, the gravel beach is often covered in sand. Despite an often narrow profile, the gravel component of this beach will act as a buffer to erosion by persisting after the sand component drifts away. These beach types are especially useful as engineered beaches in urbanized estuarine systems.

Substrate Types

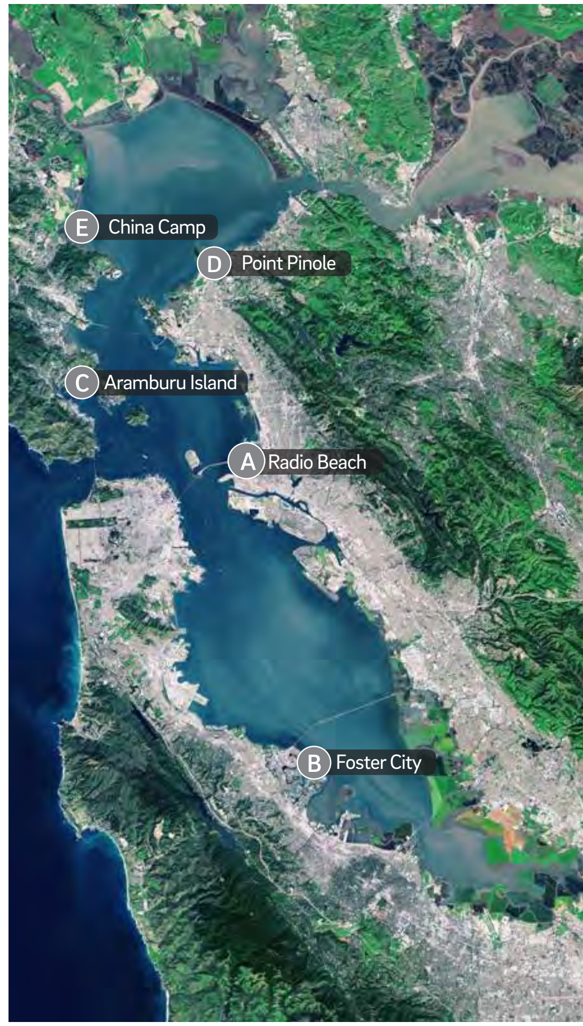


Examples of Existing Beaches

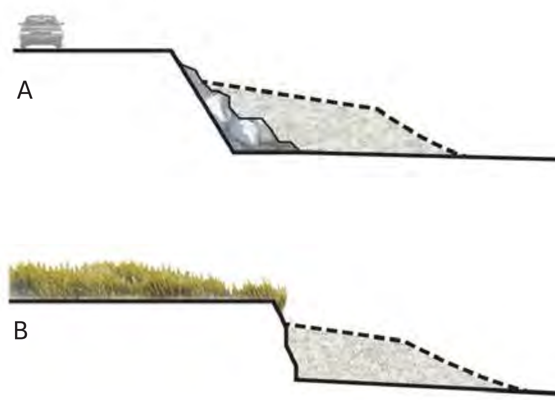


(Photo by Peter Baye)

Existing Beach Reference Sites



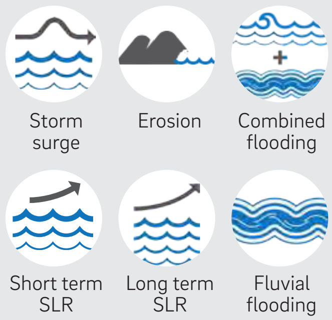
Coarse Beach Placement Concepts



Conceptualized profiles of a coarse beach as a (A) replacement or in addition to riprap, and as (B)protection for an eroding marsh scarp. Other placements and locations of beaches are possible, and all need to be piloted, monitored, and evaluated for effectiveness.

Tidal marshes

COASTAL RISKS MANAGED



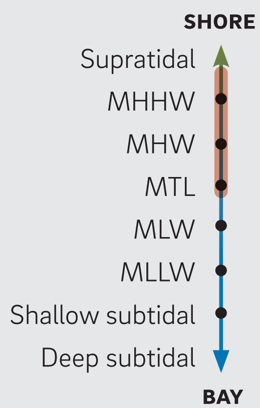
OTHER ECOSYSTEM SERVICES

• Biodiversity • Food supply •
• Climate regulation •
• Water quality improvement •
• Recreation •
• Other cultural services •

IMPACT ON SHORELINE

Protect • Accommodate • Retreat

LOCATION
WITHIN TIDAL TRANSECT



EXAMPLES

Bair Island, Sonoma Baylands, South Bay Salt Ponds, Giant Marsh and many others

DEFINITION

Protecting, maintaining, and restoring tidal marshes and their associated tidal flats is critical for sustaining their flood control services under a changing climate (Goals Project 2015). Specific actions included in this measure are restoring tidal action to diked baylands to restore marshes, planting native species to accelerate colonization, placing sediment to raise subsided areas, and creating higher areas within marshes to provide high-tide refuge. In existing marshes this measure might also include sediment placement to help maintain marsh elevation with sea level rise, though this is not currently permissible.

LANDSCAPE CONFIGURATION, DESIGN, & PROCESS GUIDELINES

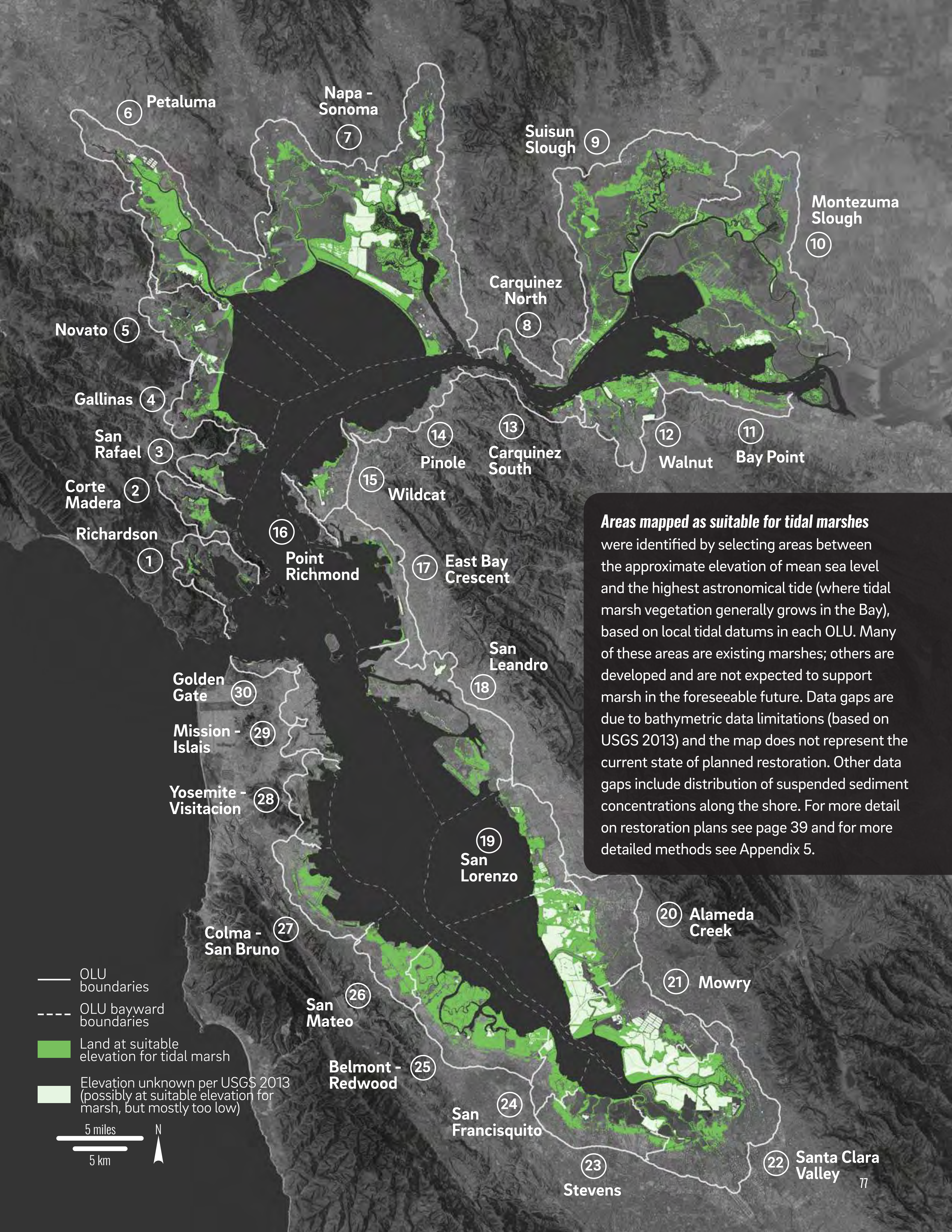
Tidal marshes, in conjunction with tidal flats, can mitigate flood risk due to storm surges, waves, and tidal currents through a combination of shoaling and friction effects. Marshes help reduce wave run-up on and erosion of levees, enabling landward seawalls or levees to be lower and reducing maintenance costs. Reed et al. (2018) summarize the role of tidal marshes in flood risk management as:

- reduce direct wave action on unprotected structures during storms;
- reduce wave run-up and overtopping of flood risk management levees during storms, thus limiting flooding;
- reduce erosion of flood risk management levees during and between storms by attenuating waves to a size that does not cause damage;
- increase net sedimentation by creating more quiescent conditions on the marsh.

There are two ways marsh vegetation attenuates waves: directly, through vegetation-induced friction, and indirectly, by contributing biomass and trapping fine sediment to maintain the elevation of the marsh platform.

The topography of the marsh and its associated mudflat plays a significant role in wave refraction, shoaling, and breaking. In particular, the rapid change in elevation associated with marsh scarps causes shoaling and breaking of waves during overmarsh events and results in significant wave attenuation within 3–5 m of the marsh edge. Similarly, marsh mounds and tidal channels within the marsh will affect how the waves propagate over the marsh.

Marsh width is one important factor that influences the degree to which a tidal marsh is able to attenuate waves. As part of this analysis, we calculated the width of high tidal marsh needed to attenuate waves during a major storms (100-year waves with 100-year water surface elevation) to 0.3 m (1 ft) in height, which was judged to reduce erosion of the levee. Maximum required widths to achieve this degree of attenuation in each OLU range from less than 75 m in the Bay Point OLU to more than 135 m in the Stevens OLU. For more detailed methods and analysis of needed marsh widths, see Appendix 5.



Areas mapped as suitable for tidal marshes were identified by selecting areas between the approximate elevation of mean sea level and the highest astronomical tide (where tidal marsh vegetation generally grows in the Bay), based on local tidal datums in each OLU. Many of these areas are existing marshes; others are developed and are not expected to support marsh in the foreseeable future. Data gaps are due to bathymetric data limitations (based on USGS 2013) and the map does not represent the current state of planned restoration. Other data gaps include distribution of suspended sediment concentrations along the shore. For more detail on restoration plans see page 39 and for more detailed methods see Appendix 5.

Wave dampening by vegetation becomes more important further away from the marsh edge. The degree of dampening depends on both the hydraulic conditions, such as water depth and wave height, and vegetation characteristics, such as canopy height, density, stem diameter, and stiffness. In numerical modeling experiments, it has been found that higher waves are dampened by vegetation more than lower waves. Thus, the range of incoming wave heights is reduced after passing through vegetation. In addition, the amount of dampening strongly depends on the wavelength of the incoming waves: tidal marshes need to be wider for waves with longer periods, which carry proportionally more energy, to achieve the same degree of dampening.

Vegetation type is also important. Taller, denser marsh plants, such as alkali bulrush (*Bolboschoenus maritimus*) are most efficient at dampening wave energy, compared with native cordgrass (*Spartina foliosa)* or pickleweed (*Salicornia*, *Sarcocornia*). Brackish transition zones at the back of the marsh (such as those created by a horizontal levees, or by seeping freshwater to the back of the salt marsh) can provide additional wave dampening capacity when the tidal marsh vegetation is deeply submerged.

In addition to dampening waves, marshes can help dampen storm surges through their effects on tidal currents. Drag forces will slow surge propagation as it crosses the marsh and lead to increased height of the surge seaward of the marsh. However, if the surge is sustained for a long period, marsh vegetation will have little influence on the surge height.

Tidal marsh vegetation is sensitive to shifts in the salinity gradient due to changes in river inflows to the Bay and, over the long term, changes in sea level. If the salinity gradient shifts further upstream (as is projected under future climate scenarios; Cloern et al. 2011), there may be a dieback and replacement of brackish vegetation in marshes in the upper estuary, which would be expected to reduce their ability to attenuate waves and increase their exposure to erosion.

Marshes do not occur in isolation: they are always associated with an unvegetated mudflat, nearshore subtidal resources and, in the past, with some form of wetland-upland transition (discussed elsewhere in this report). In many areas, particularly in the Central Bay, there has been extensive filling of the intertidal, pushing the present shoreline into deeper water. Establishing a new marsh and mudflat bayward of the historical marshes and mudflats would be difficult as it would require filling of the Bay in areas with deeper water and increased exposure to waves.

ECOSYSTEM FUNCTIONS

Tidal marshes support a number of uniquely adapted and/or rare plants and animals, including the endangered salt marsh harvest mouse (*Reithrodontomys raviventris*)and Ridgway's rail (*Rallus obsoletus*). Marshes provide habitat for a variety of waterbirds, including ducks and geese, herons and egrets, and shorebirds. Marshes provide food web support and nursery habitat for fish and pelagic species such as Dungeness crab (*Cancer magister*) and support fish that stay in the marsh throughout their lives, such as the longjaw mudsucker (*Gillichthys mirabilis*; USFWS 2013).

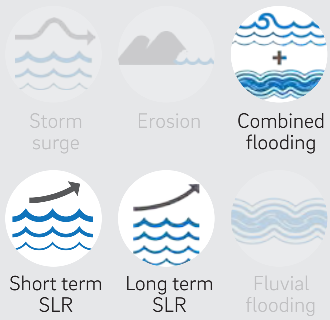
POLICY CONSIDERATIONS

Wetlands are protected under a broad range of federal and state regulations and policies. Projects that may impact wetlands, including dredging, filling, or sediment placement typically require permits from USACE, the Water Board, and BCDC, as well as consultations with the U.S. Fish and Wildlife Service (USFWS), National Marine Fisheries Service (NMFS), and CDFW. Impacts to wetlands must also be addressed under the National Environmental Policy Act (NEPA) and California Environmental Quality Act (CEQA). The Water Board's No Net Loss Policy mandates a long-term net increase in the acreage, functions, and values of the state's wetlands, including tidal marshes in San Francisco Bay.

TIDAL MARSH PROTECTING INTERSTATE 580 IN RICHMOND DURING A KING TIDE EVENT (PHOTO BY SAM SAFRAN, SFEI)

Polder management

COASTAL RISKS MANAGED



OTHER ECOSYSTEM SERVICES

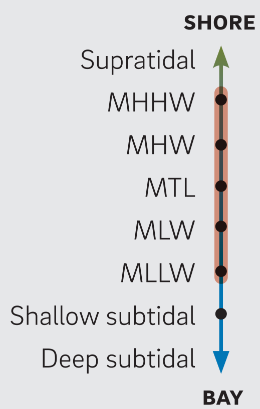
• Biodiversity • Food supply •
• Climate regulation* •
• Water quality improvement* •
• Recreation •
• Other cultural services •

* *Service dependent on chosen management approach*

IMPACT ON SHORELINE

Protect • Accommodate • Retreat

LOCATION
WITHIN TIDAL TRANSECT



EXAMPLES

Palo Alto Flood Basin, Hamilton Wetland Restoration Project

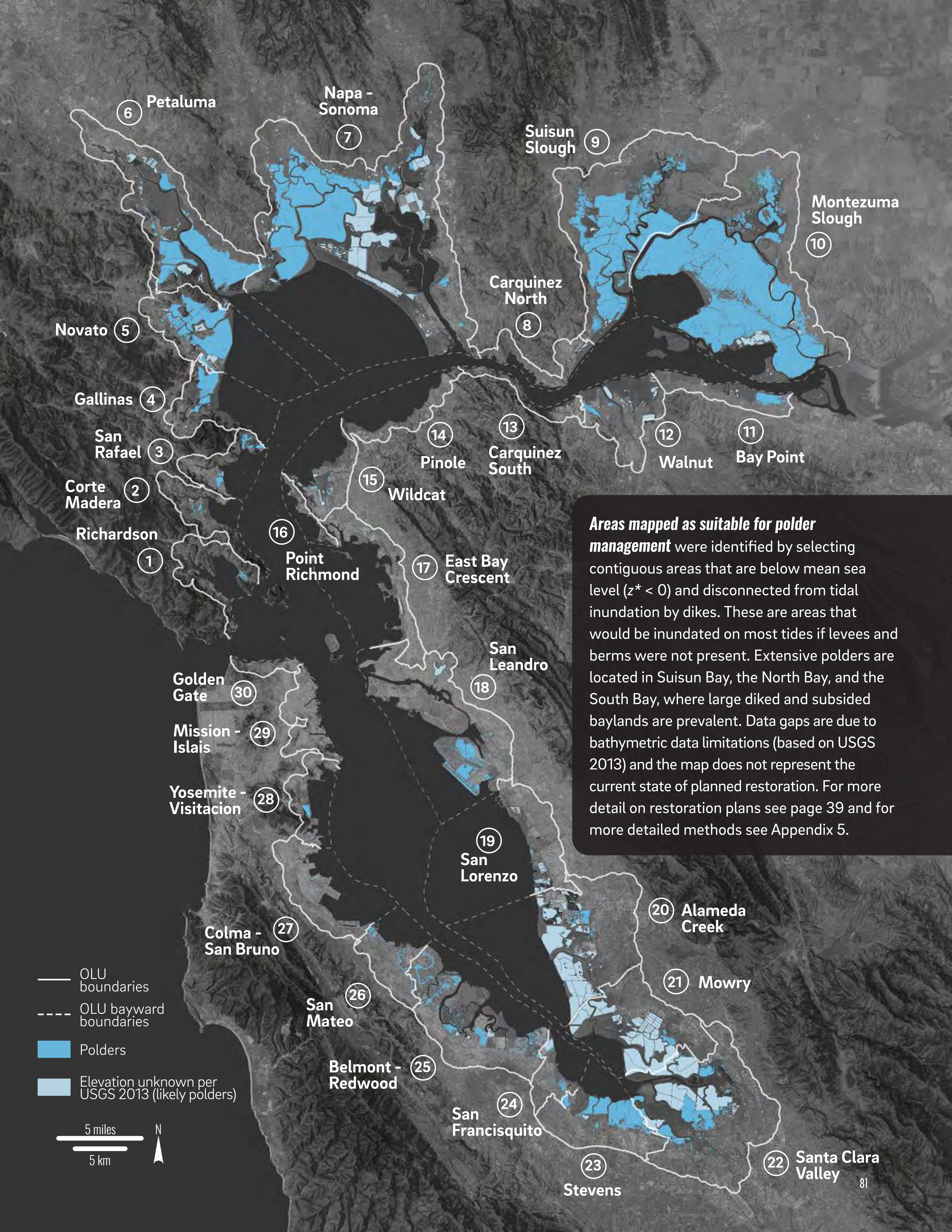
DEFINITION

Polders are low-lying areas of land that would normally be inundated by regular tides if they were not protected by dikes. Polders are the diked, ditched, and drained historical marshes and mudflats that are locally known in San Francisco Bay as “diked baylands.” Land uses within the polders vary: there are salt ponds in the North and South Bays, hay fields in San Pablo Bay, flood retention basins such as Palo Alto Flood Basin, and significant residential areas in the Central Bay such as Alameda Island, Foster City, and Redwood Shores. In many areas, the low-lying land within polders is used for infrastructure, including roads, rail lines, wastewater lines, and transmission lines that will need to be protected and accessible if the dikes are breached.

LANDSCAPE CONFIGURATION, DESIGN, & PROCESS GUIDELINES

The low-lying position of polders means that they often accumulate runoff that needs to be detained and pumped into the Bay. They are also often close to groundwater. The polders themselves have subsided due to the compaction of organic soils as fluid pore pressures drop, peat soils above the water table shrink due to desiccation, and peat soils at and above the water table are lost by microbial oxidation of the organic matter. Even if the polders remained wet, as with salt ponds, the marsh vegetation was lost so the organic contribution to accretion was also lost. Since they are cut off from tidal action, the sediment supply from the Bay is also blocked. The combination of no mineral sedimentation and collapse of the organic soils has meant that polders have subsided in relation to the present tide elevations and lack the ability to accrete to keep up with future sea level rise.

A polder, therefore, has a unique character which creates specific management issues based on its position relative to the Bay, both in terms of the degree of subsidence and in terms of its location relative to the flood risk management levee. Managing polders includes maintaining dikes, water control structures, and pumps to manage water levels at desired levels or prevent flooding, depending on their purpose. If a polder is intentionally or accidentally returned to tidal action, the additional tidal prism will need to be accommodated as will the increased demand for sediment within the polder. The location of polders relative to structures such as levees and bridges is important as the large increase in tidal prism may lead to widening of downstream channels, undermining levees, bridge abutments, and other structures. Ideally, an accidentally breached polder would rapidly accrete to vegetation colonization elevation to reduce the impact of tidal prism and to realize the benefits of a tidal marsh on the Bay shore. Polders that have to remain dry, such as agricultural or residential areas, need maintained dikes that are high enough to provide the required level of protection and that can be adapted to accommodate future sea level rise. They are also vulnerable to flooding from rainfall and runoff ponding behind the dikes; stormwater detention and pumping is likely to increase with more urbanization and climate change.



Areas mapped as suitable for polder management were identified by selecting contiguous areas that are below mean sea level ($z^* < 0$) and disconnected from tidal inundation by dikes. These are areas that would be inundated on most tides if levees and berms were not present. Extensive polders are located in Suisun Bay, the North Bay, and the South Bay, where large diked and subsided baylands are prevalent. Data gaps are due to bathymetric data limitations (based on USGS 2013) and the map does not represent the current state of planned restoration. For more detail on restoration plans see page 39 and for more detailed methods see Appendix 5.

Shallow subsided salt ponds have been restored to tidal action as part of marsh restoration projects, which have required the flood risk management levee to be relocated landward of the polder (e.g., Petaluma Marsh and Sears Point restoration projects in the North Bay).

In a planned restoration, the topography may be graded before breaching and dredged sediment may be placed to raise elevations. Filling a polder with dredged sediment, such as at Sonoma Baylands and Hamilton Airfield Wetland Restoration, requires a large dredging project such as the deepening of channels at the Port of Oakland. Methods such as warping and levee lowering may allow the more gradual introduction of sediment into polders, by natural means, to reduce the impacts of catastrophic dike failures. Warping is the process of gradually building up the height of the mudflat or marsh within a polder by opening tide gates and letting in sediment-laden water on the flood tide, closing the tide gates to allow the sediment to fall out of the water column over several tides, and then letting the clear water out slowly on a subsequent ebb tide. An alternative could be to lower the outboard levee to allow sediment-laden water to enter the site at high water and then slowly drain over time, which would trap the sediment in the polder (analogous to a washover splay). Another alternative is to reconnect creeks to their former floodplains to create micro-deltas as the creek flow slows down and deposits sediment as it enters the polder, as suggested for the reconnection of Calabazas Creek to Pond A8 in Sunnyvale (SFEI-ASC 2018).

Agricultural polders can perform a dual purpose as detention basins, employing low-lying areas for water storage during storms to reduce downstream river levels and flooding. They could possibly be used in coastal areas to delay storm surge peaks so they do not coincide with high tides, and to reduce backwater effects along fluvial channels. This would require open land that could withstand periodic flooding without unacceptable impacts.

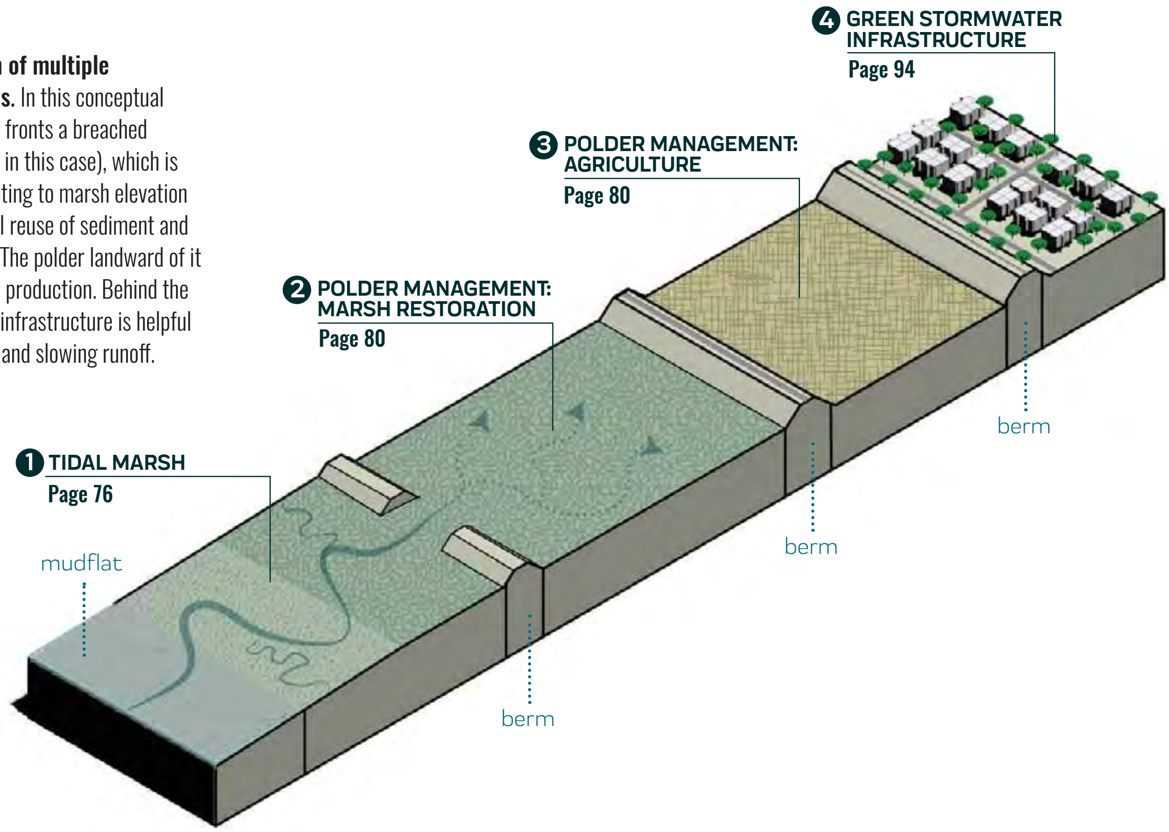
ECOSYSTEM FUNCTIONS

Ecosystem functions depend on the land use within the polder. For instance, salt ponds and agricultural fields provide habitat to large numbers of waterbirds, including ducks, geese, grebes, shorebirds, and wading birds. Waterbird densities in these areas are often considerably higher than in un-managed areas; they can be particularly important for migrating waterfowl. Certain polders that were former salt ponds, such as at Eden Landing and Ravenswood, are managed specifically to be dry, mimicking historic salt pannes or beaches to provide nesting habitat for the threatened Western snowy plover (*Charadrius nivosus* ssp. *nivosus*).

POLICY CONSIDERATIONS

Wetlands enjoy special protections under state and federal law; modifications involving fill or dredging would require permits from USACE, the Water Board, and BCDC. Salt ponds and managed ponds are part of BCDC's jurisdiction with special rules that apply. Environmental impact statements and consultations with state and federal wildlife managers are additionally required for locations supporting threatened or endangered species. Low-lying areas with no outlets may also be places that accumulate contaminants, such as mercury, PCBs, and other chemicals of concern in the Bay. These areas must be carefully managed to protect water quality to support beneficial uses, fish, and wildlife. Finally, managing water levels in ponds must consider mosquito abatement, especially where adjacent to developed areas, to avoid nuisance mosquitoes and the spread of vector-borne illness.

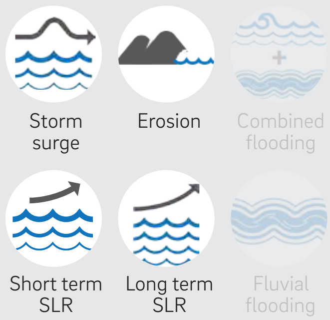
Conceptual diagram of multiple adaptation measures. In this conceptual example, a tidal marsh fronts a breached polder (diked baylands in this case), which is in the process of accreting to marsh elevation both through beneficial reuse of sediment and increased tidal action. The polder landward of it remains in agricultural production. Behind the flood risk levee, green infrastructure is helpful for spreading, sinking, and slowing runoff.



A polder (the site of Hamilton Airfield) before and after being opened to tidal action. (Image courtesy Google Earth)

Ecotone levees

COASTAL RISKS MANAGED



OTHER ECOSYSTEM SERVICES

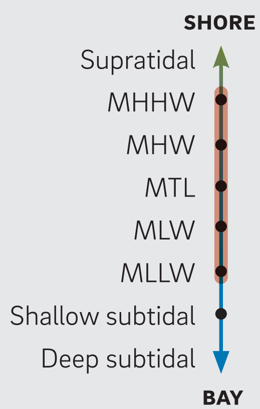
• Biodiversity • Food supply •
• Climate regulation* •
• Water quality improvement* •
• Recreation •
• Other cultural services •

* *Service dependent on chosen management approach*

IMPACT ON SHORELINE

Protect • Accommodate • Retreat

LOCATION
WITHIN TIDAL TRANSECT



EXAMPLES

Oro Loma Sanitary District

DEFINITION

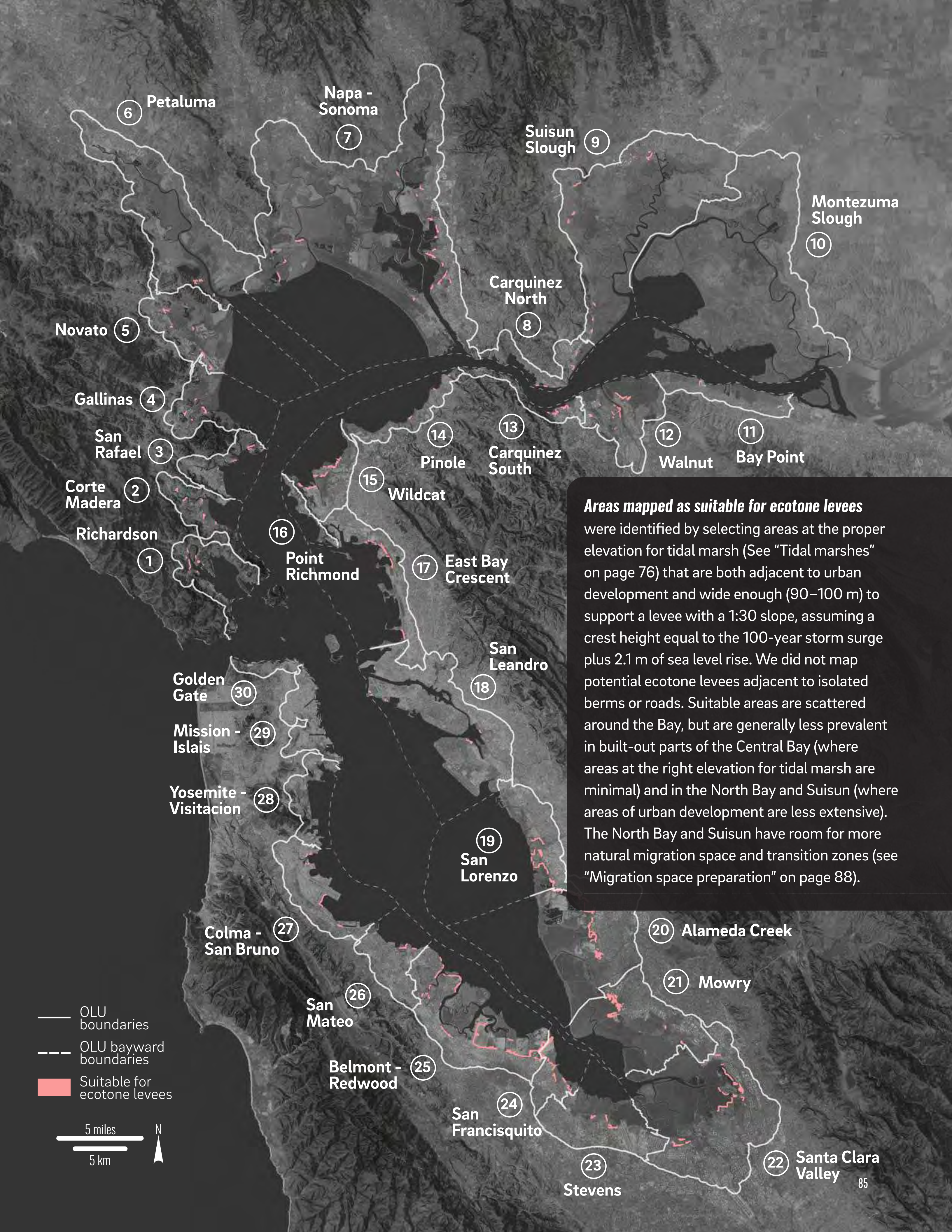
Ecotone levees are gentle slopes or ramps (with a length to height ratio of 20:1 or gentler) bayward of flood risk management levees and landward of a tidal marsh. They stretch from the levee crest to the marsh surface, and can provide wetland-upland transition zone habitat when properly vegetated with native clonal grasses, rushes, and sedges. They can attenuate waves, provide high-tide refuge for marsh wildlife, and allow room for marshes to migrate upslope with sea level rise.

LANDSCAPE CONFIGURATION, DESIGN, & PROCESS GUIDELINES

The significant flood risk management benefits that can be provided by vegetated tidal marshes have been recognized in the Bay for a long time. In parts of the Bay with wide alluvial valleys and alluvial fans/plains, there is a transition of habitat between the marsh and the adjacent upland which is habitat in its own right. This transition zone provides refuge for marsh species, attenuates waves during storms, and provides a gentle slope for marshes to migrate as sea level rises. Much of the natural transition around the Bay has been disconnected from the marshes by the construction of flood risk management levees in the historical marshes and mudflats. These levees create transition zones that are much steeper (with a length to height ratio generally between 3:1 and 4:1) and narrower than natural transition zones.

The slope of an ecotone levee is gentler than a normal flood risk management levee, more akin to the slope of a natural transition zones and so the area of transition zone will be wider—providing more space for transition zone function and services and more space for marsh migration. This slope stretches down from the crest of the flood risk management levee to tidal marsh elevation with a gradient between 20:1 and 30:1. The ecotone levee only makes sense where naturally rising upland is absent and where there is an existing marsh or potential to restore marsh in front of it. Ecotone levees could be included in the restoration of marshes in polders, in which case the toe of the ecotone levee could be initially subtidal and unvegetated, requiring a different design approach than an ecotone levee sloping down into a marsh. The low-gradient slope is outside the core of the flood risk management levee and so, unlike the core, does not need to be constructed from geotechnical material compacted to a specified level. The gentler ecotone slope may reduce wave run up and overtopping of the crest of the flood risk management levee.

Ecotone levees have been included in the South Bay Salt Ponds Restoration Project and the South San Francisco Bay Shoreline Project. An enhancement of the ecotone levee is the "horizontal levee" which introduces subsurface irrigation to support fresh to brackish wetlands on the levee at the back end of the tidal marsh, restoring some functions of the natural salinity gradients that were historically found where small creeks entered the baylands. These brackish wetlands would be expected to support dense stands of tall sedges and bulrush, which would enhance the wave dampening function of the levee and reduce erosion. A horizontal levee is being piloted at the Oro Loma Sanitary District



Areas mapped as suitable for ecotone levees were identified by selecting areas at the proper elevation for tidal marsh (See "Tidal marshes" on page 76) that are both adjacent to urban development and wide enough (90–100 m) to support a levee with a 1:30 slope, assuming a crest height equal to the 100-year storm surge plus 2.1 m of sea level rise. We did not map potential ecotone levees adjacent to isolated berms or roads. Suitable areas are scattered around the Bay, but are generally less prevalent in built-out parts of the Central Bay (where areas at the right elevation for tidal marsh are minimal) and in the North Bay and Suisun (where areas of urban development are less extensive). The North Bay and Suisun have room for more natural migration space and transition zones (see "Migration space preparation" on page 88).

where treated wastewater is being used to irrigate the slope with the additional benefit of further "polishing" of the effluent (see photo on facing page).

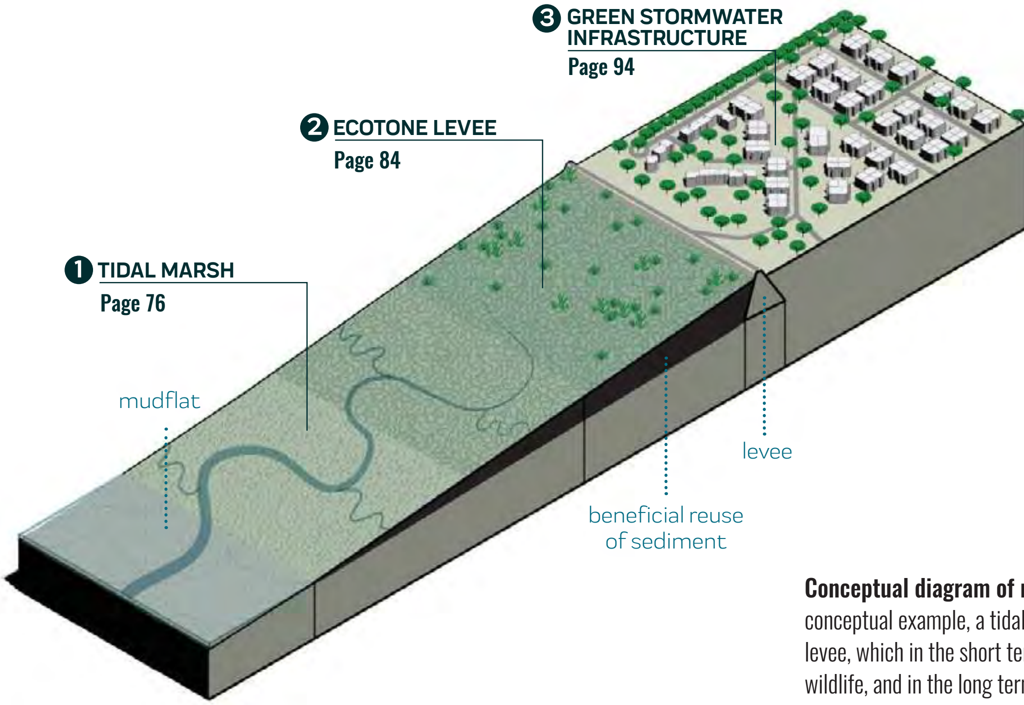
ECOSYSTEM FUNCTIONS

Ecotone levees support a broader ecotone between marsh and upland areas than traditional flood risk management levees, can support unique vegetation communities associated with the estuarine-terrestrial transition zone, and can provide high-tide refuge for marsh wildlife. Horizontal levees further mimic the natural seepages and wet meadow habitat that was historically common along the lower gradient valley sides and alluvial fans of the Bay.

POLICY CONSIDERATIONS

Ecotone levees are largely untested. They will require considerable volumes of material to construct, with high associated costs. In many places their construction would require filling the baylands, which is highly regulated. Modifying the topography of the shoreline (including its slope) requires a permit from the Water Board. Grading or modifying land within 100 ft (30.5 m) of the shoreline requires a permit from BCDC. The use of fill may also need to be permitted by USACE. Environmental impact statements and consultations with state and federal wildlife managers are additionally required for locations featuring threatened or endangered species. Horizontal levees that reuse or partially treat wastewater are at the experimental stage and have not yet been scaled up to test the feasibility, economics, or permit-worthiness of full-scale implementation. FEMA has not stated a view on the certification of a horizontal levee.

An experimental horizontal levee at the Oro Loma Sanitary District, gently sloping up to a berm in the background. (Photo by Nate Kauffman)

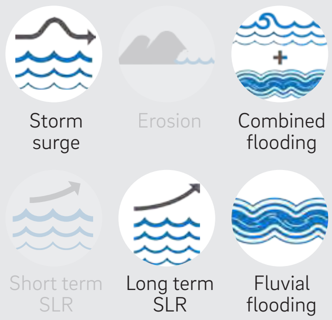


Conceptual diagram of multiple adaptation measures. In this conceptual example, a tidal marsh fronts a gently sloping ecotone levee, which in the short term provides high-tide refuge for marsh wildlife, and in the long term provides space for marsh migration. Behind the flood risk levee at the back of the ecotone levee, green infrastructure is helpful for spreading, sinking runoff, and lowering peak flows.

A suitable area for an ecotone levee at the south end of the Hamilton Wetland Restoration Project. The project design calls for the developed areas visible in the image to be protected with a gently sloping ecotone levee. (Photo courtesy Google Earth)

Migration space preparation

COASTAL RISKS MANAGED



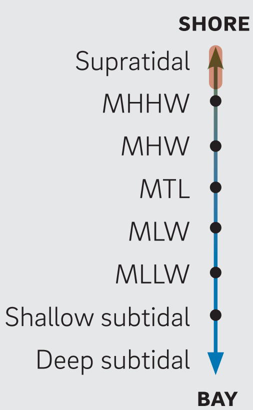
OTHER ECOSYSTEM SERVICES

• Biodiversity • Food supply •
• Climate regulation •
• Water quality improvement •
• Recreation •
• Other cultural services •

IMPACT ON SHORELINE

Protect • Accommodate • Retreat

LOCATION
WITHIN TIDAL TRANSECT



EXAMPLES

Rush Ranch Open Space Preserve, China Camp

DEFINITION

Migration space in this report refers to areas at appropriate topographic elevations that could support estuarine-upland transition zones now and in the future with sea level rise. These are often natural wetland-upland transition zone areas adjacent to present and potential marshes that could be protected, enhanced, or restored to allow marshes to migrate landward as sea level rises. Lands that provide migration space are scarce and in demand as they are generally situated between the lower limits of developed upland areas and the upper limits of diked or tidal baylands.

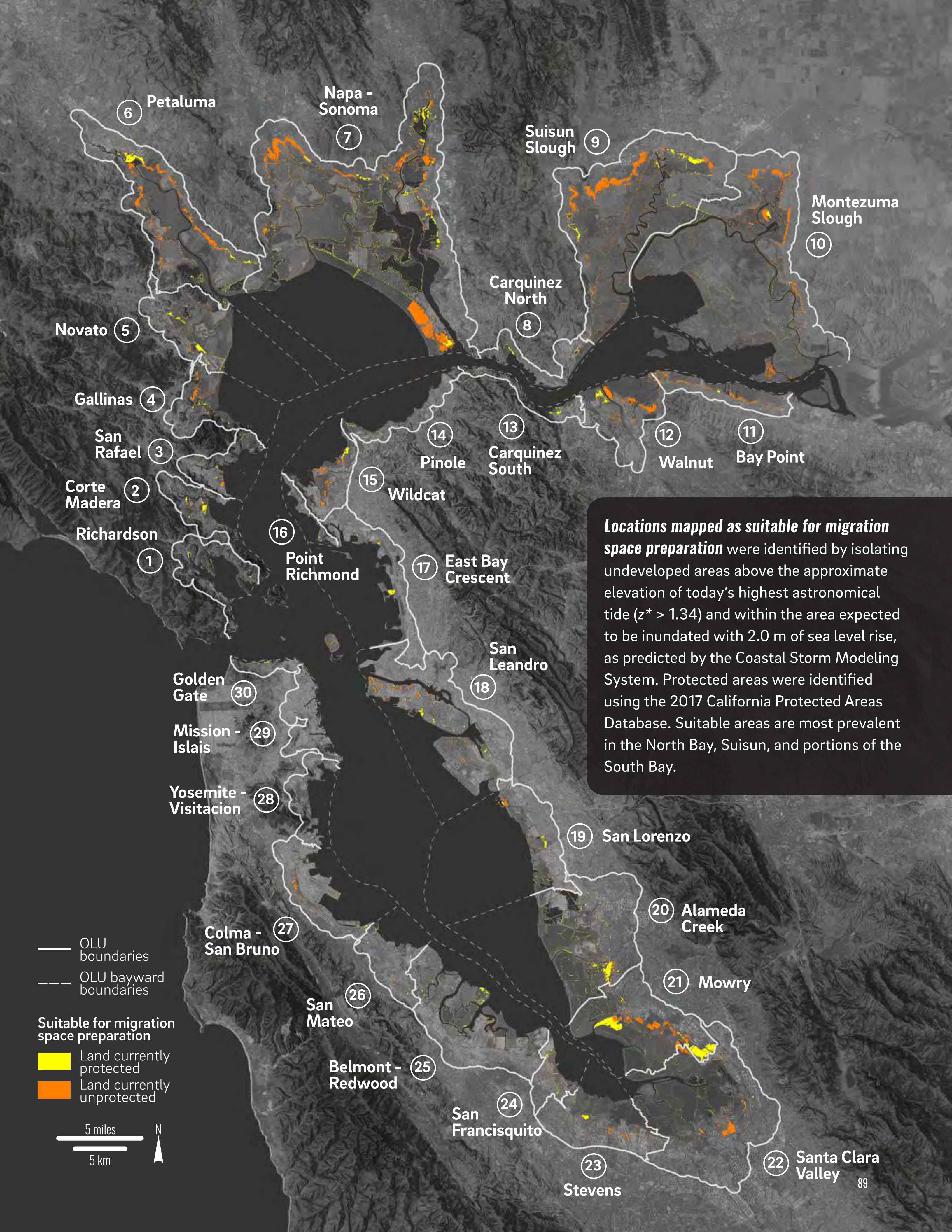
LANDSCAPE CONFIGURATION, DESIGN, & PROCESS GUIDELINES

In the face of sea level rise, areas that provide migration space will be critical for long-term adaptation of tidal marshes and offer opportunities for creative strategies such as purchasing land and restoring freshwater wetlands that could transition to salt marsh. These areas are generally limited to agricultural regions in the North Bay and Suisun Regions and are less common and less hydrologically connected in urbanized areas.

Hydrologic connectivity with the Bay is important if marshes are to migrate. Areas where streams and creeks connect to baylands are especially important to protect as they provide an important conduit for watershed-derived freshwater and sediment to tidal marshes, and generally support areas of gently sloped topographic relief that are suitable for the long-term migration of tidal wetlands upslope. At the site scale, berms that block flows will need to be removed. Land may have to be regraded where fill has been placed or removed. If the flood risk management levee is realigned, then a setback levee for flood protection has to be constructed that should accommodate future sea level rise and future marsh migration.

Areas that support migration space tend to be dominated by ruderal, weedy, often invasive vegetation with limited value for native wildlife. Management is often necessary to establish native plant communities more appropriate to these landscape settings (e.g., native grasses and clonally-spreading allies such as rushes and sedges). Once these vegetation communities are established, they tend to be relatively self-maintaining, and require limited intervention.

Where development pressures are high, updates of land use plans should take into account change in exposure to flooding with sea level rise and consider modifying zoning to increase the protection of migration space. If development has to occur within flooding zones the development should be floodable (see page 106). In some places, pipes and transmission lines could be modified or rerouted to reduce their exposure to flooding.



Locations mapped as suitable for migration space preparation were identified by isolating undeveloped areas above the approximate elevation of today's highest astronomical tide ($z^* > 1.34$) and within the area expected to be inundated with 2.0 m of sea level rise, as predicted by the Coastal Storm Modeling System. Protected areas were identified using the 2017 California Protected Areas Database. Suitable areas are most prevalent in the North Bay, Suisun, and portions of the South Bay.

ECOSYSTEM FUNCTIONS

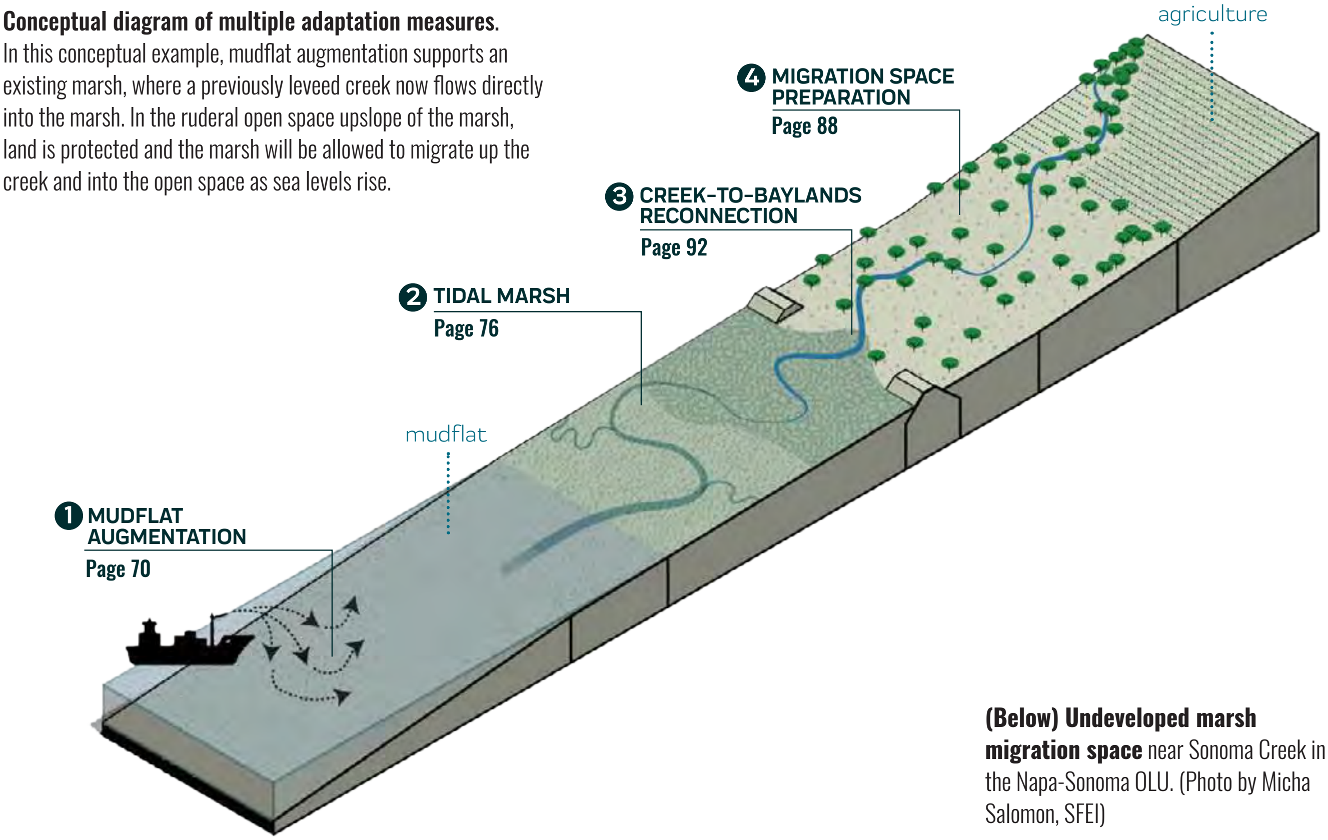
Maintaining areas adjacent to marsh for migration space can support other important estuarine-terrestrial transition zone functions such as providing high-tide refuge for marsh wildlife, providing space for terrestrial wildlife to access marshes, and supporting non-tidal habitats such as grasslands and seasonal wetlands.

POLICY CONSIDERATIONS

Preparing migration space may involve fill, grading, altering the slope of existing floodplains, and other activities that may require permits from USACE, BCDC, and the Water Board—and consultations with federal and state wildlife managers. Additionally, migration space may need to be protected, purchased, or rezoned to adjust allowable land uses and development expectations (see policy and non-structural measures described later in this chapter). Such activities are typically undertaken by local governments.

Undeveloped marsh migration space along Tolay Creek in the Napa-Sonoma OLU. (Photo by Julie Beagle, SFEI)

Conceptual diagram of multiple adaptation measures. In this conceptual example, mudflat augmentation supports an existing marsh, where a previously leveed creek now flows directly into the marsh. In the ruderal open space upslope of the marsh, land is protected and the marsh will be allowed to migrate up the creek and into the open space as sea levels rise.

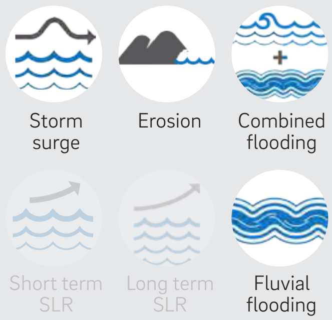


(Below) Undeveloped marsh migration space near Sonoma Creek in the Napa-Sonoma OLU. (Photo by Micha Salomon, SFEI)

NATURAL AND NATURE-BASED MEASURES

Creek-to-baylands reconnection

COASTAL RISKS MANAGED



OTHER ECOSYSTEM SERVICES

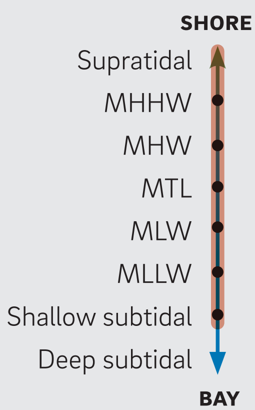
• Biodiversity • Food supply •
• Climate regulation* •
• Water quality improvement* •
• Recreation •
• Other cultural services •

* *Service dependent on chosen management approach*

IMPACT ON SHORELINE

Protect • Accommodate • Retreat

LOCATION
WITHIN TIDAL TRANSECT



EXAMPLES

Calabazas Creek, San Tomas Aquino Creek, and Pond A8 Reconnection Project (SFEI-ASC 2018)

DEFINITION

Many of the creeks draining to San Francisco Bay have been hydrologically disconnected from their historical floodplains and baylands for the sake of water supply, flood control, and development. Historically, these creeks delivered watershed-derived sediment, nutrients, and freshwater to the baylands to sustain tidal flats, marshes, and tidal-terrestrial transition zones. Today, many of these creeks are confined by flood control levees in their tidal reaches, resulting in habitat loss, land subsidence, excess in-channel sedimentation, channel dredging to maintain flood conveyance, reduced sediment supply to baylands, and thus decreased resilience to climate change. Reconnecting creeks to their adjacent baylands through levee breaching or removal is one approach to improve sediment, nutrient, and freshwater delivery to the baylands while achieving flood risk management and habitat benefits.

LANDSCAPE CONFIGURATION, DESIGN, & PROCESS GUIDELINES

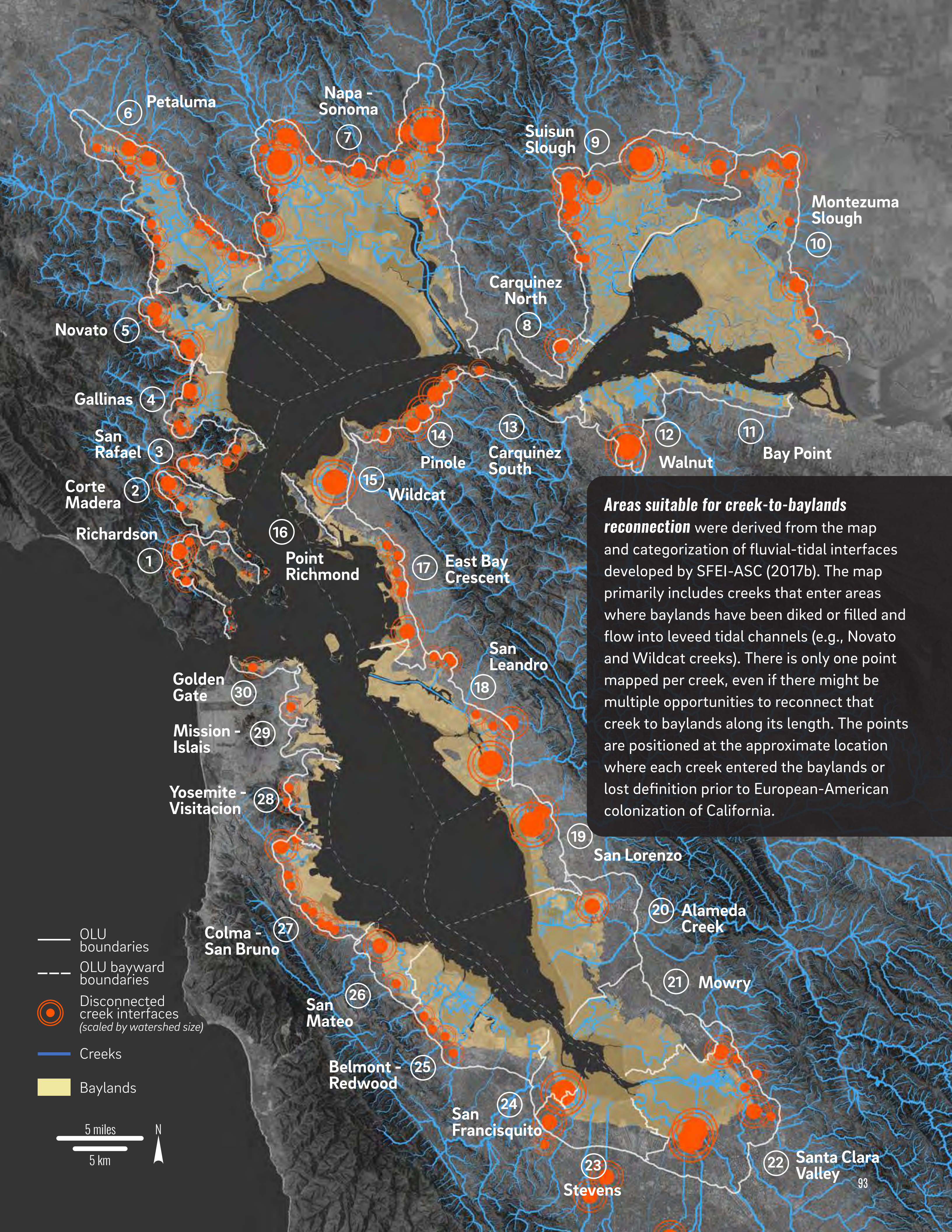
Fluvial channels that transition to an estuarine channel, and are adjacent to open space in the tidal reach, could be considered for creek-to-baylands reconnection. Creeks with abundant adjacent space (e.g., baylands, diked baylands, or undeveloped upland) have the most options in terms of design and configuration of reconnection (e.g., channel realignment, ecotone levee implementation) and could support the greatest degree of ecosystem functions. Adjacent areas undergoing or slated for habitat restoration would benefit from additional sediment, nutrient, and freshwater deposition through creek reconnection, which would improve the baylands' resilience to sea level rise. Stream power and watershed sediment supply are important considerations to evaluate whether creeks have the appropriate landscape setting to move sediment to the baylands. Hybrid solutions that employ a combination of creek-to-baylands reconnection and beneficial sediment reuse may be necessary for creeks with less stream power, sediment supply, or adjacent open space.

ECOSYSTEM FUNCTIONS

Creek-to-baylands reconnections can create pathways for marsh migration with sea level rise and improve ecosystem functioning and resilience through the reestablishment of estuarine-terrestrial transition zones.

POLICY CONSIDERATIONS

Projects in creeks and inland areas commonly involve local flood control districts. Modifying the shoreline, including the slope, of any stream channel or floodplain requires a permit from the Water Board. Grading or modifying land within 100 ft (30.5 m) of the shoreline requires a permit from BCDC. Most work in streams and wetlands also requires permits from USACE. Environmental impact statements and consultations with state and federal wildlife managers are additionally required for locations featuring threatened or endangered species.

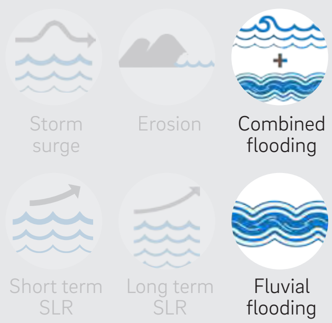


Areas suitable for creek-to-baylands reconnection were derived from the map and categorization of fluvial-tidal interfaces developed by SFEI-ASC (2017b). The map primarily includes creeks that enter areas where baylands have been diked or filled and flow into leveed tidal channels (e.g., Novato and Wildcat creeks). There is only one point mapped per creek, even if there might be multiple opportunities to reconnect that creek to baylands along its length. The points are positioned at the approximate location where each creek entered the baylands or lost definition prior to European-American colonization of California.

NATURAL AND NATURE–BASED MEASURES

Green stormwater infrastructure

COASTAL RISKS MANAGED



OTHER ECOSYSTEM SERVICES

• Biodiversity • Food supply •
• Climate regulation •
• Water quality improvement •
• Recreation •
• Other cultural services •

IMPACT ON SHORELINE

Protect • Accommodate • Retreat

LOCATION
WITHIN TIDAL TRANSECT

EXAMPLES

- Philadelphia, “Green City, Clean Waters” (City of Philadelphia Water Department 2011)
- Portland Bureau of Environmental Services (Entrix 2010)
- The Greater New Orleans Urban Water Plan (Papacharalambous et al. 2013)

DEFINITION

Green infrastructure tools include rain gardens, bioswales, cisterns/rainwater harvesting, permeable pavement, creek daylighting, green roofs, urban forestry and more. These tools help retain stormwater upland in an urban watershed to slow it down, sink it into the ground, or reuse it for beneficial purposes like irrigation before it is collected in storm drains and shunted to receiving waters. This can reduce storm sewer, creek, and combined sewer-related flooding, which will become increasingly important with sea level rise and increased storminess.

LANDSCAPE CONFIGURATION, DESIGN, & PROCESS GUIDELINES

Undetained, stormwater can cause creeks to flood and contribute to combined flooding near the Bay shore. Stormwater also acts as the primary conduit for the movement of pollution and trash from urban areas to the Bay. Stormwater typically causes flooding problems where there is a high degree of connected, impervious surface, as is often found in heavily urbanized areas. Design considerations for green infrastructure include slope, the permeability/compactness of underlying soil, utility conflicts, the amount of space available, and property ownership. Site-scale tools such as GreenPlan-IT can be used for planning, and stormwater professionals should be consulted for the design of facilities. For green infrastructure to be effective it needs wholesale implementation at scales of whole neighborhoods and whole cities.

Aside from reducing the volume of stormwater, green infrastructure can result in significant improvements in water quality by reducing or transforming common pollutants in urban runoff, including nutrients, metals, hydrocarbons, pesticides, herbicides, and many others.

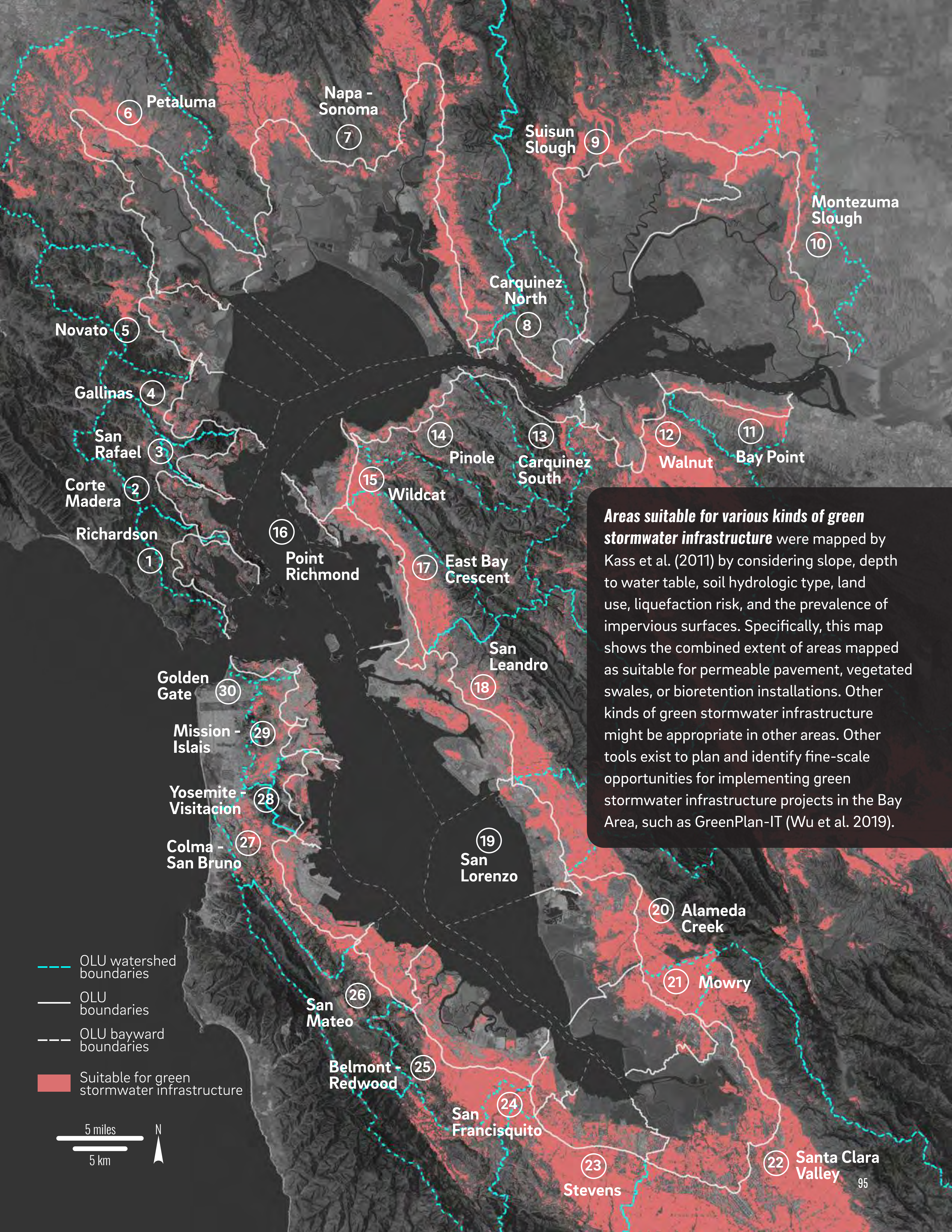
ECOSYSTEM FUNCTIONS

Green stormwater infrastructure has the potential to provide habitat for wildlife, particularly when native species are used in bioswales and rain gardens. When coordinated across the landscape, green infrastructure and urban greening measures can support creek and wetland wildlife by improving subsurface hydrological conditions.

POLICY CONSIDERATIONS

Stormwater is a major source of pollution in the Bay and its tributary streams. Under permits from the Water Board, construction sites and industrial facilities must manage runoff through best management practices and monitoring. Bay Area cities covered by the Water Board’s Municipal Regional Stormwater Permit (Order No. 2015-0049) are developing green infrastructure plans to manage pollutants of concern. Green infrastructure in strategic locations can also contribute to flood detention and retention in upland areas and contribute to watershed management goals, including reducing combined flooding. Local governments can design and develop green infrastructure projects in the right of way and at the scale of entire neighborhoods. By ordinance, they can require new private development to manage a certain amount of rainfall on site.

For more information, please visit *greenplanit.sfei.org.*



Areas suitable for various kinds of green stormwater infrastructure were mapped by Kass et al. (2011) by considering slope, depth to water table, soil hydrologic type, land use, liquefaction risk, and the prevalence of impervious surfaces. Specifically, this map shows the combined extent of areas mapped as suitable for permeable pavement, vegetated swales, or bioretention installations. Other kinds of green stormwater infrastructure might be appropriate in other areas. Other tools exist to plan and identify fine-scale opportunities for implementing green stormwater infrastructure projects in the Bay Area, such as GreenPlan-IT (Wu et al. 2019).

Super levees

COASTAL RISKS MANAGED

Storm surge · Erosion · Combined flooding

Short term SLR · Long term SLR · Fluvial flooding

OTHER ECOSYSTEM SERVICES

• Biodiversity • Food supply •
• Climate regulation •
• Water quality improvement •
• Recreation •
• Other cultural services •

IMPACT ON SHORELINE

Protect • Accommodate • Retreat

LOCATION WITHIN TIDAL TRANSECT

SHORE

Supratidal
MHHW
MHW
MTL
MLW
MLLW
Shallow subtidal
Deep subtidal

BAY

EXAMPLES

- Rotterdam
- Tokyo (Arakawa and Edogawa Rivers)
- New York (The Big U—proposed)

DEFINITION

Super levees are extremely tall and wide levees that may accommodate other functions besides flood protection, including buildings, transportation, and recreational amenities, integrated on top or within the structure.

LANDSCAPE CONFIGURATION, DESIGN, & PROCESS GUIDELINES

Super levees require large amounts of land. Pioneered in Japan, super levees there are up to 300 m wide and 9 m high and are constructed to prevent urban river flooding and damage from tsunamis. They provide re-development opportunities while being resilient to earthquakes, seepage, and overtopping. Like ecotone levees (see page 84), they require a significant source of fill, have potential geotechnical constraints, and require a large area of land adjacent to the shoreline. In Japan, super levees are often constructed in a terraced form to accommodate multiple uses, which can include habitat, recreation and better water access for people. Potentially in combination (back to back) with a ecotone levee on the Bay shore, a super levee could create a new space for recreation and urban uses, making a safer and more usable place out of what would otherwise be liquefiable and flood-prone land. However placement of large quantities of fill can lead to compaction and subsidence as well as disturbance to adjacent unfilled areas, especially on baylands soils.

ECOSYSTEM FUNCTIONS

Building green elements into super levee projects by, for example, including native plants and mimicking riparian or coastal processes on the water side (instead of employing a typical revetment), could provide some ecosystem function benefits.

POLICY CONSIDERATIONS

New super levees would require the demolition of pre-existing structures to raise the ground elevation, so this strategy could be difficult to implement in an already urbanized or developed area. Construction may cause significant displacement of people, wildlife, and infrastructure, and would require substantial cooperation from property owners. Any levee construction that modifies land near the shoreline requires a permit from the Water Board. Permits could also be required from BCDC, USACE, and state and federal wildlife managers. Construction would likely trigger CEQA and an environmental impact study. New land and its uses would be designated and regulated under zoning, subdivision, and other development regulations.

Edogawa super levee in Tokyo, Japan (Photo by Marufish, CC BY-SA 2.0)

Elevate land

DEFINITION

Elevating land at the site or district scale above a design flood elevation to lift future development and transportation assets out of the flood zone.

LANDSCAPE CONFIGURATION, DESIGN, & PROCESS GUIDELINES

Elevating the height of land for new buildings or other uses can flood-proof a site for a designed flood elevation, plus a margin of safety (also known as freeboard). Site elevation can ready low-lying, underutilized areas for new development and new uses in places that would otherwise be flood-prone. In the process, adding height to land may help remediate brownfields, improve seismic safety and create a re-development opportunity while reducing flood insurance rates. It might also bring noncompliant structures (once they are replaced or rebuilt at a higher grade) into compliance with the National Flood Insurance Program.

However, site elevation is hard to modify over time and, like super levees, would require a significant amount of clean dirt or fill. Some areas would not be practical to elevate, or are so densely developed and used that the structures cannot be modified for a raised grade. Raising elevations in a patchwork pattern may make it hard to maintain connectivity of transportation and drainage networks in existing urbanized areas. Placement of large quantities of fill can lead to compaction and subsidence as well as disturbance to adjacent unfilled areas, especially on baylands soils. Construction would cause significant disruption to existing land uses, and likely require their temporary or permanent relocation. An example of land elevation for redevelopment is Arverne-by-the-Sea, a neighborhood in the Rockaways in Queens, New York, where the entire 49 hectare (120 acre) site was raised 8 ft (2 m) with new fill to enable the construction of 2,000 new townhomes more resilient to sea level rise and hurricane-related storm surge.

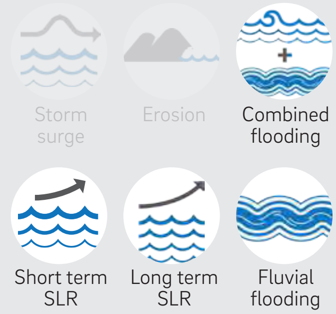
ECOSYSTEM FUNCTIONS

Building green elements into land elevation projects (for example, by supporting native plants in these areas) can provide some benefits for ecosystem function.

POLICY CONSIDERATIONS

Land elevation is not a flexible strategy and may only work over the short-term, depending on how fast sea levels rise and how much the land is elevated. Any construction that modifies land near the shoreline, including its elevation, requires a permit from the Water Board. Permits could also be required from BCDC, USACE, and state and federal wildlife managers. Construction would likely trigger CEQA and an environmental impact study. New land uses would be designated and regulated under zoning, subdivision, and other development regulations.

COASTAL RISKS MANAGED



OTHER ECOSYSTEM SERVICES

• Biodiversity • Food supply •
• Climate regulation •
• Water quality improvement •
• Recreation •
• Other cultural services •

IMPACT ON SHORELINE

Protect • Accommodate • Retreat

LOCATION
WITHIN TIDAL TRANSECT

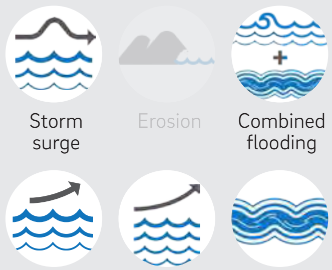
EXAMPLES

- Treasure Island (San Francisco; Moffatt and Nichol 2008)
- Arverne-by-the-Sea in Queens, NYC (raised 120-acre redevelopment site for over 2,000 new townhomes by over 2 m)

GREY INFRASTRUCTURE

Flood walls

COASTAL RISKS MANAGED



Storm surge • Erosion • Combined flooding • Short term SLR • Long term SLR • Fluvial flooding

OTHER ECOSYSTEM SERVICES

• Biodiversity • Food supply •
• Climate regulation •
• Water quality improvement •
• Recreation •
• Other cultural services •

IMPACT ON SHORELINE

Protect • Accommodate • Retreat

LOCATION WITHIN TIDAL TRANSECT

SHORE

Supratidal
MHHW
MHW
MTL
MLW
MLLW
Shallow subtidal
Deep subtidal

BAY

EXAMPLES

- Red Hook, NY
- Marina Bay, Richmond, CA

DEFINITION

Flood walls can be built at the site or district scale to provide protection during infrequent flooding and extreme weather; these can be permanent or demountable.

LANDSCAPE CONFIGURATION, DESIGN, & PROCESS GUIDELINES

Flood walls are best suited to individual buildings or sites, while berms can be designed around multiple streets and buildings to prevent occasional flooding and overtopping in low-lying developed areas. Flood walls require less space than levees and may be more suitable in urban locations where there is less room. They are typically constructed only a meter or so above grade (FEMA 2012) and are not meant to manage waves or strong erosive forces near a shoreline. Demountable or temporary flood walls have high operational and maintenance requirements, and must be installed with a site plan for management, operations, and maintenance. Permanent flood walls may impede pedestrian circulation, building access, and transportation, and must be designed to avoid trapping stormwater and creating additional drainage problems.

ECOSYSTEM FUNCTIONS

None known. Flood walls can have many negative impacts on ecosystem functions, such as limiting connectivity between aquatic and upland resources or cutting off wildlife corridors.

POLICY CONSIDERATIONS

Flood walls around buildings or streets may trigger additional accommodations under Americans with Disabilities Act (ADA) or fire codes. Flood walls, like levees, may not be used to bring non-compliant structures into compliance under the National Flood Insurance Program.

Flood wall in front of residential housing located along Hamilton Wetlands in Novato (Photo by Shira Bezalel, SFEI)

Elevate or realign transportation

DEFINITION

Roads and rail can be moved out of the sea level rise hazard zone by raising them on a levee, causeway, or bridge, moving them to a new upland location, or rerouting service to other existing transportation routes.

LANDSCAPE CONFIGURATION, DESIGN, & PROCESS GUIDELINES

Transportation infrastructure may already serve as a levee or a line of defense for flooding and sea level rise. Elevation of structures to a new grade may require significant amounts of fill, and must take into account potential drainage impacts to avoid trapping stormwater and worsening flooding. Connectivity for transportation routes, or alternative routes, must be considered during construction.

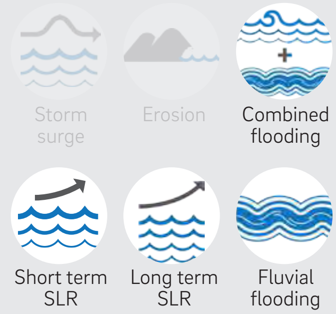
ECOSYSTEM FUNCTIONS

Elevating transportation structures could improve wildlife habitat and corridors, and create additional room for marsh migration and transition zone restoration.

POLICY CONSIDERATIONS

Transportation infrastructure is hard to relocate, potentially requiring the acquisition of new rights-of-way, with associated land costs. Permitting and planning for transportation is complex, involving federal, state, and local agencies such as the Federal Transit Administration/Federal Highway Administration, Caltrans, county congestion management agencies, and others. Elevated structures may only work for the short-term, depending on how fast sea levels rise and how much freeboard is built into the elevation. Any construction that modifies land near the shoreline, including its elevation, requires a permit from the Water Board. Permits could also be required from BCDC, USACE, and state and federal wildlife managers. Construction would likely trigger NEPA/CEQA and an environmental impact study.

COASTAL RISKS MANAGED



OTHER ECOSYSTEM SERVICES

• Biodiversity • Food supply • Climate regulation • Water quality improvement • Recreation • Other cultural services •

IMPACT ON SHORELINE

Protect • Accommodate • Retreat

LOCATION WITHIN TIDAL TRANSECT

EXAMPLES

- Miami Beach, FL
- St. Tammany Parish, LA: requires elevation of new/rebuilt roads at least 6 ft above the local datum

GREY INFRASTRUCTURE

Seawalls

COASTAL RISKS MANAGED

Storm surge • Erosion • Combined flooding

Short term SLR • Long term SLR • Fluvial flooding

OTHER ECOSYSTEM SERVICES

• Biodiversity • Food supply •
• Climate regulation •
• Water quality improvement •
• Recreation •
• Other cultural services •

IMPACT ON SHORELINE

Protect • Accommodate • Retreat

LOCATION
WITHIN TIDAL TRANSECT

SHORE

Supratidal
MHHW
MHW
MTL
MLW
MLLW
Shallow subtidal
Deep subtidal

BAY

EXAMPLES

- Ocean Beach and the Embarcadero, San Francisco, CA
- Broad Beach, Malibu, CA
- Seattle, WA

DEFINITION

Large stone, rock, or concrete structures designed to protect upland areas from coastal flooding, especially in high-wave energy environments. They are built at the land-water interface and are meant to withstand large storms.

LANDSCAPE CONFIGURATION, DESIGN, & PROCESS GUIDELINES

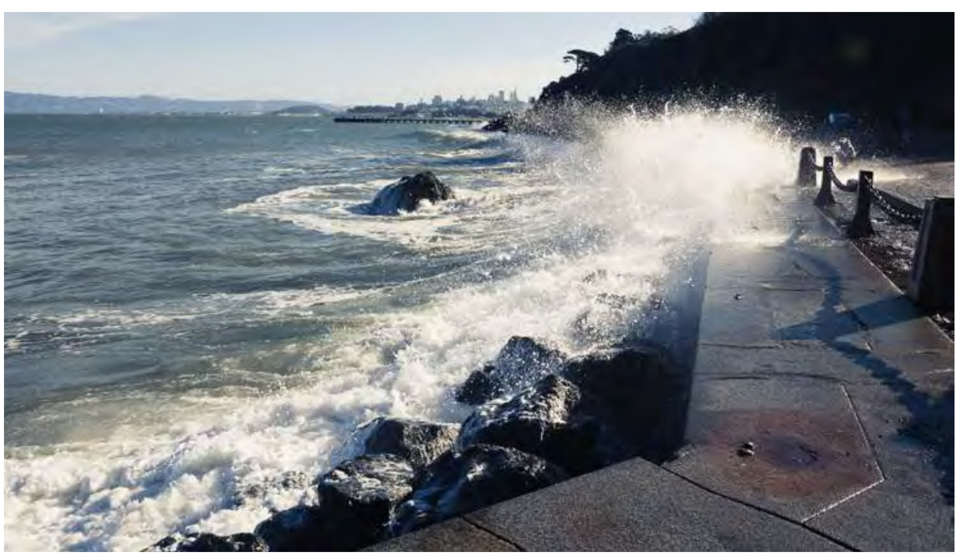
The height of the seawall is chosen and designed to avoid overtopping and wave run-up. Seawalls are used in areas of high wave action and storm surges. Common designs are curved, vertical (employing sheet-pile walls), or gravity (large stones). Seawalls are less space-intensive than other shoreline measures like levees or beaches, and are not suited for natural shorelines. They can intensify beach erosion by interfering with sediment transport and reflecting wave energy back into the beach. Typically, they are constructed by the U.S. Army Corps of Engineers as part of a larger flood control project and must undergo a lengthy permit process. If the seawall impedes gravity drainage of upland areas, pumping will be required inland of the seawall. Seawalls are not suitable solutions for areas where there is a desire to maintain natural shorelines, because seawalls can worsen scour and accelerate beach and sediment loss in front.

ECOSYSTEM FUNCTIONS

Building green elements into seawalls, such as spaces for aquatic plants and invertebrates to occupy, can provide some benefits for ecosystem function.

POLICY CONSIDERATIONS

Any fortifications that alter the shoreline require a permit from USACE, the Water Board, BCDC, and potentially state and federal wildlife managers if wildlife species are involved. Construction would likely trigger CEQA/NEPA and an environmental impact study. New FEMA-certified flood protection structures may enable certain neighborhoods, infrastructure, and developed areas to be eligible for reduced or eliminated flood insurance rates under the National Flood Insurance Program.



Seawall at Fort Point in the Golden Gate OLU (Photo by Shira Bezalel, SFEI)

Bulkheads

DEFINITION

Vertical retaining structures built to stabilize the existing shoreline and limit shoreline erosion.

LANDSCAPE CONFIGURATION, DESIGN, & PROCESS GUIDELINES

Bulkheads stabilize the shoreline and prevent soil erosion; they are not typically designed to resist waves and surge and can fail after many overtoppings and soil saturation on the upland side. Bulkheads are best suited to sites with already hardened shorelines, to improve waterfront access and maritime use. Like a seawall or groin, bulkheads reflect wave energy by fixing the shoreline in place. They can be designed to facilitate boat access via boardwalk or roadway. Bulkheads are very narrow and space-efficient. They are unsuitable for high wave-energy environments, or areas where there is a desire to maintain natural shorelines.

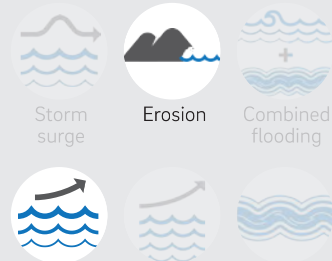
ECOSYSTEM FUNCTIONS

None known.

POLICY CONSIDERATIONS

Any fortifications that alter the shoreline require a permit from USACE, the Water Board, BCDC, and potentially state and federal wildlife managers if wildlife species are involved. Construction would likely trigger CEQA/NEPA and an environmental impact study. New FEMA-certified flood protection structures may enable certain neighborhoods, infrastructure, and developed areas to be eligible for reduced or eliminated flood insurance rates under the National Flood Insurance Program.

COASTAL RISKS MANAGED



Storm surge · Erosion · Combined flooding

Short term SLR · Long term SLR · Fluvial flooding

OTHER ECOSYSTEM SERVICES

• Biodiversity • Food supply • Climate regulation • Water quality improvement • Recreation • Other cultural services •

IMPACT ON SHORELINE

Protect • Accommodate • Retreat

LOCATION WITHIN TIDAL TRANSECT

SHORE

Supratidal
MHHW
MHW
MTL
MLW
MLLW
Shallow subtidal
Deep subtidal

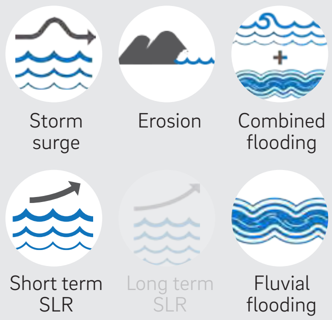
BAY

Bulkhead along the North Carolina coast (Photo courtesy USFWS)

GREY INFRASTRUCTURE

Revetments and riprap

COASTAL RISKS MANAGED



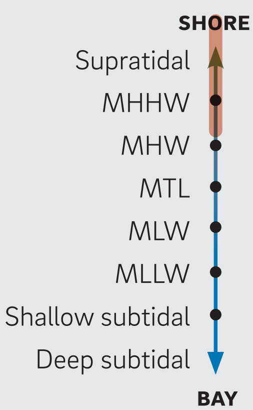
OTHER ECOSYSTEM SERVICES

• Biodiversity • Food supply •
• Climate regulation •
• Water quality improvement •
• Recreation •
• Other cultural services •

IMPACT ON SHORELINE

Protect • Accommodate • Retreat

LOCATION
WITHIN TIDAL TRANSECT



DEFINITION

Revetments are hardened structures made of concrete, rocks, wood, or other materials that are placed along waterways to stabilize them against waves and erosion. Riprap, which is made of rock or concrete rubble, is the most common form of shoreline protection revetment structure in San Francisco Bay.

LANDSCAPE CONFIGURATION, DESIGN, & PROCESS GUIDELINES

Revetments are cheaper than bulkheads or seawalls but typically require more space (typically 2:1 slope). Increasingly they are being designed to incorporate habitat/plants and facilitate public water access. They are most effective in areas with stable underlying soil, and are relatively easy to maintain. Properly designed riprap requires an underlayer of finer-grained rock or filter fabrics to prevent fine-sediments behind the large rocks from washing out.

Individual rocks used for riprap are sized based on local calculated wave energy. In SF Bay they typically weigh 0.25-1 ton (230-900 kg). To discourage people from moving on riprap (which can be dangerous), angular rocks are generally favored.

ECOSYSTEM FUNCTIONS

Revetments and riprap can provide habitat for oysters, shellfish, and other aquatic species.

POLICY CONSIDERATIONS

Any fortifications that alter the shoreline require a permit from USACE, the Water Board, BCDC, and potentially state and federal wildlife managers if wildlife species are involved. Construction would likely trigger CEQA/NEPA and an environmental impact study. Because they are easier to engineer and build than seawalls, rip rap and revetments are sometimes deployed under emergency circumstances to stabilize slopes or beaches experiencing erosion.

Rip rap along the shoreline of Point Isabel, Contra Costa County (Photo by Shira Bezalel, SFEI)

GREY INFRASTRUCTURE

Levees and dikes

DEFINITION

Earthen embankments at the shoreline used to prevent flooding.

LANDSCAPE CONFIGURATION, DESIGN, & PROCESS GUIDELINES

Levees are earthen structures built to reduce flood risk. Levees are very common water control structures used in diked areas of the Bay and along major waterways in the Bay-Delta. Levees are not well suited to areas of high wave action. They are best for low-lying areas that need protection from occasional surge, storm-related flooding, or extreme high tides. If their construction impedes gravity drainage on the inland side, these areas behind the levee may require pumping stations to remove groundwater or stormwater. Levees require a large amount of land for their construction (80–100 ft [24–30 m] toe-to-toe) that must be contiguous. They can block views. If levees are built with 1:10 (or greater) slopes they can be vegetated—as opposed to concrete or riprap—serving some ecosystem functions.

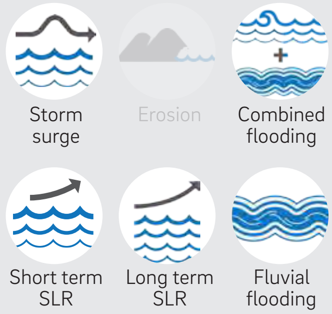
ECOSYSTEM FUNCTIONS

Levees are increasingly being constructed to provide multiple benefits besides flood protection, including recreation and habitat. For example, the U.S. Army Corps of Engineers, together with the Coastal Conservancy and the Santa Clara Valley Water District, is building the South San Francisco Bay Shoreline Project, a 6 km (4 mi) engineered flood risk management levee that includes some ecotone levee sections. This project will also facilitate the restoration of over 3,000 acres of former salt ponds to tidal marsh. The SAFER Bay project in San Mateo and Santa Clara Counties is also constructing an engineered flood risk management levee along several miles of shoreline between Menlo Park, East Palo Alto, and Redwood City. The project will support baylands restoration, provide multi-benefit floodplain management, and reduce flood risk and flood insurance costs for over 1,000 properties.

POLICY CONSIDERATIONS

Any fortifications that alter the shoreline require a permit from USACE, the Water Board, BCDC, and potentially state and federal wildlife managers if wildlife species are involved. Construction would likely trigger CEQA/NEPA and an environmental impact study. Levees for flood risk management may be accredited by FEMA to reduce flood insurance requirements for property owners being protected by them.

COASTAL RISKS MANAGED



OTHER ECOSYSTEM SERVICES

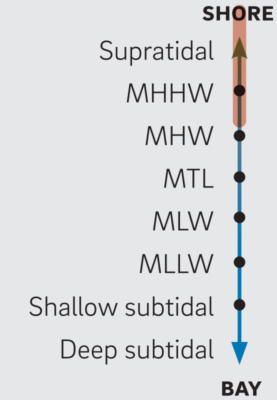
• Biodiversity • Food supply •
• Climate regulation •
• Water quality improvement •
• Recreation •
• Other cultural services •

IMPACT ON SHORELINE

Protect • Accommodate • Retreat

LOCATION

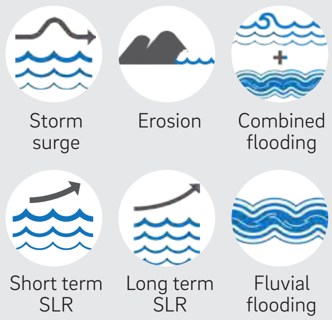
WITHIN TIDAL TRANSECT



Levee along Foster City's shoreline (Photo by Katie McKnight, SFEI)

Zoning and overlay zones

COASTAL RISKS MANAGED



CO-BENEFITS

• Biodiversity • Food supply •
• Climate regulation •
• Water quality improvement •
• Recreation •
• Other cultural services •

IMPACT ON SHORELINE

Protect • Accommodate • Retreat

LOCATION
WITHIN TIDAL TRANSECT

DEFINITION

Zoning is a local government regulatory tool that controls land uses, urban density, structure height and size, setbacks (see page 105), and more. Overlay zones, which are a type of zoning, may add restrictions onto existing zoned areas related to historic preservation and flood or erosion preparedness.

LANDSCAPE CONFIGURATION, DESIGN, & PROCESS GUIDELINES

Zoning is among the most powerful local government tools for hazard prevention and mitigation. Overlay zones may be imposed on existing zoned areas and create new requirements specifically to deal with flooding, habitat, or other priorities. For example, a sea level rise overlay zone could require specific building flood resilience measures, widen setbacks from the shoreline, change density controls, cluster development away from water, restrict rebuilding after a major flood, and more. Overlay zones are flexible and can be imposed without any additional policies or restrictions. Over time, based on certain triggers or thresholds in observable conditions and/or adverse events, additional conditions can be applied such as rebuilding or redevelopment restrictions.

Overlay zones offer municipalities the opportunity to delineate and demarcate areas that may be subject to certain risks, and in which new development patterns and requirements may improve resilience. One example of an area that has implemented overlay zones is the City of Goleta (CA), which adopted a Hazard Zone Overlay District that imposed real-estate disclosures for coastal hazards, building code revisions, and development setbacks that account for accelerating sea level rise and erosion.

POLICY CONSIDERATIONS

Zoning changes and the establishment of overlay zones are a regulatory act of local government. Overlay zones are flexible and can be applied with many other adaptation measures. They can be tailored for site-specific vulnerabilities, while allowing for adaptive management. Zoning changes or overlay zone designation that is accompanied by new land use restrictions, or will be in the future, may face legal challenges as a regulatory taking. Regulations that deprive a landowner of all economic value will generally be considered a taking, while regulations below that threshold will be considered according to certain factors, such as investment-backed expectations. The ease of implementing zoning changes may depend on different existing land uses. For example, reducing or constraining future development potential may be less difficult on public or vacant property, while existing residential or mixed use areas might be the most politically challenging to rezone or overlay.

Setbacks, buffers, and clustering

DEFINITION

Setbacks and buffers require that development be set back a certain distance from the shoreline or high tide line, and that certain natural features be maintained (marsh, vegetation, sills, etc.) between development and the shore to allow for marsh or beach migration. Clustering is a zoning strategy that groups buildings within a developing area together, to preserve bigger areas for open space or habitat.

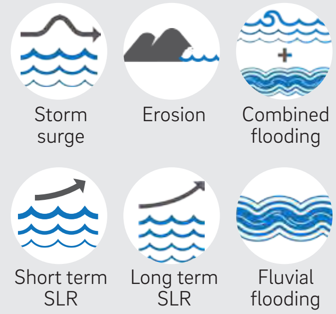
LANDSCAPE CONFIGURATION, DESIGN, & PROCESS GUIDELINES

Setbacks from the shoreline could be increased based on future sea level rise or flood hazard projections. Setback distance could be determined based on the size and expected life of the structure, as well as erosion rates. For example, on Kauai (Hawaii), setbacks from the coast are determined by a multiplier of expected erosion rate, up to 30 m (100 ft). Developments could be required to remove structures in a buffer area to promote natural functions and flood protection, or to cluster development together to maintain open space closer to water. For example, in the Chesapeake Bay Area of Maryland, state law and local ordinances require a minimum 100 ft (30.5 m) buffer adjacent to all tidal waters, tidal wetlands, and tributary streams. This buffer is expanded beyond 100 ft (30.5 m) where there are adjacent sensitive resources, such as steep slopes. Setbacks are hard to implement in areas of high parcelization (i.e., areas with many landowners), and are difficult to apply to an already or partially developed area.

POLICY CONSIDERATIONS

Setbacks may help create available space for marsh transition zones as sea levels rise. Setbacks or buffers may also keep new development away from hazards or future hazards. Setbacks, buffers, and clustering are policies that may be implemented through zoning or an overlay zone.

COASTAL RISKS MANAGED



CO-BENEFITS

• Biodiversity • Food supply •
• Climate regulation •
• Water quality improvement •
• Recreation •
• Other cultural services •

IMPACT ON SHORELINE

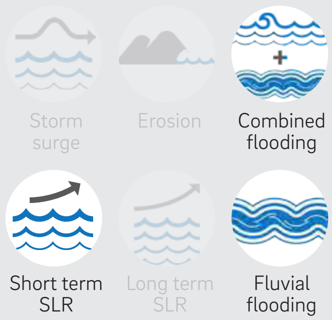
Protect • Accommodate • Retreat

LOCATION
WITHIN TIDAL TRANSECT

POLICY AND REGULATORY MEASURES

Building codes and building retrofits

COASTAL RISKS MANAGED



CO-BENEFITS

• Biodiversity • Food supply •
• Climate regulation •
• Water quality improvement •
• Recreation •
• Other cultural services •

IMPACT ON SHORELINE

Protect • Accommodate • Retreat

LOCATION WITHIN TIDAL TRANSECT

DEFINITION

Building codes regulate new construction to help development withstand flooding. For the existing built environment, building retrofits may be imposed by ordinance, through an overlay zone, or may be implemented by incentives instead of regulation.

LANDSCAPE CONFIGURATION, DESIGN, & PROCESS GUIDELINES

Building codes and permit conditions can require new development to accommodate or to avoid future, more-frequent flooding. Buildings can be required to elevate mechanical equipment, flood-proof ground floors, or themselves be raised above the base flood elevation. New building codes may reduce the cost of future floods for building workers or inhabitants. However, they will not address neighborhood connectivity, ensure public safety during flooding, or help existing buildings nearby.

For existing buildings, some building types—generally, smaller, shorter types—can be raised up on piles or fill, typically about a meter or more above a design flood elevation to prevent structural damage. Others can be flood-proofed with water-resistant materials, flood vents, and/or water-tight gates at entry points to prevent water infiltration. Retrofitting buildings individually does not address transportation, accessibility, or public realm flooding problems. And flood-proofing systems will eventually leak, especially if subject to frequent exposure. Benefits of this measure include possible reduction in cost of future adaptation or flood response, protection of property values, and improved safety.

POLICY CONSIDERATIONS

The National Flood Insurance Program requires new construction, depending on the riskiness of the flood zone, to either be raised above the base-flood elevation (BFE), flood-proofed (for nonresidential buildings) with elevated building equipment, or elevated on piles. But local governments could extend these requirements in currently unregulated areas, or increase freeboard requirements so that building elevations consider future sea level rise and storm surge height. For example, New Orleans and New Jersey have adopted higher base flood elevations for rebuilding and redevelopment following the major hurricanes that hit those regions. Flood-proof building codes are recommended in the California Adaptation Strategy. Retrofit incentives or requirements may be imposed within overlay zones to prepare existing buildings for increasing flood risk. However, some buildings cannot be retrofitted, and in seismically active areas some buildings cannot be safely raised. Elevating buildings might trigger additional accommodations under the Americans with Disabilities Act. Finally, increasing building elevation or ground floor flood-proofing may have urban design implications—walls can affect access, pedestrian circulation, and streetscape appearance.

Elevation is not a very flexible strategy and may only work for the short term, depending on how fast sea levels rise.

POLICY AND REGULATORY MEASURES

Rebuilding and redevelopment restrictions

DEFINITION

Limits on rebuilding structures destroyed by hazards.

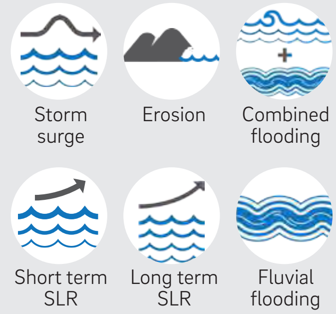
LANDSCAPE CONFIGURATION, DESIGN, & PROCESS GUIDELINES

Rebuilding and redevelopment restrictions are imposed when a structure or set of structures is flooded or damaged beyond repair. The thresholds that trigger restrictions are set and made public well before any damage occurs, allowing continued economic use of a property or infrastructure until impacts occur. Under the National Flood Insurance Program, rebuilding restrictions are only triggered when structures are substantially damaged. Redevelopment restrictions can restrict the expansion or intensification of development in high-risk areas. They may be especially suitable where there are structures or uses that do not conform to current zoning and where there is a high likelihood of repetitive loss. For example, Maine's Sand Dune Rule prevents reconstruction of coastal properties if hazard-related damage exceeds 50% of a property's appraised value. In South Carolina, hazard-damaged structures may only be rebuilt on the landward lot line, and replacement buildings may not be rebuilt any larger.

POLICY CONSIDERATIONS

Rebuilding and redevelopment restrictions can be implemented through a zoning ordinance or an overlay zone. They can also be accompanied by building code changes that require elevation or other flood-proofing strategies. Local governments that are considering implementing these types of event-triggered restrictions might consider developing community-led recovery plans in advance of hazardous events that may occur in their areas. These recovery plans can help the community secure both political support and financial resources, such as catastrophe bonds, to aid implementation of different land uses after a loss event.

COASTAL RISKS MANAGED



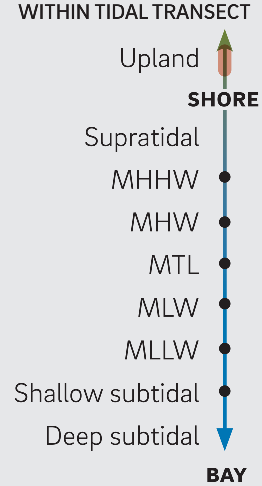
CO-BENEFITS

• Biodiversity • Food supply • • Climate regulation • • Water quality improvement • • Recreation • • Other cultural services •

IMPACT ON SHORELINE

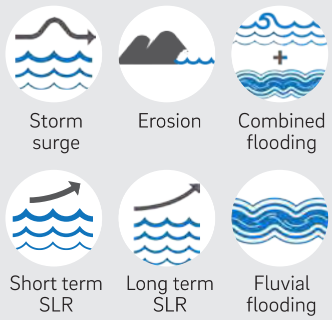
Protect • Accommodate • Retreat

LOCATION
WITHIN TIDAL TRANSECT



Conservation easements

COASTAL RISKS MANAGED



CO-BENEFITS

• Biodiversity • Food supply • Climate regulation • Water quality improvement • Recreation • Other cultural services •

IMPACT ON SHORELINE

Protect • Accommodate • Retreat

LOCATION
WITHIN TIDAL TRANSECT

DEFINITION

Conservation easements are voluntary agreements not to develop on a property to preserve it for habitat, open space, recreation, or farmland, in exchange for compensation or tax benefits.

LANDSCAPE CONFIGURATION, DESIGN, & PROCESS GUIDELINES

Conservation easements allow a property to remain in private ownership, with land development limited by certain terms that bind all future owners of the property. In exchange for maintaining land as open space, a property owner obtains tax relief or incentives, and compensation for forgoing the right to develop. Easements may include terms that specify allowable types of shoreline treatment, erosion control, or other activities, and can stipulate that space must be set aside for the upland migration of marsh or beaches. "Rolling" conservation easements could prevent certain activities on the shoreline, the terms of which would "roll" upward as the high-tide line moves inland, but maintain economic uses until certain levels of sea level rise are reached. The new high-tide line, and the area subject to restrictions under the easement, would typically be reset after a major storm event. For example, Maryland created a "coastal resilience" easement on 221 acres adjacent to the Blackwater National Wildlife Refuge to prevent future development there and create room for wetlands to migrate. Conservation easements may not be suitable as a sea level rise management strategy in areas with significant parcelization and many landowners. In such cases, easements could lead to a fragmented treatment of the shoreline or sensitive habitat areas, and thus may not improve ecological or flood resiliency.

POLICY CONSIDERATIONS

Easements are a voluntary mechanism that may be more politically popular than regulation as a way of restricting development. They are typically less expensive than land acquisition. All 50 states have statutes enabling acquisition of conservation easements. In California, only certain nonprofit and governmental organizations are permitted to acquire and hold conservation easements.

FINANCIAL MEASURES

Tax incentives and special assessments

DEFINITION

Tax policy creates incentives and disincentives for various land uses and the location of development. Special assessments are fees added to property taxes to pay for benefits that serve the whole area or district that pays these fees.

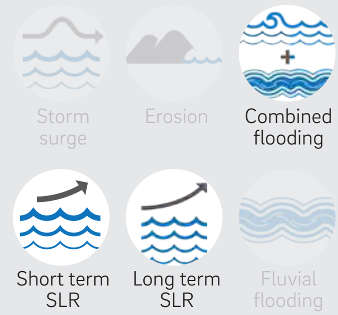
LANDSCAPE CONFIGURATION, DESIGN, & PROCESS GUIDELINES

Tax credits can encourage relocation or retrofit of flood-prone properties, or support development in low risk, infill-type areas. Tax credits attached to conservation easements can support the prevention of further development. Special assessments may provide resources for flood protection or resiliency over and above what the general public has to work with, or that any one property owner can afford. Tax incentives can allow economic use of property until impacts occur, and can align private and public incentives to not overbuild or rebuild in high-hazard areas that may suffer repeat losses.

POLICY CONSIDERATIONS

Tax policy will ideally be applied in a comprehensive rather than a piecemeal way within a large jurisdiction, to improve equity among those paying for resilience, and to ensure that public resources serve a broad public purpose and don't just socialize private flood protection costs. Special assessments can pool resources for adaptation that would otherwise not be deployed in a coordinated fashion. But they can also be regressive, as the basis is typically property tax, which some owners can more readily afford than others. In California, under Proposition 218 and other voter-approved measures, new fees and taxes are typically subject to voter approval, and require approval from two-thirds of those who will be assessed.

COASTAL RISKS MANAGED



CO-BENEFITS

• Biodiversity • Food supply •
• Climate regulation •
• Water quality improvement •
• Recreation •
• Other cultural services •

IMPACT ON SHORELINE

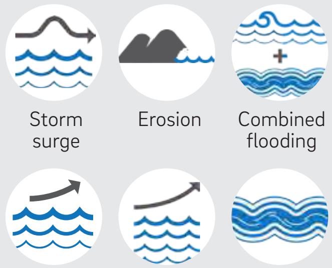
Protect • Accommodate • Retreat

LOCATION
WITHIN TIDAL TRANSECT

FINANCIAL MEASURES

Geologic Hazard Abatement District (GHAD)

COASTAL RISKS MANAGED



Storm surge · Erosion · Combined flooding · Short term SLR · Long term SLR · Fluvial flooding

CO-BENEFITS

• Biodiversity • Food supply •
• Climate regulation •
• Water quality improvement •
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• Other cultural services •

IMPACT ON SHORELINE

Protect • Accommodate • Retreat

LOCATION WITHIN TIDAL TRANSECT

Upland
SHORE
Supratidal
MHHW
MHW
MTL
MLW
MLLW
Shallow subtidal
Deep subtidal
BAY

DEFINITION

Geologic Hazard Abatement Districts are independent governmental districts that can assess properties within a defined area and dedicate the revenue to abating or controlling hazards such as landslides, earthquakes, and erosion.

LANDSCAPE CONFIGURATION, DESIGN, & PROCESS GUIDELINES

GHADs are formed to identify, monitor, address, and mitigate geologic hazards through district-wide or individual property improvements. Through special assessments GHADs provide a means to pay for maintenance, monitoring of hazards, and other upgrades necessary for flood protection and erosion management, thereby providing long-term security of property values, or a form of insurance for probable geologic issues. The money can be used to construct coastal resilience measures, pay for seismic upgrades, build green infrastructure, and more. There are no limits to size, number of units, or contiguity of the property within the GHAD.

To establish a GHAD, 10% of property owners within the proposed district must petition for its creation; assessments then must go through the Proposition 218 process and be adopted by the city council/board of supervisors. The GHAD is governed by a Plan of Control and a Board of Directors, often an existing legislative body. GHADs can own and acquire land, and conduct preventive work. There are over 30 GHADs in California including in Contra Costa, Alameda, and Santa Cruz counties. In the City of Malibu, a GHAD formed to restore and nourish an eroding beach and dune system, and thus protect coastal properties.

POLICY CONSIDERATIONS

As with other types of tax assessments, GHADs can pool resources for adaptation that would otherwise not be deployed in a coordinated fashion. But they can also be regressive, as the basis is typically property tax, which some owners can more readily afford than others. These resources should ideally be put toward an adaptation strategy or vision that has broad public and governmental support, or else they could result in payment for short-term solutions at the expense of a more holistic and resilient approach. GHADs were enabled by California state law in 1979 and are exempt from Local Agency Formation Commissions (LAFCOs) and CEQA. One disadvantage is that they cannot be easily dissolved after they are formed.

FINANCIAL MEASURES

Transfer of Development Rights (TDR)

DEFINITION

In a TDR program, local governments support smart growth and infill development away from high-hazard areas by designating "sending" areas and "receiving" areas through zoning. Property owners in "sending" areas can sell development credits in exchange for a conservation easement on their property and forgoing additional development; property owners/developers in "receiving" areas can buy credits to exceed allowable densities, heights, or floor areas. These programs create market incentives to shift development to preferred areas without "takings."

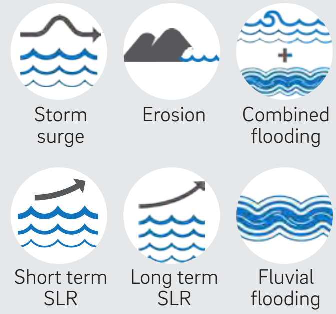
LANDSCAPE CONFIGURATION, DESIGN, PROCESS GUIDELINES

As one measure to address sea level rise and flooding, local governments could designate sending areas in vulnerable locations, designate receiving areas on higher ground where development should occur, and then establish a credit market. For example, Montgomery County, Maryland, established sending areas to preserve agricultural lands and receiving areas to add density along transportation corridors. A regional program could include one or more jurisdictions. Sending areas could be converted to conservation easements or downzoned in the future once development rights have been sold. For example, a well-known example of TDR use is in the New Jersey Pinelands, where a TDR program administered by a state agency covers 60 jurisdictions and uses a development credit bank to transfer credits. It has permanently restricted over 8,000 hectares (20,000 acres) from development.

POLICY CONSIDERATIONS

TDRs may be complicated to set up and to administer, especially in an environment where "receiving" areas may be hard to find or designate. Because they are voluntary, they might not work as designed if sellers are unwilling to participate.

COASTAL RISKS MANAGED



CO-BENEFITS

• Biodiversity • Food supply •
• Climate regulation •
• Water quality improvement •
• Recreation •
• Other cultural services •

IMPACT ON SHORELINE

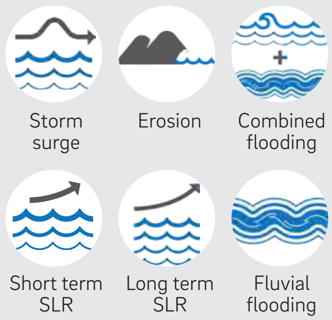
Protect • Accommodate • Retreat

LOCATION WITHIN TIDAL TRANSECT

FINANCIAL MEASURES

Buyouts

COASTAL RISKS MANAGED



CO-BENEFITS

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IMPACT ON SHORELINE

Protect • Accommodate • Retreat

LOCATION WITHIN TIDAL TRANSECT

EXAMPLES

- New Orleans post-Katrina and New York post-Sandy (Freudenberg et al. 2016)

DEFINITION

Buyouts employ public funds to remove development from repeat-hazard areas, to reduce future property damage and to promote public safety

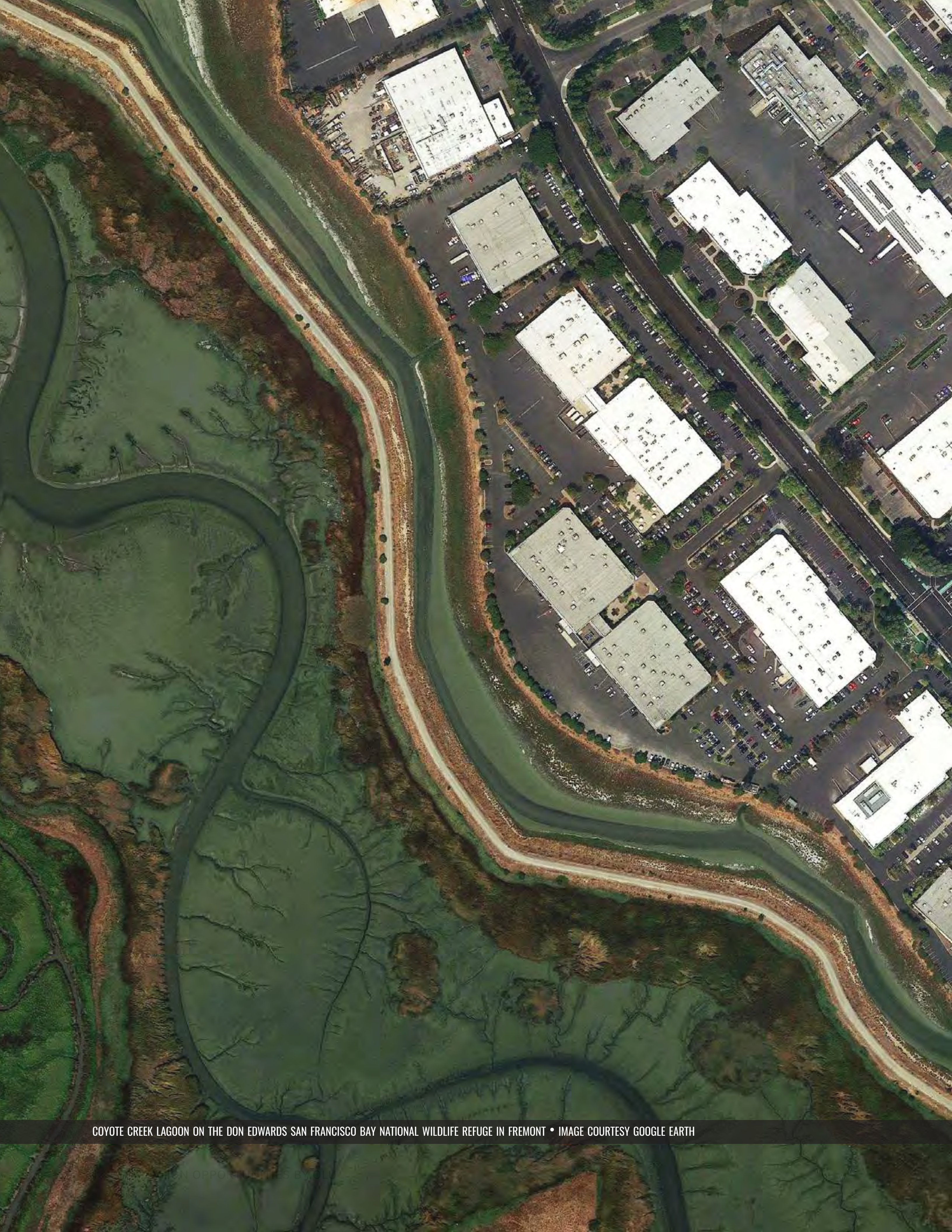
LANDSCAPE CONFIGURATION, DESIGN, PROCESS GUIDELINES

Voluntary buyout programs use public resources to acquire land and demolish buildings for hazard mitigation and to promote public safety. They may be most suitable for high-hazard areas to prevent repeat losses and to reduce overall community vulnerability. They can be a practical approach for property owners who no longer want to live in high-risk areas to move somewhere safer. Buyouts can be used at a variety of scales from individual buildings to neighborhoods. For example, buyouts were used in the New York-New Jersey region after Hurricanes Sandy and Irene to buy out over 1,500 properties; they have also been used in New Orleans, North Dakota, Florida, and many other states following major storms and flooding. Buyouts are a mechanism for managed retreat; however, if they are implemented voluntarily and not everyone participates, they may create a “checkerboard effect” causing blight and making complete retreat difficult. This may also limit reuse of the land for other resilience strategies such as a floodplain buffer. Mandatory buyouts, or eminent domain, may be used to prevent immediate health, safety ,and life risks, but are typically not eligible for cost-sharing by the federal government so are much more expensive and difficult. Leasebacks are buyout programs in which properties are leased to their current owners for a specified period so that they can continue to use them without economic loss.

POLICY CONSIDERATIONS

In practice, buyout programs have been supported by federal hazard mitigation grant programs after disasters, or with pre-disaster assistance; these federal programs typically require a local match, with the source of local funding usually being taxes, fees or bonds. A fiscal challenge of buyouts is that they may potentially reduce the local government’s tax base. Land purchase programs are also likely to be very costly in the Bay Area. Buyouts may also be used with TDR programs or other adaptation strategies to encourage voluntary managed retreat. Voluntary buyouts may be hard to build political will and consensus around, but may help people who have suffered repeat losses. For example, the Blue Acres program in New Jersey uses state money to buy out homeowners in repeat-flood coastal areas at their home’s pre-storm value, on a voluntary basis.

BAY TRAIL ALONG THE SAN MATEO COUNTY SHORELINE • IMAGE COURTESY GOOGLE EARTH



COYOTE CREEK LAGOON ON THE DON EDWARDS SAN FRANCISCO BAY NATIONAL WILDLIFE REFUGE IN FREMONT • IMAGE COURTESY GOOGLE EARTH

5 ADAPTATION OPPORTUNITIES BY OLU

Chapter 4 describes a number of adaptation measures. The natural and nature-based measures have been widely discussed in adaptation planning, but in other cases there is little practical guidance on how to locate and construct adaptation measures. The purpose of this chapter is to illustrate, within each OLU, where there are suitable locations for a subset of these natural and nature-based measures to be applied, based on the analyses undertaken in Chapter 4.

For each of the 30 OLUs, this chapter presents:

(1) an opportunity map, showing where a subset of natural and nature-based measures are suitable, based on the analyses described in Chapter 4;

(2) a brief discussion of the suitability of measures in the context of ongoing adaptation and restoration progress and regional ecological goals such as those set by the Goals Project (2015) and the Subtidal Goals (2010) project; and

(3) a discussion of policy, regulatory, and financial adaptation approaches that may be suitable based on an analysis of place types as described in Chapter 3.

This chapter does not constitute a sea level rise (SLR) vulnerability analysis nor an adaptation plan, and should not be interpreted as such. These maps and accompanying materials should be considered tools for use during an adaptation planning process, and provide background on physical suitability of some natural and nature-based measures under existing conditions, and with existing data, as well as policy and regulatory tools which could be explored. A brief discussion of how this information might be used in an adaptation planning process involving the communities who live and work in each OLU is given in Chapter 6.

These maps only describe the current suitability of a set of measures based on existing topography, landscape configuration, and projections of future water levels. These maps will need to be updated as habitat restoration and adaptation projects are implemented, and as other changes occur along the shoreline. The measures shown do not imply any specific level of flood protection, and all measures would need to be engineered (and many combined with hybrid and grey infrastructure).

These maps do not suggest co-location or contingencies of measures. Many of these measures will be more, and perhaps only, effective when applied together. For example, a marsh restoration necessitates a bayward mudflat when Eelgrass beds and nearshore reefs are likewise complementary. Conversely, some measures are not well suited together, such as mudflat augmentation and eelgrass beds. These combinations of measures need to continue to be piloted, monitored, and redesigned as the land evolves and the seas rise.

This information will be available online as a series of interactive web maps, available at *adaptationatlas.sfei.org*.

Suitability of natural and nature-based measures by OLU

The suitability of each measure was evaluated on an OLU-by-OLU basis based on the results of the mapping described in *Chapter 4: Adaptation Measures*. Suitability ratings were determined for each measure in each OLU by calculating the proportion of the total suitable area for the measure present in the OLU, normalized by the OLU's size (relative to the total area of all OLUs). For subtidal measures, the same proportions were calculated for only the subtidal portions of OLUs (more discussion in Appendix 6). Final ratings were binned into three categories: (1) limited suitability; (2) some suitability; and (3) high suitability. The thresholds between each category, described in Appendix 6, vary by measure and were determined by analyzing data distributions and applying best professional judgment.

The resulting suitability ratings, summarized in the matrix to the right, can be used to compare across OLUs, determine which OLUs are more suitable for specific measures, and highlight which measures have limited suitability within a given OLU. Similar suitability ratings also accompany the individual OLU maps on subsequent pages. These maps are intended to synthesize the main opportunities for natural and nature-based measures in a particular OLU. Measures that received a "limited suitability" rating may be possible, albeit in a limited geography.

Suitability Rating

○ Limited suitability

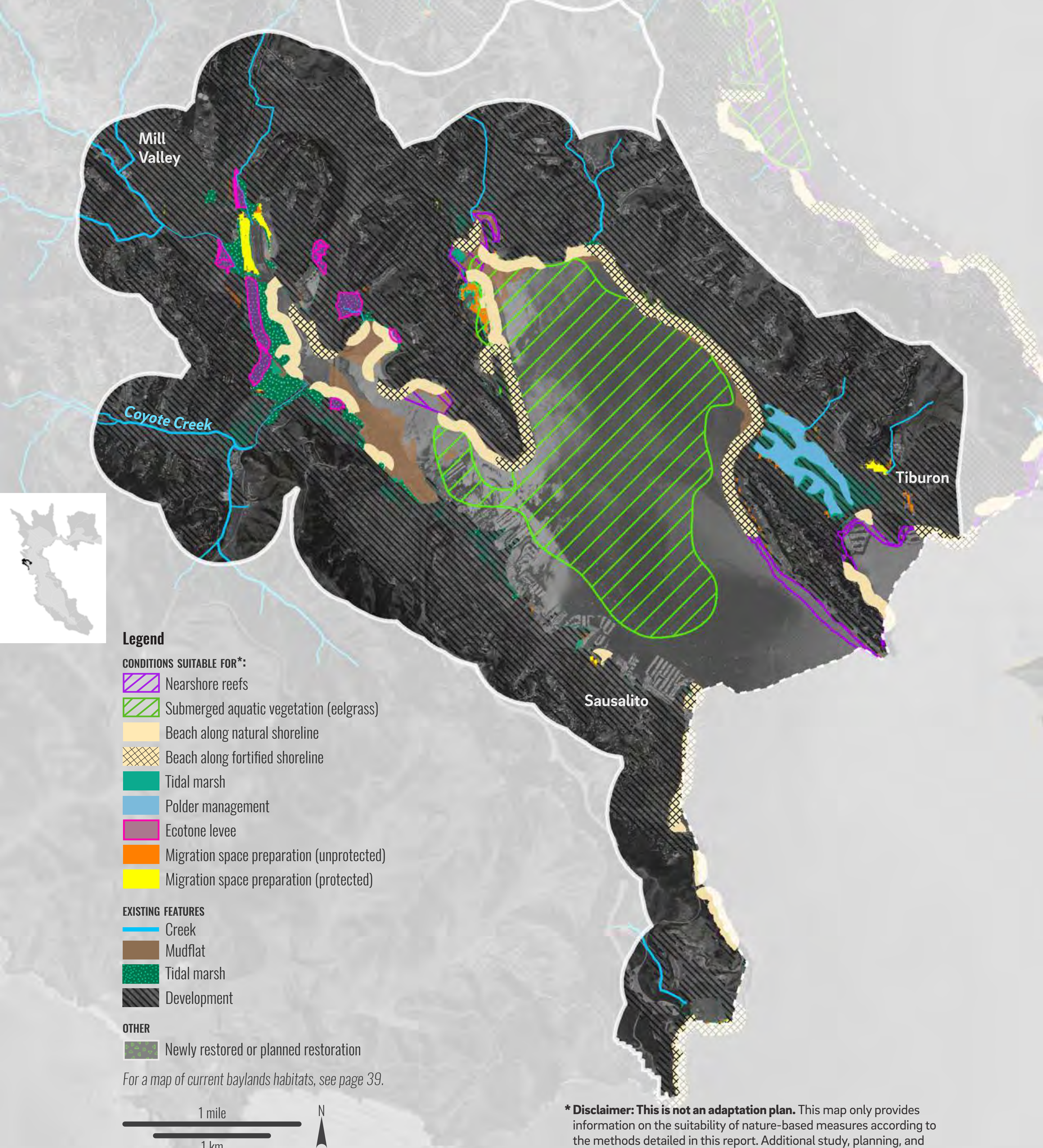
◓ Some suitability

● High suitability

Final suitability ratings were binned into one of three categories: (1) limited suitability; (2) some suitability; and (3) high suitability. The threshold suitability values between each category, detailed in Appendix 6, vary by measure and were determined by analyzing data distributions. Best professional knowledge was used to determine where the threshold values between categories fell, and in some cases OLUs were moved from one category to another, also based on best professional judgement. These exceptions are documented in Appendix 6.

	Nearshore reefs (p. 66)	Submerged aquatic vegetation (eelgrass) (p. 68)	Beaches (p. 72)	Tidal marshes (p. 76)	Polder management (p. 80)	Ecotone levees (p. 84)	Migration space preparation (p. 88)
1. Richardson	●	●	●	◐	○	◐	○
2. Corte Madera	●	●	●	◐	◐	◐	◐
3. San Rafael	●	●	●	◐	◐	◐	○
4. Gallinas	◐	●	○	●	●	◐	●
5. Novato	○	○	○	●	●	◐	●
6. Petaluma	○	○	○	●	●	○	●
7. Napa - Sonoma	○	○	○	●	●	◐	●
8. Carquinez North	○	○	○	●	○	◐	●
9. Suisun Slough	○	○	○	●	●	◐	●
10. Montezuma Slough	○	○	○	●	●	○	●
11. Bay Point	○	○	○	●	●	◐	●
12. Walnut	○	○	○	●	●	●	●
13. Carquinez South	○	○	○	◐	○	●	●
14. Pinole	●	○	●	◐	○	◐	○
15. Wildcat	●	●	●	●	◐	●	●
16. Point Richmond	●	●	●	○	○	○	○
17. East Bay Crescent	●	●	●	◐	○	●	○
18. San Leandro	○	●	●	◐	◐	○	○
19. San Lorenzo	○	●	●	●	◐	●	◐
20. Alameda Creek	○	○	●	●	●	●	●
21. Mowry	○	○	○	●	●	●	●
22. Santa Clara Valley	○	○	○	●	●	●	●
23. Stevens	◐	○	○	●	●	◐	◐
24. San Francisquito	●	○	○	●	◐	●	◐
25. Belmont - Redwood	○	○	●	●	●	●	○
26. San Mateo	○	●	●	◐	◐	◐	○
27. Colma - San Bruno	○	●	●	◐	○	◐	○
28. Yosemite - Visitacion	●	●	●	○	◐	○	○
29. Mission - Islais	○	●	●	○	○	○	○
30. Golden Gate	○	○	●	○	○	○	○

Richardson



* **Disclaimer: This is not an adaptation plan.** This map only provides information on the suitability of nature-based measures according to the methods detailed in this report. Additional study, planning, and engineering will be required to further refine these opportunities.

Nature-based Adaptation Measures

The Richardson OLU has limited space near the Bay with steep headlands confining a small valley that restricts both where flooding can occur and also opportunities for natural and nature-based adaptation such as marshes. The mouth of Coyote Creek is an area prone to flooding and has space for enhancing the Bothin Marsh and for creating an ecotone levee. Sediment supply to the marsh has been impeded by the presence of levees as well as low ambient suspended sediment concentrations in the Bay, and so thin-layer placement of sediment should be considered. Setting back the levees near the mouth of Coyote Creek could reduce backwater effects along the creek by opening up the floodplain. Nearshore reefs and submerged aquatic vegetation would provide habitat while attenuating wave energy. Beaches could replace riprap along the narrower, steeper shorelines, or along eroding shorelines such as has been piloted at Aramburu Island. Coarse beach faces could also be used to protect existing marsh scarps from wave erosion. Green stormwater infrastructure could be implemented in the upper watershed to slow down runoff, reduce fluvial flooding in the developed valleys, and slow the conveyance of floodwater to the Bay.

Selected Measures

	Selected Measures	Suitability
NATURE-BASED	Nearshore reefs	●
	Submerged aquatic vegetation	●
	Beaches	●
	Tidal marshes	◐
	Polder management	○
	Ecotone levees	◐
	Migration space preparation	○

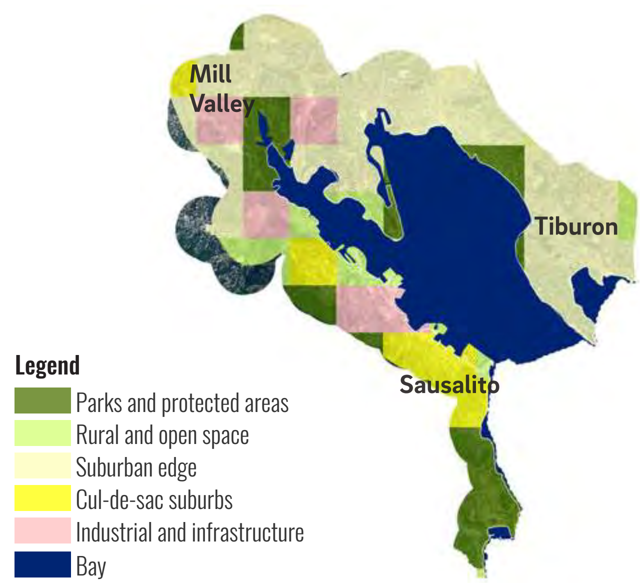
○ Limited suitability ◐ Some suitability ● High suitability

Housing along Sausalito's shoreline in Richardson OLU (Photo by Shira Bezalel, SFEI)

Other Adaptation Opportunities

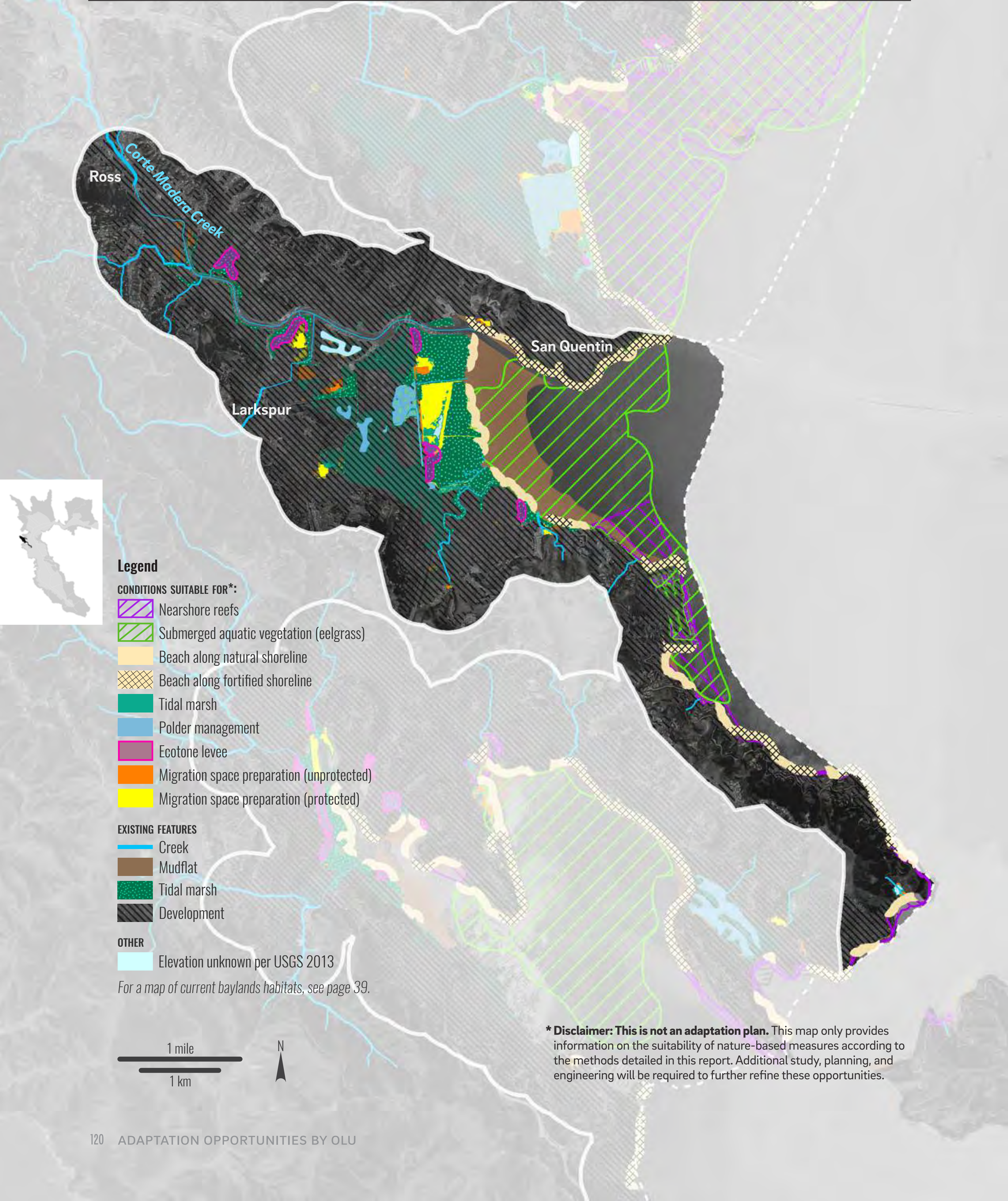
The predominant place types in Richardson are suburban edge (52%), open space and protected areas (27%), cul-de-sac suburbs (12%) and industrial and infrastructure (10%). Over time, the place types most vulnerable to sea level rise are industrial/infrastructure, parks and protected areas, and cul-de-sac suburbs. For parks and protected areas, suitable adaptation strategies include securing wetlands transition zone through easements or buyouts, allowing sea level rise to take its course. For industrial and infrastructure, and cul-de-sac suburbs—which are low-density single-family residential areas—suitable strategies include not intensifying land development, possibly elevating roads and buildings, and within repeat-flood areas moving infrastructure or commercial activities to higher ground through buyouts, relocation incentives, or rezoning.

Place Types Map



NATURE-BASED ADAPTATION OPPORTUNITIES MAP

2 Corte Madera



For a map of current baylands habitats, see page 39.

* **Disclaimer: This is not an adaptation plan.** This map only provides information on the suitability of nature-based measures according to the methods detailed in this report. Additional study, planning, and engineering will be required to further refine these opportunities.

Nature-based Adaptation Measures

Corte Madera OLU has headlands flanking the developed baylands, and most of the natural and nature-based opportunities are to the east of Highway 101 and the former railroad. Muzzi and Heerdt marshes constitute the largest contiguous marsh in Southern Marin, although with the continuing erosion of the outboard levee edge, the Muzzi marsh scarp is rapidly retreating. Enhancing the existing marsh by reusing sediments dredged from the nearby ferry terminal, placing coarse beaches in front of the scarps, and creating ecotone levees along the berm of the former railroad behind the marsh, could reduce the loss of marsh to erosion and drowning. Green stormwater infrastructure and floodplain restoration could be implemented in the upper watershed to reduce fluvial flooding along Corte Madera Creek. Submerged aquatic vegetation and nearshore reefs are also suitable in this OLU.

Selected Measures

	Selected Measures	Suitability
NATURE-BASED	Nearshore reefs	High suitability
	Submerged aquatic vegetation	High suitability
	Beaches	High suitability
	Tidal marshes	Some suitability
	Polder management	Some suitability
	Ecotone levees	Some suitability
	Migration space preparation	Some suitability

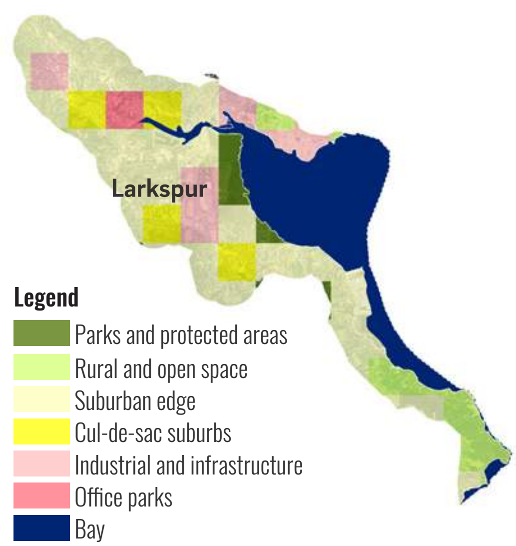
Limited suitability · Some suitability · High suitability

Aerial view of the San Quentin shoreline in the Corte Madera OLU (Photo by Shamim Mohamed. CC BY-SA 2.0)

Other Adaptation Opportunities

The predominant place types in Corte Madera are suburban edge (57%), industrial and infrastructure (14%), cul-de-sac suburbs (11%) and rural and open space (11%). This OLU has more suburban edge place type than any other OLU, which is the place type most vulnerable within this OLU to sea level rise (followed by industrial/infrastructure). Suburban edge is a very low-density type of residential land use, typically comprised of large-lot, high-value, and recently-built properties. Property owners in these areas could choose to self-finance protection measures through a GHAD, could retrofit homes, or could eventually retreat from repeat flood areas with selective buyouts. Corte Madera is subject to fluvial flooding from Corte Madera Creek; this risk may be reduced by adding green infrastructure and floodable spaces upland in the watershed.

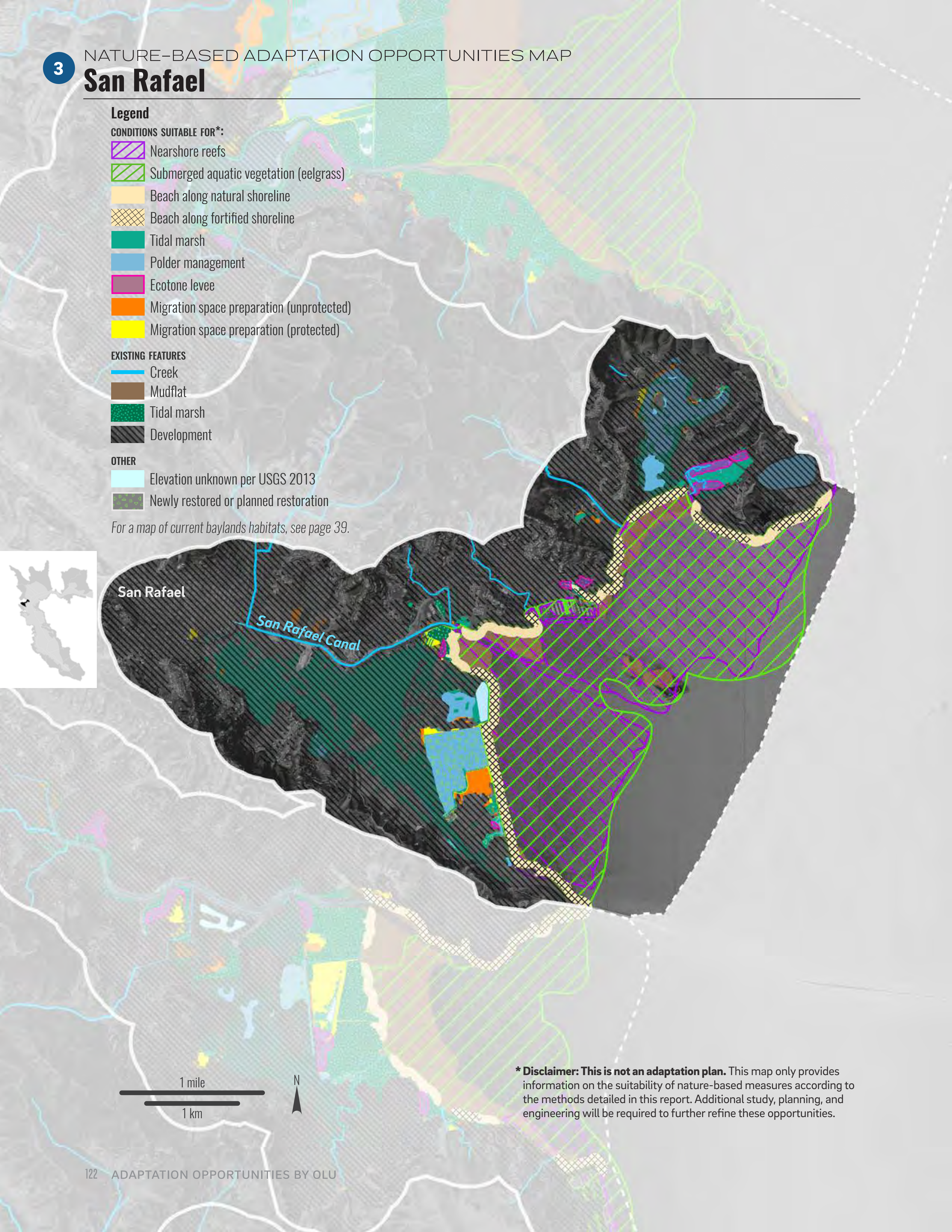
Place Types Map



3

NATURE-BASED ADAPTATION OPPORTUNITIES MAP

San Rafael



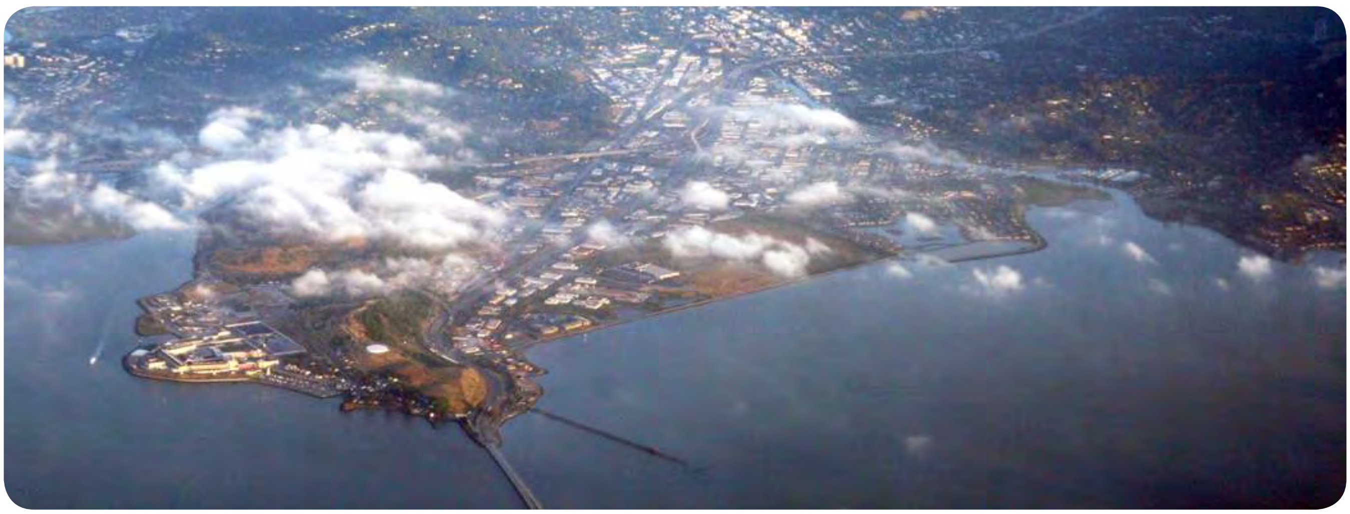
*** Disclaimer: This is not an adaptation plan.** This map only provides information on the suitability of nature-based measures according to the methods detailed in this report. Additional study, planning, and engineering will be required to further refine these opportunities.

Nature-based Adaptation Measures

The San Rafael OLU is space-limited due to its geomorphic setting in a small valley confined by headlands and by the degree of urban development, particularly along San Rafael Canal. Most of the historical marshes have been filled, often bayward of historical limits. Only Tiscornia Marsh and the undeveloped polders to the south provide opportunities for marsh enhancement and creation as well as the construction of ecotone levees. Nearshore reefs and submerged aquatic vegetation could provide habitat value while attenuating wave energy in front of the marshes and riprap; this approach is being tested by the San Francisco Bay Living Shorelines Project. Coarse beaches could replace riprap along the shorelines and also protect existing marsh edges from erosion. Green stormwater infrastructure could be implemented in the upper watershed to reduce fluvial flooding in the developed valleys of San Rafael Creek.

	Selected Measures	Suitability
NATURE-BASED	Nearshore reefs	●
	Submerged aquatic vegetation	●
	Beaches	●
	Tidal marshes	◐
	Polder management	◐
	Ecotone levees	◐
	Migration space preparation	○

○ Limited suitability ◐ Some suitability ● High suitability

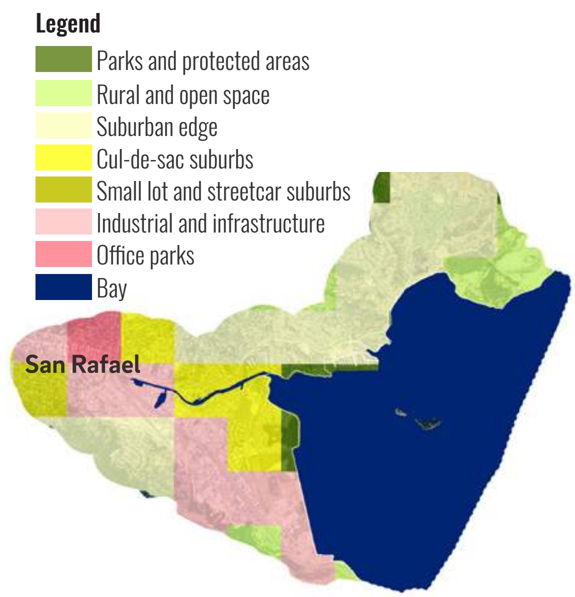


Aerial view of the San Rafael OLU shoreline, from the Richmond Bridge to the mouth of San Rafael Creek (Photo by Doc Searls, CC A-SA 2.0)

Other Adaptation Opportunities

San Rafael, like the other Marin County OLUs, is largely comprised of suburban edge (42%), industrial and infrastructure (25%), cul-de-sac suburbs (14%), and rural and open space (10%). This OLU has more industrial and infrastructure-devoted land of any in the North Bay, and a large portion of all of its developed land uses are subject to near-term inundation from sea level rise. Adaptation opportunities for the San Rafael OLU include elevation of streets and buildings, use of zoning and overlay zones to implement building codes and restrictions, and potentially use of tax incentives for businesses (especially large footprint/low job-density commercial uses) to relocate to higher ground. Establishing a GHAD or creating a TDR program to incentivize development to move to less vulnerable areas could be viable financial strategies. As San Rafael has less protected land and parks than all the other Marin OLUs, public agencies could buy more land or easements to create floodable spaces, including room for the shoreline.

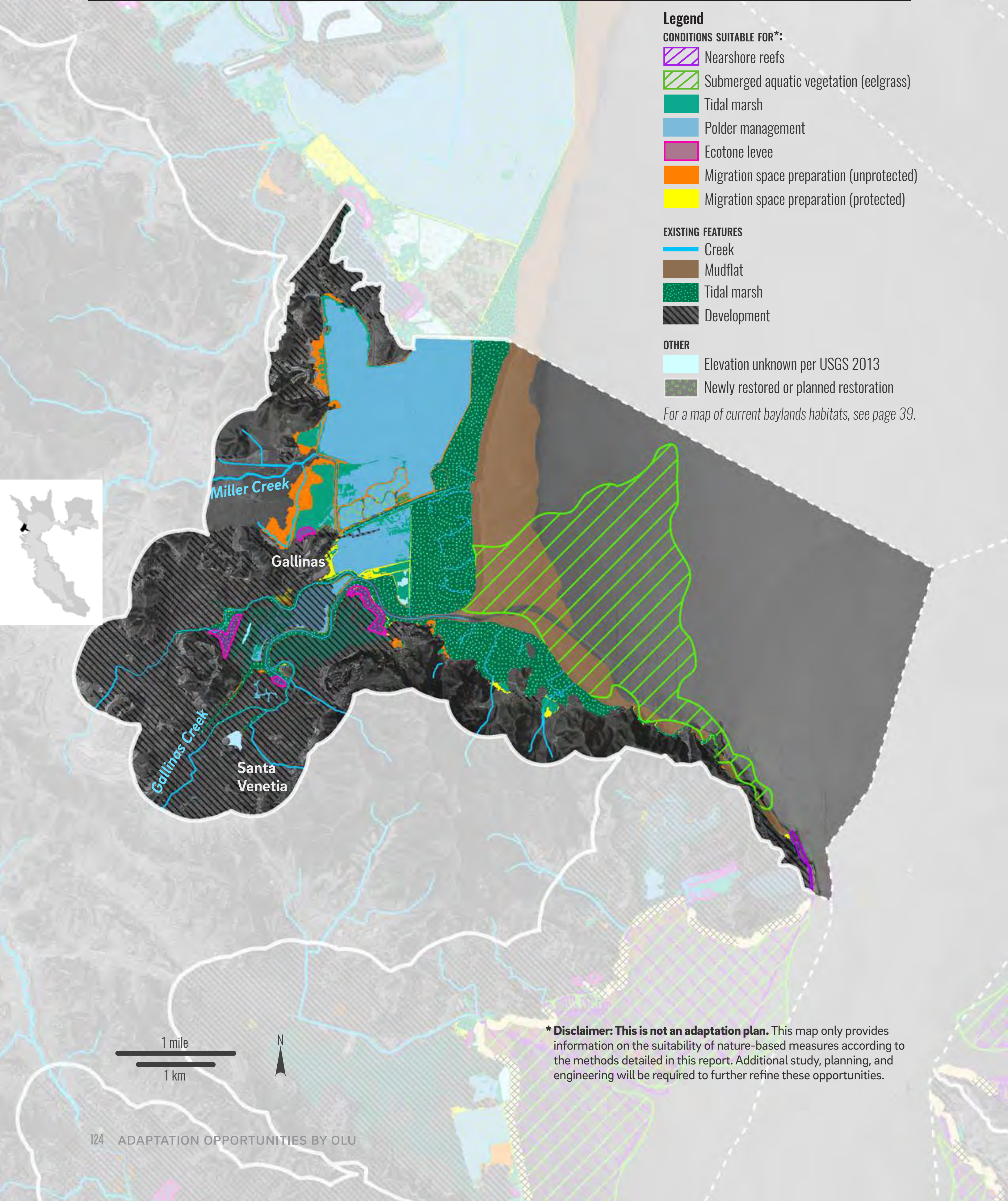
Place Types Map



4

NATURE-BASED ADAPTATION OPPORTUNITIES MAP

Gallinas



*** Disclaimer: This is not an adaptation plan.** This map only provides information on the suitability of nature-based measures according to the methods detailed in this report. Additional study, planning, and engineering will be required to further refine these opportunities.

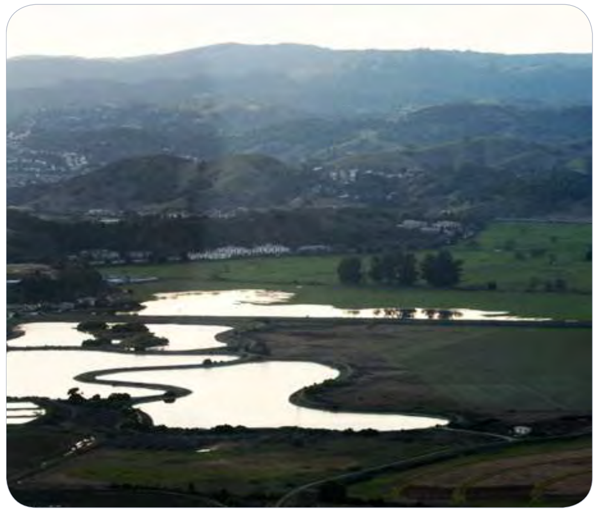
Nature-based Adaptation Measures

Gallinas is a semi-sheltered creek valley on the north side of Point San Pedro, fronted by relatively wide marshes including China Camp, one of the few ancient marshes in the Bay. Opportunities exist to increase the resilience of tidal marshes to sea level rise by augmenting the fronting mudflat with fine sediment or restoring eelgrass beds to increase sediment trapping, raise mudflat elevations and attenuate waves. Fluvial flooding and backwater effects along Gallinas Creek make the neighborhood of Santa Venetia vulnerable. Detaining floodwater along Gallinas Creek and widening the floodplain as well as raising existing levees and constructing ecotone levees should be considered where there is space. North of Gallinas Creek, the diking and draining of historical baylands has created large polders, yet this area also has one of the largest continuous swaths of marsh migration space adjacent to areas of potential marsh. This area could be protected and restored to reestablish transition zones and buffers adjacent to tidal marsh and provide space for landward migration. Miller Creek could be reconnected to the baylands at McGinnis Marsh. There may be potential to reuse clean sediment dredged from the south fork of Gallinas Creek to partially fill the subsided polders in this OLU and bring them to marsh elevation.

Selected Measures

	Selected Measures	Suitability
NATURE-BASED	Nearshore reefs	◐
	Submerged aquatic vegetation	●
	Beaches	○
	Tidal marshes	●
	Polder management	●
	Ecotone levees	◐
	Migration space preparation	●

○ Limited suitability ◐ Some suitability ● High suitability

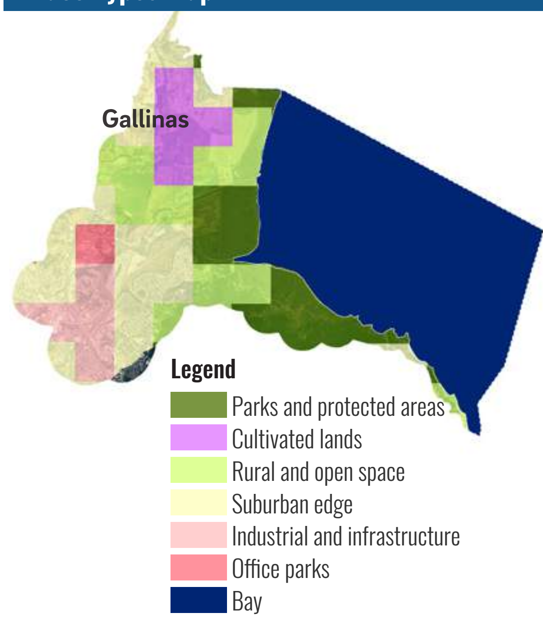


Aerial view of open space and polders fronting residential areas in Gallinas OLU (Photo by Micha Salomon, SFEI)

Other Adaptation Opportunities

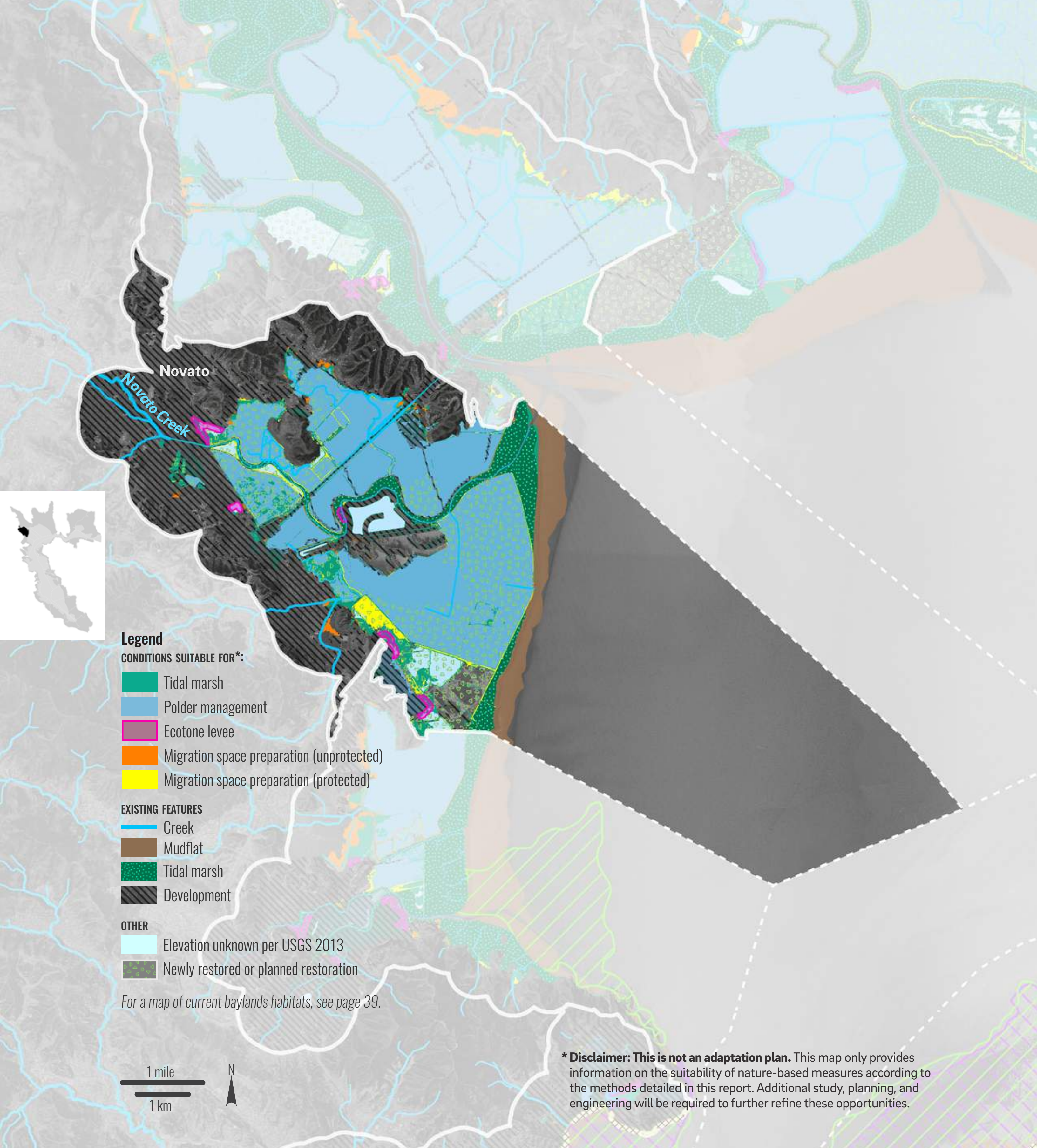
The predominant place types in Gallinas are suburban edge (33%), rural and open space (23%), parks and protected areas (20%), industrial and infrastructure (10%), and cultivated land (10%). The types closest to the shoreline are mostly rural, protected, and farmland: types that are among the region's best places to allow sea levels to rise somewhat naturally. Managed retreat from the shoreline is less difficult in these types of less-densely-developed locations than in others; over time, uses can convert from agricultural or recreational to more ecological uses as flooding frequency increases. Conservation easements, tax incentives, and potentially buyouts can help to make this transition easier financially. With a lot of "room" between the current shoreline and suburban-edge neighborhoods, opportunity exists in Gallinas to create space for wetlands and marsh migration, providing flood control and protection benefits for adjacent neighborhoods.

Place Types Map



5 NATURE-BASED ADAPTATION OPPORTUNITIES MAP

Novato



* **Disclaimer: This is not an adaptation plan.** This map only provides information on the suitability of nature-based measures according to the methods detailed in this report. Additional study, planning, and engineering will be required to further refine these opportunities.

Nature-based Adaptation Measures

The Novato OLU is characterized by the subsided diked baylands at the mouth of Novato Creek. Novato has the highest proportion of polders by area of the Baylands OLUs, and the deepest in San Pablo Bay. These polders are large and have long internal fetches which could result in significant waves being generated internally which could lead to more erosion and overtopping. As such, any adaptation strategy needs to address how to maintain the existing dikes, or accelerate the accretion of sediment to fill the polder with marsh and manage additional tidal prism. With such deeply subsided polders, elevations may be raised by lowering levees adjacent to Novato Creek to allow sediment laden water to spill over, by placing clean dredged sediment, or by geomorphic dredging. Other ways to raise elevations of subsided baylands are under development through the restoration of Hamilton Wetlands and Bel Marin Keys Unit V. There is limited existing marsh in front of the outboard levee, which is being eroded by waves, particularly to the south of Novato Creek. Coarse beaches could be useful in attenuating waves and stabilizing currently eroding sections of shoreline, though Novato OLU is not within the historical extent of beaches and thus beaches are not included on the opportunity map. Without realignment of the levees, limited areas of marsh enhancement or restoration exist. Ecotone levees are suitable where existing or potential marsh are adjacent to development, particularly if the levee is realigned. A horizontal levee could make use of treated wastewater from the Novato Sanitary District's water treatment plant to create brackish marshes to reduce wave action on the downwind edges of polders. Green stormwater infrastructure should continue to be implemented in the upper watershed to reduce fluvial flooding in the developed areas, and lower peak flows in the main channel. Highway 37 and the adjacent railroad are major assets running through the OLU. In the future, the possibility of raising Highway 37 would allow the tidal restoration of many of the polders in the OLU.

Selected Measures

	Selected Measures	Suitability
NATURE-BASED	Nearshore reefs	○
	Submerged aquatic vegetation	○
	Beaches	○
	Tidal marshes	●
	Polder management	●
	Ecotone levees	◐
	Migration space preparation	●

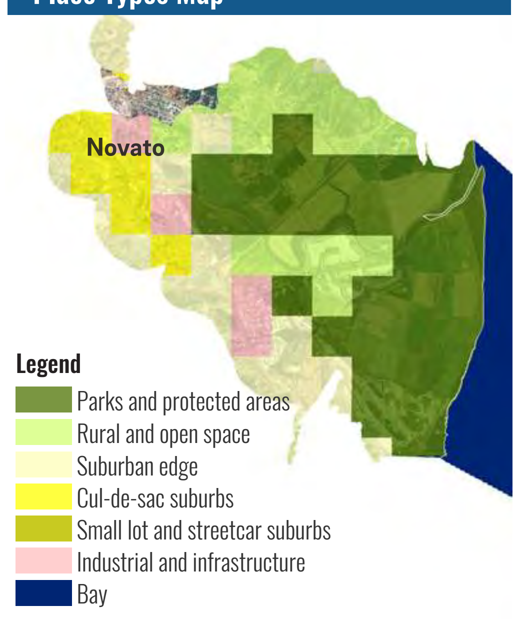
○ Limited suitability ◐ Some suitability ● High suitability

Aerial view of Novato Creek and surrounding baylands looking towards San Pablo Bay (Photo by Sue Lattanzio)

Other Adaptation Opportunities

Novato has more parks and protected areas (45%) than most other OLUs; it is also comprised of 20% rural and open space, 20% suburban edge, and 9% cul-de-sac suburbs. 90% of the area subject to near-term flooding from sea level rise is in already-protected areas, and most of the low-density residential development at risk is farther away from the shoreline. There is a lot of "room" between the current shoreline and locations where people live, which presents an opportunity to create space for wetlands that provide flood control and protection benefits for adjacent neighborhoods. Over time, these open spaces can convert from agricultural or recreational uses to ecological uses as flooding frequency increases. These areas are not good candidates for intensifying development, but rather for using easements and other strategies to acquire transition zones. For the suburban areas of the OLU that may experience sea level rise further in the future, building retrofits, site elevation, and road elevation might be suitable alternatives to relocation or voluntary buyouts, depending on what the community prefers to invest in.

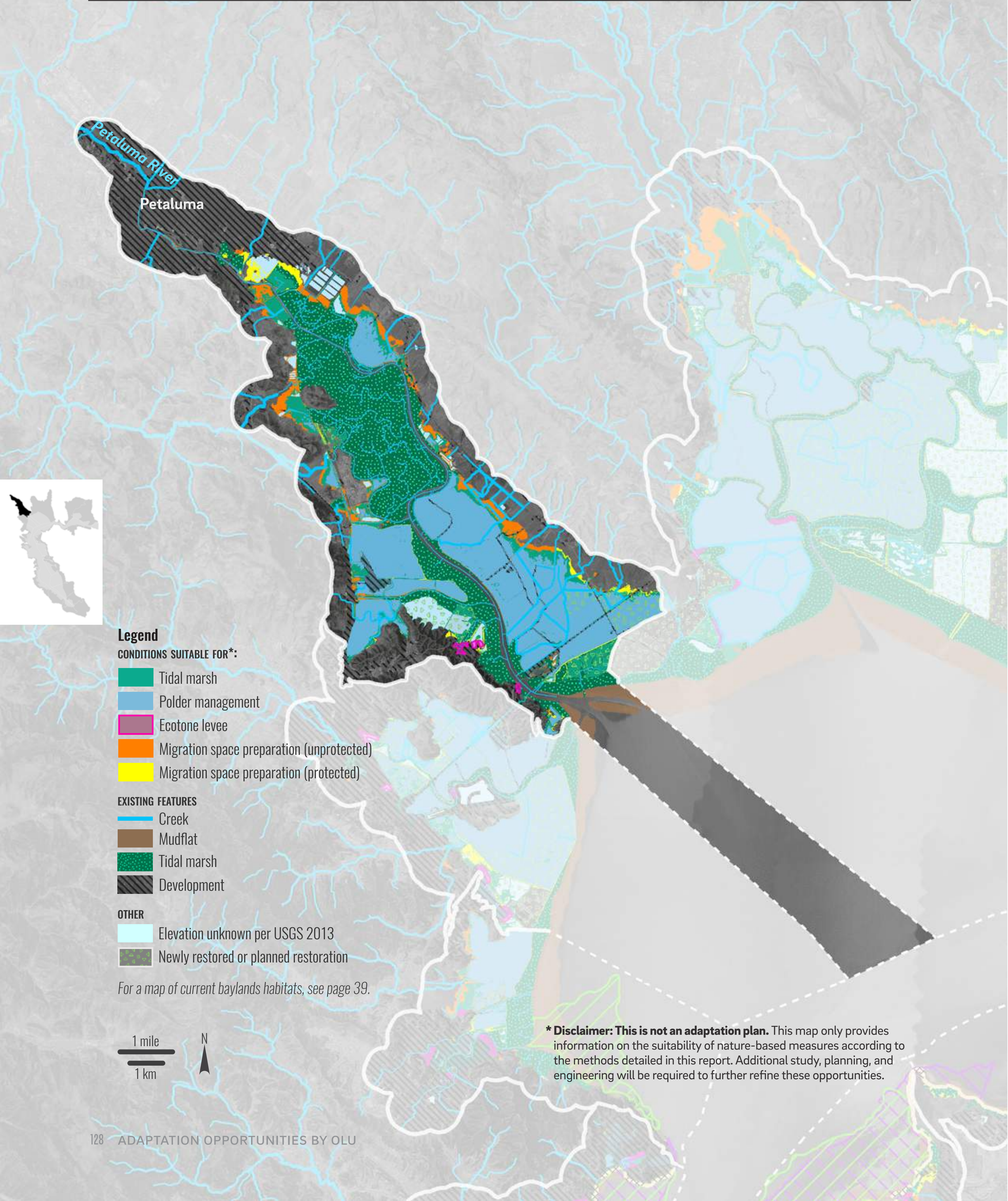
Place Types Map



6

NATURE-BASED ADAPTATION OPPORTUNITIES MAP

Petaluma



For a map of current baylands habitats, see page 39.

*** Disclaimer: This is not an adaptation plan.** This map only provides information on the suitability of nature-based measures according to the methods detailed in this report. Additional study, planning, and engineering will be required to further refine these opportunities.

Nature-based Adaptation Measures

The Petaluma OLU is made up of the baylands of the Petaluma River. The surviving ancient Petaluma Marsh, and the restored marshes of Bahia Marsh, Carl's Marsh, and Sonoma Baylands, together with the potential restoration of diked baylands and the relative lack of development in the adjacent uplands, provide opportunities to increase the resilience of the area to sea level rise. Petaluma OLU is unique in that there is an almost continuous swath of land at elevations suitable for marsh migration both adjacent to the tidal wetland and adjacent to polders. Historically, False Bay was a large shallow subtidal bay which was diked and drained for agriculture. This shallow water habitat could be restored after realigning levees further inland, which could also allow the existing areas of marsh to be both expanded and connected to the uplands. Highway 37 lies within these polders and is protected by the same levees; the realignment of levees will, therefore, need to consider the continued protection of the road. Multiple streams from small tributaries could be reconnected to the polders to bring sediment to the baylands in small alluvial fans. Green stormwater infrastructure should continue to be implemented in the upper watershed to reduce fluvial flooding in the developed areas, and lower peak flows in the main channel. Petaluma OLU does have the opportunity to use wastewater treatment plant discharges (Ellis Creek) for organic sea level rise adaptation through peat accretion, and slope wetlands with transition zones, with or without horizontal levees.

	Selected Measures	Suitability
NATURE-BASED	Nearshore reefs	Limited
	Submerged aquatic vegetation	Limited
	Beaches	Limited
	Tidal marshes	High
	Polder management	High
	Ecotone levees	Limited
	Migration space preparation	High

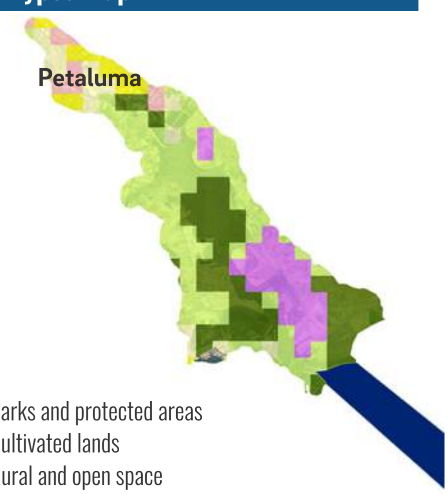
Limited suitability · Some suitability · High suitability

Petaluma Creek mouth as viewed from above entering San Pablo Bay (Photo courtesy of U.S. Army Corps of Engineers)

Other Adaptation Opportunities

Petaluma is a unique OLU with almost 85% of land in rural or open space uses, protected areas, and cultivated land; it has the second highest percentage of farmland of any OLU. In places like this, suitable adaptation strategies include allowing flooding to occur and transitioning recreational and agricultural uses to habitat or ecological uses over time through restoration work, transition zone acquisition, and realigning public access. These are areas where shoreline adaptations can maximize nature-based solutions and development should not be intensified. A financial strategy to enable land use transitions could include conservation easements or voluntary buyouts. For the suburban areas of the OLU that may experience sea level rise further in the future, building retrofits, site elevation, and road elevation might be suitable alternatives to relocation or voluntary buyouts, depending on what the community prefers to invest in. Elevating Highway 37 and portions of Lakeville Highway would facilitate tidal restoration of the extensive diked baylands and associated migration space to the north and east of these roads, respectively.

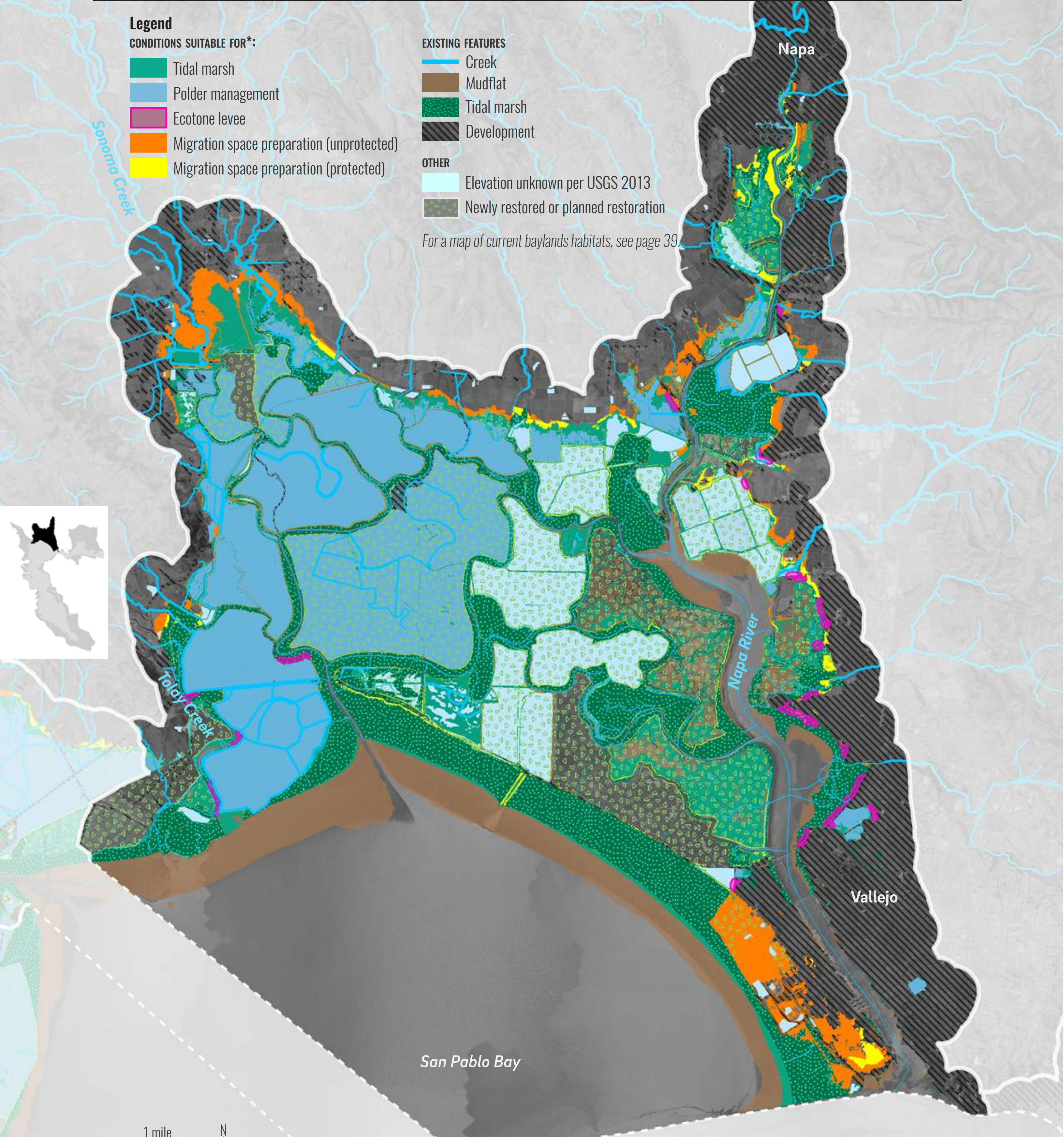
Place Types Map



Legend
- Parks and protected areas
- Cultivated lands
- Rural and open space
- Suburban edge
- Cul-de-sac suburbs
- Industrial and infrastructure
- Bay

NATURE–BASED ADAPTATION OPPORTUNITIES MAP

7 Napa-Sonoma



*** Disclaimer: This is not an adaptation plan.** This map only provides information on the suitability of nature-based measures according to the methods detailed in this report. Additional study, planning, and engineering will be required to further refine these opportunities.

Nature-based Adaptation Measures

In the Napa-Sonoma OLU there has been significant landscape-scale marsh restoration in areas such as the Napa-Sonoma Salt Ponds and Cullinan Ranch along the Napa River. There are considerable opportunities to restore large connected patches of tidal marsh in the remaining diked baylands closer to Sonoma Creek. Road and rail corridors that cross the marshes, particularly Highway 37, are considerable constraints to the restoration of the marshes: they need existing levees to protect them from flooding, their creek crossings are narrow, and they act as barriers across the wetland-upland transition zone. All of the existing and potential tidal marsh will benefit from preparing migration space for the marsh to move upland as sea level rises. The majority of migration space opportunity is on unprotected land, much of it being managed as vineyards, so acquiring and protecting these areas will be key to creating marsh migration pathways. Much of the existing tidal marsh is adjacent to the creeks and is disconnected from undeveloped migration space by large and deep polders such as Skaggs Island. If raised to intertidal elevations, these polders could be converted to tidal marsh. However, the amount of sediment needed is considerable and realigning the shoreline may be more feasible. Significant opportunities exist to improve the delivery of freshwater, nutrients, and sediment from Sonoma Creek and the Napa River to build better elevation capital closer to upland in these subsided baylands, and to reduce flooding issues. There are also opportunities for widening the bridge crossings at Sonoma Creek and Tolay Creek if Highway 37 is raised on some combination of embankment and pilings. Ecotone levee creation is less critical in this OLU due to limited presence of development in need of protection, but ecotone levees could be incorporated into the design of embankments to raise Highway 37 or the railroads.

	Selected Measures	Suitability
NATURE-BASED	Nearshore reefs	Limited suitability
	Submerged aquatic vegetation	Limited suitability
	Beaches	Limited suitability
	Tidal marshes	High suitability
	Polder management	High suitability
	Ecotone levees	Some suitability
	Migration space preparation	High suitability

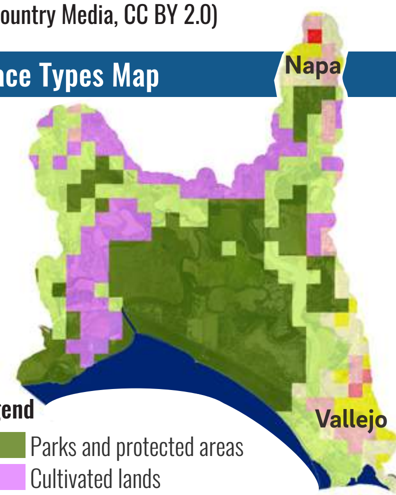
Limited suitability · Some suitability · High suitability

Aerial view looking downstream of the Napa River towards the Napa-Sonoma baylands (Photo by WineCountry Media, CC BY 2.0)

Other Adaptation Opportunities

Like Petaluma, the very large Napa-Sonoma OLU—by far the largest of all OLUs—is comprised of 85% rural and open space uses, protected areas, and cultivated land. This makes it a good candidate for adaptation measures that allow flooding to occur and that facilitate transition from recreational and agricultural uses to habitat or ecological uses over time, through restoration work, transition zone acquisition, and realigning public access. This OLU is not a good place to intensify development or to harden the shoreline; rather, shoreline adaptations here can maximize nature-based solutions. A financial strategy to enable land use transitions could include conservation easements or voluntary buyouts. For the suburban areas of the OLU that may experience sea level rise further in the future, building retrofits, site elevation, and road elevation might be suitable alternatives to relocation or voluntary buyouts, depending on what the community prefers to invest in. Elevating Highway 37 to allow tidal action northwards toward formerly diked wetlands would significantly support the large areas of restoration possible in this OLU.

Place Types Map

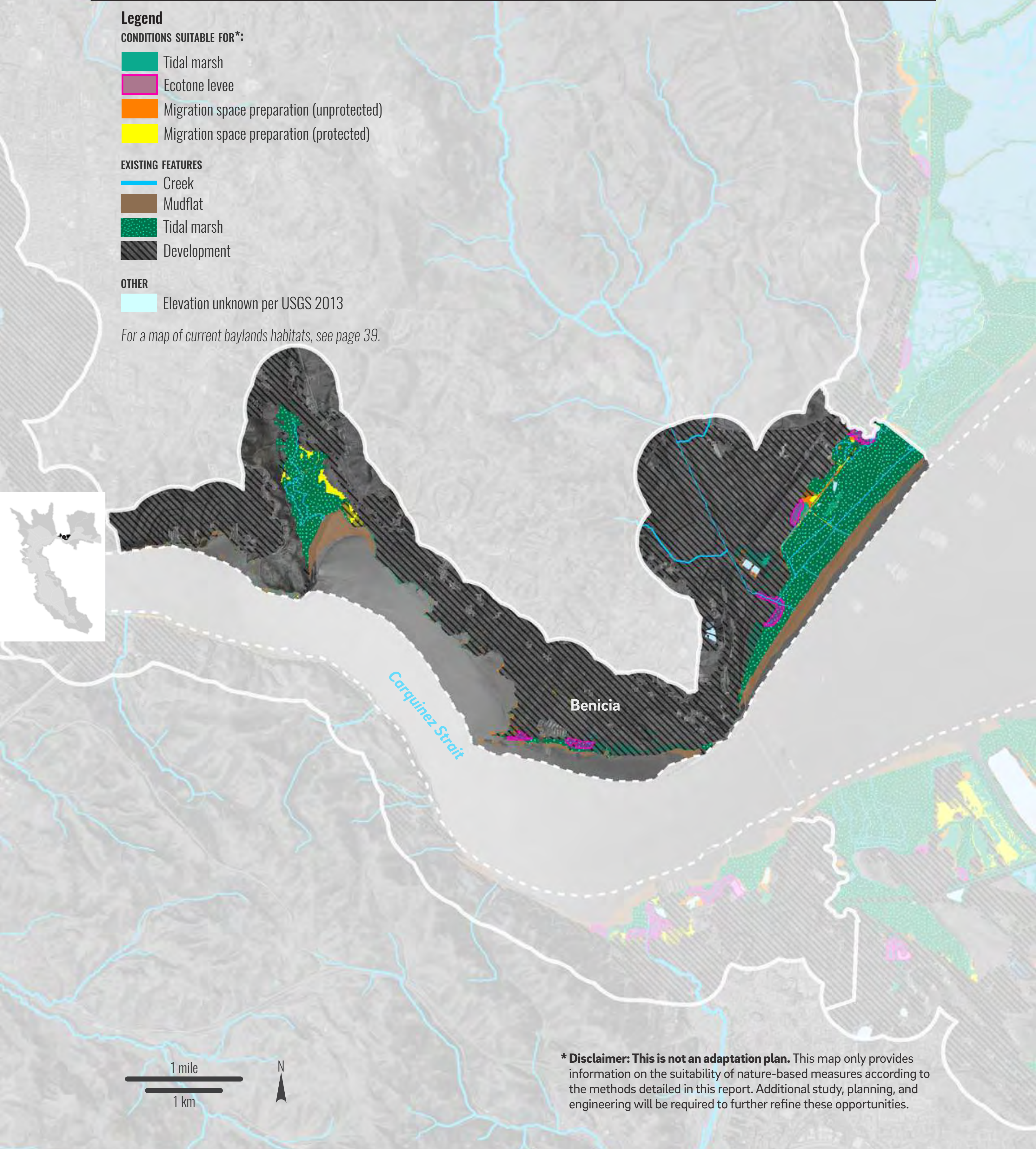


Legend
- Parks and protected areas
- Cultivated lands
- Rural and open space
- Suburban edge
- Cul-de-sac suburbs
- Small lot and streetcar suburbs
- Industrial and infrastructure
- Office parks
- Job centers
- Bay

8

NATURE–BASED ADAPTATION OPPORTUNITIES MAP

Carquinez North



***Disclaimer: This is not an adaptation plan.** This map only provides information on the suitability of nature-based measures according to the methods detailed in this report. Additional study, planning, and engineering will be required to further refine these opportunities.

Nature-based Adaptation Measures

Carquinez North OLU is relatively steep and narrow like other headlands types, with limited areas of shallow water, and has a small area vulnerable to future sea level rise. The marsh in Southampton Bay, at Benicia State Recreation Area, is unique in that it is ringed by land suitable for migration space that has also been protected. Marsh enhancement and ecotone or horizontal levees would also be suitable in front of the industrial areas in Benicia, at the eastern edge of the OLU, though changes in salinity related to Delta outflows and changing snow melt, as well as sea level rise, need to be considered when planning marsh restoration activities.

	Selected Measures	Suitability
NATURE-BASED	Nearshore reefs	Limited suitability
	Submerged aquatic vegetation	Limited suitability
	Beaches	Limited suitability
	Tidal marshes	High suitability
	Polder management	Limited suitability
	Ecotone levees	Some suitability
	Migration space preparation	High suitability

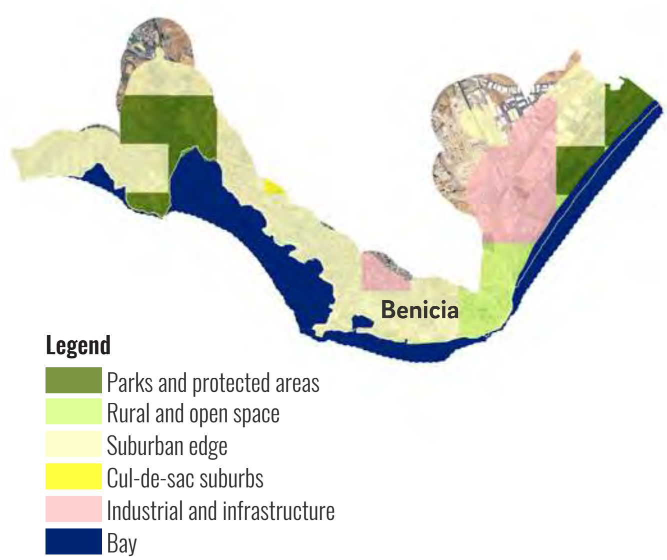
Limited suitability · Some suitability · High suitability

View looking north of the Benicia-Martinez Bridge in the Carquinez Strait, showing heavy industry fronted by marsh in the Carquinez North OLU (Photo by Doc Searls, CC BY-SA 2.0)

Other Adaptation Opportunities

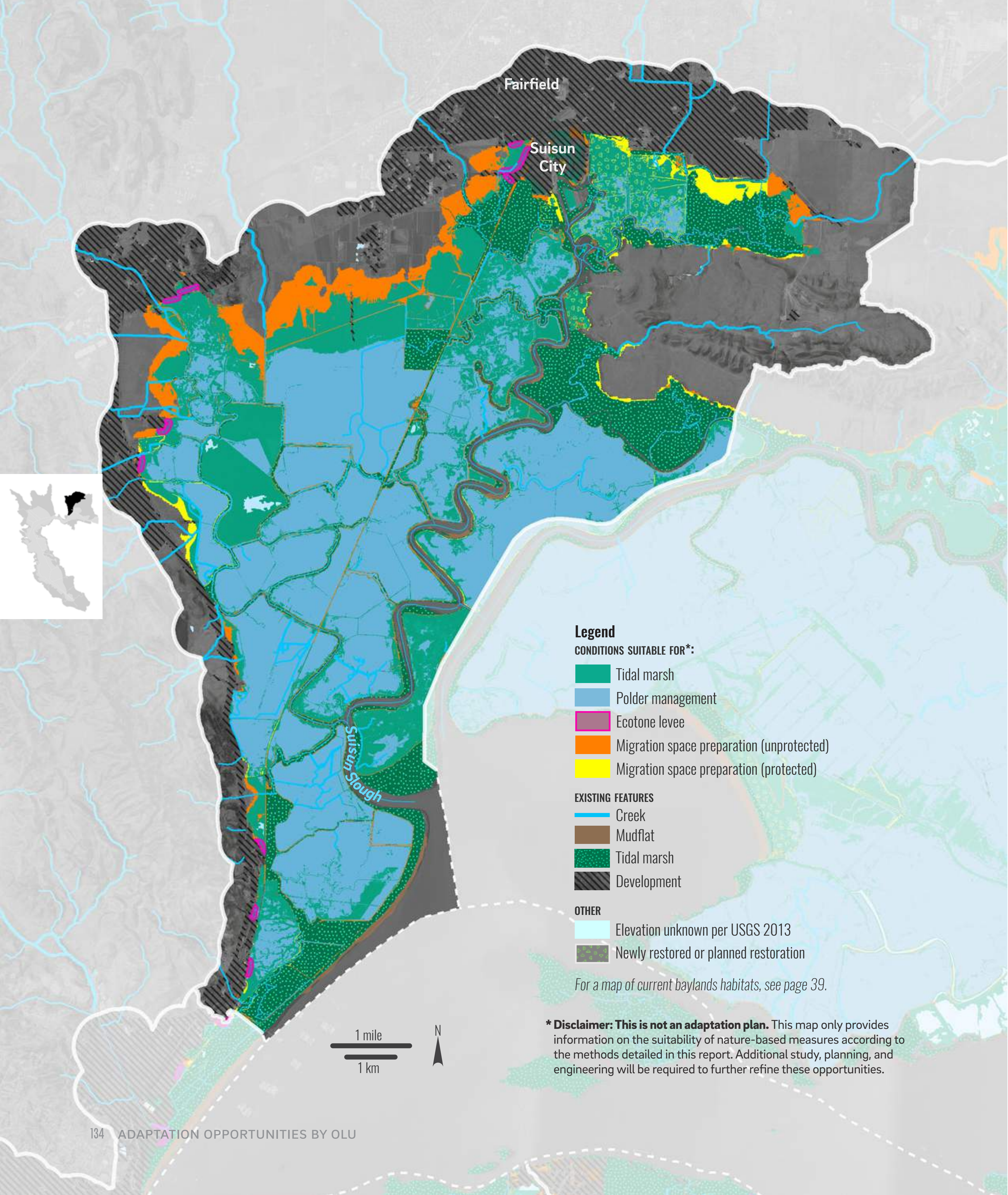
This OLU has the second-highest percentage of the suburban edge place type (very low-density residential) among all OLUs. In the near term, most of the area at risk of flooding is in parks or already-protected areas; adaptation opportunities here include acquiring transition zone and leveraging available open space for wetlands restoration and flood protection. Financial strategies to enable these land use transitions could include conservation easements or voluntary buyouts. Over the long-term, suburban edge communities could adapt to sea level rise by retrofitting buildings, raising roads, or building inland flood walls or berms, and could potentially self-finance some of these flood protection measures by establishing a GHAD. Retreating from developed areas that repeatedly flood is another option; the community could identify and establish these areas through zoning changes, and/or fund relocation to safer areas with selective property buyouts.

Place Types Map



9 NATURE–BASED ADAPTATION OPPORTUNITIES MAP

Suisun Slough



For a map of current baylands habitats, see page 39.

*** Disclaimer: This is not an adaptation plan.** This map only provides information on the suitability of nature-based measures according to the methods detailed in this report. Additional study, planning, and engineering will be required to further refine these opportunities.

Nature-based Adaptation Measures

The Suisun Slough OLU presents unique opportunities for marsh migration compared to much of the urbanized estuary. While much of the baylands within the OLU consist of managed wetlands for duck clubs, this situation may change in the future if climate change impacts the habitat conditions that support these land uses. There are opportunities for large areas of marsh restoration and enhancement of managed marshes, and also large continuous swaths of undeveloped, though unprotected, migration space. These areas are critical for allowing marshes to migrate and persist with sea level rise. However, of critical importance is the future management of the deeply subsided polders faced with increasing sea level rise, reduced mineral sediment supply from the Delta, and increasing salinity as Bay water intrudes further inland leading to elevated summer salinities. All of these factors point to a reduction in peat accretion, mineral sedimentation, and loss of elevation capital. Though it only captures drainage from small watersheds, this OLU presents many opportunities to reconnect small creeks to the back end of marshes, which could potentially increase freshwater and mineral sediment supply to the marshes. Green stormwater infrastructure could be implemented in the upper watershed to reduce fluvial flooding in the developed areas, and potentially increase peat production in polders to help reverse subsidence.

Selected Measures

	Selected Measures	Suitability
NATURE-BASED	Nearshore reefs	Limited suitability
	Submerged aquatic vegetation	Limited suitability
	Beaches	Limited suitability
	Tidal marshes	High suitability
	Polder management	High suitability
	Ecotone levees	Some suitability
	Migration space preparation	High suitability

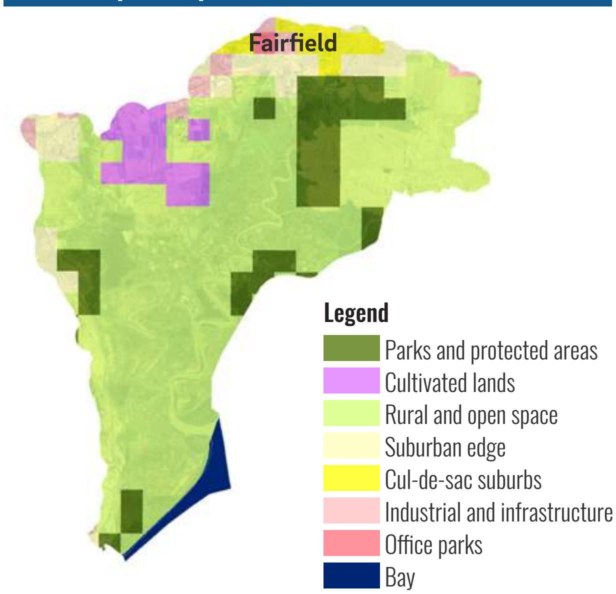
Limited suitability · Some suitability · High suitability

View of marsh from a passenger train in the Suisun Slough OLU (Photo by SFEI)

Other Adaptation Opportunities

Like Napa-Sonoma and Petaluma, the Suisun OLU has just over 85% of land in open space and rural uses, including the second-highest percentage of the rural and open space place type among all OLUs. This open space presents a key opportunity to leverage nature-based solutions and restore marsh. This area is not a good opportunity site for intensifying development or adding critical infrastructure; over time, existing agricultural or recreational uses can convert to ecological uses as flooding frequency increases, and infrastructure can be raised or relocated. Conservation easements are a financial strategy that can help to make this transition easier. Development in this OLU is concentrated on the upland side; all of this “room” between the current shoreline and locations where people live creates an opportunity for leveraging nature-based solutions and providing flood control and protection benefits for adjacent neighborhoods.

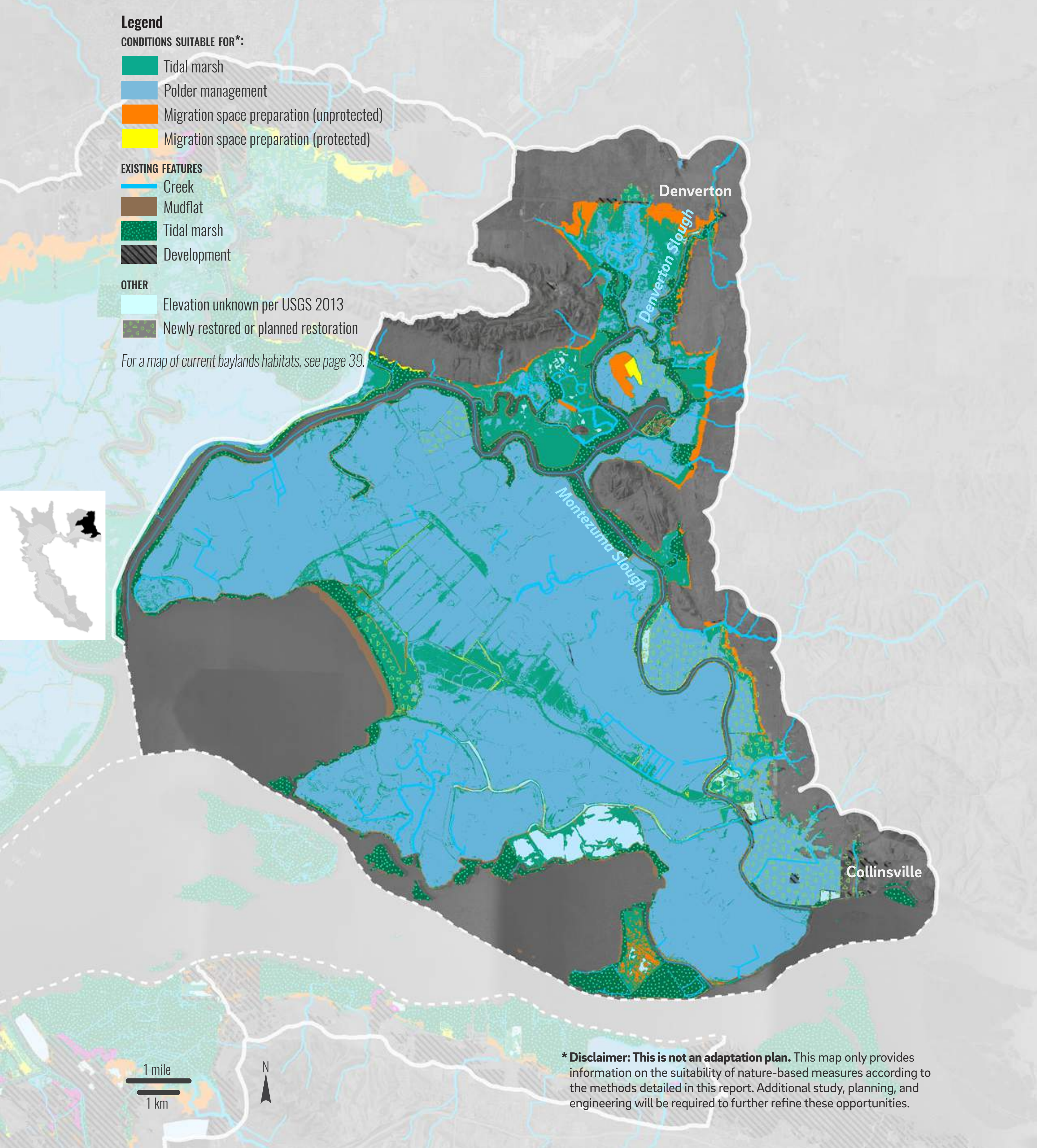
Place Types Map



NATURE-BASED ADAPTATION OPPORTUNITIES MAP

10

Montezuma Slough



*** Disclaimer: This is not an adaptation plan.** This map only provides information on the suitability of nature-based measures according to the methods detailed in this report. Additional study, planning, and engineering will be required to further refine these opportunities.

Nature-based Adaptation Measures

The Montezuma Slough OLU is predominantly polders managed by duck clubs. Management of these polders will be important as sea levels rise, since they will continue to subside with reduced mineral sediment supply from the Delta, increasing summer salinity, and reduced peat accretion. There are significant opportunities for tidal marsh restoration adjacent to narrow but continuous swaths of undeveloped, but unprotected, migration space. These areas are critical for allowing marshes to migrate and persist with sea level rise. Though it drains small watersheds, this OLU presents many opportunities to reconnect small creeks, such as Denverton and Nurse sloughs, to the back of the marshes, which could potentially increase mineral sediment supply to the wetlands. Montezuma Slough is the only OLU which does not have urban development in its contributing watersheds, and as such, green stormwater infrastructure is not as important.

Selected Measures

	Selected Measures	Suitability
NATURE-BASED	Nearshore reefs	Limited suitability
	Submerged aquatic vegetation	Limited suitability
	Beaches	Limited suitability
	Tidal marshes	High suitability
	Polder management	High suitability
	Ecotone levees	Limited suitability
	Migration space preparation	High suitability

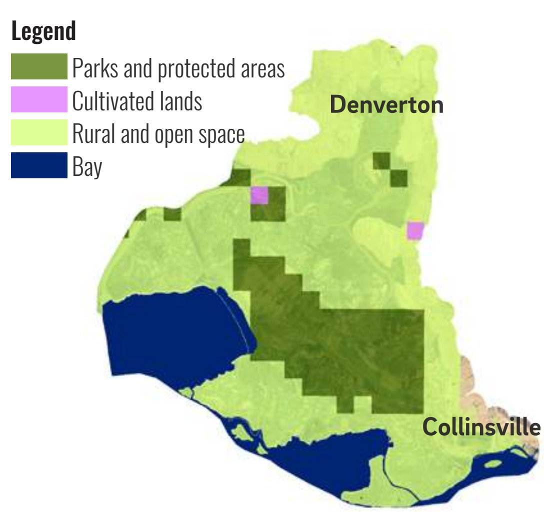
Limited suitability | Some suitability | High suitability

Aerial view looking north towards Collinsville, the southeastern edge of the Montezuma Slough OLU, and adjacent open space (Photo by Doc Searls, CC BY-SA 2.0)

Other Adaptation Opportunities

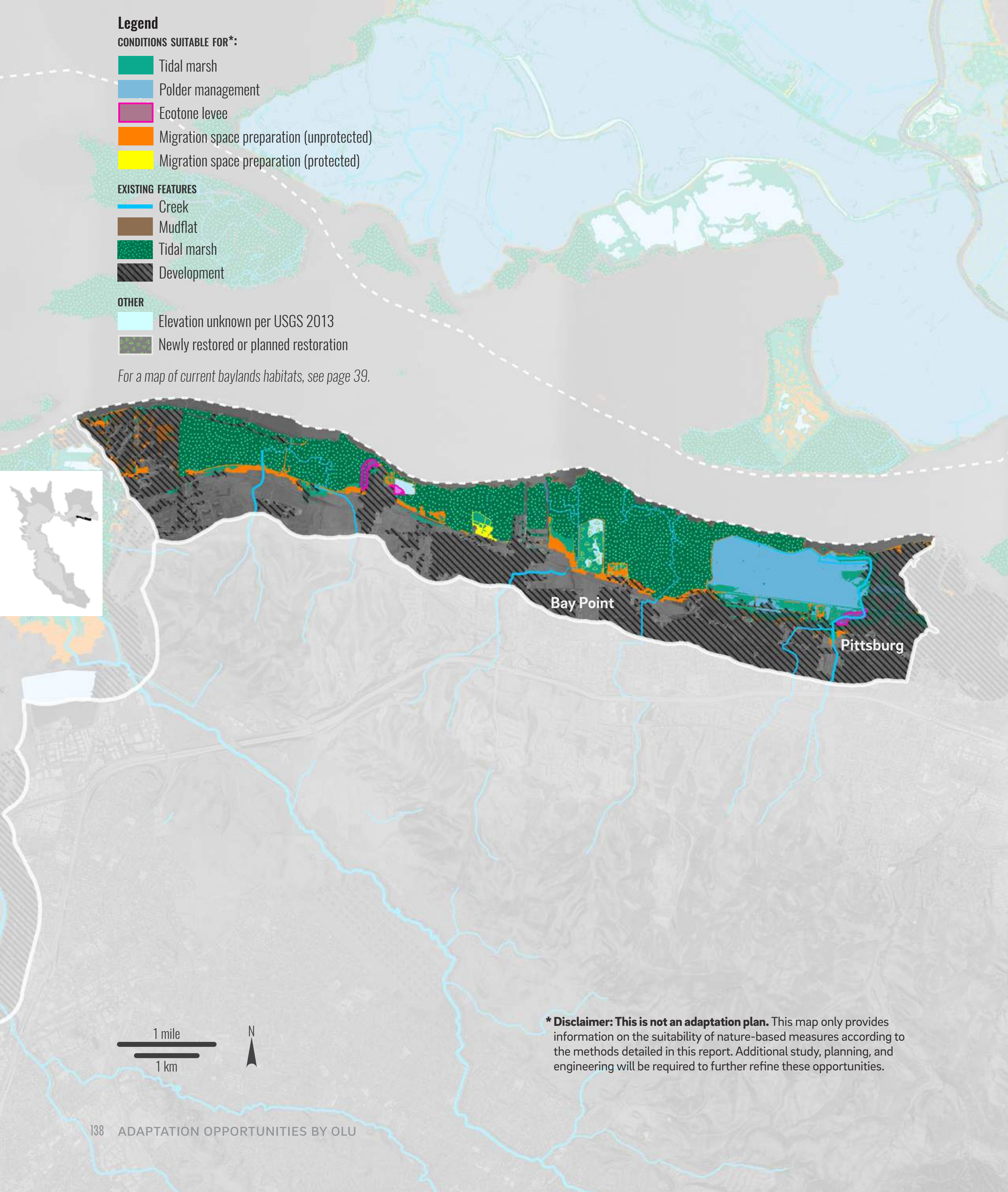
Montezuma Slough is a unique OLU in that most land uses are open space and protected areas, including a very large public parcel, the Grizzly Island Wildlife Area. Montezuma Slough has the lowest number of jobs and residents among all OLUs. Without any developed land other than a few buildings and roads, this OLU's most suitable adaptation opportunities are leveraging open space to employ nature-based solutions, and letting nature take its course through managed retreat from the shoreline. Over time these places can convert from agricultural or recreational uses to ecological uses as flooding frequency increases. Transportation corridors may need to be raised or realigned to allow for marshes to migrate. Conservation easements and buyouts are a financial strategy that can help to make this transition easier.

Place Types Map



11 NATURE-BASED ADAPTATION OPPORTUNITIES MAP

Bay Point



*** Disclaimer: This is not an adaptation plan.** This map only provides information on the suitability of nature-based measures according to the methods detailed in this report. Additional study, planning, and engineering will be required to further refine these opportunities.

Nature-based Adaptation Measures

The Bay Point OLU occupies the distal edges of small alluvial plains descending down from the northern edge of the Diablo Range. The historically narrow baylands act as a buffer between the estuary and communities. Maintaining and enhancing existing marshes and acquiring appropriate unprotected migration space should be considered, as the deep water limits bayward marsh expansion. While not mapped here, subtidal management of native SAV such as *Stuckenia pectinata* could reduce erosion impacts along the shoreline. Polder management will become more difficult as relative sea level rises, due to continued subsidence, reduction in mineral sediment supply from the Delta, increasing summer salinity, and reduction in peat accretion. Green stormwater infrastructure could be implemented in the upper watershed to reduce fluvial flooding in the developed areas.

Selected Measures		Suitability
NATURE-BASED	Nearshore reefs	○ Limited
	Submerged aquatic vegetation	○ Limited
	Beaches	○ Limited
	Tidal marshes	● High
	Polder management	● High
	Ecotone levees	◐ Some
	Migration space preparation	● High

○ Limited suitability ◐ Some suitability ● High suitability

Aerial view from the hills looking northwest to the eastern edge of the Bay Point OLU shoreline, from the marsh at Mallard Island to heavy industry at Riverview Park (Photo by Doc Searls, CC BY-SA 2.0)

Other Adaptation Opportunities

The land uses in the Bay Point OLU are a mix of mostly rural and open space and low density residential/suburban edge, with limited industrial and military facilities. There is very little near-term flood risk in Bay Point, and almost all of the at-risk areas are in existing open space, bayward of a major rail line—this can be leveraged to provide flood protection to the suburban edge communities upland of these land uses. For the suburban edge areas of the OLU that may experience sea level rise further in the future, building retrofits, site elevation, and road elevation might be suitable alternatives to relocation or voluntary buyouts, depending on what the community prefers to invest in. Very little of Bay Point's open space (1% of land) is publicly owned or protected, so public agencies may consider buying land or easements near the shoreline to prevent further intensification of development in areas of future flood risk.

Place Types Map

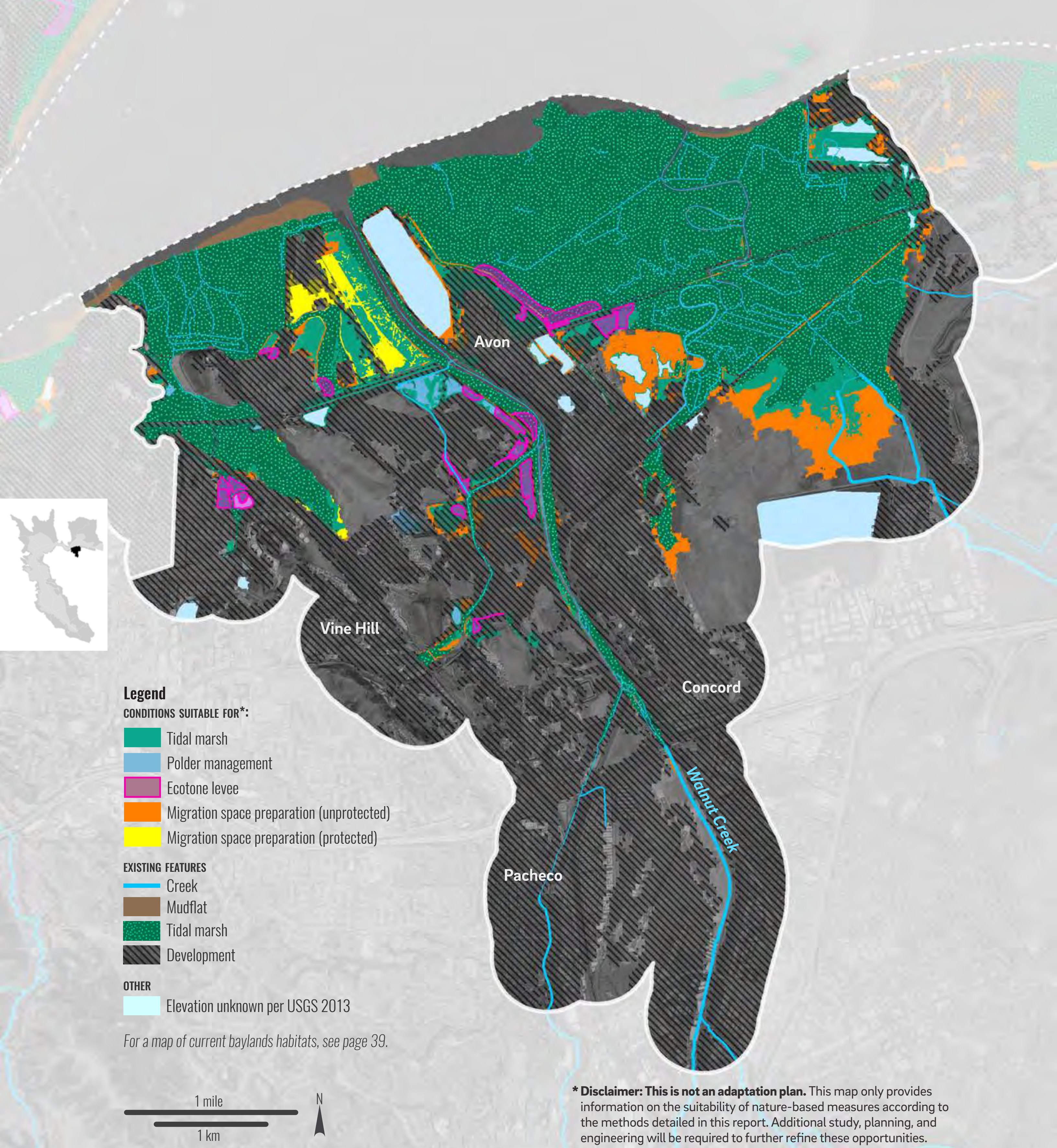
Legend

- Parks and protected areas
- Cultivated lands
- Rural and open space
- Suburban edge
- Cul-de-sac suburbs
- Industrial and infrastructure
- Bay

12

NATURE-BASED ADAPTATION OPPORTUNITIES MAP

Walnut



* **Disclaimer: This is not an adaptation plan.** This map only provides information on the suitability of nature-based measures according to the methods detailed in this report. Additional study, planning, and engineering will be required to further refine these opportunities.

Nature-based Adaptation Measures

The Walnut OLU sits in a relatively wide alluvial valley, with wide fronting baylands, but with little to no mudflats, as the main channel of the Carquinez Strait impinges on the south bank. There are large areas of marsh at the mouth of Walnut Creek, and to the east at Point Edith, where a wide swath of undeveloped, unprotected land is adjacent to existing marsh and could provide critical marsh migration with sea level rise. There are plans to reconnect Walnut Creek with its baylands, widening the floodplain and increasing the resilience of the marsh to sea level rise (SFEI-ASC 2016). Ecotone levees are appropriate in some locations where existing or potential marsh abuts development. Several polders in this OLU could serve as flood retention ponds, or be filled to create marsh with beneficial reuse of dredged sediments from Walnut Creek. Green stormwater infrastructure should continue to be implemented in the upper watershed to reduce fluvial flooding in the developed areas and lower peak flows in the main channel.

Selected Measures

	Selected Measures	Suitability
NATURE-BASED	Nearshore reefs	○
	Submerged aquatic vegetation	○
	Beaches	○
	Tidal marshes	●
	Polder management	●
	Ecotone levees	●
	Migration space preparation	●

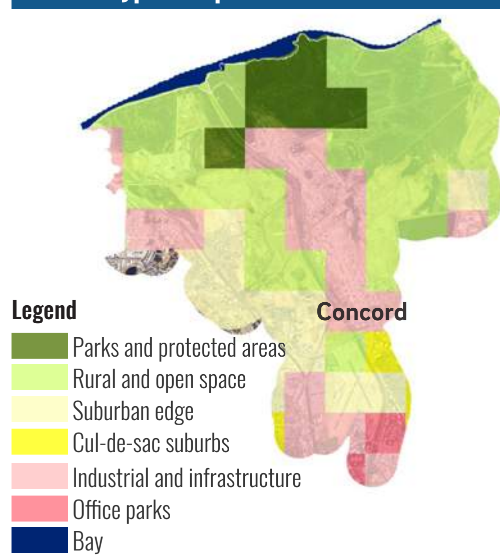
○ Limited suitability ◐ Some suitability ● High suitability

Aerial view from the Walnut OLU shoreline looking northwest towards the southwest edge of Suisun Slough OLU at the Suisun Bay Reserve Fleet (Photo by Doc Searls, CC BY-SA 2.0)

Other Adaptation Opportunities

Walnut has a high degree of open space and rural land. Though somewhat vulnerable to near-term sea level rise, nature-based strategies can help these areas to adapt, especially since much of the OLU is already protected land, such as the Point Edith Wildlife Area. This open space presents an opportunity to let nature take its course through managed retreat from the shoreline. This OLU also has a major oil refinery and other industrial uses, as well as low-lying infrastructure such as roads and rail that service those industries, close to Walnut Creek; this industrial footprint could be floodproofed and protected—or moved elsewhere via zoning changes, tax incentives, or a TDR program if repeat flooding becomes a problem.

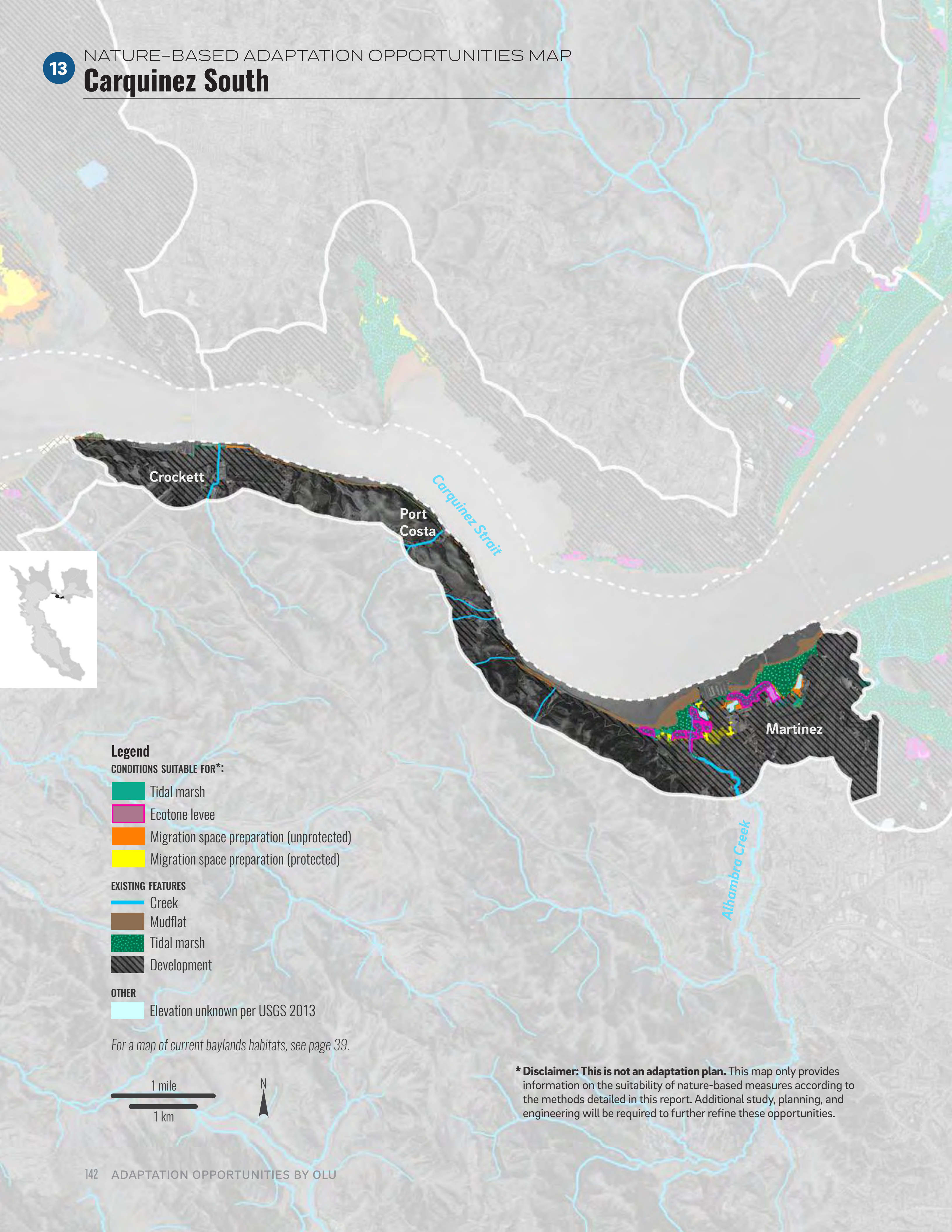
Place Types Map



13

NATURE-BASED ADAPTATION OPPORTUNITIES MAP

Carquinez South



Legend

CONDITIONS SUITABLE FOR*:

- Tidal marsh
- Ecotone levee
- Migration space preparation (unprotected)
- Migration space preparation (protected)

EXISTING FEATURES

- Creek
- Mudflat
- Tidal marsh
- Development

OTHER

- Elevation unknown per USGS 2013

For a map of current baylands habitats, see page 39.

1 mile

1 km

N

***Disclaimer: This is not an adaptation plan.** This map only provides information on the suitability of nature-based measures according to the methods detailed in this report. Additional study, planning, and engineering will be required to further refine these opportunities.

Nature-based Adaptation Measures

The Carquinez South OLU encompasses the headlands along Carquinez Strait and the Martinez Regional Shoreline at the mouth of Alhambra Creek. There has been considerable marsh restoration and floodplain widening over the last decade. Opportunities exist to enhance the marsh at Alhambra Creek, and to use ecotone levees at the back of the marsh to create transition zones and high-tide refuge. Small areas of protected migration space flank the marsh on the west side of the creek and should be integrated into sea level rise planning. Green stormwater infrastructure, and floodplain widening and reconnection, could be implemented in the upper watershed to reduce fluvial flooding in the developed valleys.

	Selected Measures	Suitability
NATURE-BASED	Nearshore reefs	Limited suitability
	Submerged aquatic vegetation	Limited suitability
	Beaches	Limited suitability
	Tidal marshes	Some suitability
	Polder management	Limited suitability
	Ecotone levees	High suitability
	Migration space preparation	High suitability

Limited suitability · Some suitability · High suitability

View of the Carquinez South OLU shoreline looking towards Mount Diablo, from Mococo (left) to Martinez (right) (Photo by Bill Williams, CC BY 2.0)

Other Adaptation Opportunities

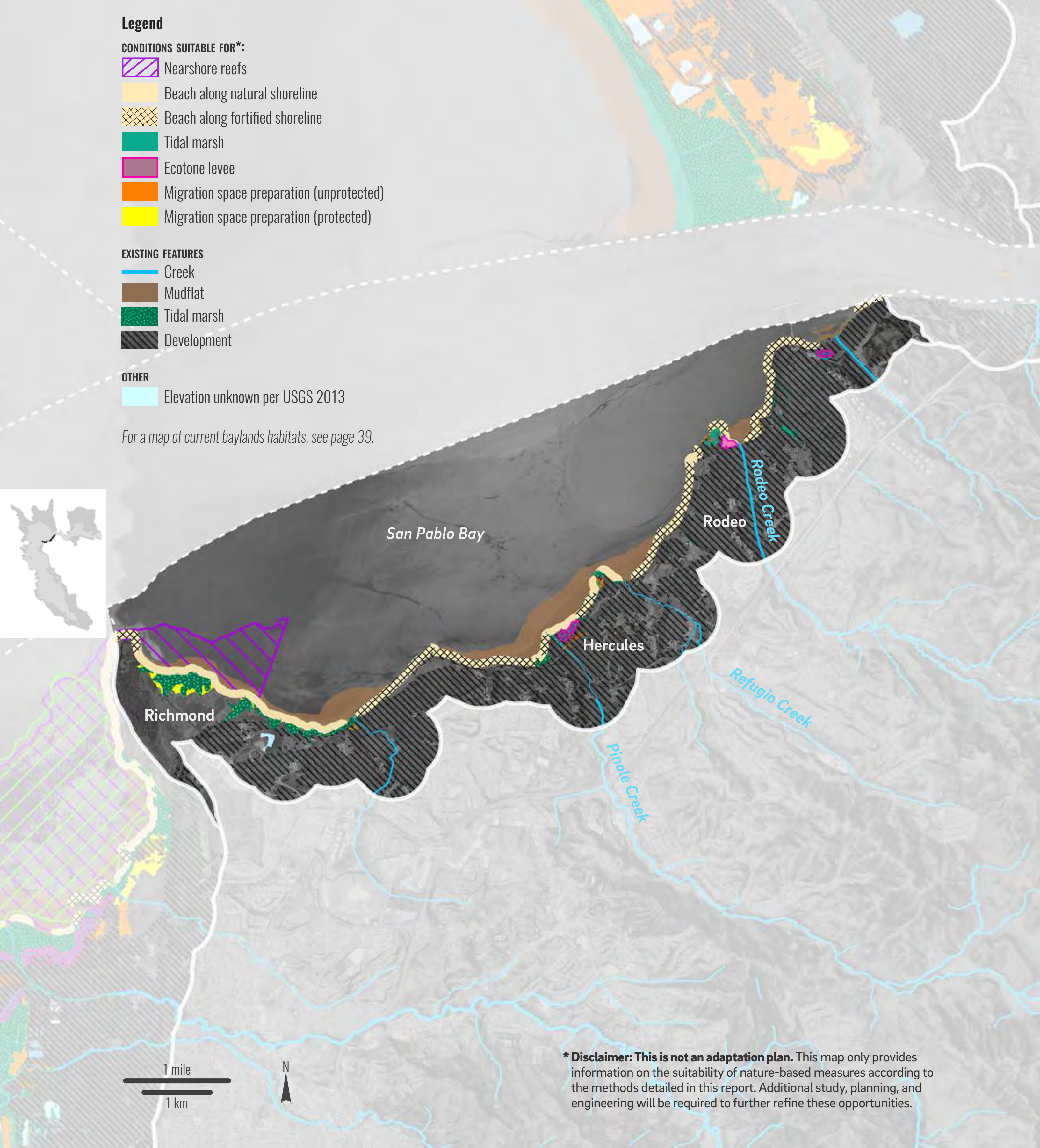
Carquinez South is a small, steep, and narrow OLU, much of which is fronted by a rail line and backed by protected open space. It is not especially vulnerable to near-term sea level rise. In the long run, relocating or elevating the railroad tracks could allow the shoreline to naturally migrate landward into these protected areas while minimizing flood-related closures for rail users, including passengers and freight. For the areas closer to Crockett and Martinez that may experience nearer-term sea level rise and flooding, land uses at risk include industrial and infrastructure and very low-density residential areas. Adaptation opportunities for these uses include relocation through incentives or buyouts, land elevation, or improving site-scale flood protection through building codes and zoning changes. Establishing a GHAD could help fund community-chosen flood protection measures.

Place Types Map

14

NATURE-BASED ADAPTATION OPPORTUNITIES MAP

Pinole



For a map of current baylands habitats, see page 39.

*** Disclaimer: This is not an adaptation plan.** This map only provides information on the suitability of nature-based measures according to the methods detailed in this report. Additional study, planning, and engineering will be required to further refine these opportunities.

Nature-based Adaptation Measures

The Pinole OLU is characterized by steep bluffs, pocket marshes, small creeks, and coves of shallow subtidal open water. Coarse beaches could be explored as a potential adaptation measure which is a better ecological alternative to rip rap; Point Pinole Regional Shoreline already has examples of barrier beaches fronting wetlands, which could serve as a model for beaches in other OLUs. Mudflat augmentation and some limited areas of nearshore reefs could be considered in parallel with other measures. The western end of the Pinole OLU has opportunities for marsh migration adjacent to, and upslope of, existing tidal marsh. In other areas, ecotone levees could provide high-tide refuge and transition zone behind pocket marshes. Green stormwater infrastructure could be implemented in the upper watershed to reduce fluvial flooding in the developed areas.

Selected Measures

	Selected Measures	Suitability
NATURE-BASED	Nearshore reefs	●
	Submerged aquatic vegetation	○
	Beaches	●
	Tidal marshes	◐
	Polder management	○
	Ecotone levees	◐
	Migration space preparation	○

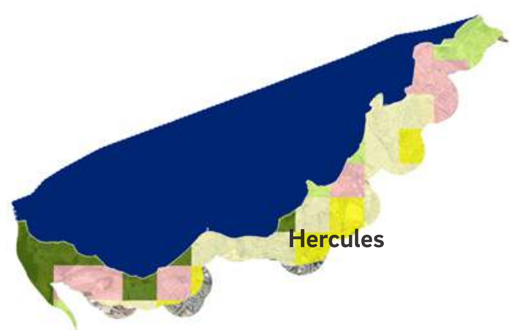
○ Limited suitability ◐ Some suitability ● High suitability

Bluffs along the northern section of Point Pinole Regional Shoreline, looking towards Tara Hills in the Pinole OLU (Photo by Katie McKnight, SFEI)

Other Adaptation Opportunities

Like Carquinez South, most of the Pinole shoreline is fronted by railroad tracks that could be relocated or elevated to reduce flooding, possibly onto a levee or berm that prevents further flooding inland of this OLU's diverse land uses. Pinole has a fairly balanced mix of open space and rural uses, industrial/infrastructure, and low-density suburban/residential neighborhoods, begetting a wide range of potential adaptation opportunities. For residential areas, these include building retrofits, road and site elevation, establishment of a sea level rise overlay zone, and/or payment for infrastructural changes via establishment of a GHAD. For industrial areas, zoning changes, tax incentives, or a TDR program may help relocate businesses to safer locations, especially once repeat flooding becomes a problem.

Place Types Map



Legend

- Parks and Protected Areas
- Rural and Open Space
- Suburban Edge
- Cul-de-sac Suburbs
- Industrial and Infrastructure
- Bay

15

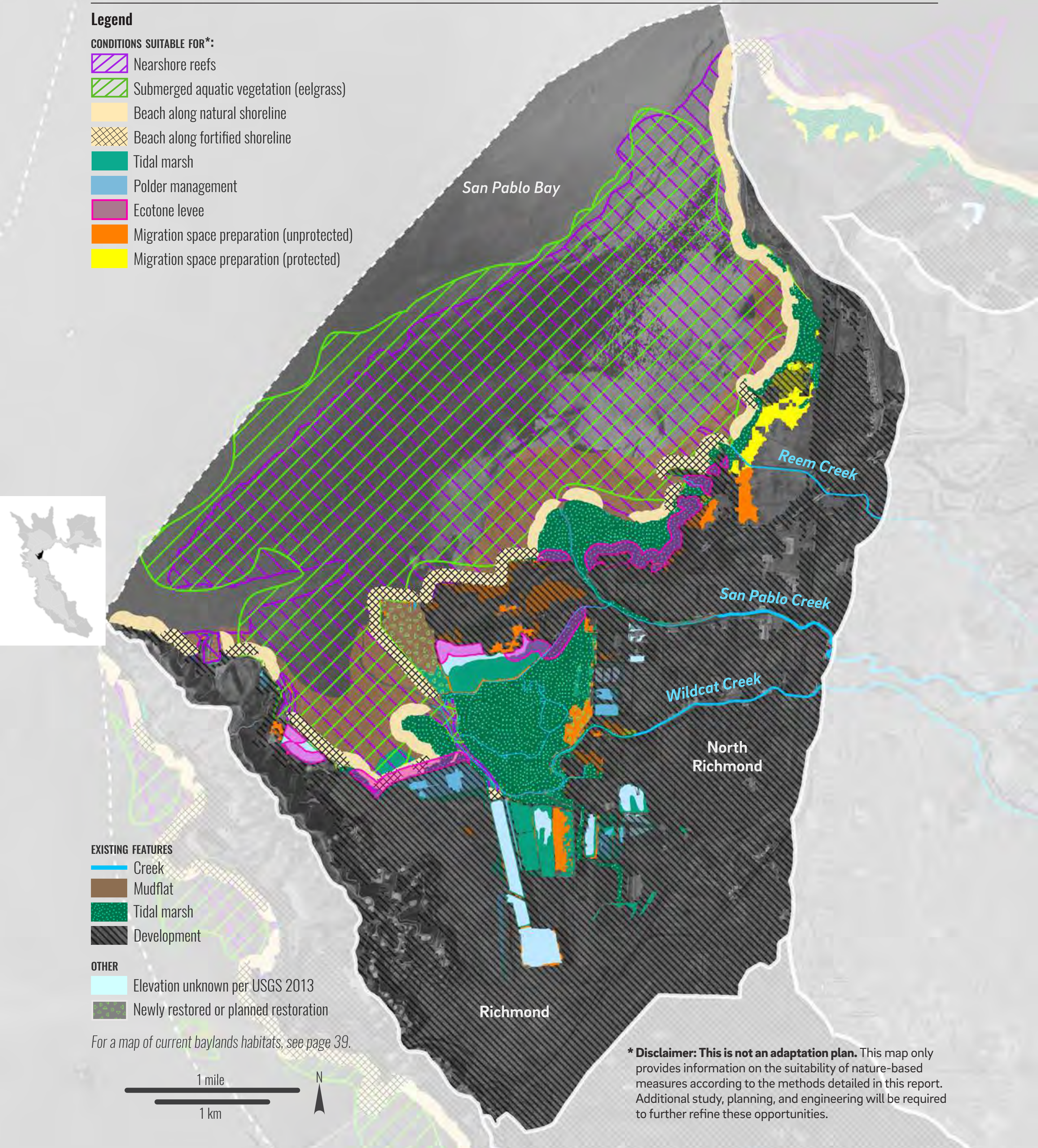
NATURE-BASED ADAPTATION OPPORTUNITIES MAP

Wildcat

Legend

CONDITIONS SUITABLE FOR*:

- Nearshore reefs
- Submerged aquatic vegetation (eelgrass)
- Beach along natural shoreline
- Beach along fortified shoreline
- Tidal marsh
- Polder management
- Ecotone levee
- Migration space preparation (unprotected)
- Migration space preparation (protected)



EXISTING FEATURES

- Creek
- Mudflat
- Tidal marsh
- Development

OTHER

- Elevation unknown per USGS 2013
- Newly restored or planned restoration

For a map of current baylands habitats, see page 39.

1 mile
1 km
N

*** Disclaimer: This is not an adaptation plan.** This map only provides information on the suitability of nature-based measures according to the methods detailed in this report. Additional study, planning, and engineering will be required to further refine these opportunities.

Nature-based Adaptation Measures

The Wildcat OLU has opportunities for all of the nature-based adaptation measures analyzed in this report. Both oysters and eelgrass have potential in this area, and these measures are being tested as part of the San Francisco Bay Living Shorelines Project at the Giant Marsh. Creek connection to marshes could be enhanced to steer sediment loads directly into tidal marshes, or to support micro-deltas. Coarse or composite beaches could reduce erosion along the edges of pocket marshes as well as at the toe of bluffs and railroad berms, as an alternative to riprap. In some locations there is unprotected, undeveloped land behind the marshes which could be prepared for marsh migration with sea level rise. In other locations, where the marshes abut development, ecotone levees would be suitable to support high-tide refuge and transition zones.

	Selected Measures	Suitability
NATURE-BASED	Nearshore reefs	●
	Submerged aquatic vegetation	●
	Beaches	●
	Tidal marshes	●
	Polder management	◐
	Ecotone levees	●
	Migration space preparation	●

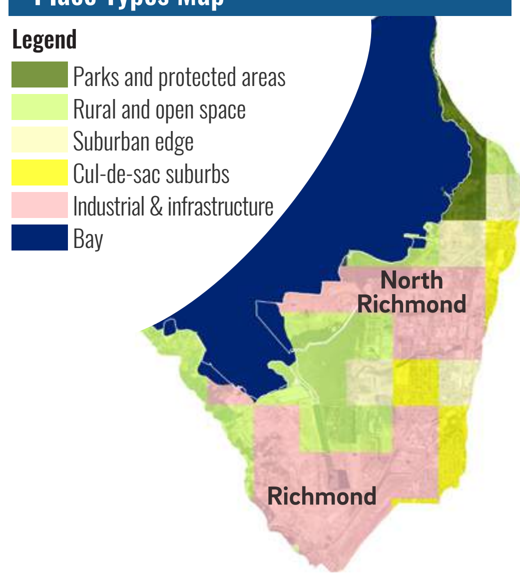
○ Limited suitability ◐ Some suitability ● High suitability

Tidal marsh fronting wastewater treatment ponds and industrial areas along Richmond's shoreline in the Wildcat OLU (Photo by Micha Salomon, SFEI)

Other Adaptation Opportunities

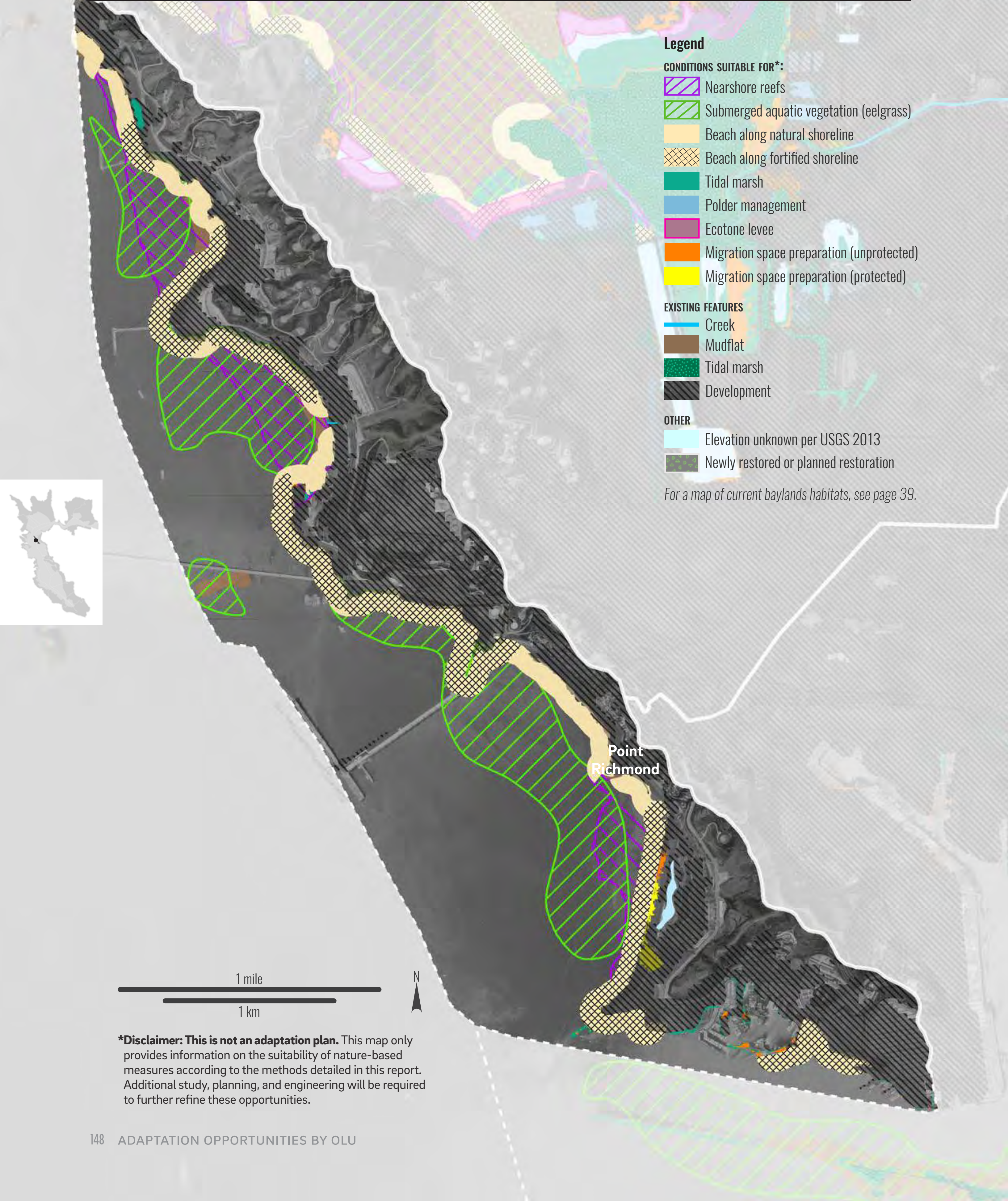
The Wildcat OLU has the second-highest percentage of industrial and infrastructure land among all OLUs (47%); however, the majority of the land that is at risk of near-term flooding from sea level rise is open rather than developed land. Little of this land is publicly owned, so one adaptation opportunity for this OLU is for public agencies to buy more land or easements to create floodable spaces, along the shoreline and along Wildcat and San Pablo creeks. Private industrial landowners, especially the refineries, should collaborate with communities to develop sea level rise adaptation plans that protect public health. For industrial uses that are vulnerable to flooding, some sites may be able to protect themselves by raising the site elevation or flood-proofing, while others might be better off relocating. Policy tools to support the latter include rezoning, tax incentives to relocate, buyouts, and a TDR program—all followed by environmental cleanup.

Place Types Map



16 NATURE-BASED ADAPTATION OPPORTUNITIES MAP

Point Richmond



***Disclaimer: This is not an adaptation plan.** This map only provides information on the suitability of nature-based measures according to the methods detailed in this report. Additional study, planning, and engineering will be required to further refine these opportunities.

Nature-based Adaptation Measures

The Point Richmond OLU is characterized by steep bluffs with pocket beaches. It has minimal vulnerability to short-term sea level rise, but has potential for offshore ecological habitat enhancement and nature-based adaptation measures. Coarse or composite beaches are appropriate along the edges of pocket marshes as well as at the toe of bluffs and along railroad berms, as an alternative to riprap. Rocky intertidal habitat could be explored and augmented at offshore islands; nearshore reefs and eelgrass beds are also suitable.

Selected Measures

	Selected Measures	Suitability
NATURE-BASED	Nearshore reefs	High suitability
	Submerged aquatic vegetation	High suitability
	Beaches	High suitability
	Tidal marshes	Limited suitability
	Polder management	Limited suitability
	Ecotone levees	Limited suitability
	Migration space preparation	Limited suitability

Limited suitability · Some suitability · High suitability

Residential area within the Point Richmond OLU, looking northwest towards the Richmond-San Rafael Bridge approach (Photo by Kate Merriman, CC BY 2.0)

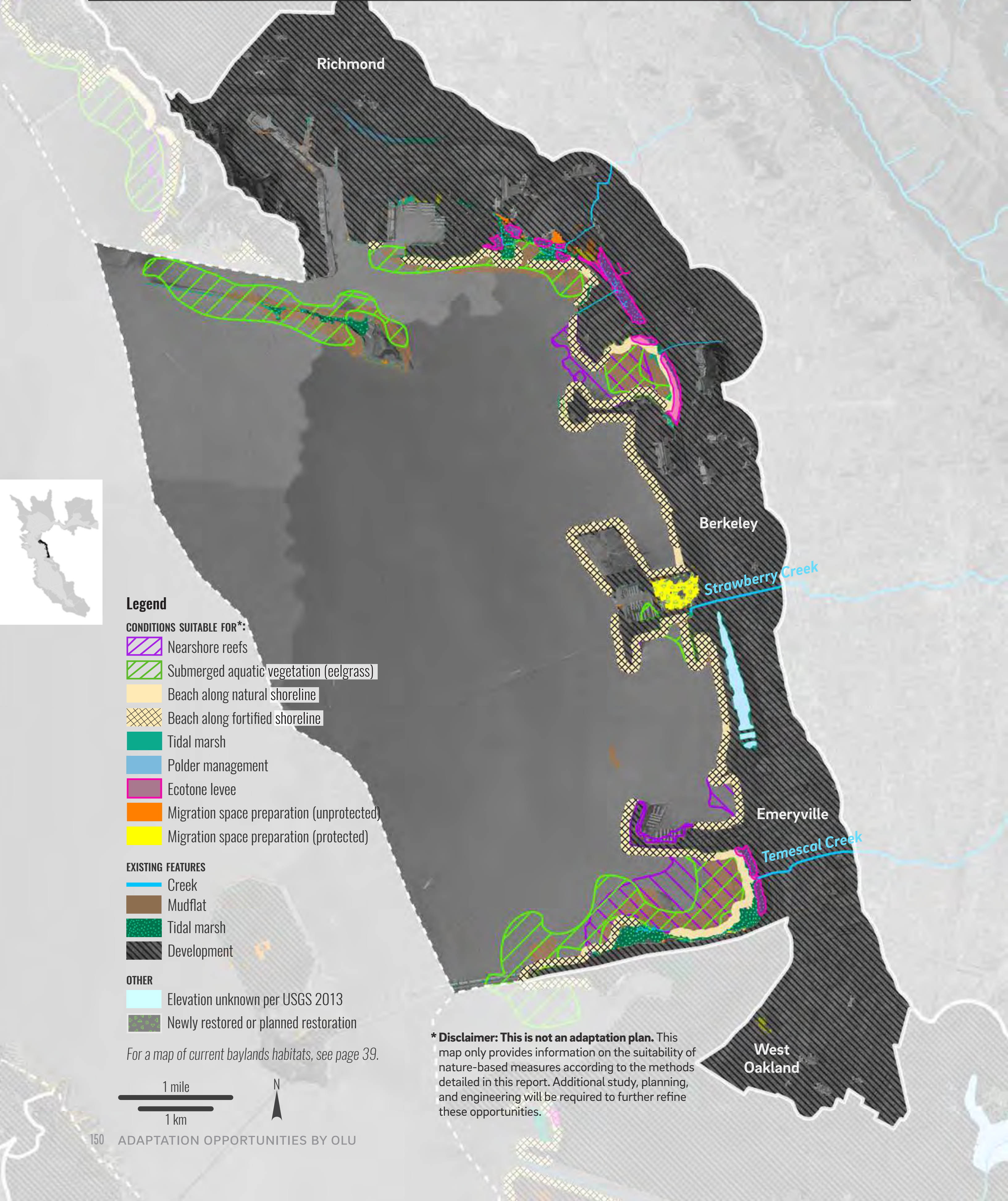
Other Adaptation Opportunities

Point Richmond, the smallest of all OLUs in terms of land area, is steep, narrow, mostly open land that is at very low risk of near-term sea level rise. In its northern section, which is largely comprised of the former Point Molate Naval Fuel Depot that is slated for redevelopment, one key adaptation opportunity is to avoid intensifying development near the shoreline by using setbacks and clustering development upland. This OLU also has some smaller residential communities at risk over the long term. These areas could choose to self-finance shoreline protection measures through establishment of a GHAD, retrofitting homes, or selective buyouts.

Place Types Map

17 NATURE-BASED ADAPTATION OPPORTUNITIES MAP

East Bay Crescent



For a map of current baylands habitats, see page 39.

*** Disclaimer: This is not an adaptation plan.** This map only provides information on the suitability of nature-based measures according to the methods detailed in this report. Additional study, planning, and engineering will be required to further refine these opportunities.

Nature-based Adaptation Measures

The East Bay Crescent is characterized by the headlands and landfills of Emeryville, Berkeley Marina, Albany Bulb, and Point Isabel. The I-80 and I-580 highway corridors have buried the historical Fleming Beach, constrained the present-day marshes, and limited opportunities for marsh migration. In the short term, opportunities are limited to nearshore- and shoreline-focused natural and nature-based strategies. Both nearshore reefs and eelgrass beds are suitable. Creeks draining to the Bay, such as Temescal, Strawberry, Codornices, and Cerrito, have been significantly modified by culverting and channelizing. Their connection to the baylands could be enhanced to direct sediment loads to support mudflats or beaches. Coarse or composite beaches are appropriate along the length of shoreline as an alternative to riprap, and could be stabilized by the artificial headlands. The small areas of marsh could be enhanced with ecotone or horizontal levees that back up to the roads. These measures are meant to be layered and have been shown to have more adaptation potential when used in combination.

Selected Measures		Suitability
NATURE-BASED	Nearshore reefs	High suitability
	Submerged aquatic vegetation	High suitability
	Beaches	High suitability
	Tidal marshes	Some suitability
	Polder management	Limited suitability
	Ecotone levees	High suitability
	Migration space preparation	Limited suitability

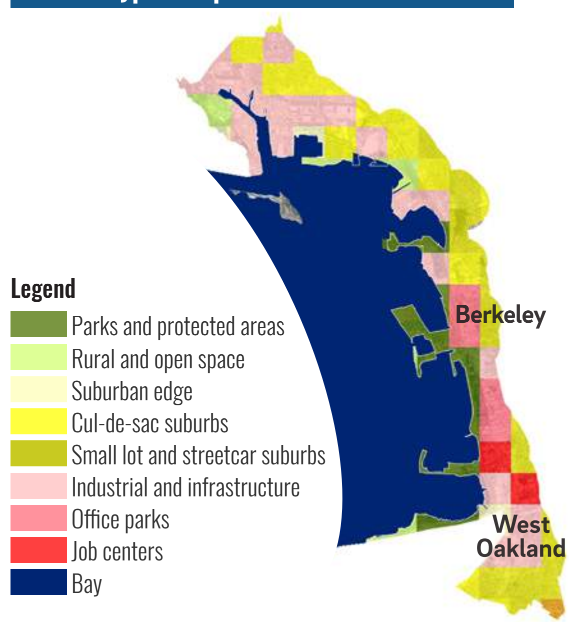
Limited suitability · Some suitability · High suitability

Highways I-580/I-80 located next to tidal marsh in the East Bay Crescent OLU (Photo by Jay Huang Photography, CC BY 2.0)

Other Adaptation Opportunities

This OLU has a mixed set of relatively intensive land uses, including a significant amount of low-density and moderate-density residential suburbs. It has the most small lot “streetcar” suburbs of any OLU—reflecting older neighborhoods—and it also has some suburban job centers, office parks, and industrial lands. As a result of these diverse uses, the East Bay Crescent has many adaptation options, including perimeter protection with grey or hybrid green/grey infrastructure, inland protection, and opening up floodable areas to retain water and reduce combined flooding—most likely with green infrastructure. This area is complex, with many parcels, landowners, tenants, and business owners, so private funding through a GHAD or other avenue may be a good option to help pay for infrastructure investments. Some commercial buildings or businesses in these areas may eventually find it a better investment to move out rather than protect in place. Highways I-580/I-80 near the bayward edge of the OLU could be redesigned or elevated to a levee to provide upland flood protection.

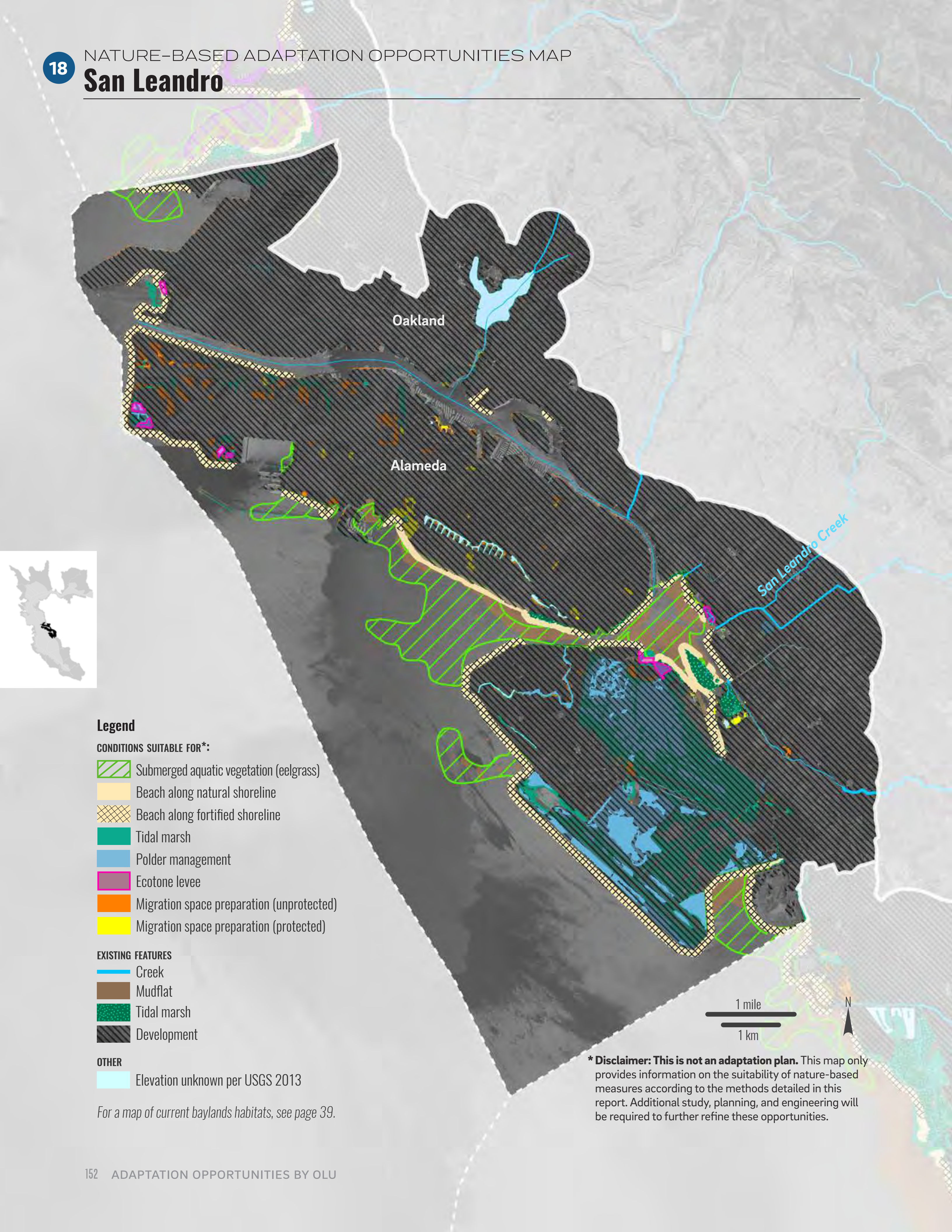
Place Types Map



18

NATURE-BASED ADAPTATION OPPORTUNITIES MAP

San Leandro



Legend

CONDITIONS SUITABLE FOR*:

- Submerged aquatic vegetation (eelgrass)
- Beach along natural shoreline
- Beach along fortified shoreline
- Tidal marsh
- Polder management
- Ecotone levee
- Migration space preparation (unprotected)
- Migration space preparation (protected)

EXISTING FEATURES

- Creek
- Mudflat
- Tidal marsh
- Development

OTHER

- Elevation unknown per USGS 2013

For a map of current baylands habitats, see page 39.

* **Disclaimer: This is not an adaptation plan.** This map only provides information on the suitability of nature-based measures according to the methods detailed in this report. Additional study, planning, and engineering will be required to further refine these opportunities.

Nature-based Adaptation Measures

San Leandro is a highly urbanized, densely settled, mixed-use OLU including the Port of Oakland, the islands of Alameda and Bay Farm, the Oakland Coliseum, and Oakland Airport. There is very little open space, and the significant opportunities for natural and nature-based strategies are on the shoreline or in the subtidal areas, particularly around San Leandro Bay. Eelgrass beds and other submerged aquatic vegetation are suitable and could help increase ecosystem services and attenuate wave energy. Coarse beaches which can buffer wave energy and soften shorelines for habitat and recreation may be suitable when combined with stabilizing groins and nourishment. Management of these beaches would have to take into account the significant longshore transport of material into the Bay and nearshore areas. Parts of Alameda and Bay Farm islands are polders and will need to be managed accordingly. There are some limited opportunities for reconnecting creeks to San Leandro Bay and Lake Merritt, which could help manage combined flooding. Green stormwater infrastructure could be implemented in the upper watershed to reduce fluvial flooding in the developed areas. There is little room for ecotone levees adjacent to existing marshes, though in particular locations, and following the realignment of levees, they may be more appropriate. Though small, the San Leandro OLU has significant but isolated habitat patches, such as Arrowhead Marsh and the restored marsh at Martin Luther King Jr. Regional Shoreline, both of which provide critical habitat to endangered species.

(right) Aerial view of Coast Guard Island and Inner Harbor in Alameda (Photo by Craig Howell, CC BY 2.0)

Selected Measures — Suitability

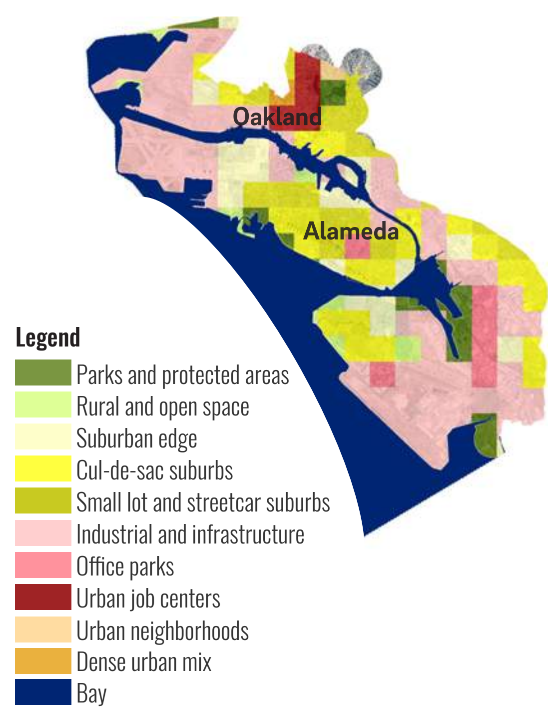
NATURE-BASED	Suitability
Nearshore reefs	Limited
Submerged aquatic vegetation	High
Beaches	High
Tidal marshes	Some
Polder management	Some
Ecotone levees	Limited
Migration space preparation	Limited

Limited suitability · Some suitability · High suitability

Other Adaptation Opportunities

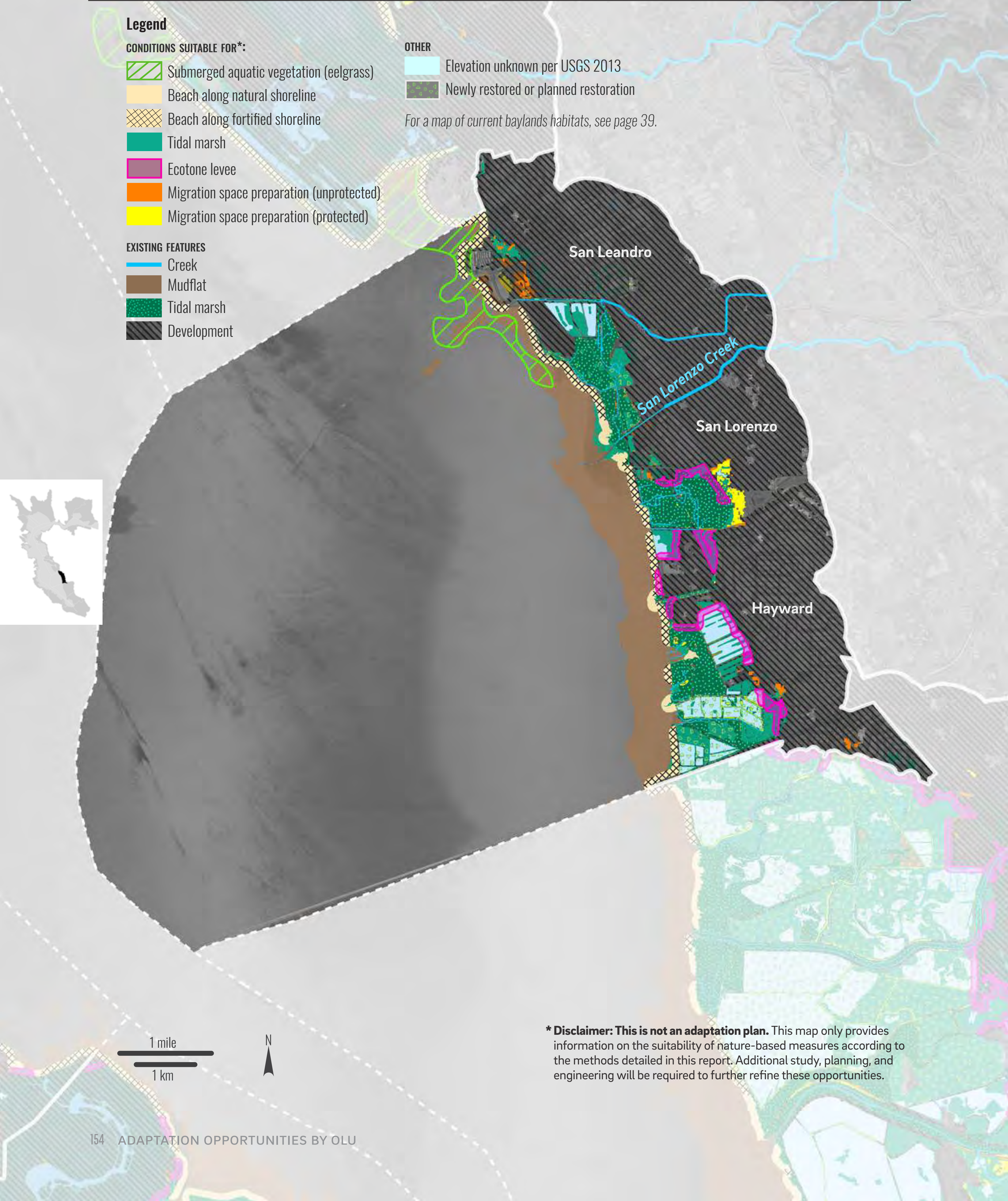
The San Leandro OLU has a significant amount of low- to moderate-density residential suburbs, and quite a lot of industrial land—much of it overlying fill that is subject to liquefaction and rising groundwater levels. Home to downtown Oakland, this OLU has the second highest amount of the urban job centers place type among all OLUs. Near-term sea level rise will most affect industrial and protected lands near the Oakland Airport and San Leandro Bay; over the long run, every place type is at risk. This is a highly complex OLU with many landowners, parcels, and densely developed areas. Opportunities exist to elevate land and roads, require retrofits of buildings and flood-proofing of ground floors, create floodable spaces upland in the watershed to minimize combined flooding, add green infrastructure, establish a sea level rise overlay zone to identify high-hazard areas and the policies and financial strategies that may be used to help them adapt, and build inland flood walls and berms as needed. A mix of grey and green infrastructure will likely be needed depending on the specific vulnerabilities along this OLU's long shoreline. Some businesses or industrial areas with repeat-flood issues in the future may be supported in moving to higher ground through a TDR program or tax incentives; residential neighborhoods could establish a GHAD to finance needed protections.

Place Types Map



NATURE-BASED ADAPTATION OPPORTUNITIES MAP

19 San Lorenzo



***Disclaimer: This is not an adaptation plan.** This map only provides information on the suitability of nature-based measures according to the methods detailed in this report. Additional study, planning, and engineering will be required to further refine these opportunities.

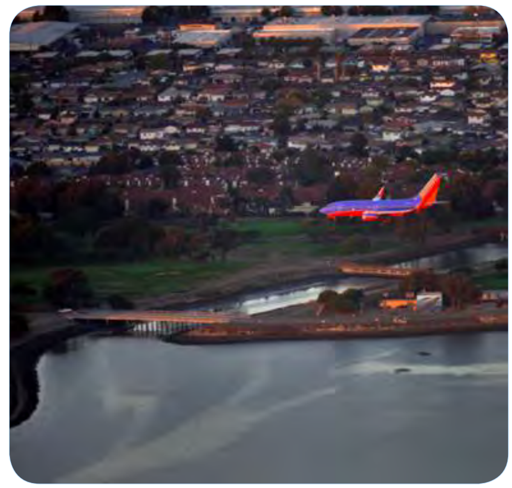
Nature-based Adaptation Measures

The San Lorenzo OLU, which includes the marshes of Roberts Landing, Oro Loma, and Cogswell Marshes, has a band of narrow but significant diked baylands which should be managed, enhanced, and restored. Landward of the marshes there is limited potential marsh migration space and connectivity is limited because of flood risk management levees and a railroad berm. Limited areas of undeveloped, unprotected migration space exist at the southern end of the OLU and should be explored for acquisition or protection. In many locations where existing or potential tidal marsh is adjacent to development and to treated wastewater, horizontal levees may be appropriate. Along the shoreline, coarse beaches are suitable, especially where the marsh scarp is eroding. Mudflat augmentation may also be necessary for limiting erosion of the marshes. Eelgrass beds may be suitable in the northern part of the OLU. Enhancing riparian zones in places such as San Lorenzo Creek, and reconnecting creeks to the baylands, is an appropriate measure here which could also facilitate the direction of sediment to the shoreline. Green stormwater infrastructure could be implemented in the upper watershed to reduce fluvial flooding in the developed areas.

Selected Measures

	Selected Measures	Suitability
NATURE-BASED	Nearshore reefs	○
	Submerged aquatic vegetation	●
	Beaches	●
	Tidal marshes	●
	Polder management	◐
	Ecotone levees	●
	Migration space preparation	◐

○ Limited suitability ◐ Some suitability ● High suitability

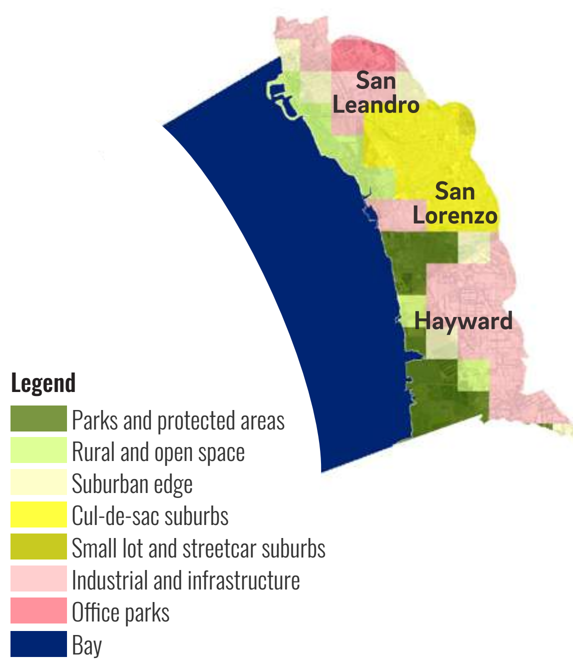


(right) **Aerial view of a golf course and surrounding residences** on the Estudillo Canal in San Leandro (Photo by Craig Howell, CC BY 2.0)

Other Adaptation Opportunities

The San Lorenzo OLU is roughly split in three types of land use: open space closer to the Bay, low-density suburban neighborhoods (cul-de-sac suburbs) in its center, and buildings with large footprints (industrial and infrastructure) on its north and south sides, set back from the shoreline. This OLU will require flood protection for its significant amount of housing and workplaces, but it has the flexibility to do some perimeter protection through land or road elevation and other grey or hybrid infrastructure. It could also add inland protection such as flood walls and berms, require site-scale protection such as flood proofing for buildings, and open up floodable areas with green stormwater infrastructure to retain water near the shoreline and along San Lorenzo Creek. This is a complex OLU with many landowners, tenants, and business owners; neighborhoods and businesses may pool private funding through a GHAD to pay for infrastructure investments. Some commercial buildings or businesses in these areas may find it a better investment to move out rather than protect in place. One adaptation opportunity here is to avoid intensifying development near the shoreline in open areas that are not in public ownership. Conservation easements, acquisitions, and zoning or overlay zones can support this strategy.

Place Types Map



Alameda Creek

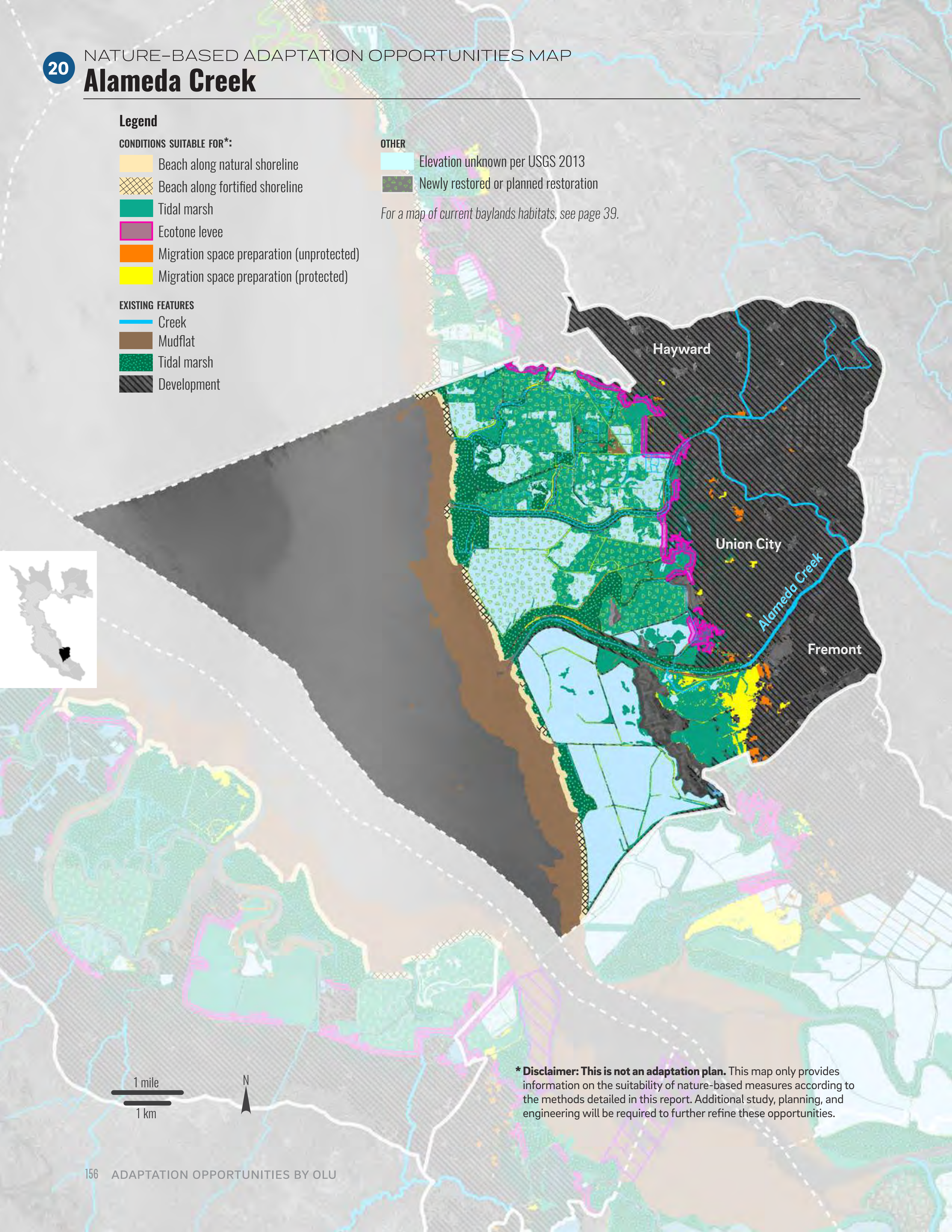
Legend

CONDITIONS SUITABLE FOR*:
- Beach along natural shoreline
- Beach along fortified shoreline
- Tidal marsh
- Ecotone levee
- Migration space preparation (unprotected)
- Migration space preparation (protected)

EXISTING FEATURES
- Creek
- Mudflat
- Tidal marsh
- Development

OTHER
- Elevation unknown per USGS 2013
- Newly restored or planned restoration

For a map of current baylands habitats, see page 39.



*** Disclaimer: This is not an adaptation plan.** This map only provides information on the suitability of nature-based measures according to the methods detailed in this report. Additional study, planning, and engineering will be required to further refine these opportunities.

Nature-based Adaptation Measures

The Alameda Creek OLU encompasses the baylands between the San Mateo and Dumbarton bridges that were historically influenced by Alameda Creek. Though much of the former salt ponds are already planned for restoration, there are additional opportunities for marsh restoration and enhancement. On the north side of Old Alameda Creek, the baylands abut development, and ecotone levees are suitable to provide high-tide refugia and limited migration for marshes with sea level rise. On the south side of Alameda Flood Control Channel, where the managed wetlands of the DUST marsh and J-Ponds are located, there is a rare opportunity for the marsh to migrate, on protected open space, with limited unprotected open space interspersed. Plans exist to reconnect Alameda Creek to its former floodplain by restoring tidal action to the adjacent salt ponds north of the creek (South Bay Salt Pond Restoration Project Phase 2). On the shoreline, coarse beaches currently exist in some places like Roberts Landing, and are suitable in other locations with eroding fringing marshes. Such beach faces can provide multiple benefits by reducing erosion, reducing overtopping, and providing habitat along any bayfront levee system or marsh scarp. Management of these beaches would have to take into account the significant longshore transport of material into the Bay and nearshore areas. Green stormwater infrastructure could continue to be implemented in the upper watershed to reduce fluvial flooding in the developed areas.

Selected Measures

	Selected Measures	Suitability
NATURE-BASED	Nearshore reefs	○
	Submerged aquatic vegetation	○
	Beaches	●
	Tidal marshes	●
	Polder management	●
	Ecotone levees	●
	Migration space preparation	●

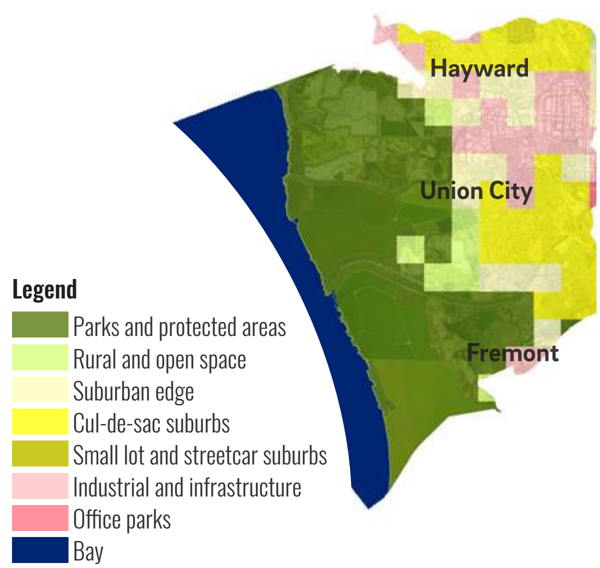
○ Limited suitability ◒ Some suitability ● High suitability

Aerial view of Alameda Creek and surrounding restoration projects, looking towards Union City (Photo by Doc Searls, CC BY 2.0)

Other Adaptation Opportunities

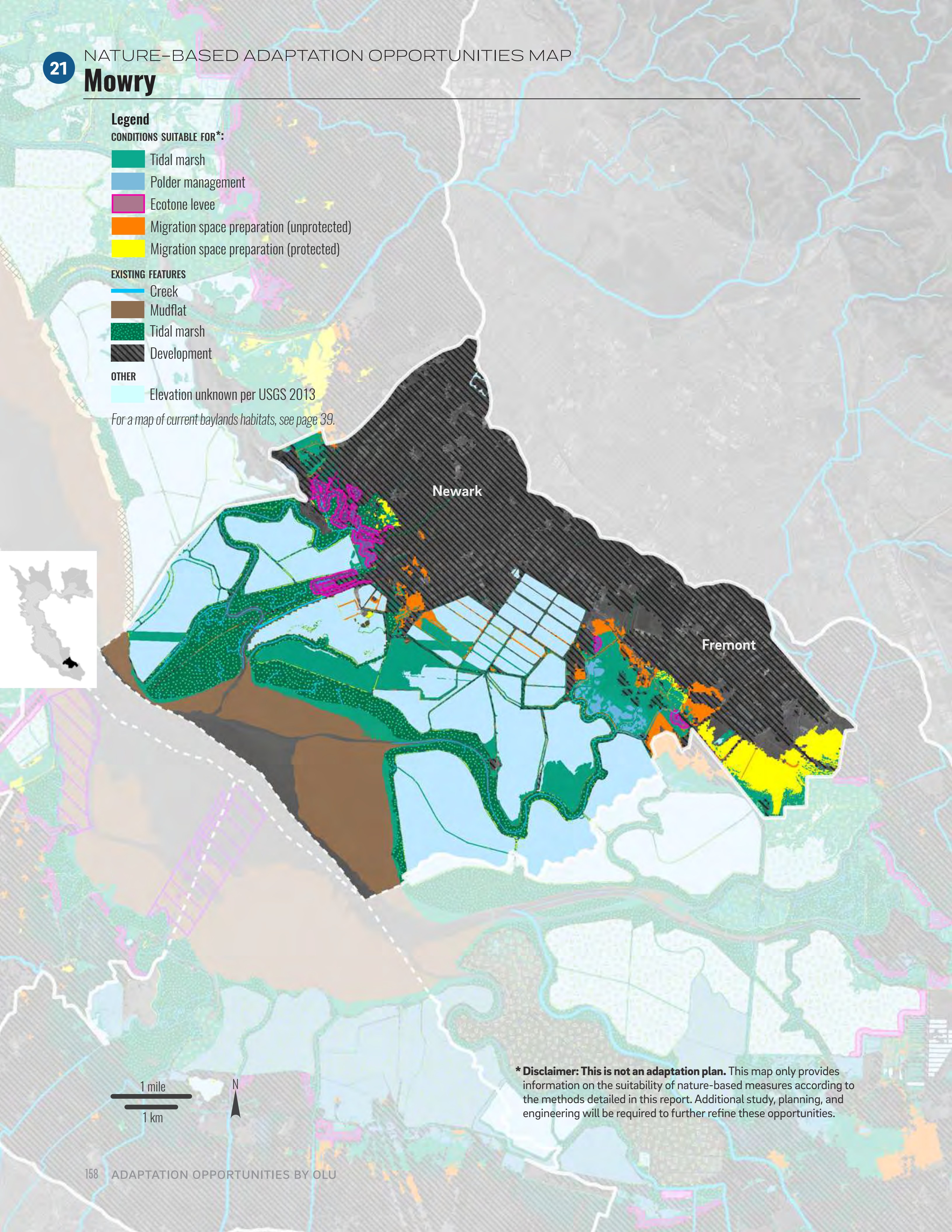
Alameda Creek OLU has the most protected land of any OLU (51%), all of which is bayward of the urban land uses in the OLU, which include suburban neighborhoods, industrial and infrastructure, and retail uses. The protected areas, including Eden Landing Ecological Reserve, are a key leverage point to protect developed areas from future flooding. Other adaptation opportunities include elevating roads and creating floodable spaces in the Alameda Creek corridor. For ponds south of the Alameda Creek Flood Control Channel, the areas noted as “Elevation unknown per USGS 2013” on the opportunities map (west of Coyote Hills) are all managed ponds. These ponds are owned by the U.S. Fish and Wildlife Service as part of the Don Edwards San Francisco Bay National Wildlife Refuge but are still used for commercial salt-making. Therefore, those ponds are likely to remain as managed ponds (polders) for many years into the future.

Place Types Map



21 NATURE-BASED ADAPTATION OPPORTUNITIES MAP

Mowry



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Nature-based Adaptation Measures

The Mowry OLU encompasses the baylands that were historically at the edges of the Alameda Creek alluvial fan. They have been isolated from the creek for over 200 years, and experience little freshwater influence from contributing watersheds. Historically comprised of alkali wetlands, these baylands are currently in salt production and are likely to remain as managed ponds for many years into the future. However, the baylands in this OLU provide a rare buffer between the Bay and developed communities, and should restoration opportunities become available they can be used to increase the climate resilience of both ecosystems and those developed communities. Where marsh opportunities abut development, ecotone levees are suitable to provide high-tide refugia and limited migration for marshes with sea level rise. However, towards the southeastern end of this OLU, unique opportunities exist to protect and prepare open space for marsh migration if a complete marsh is restored. Green stormwater infrastructure could continue to be implemented in the upper watershed to reduce fluvial flooding in the developed areas.

	Selected Measures	Suitability
NATURE-BASED	Nearshore reefs	○
	Submerged aquatic vegetation	○
	Beaches	○
	Tidal marshes	●
	Polder management	●
	Ecotone levees	●
	Migration space preparation	●

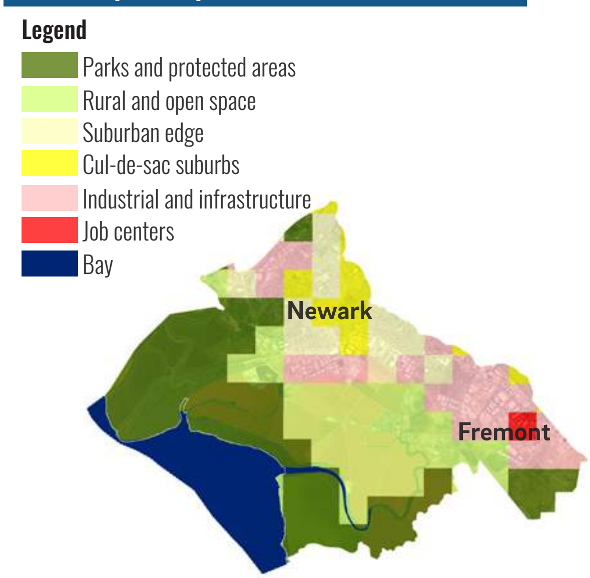
○ Limited suitability ◑ Some suitability ● High suitability

Aerial view of active salt ponds along Mowry Slough in the Mowry OLU (Photo by Craig Howell, CC BY-SA 2.0)

Other Adaptation Opportunities

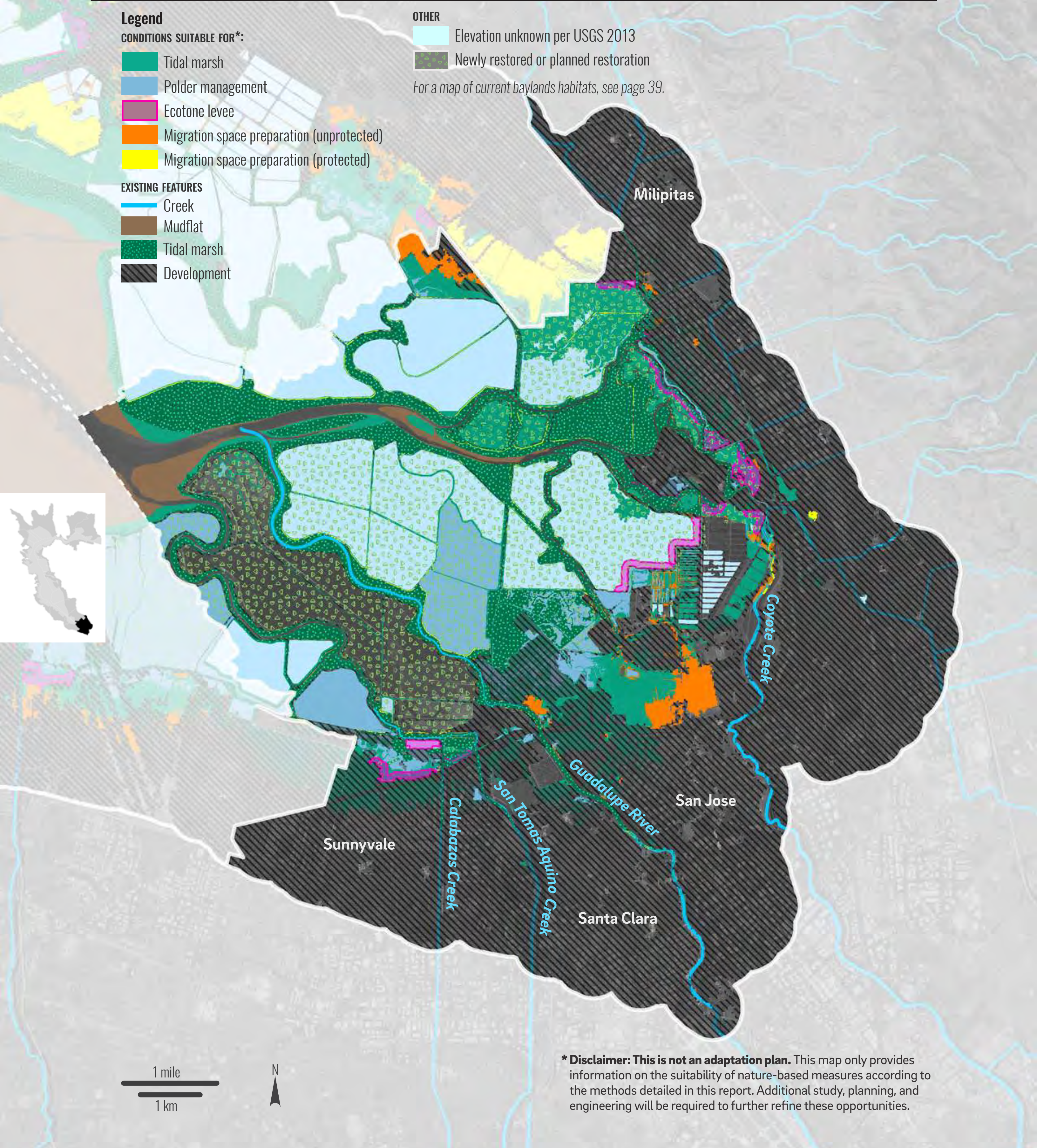
Like the neighboring OLUs of Alameda Creek and Santa Clara Valley, the Mowry OLU has a significant amount of open space, some of which is protected diked baylands and some of which is in commercial salt ponds. Near-term sea level rise will be limited to these more vulnerable baylands. Over the long term, place types within Mowry that are at risk include some industrial and infrastructure land uses, as well as low-density suburban neighborhoods. Adaptation opportunities for these areas include preventing intensification of development in future flood areas, elevating or raising roads (such as Highway I-880) to serve as levees providing upland protection, and creating green infrastructure and floodable spaces in the Coyote and Berryessa creek watersheds.

Place Types Map



22 NATURE-BASED ADAPTATION OPPORTUNITIES MAP

Santa Clara Valley



* **Disclaimer: This is not an adaptation plan.** This map only provides information on the suitability of nature-based measures according to the methods detailed in this report. Additional study, planning, and engineering will be required to further refine these opportunities.

Nature-based Adaptation Measures

Santa Clara Valley is a large OLU with significant opportunities to restore wetlands, improve watershed-baylands connections, and beneficially reuse treated wastewater. There are limited opportunities for upland transgression, but these could be increased by strategic placement of ecotone and/or horizontal seepage levees utilizing treated freshwater from the San Jose-Santa Clara Regional Wastewater Facility. The Santa Clara Valley OLU encompasses the watersheds of the two largest creeks flowing north to the Bay, Coyote Creek and the Guadalupe River. The connections between these and other tributaries to their floodplains in the baylands could be enhanced to provide more freshwater and sediment to these marshes and subsided baylands. Plans are being developed to reconnect Calabazas and San Tomas Aquino creeks into the deeply subsided Pond A8. Many of the baylands in this OLU are already planned for restoration or have been restored through the South Bay Salt Ponds Restoration Project (SBSPRP) phases 1 and 2. Ecotone levees are planned and can be suitable where areas of restored marsh abut areas of development or infrastructure. Some areas of unprotected open space at elevations suitable for marsh migration do exist and should be considered for restoration. Most of the polders in this OLU are either already managed or planned for restoration through SBSPRP or the South Bay Shoreline project. The availability of sediment needed to raise elevations in these polders will be dependent upon watershed reconnection and the supply of sediment within South Bay mudflats, which is an area of active research.

Selected Measures

	Selected Measures	Suitability
NATURE-BASED	Nearshore reefs	Limited
	Submerged aquatic vegetation	Limited
	Beaches	Limited
	Tidal marshes	High
	Polder management	High
	Ecotone levees	High
	Migration space preparation	High

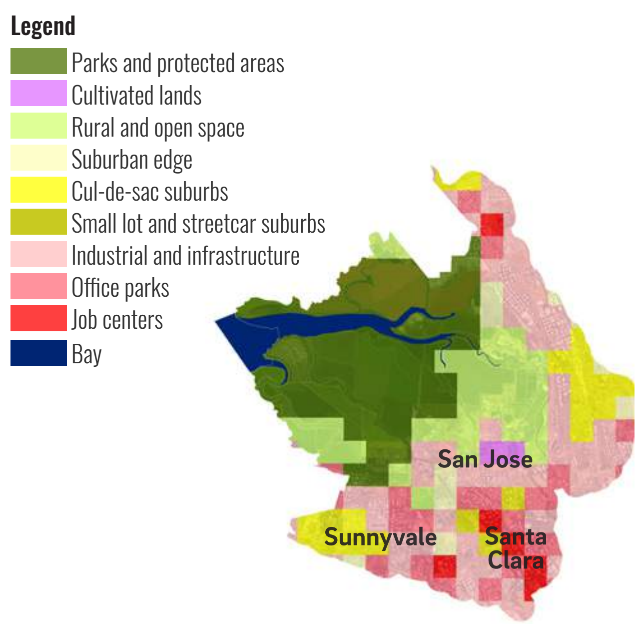
○ Limited suitability ◐ Some suitability ● High suitability

Aerial view of marsh and former salt ponds fronting development in the Santa Clara Valley OLU (Photo by Patrick Nouhailler, CC BY-SA 2.0)

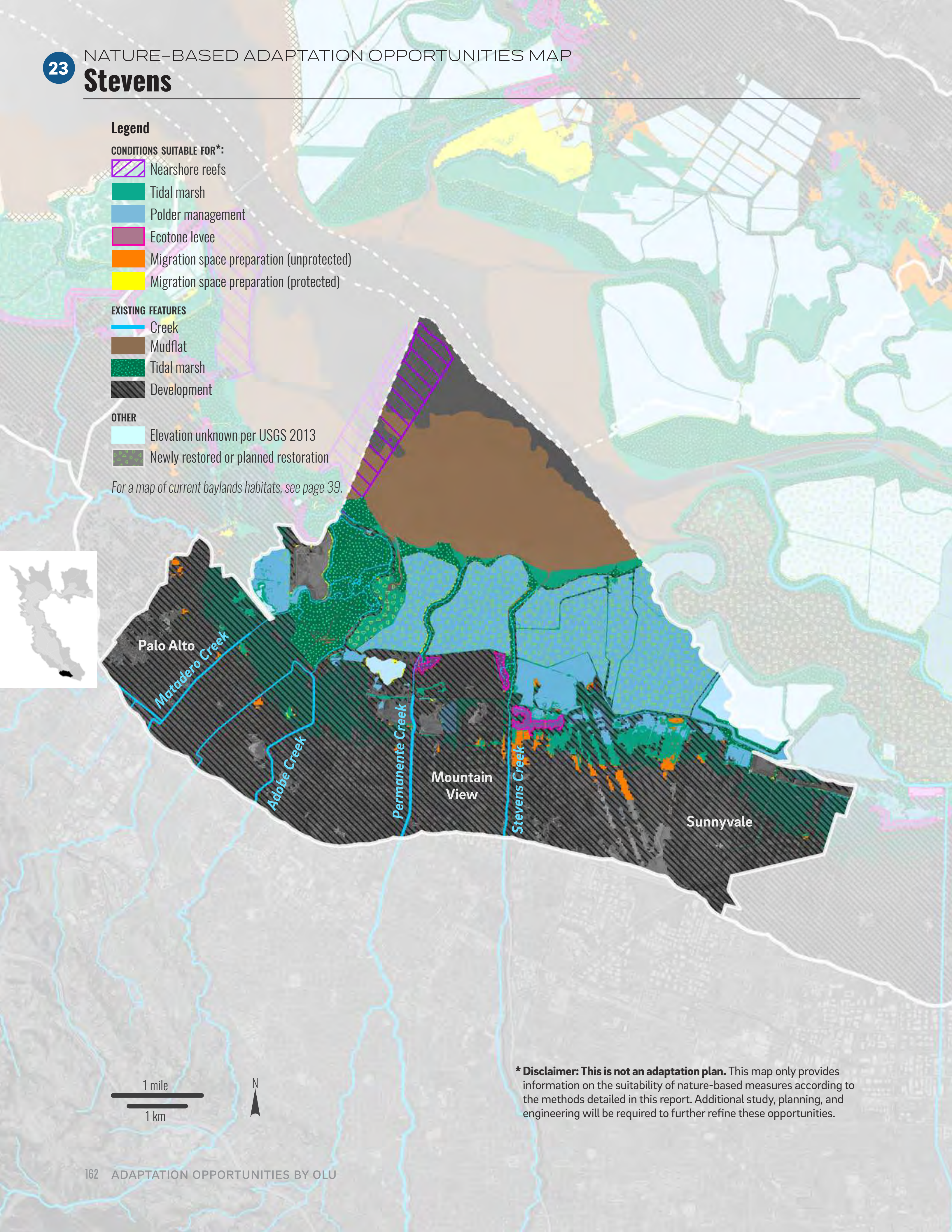
Other Adaptation Opportunities

Santa Clara Valley is a wide alluvial valley that is home to a very large number of jobs and residents. Like San Leandro, it is complex, dense, and contains a broad mix of land uses—but like the Mowry and Alameda Creek OLUs it has a large area of open space and protected area between the Bay and most development. Ninety seven percent of the area at risk of near-term sea level rise is in this undeveloped zone. One adaptation opportunity is for public agencies to identify and purchase conservation easements in those areas of open space that are not protected and might otherwise induce development into the future flood zone. Other adaptation opportunities, besides leveraging open space and parks to provide flood resiliency, include raising roads (such as Highway 237) onto levees, constructing inland flood walls and berms in areas at risk (such as Alviso), and adding green infrastructure and floodable spaces upland and in the floodplains of the Guadalupe River.

Place Types Map



Stevens



* **Disclaimer: This is not an adaptation plan.** This map only provides information on the suitability of nature-based measures according to the methods detailed in this report. Additional study, planning, and engineering will be required to further refine these opportunities.

Nature-based Adaptation Measures

Like other South Bay OLUs, Stevens has space between the open Bay and developed areas. These areas are characterized by wide mudflats, marsh, subsided polders, and landfills which are largely protected. Stevens is different from Mowry and Santa Clara Valley OLUs, however, in that there is more developed area at risk of near-term flooding. Ecotone levees are planned for the backs of marshes and salt ponds restored to tidal action and brought up to marsh elevation. Some areas of currently undeveloped migration space exist, but most of these are planned for development. Creeks draining to the Bay, such as Matadero, Adobe, Permanente, and Stevens, have been significantly modified by culverting and channelizing. The connections between these creeks and their floodplains could be enhanced to provide more freshwater and sediment to the baylands. Green stormwater infrastructure could continue to be implemented in the upper watershed to reduce fluvial flooding in the developed areas.

	Selected Measures	Suitability
NATURE-BASED	Nearshore reefs	Some suitability
	Submerged aquatic vegetation	Limited suitability
	Beaches	Limited suitability
	Tidal marshes	High suitability
	Polder management	High suitability
	Ecotone levees	Some suitability
	Migration space preparation	Some suitability

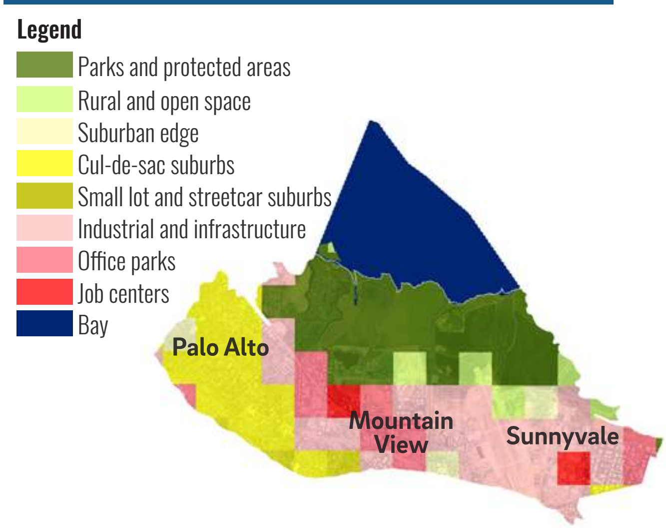
Legend: Limited suitability · Some suitability · High suitability

Aerial view of office parks and golf courses fronted by managed ponds in the Stevens OLU (Photo by Craig Howell, CC BY 2.0)

Other Adaptation Opportunities

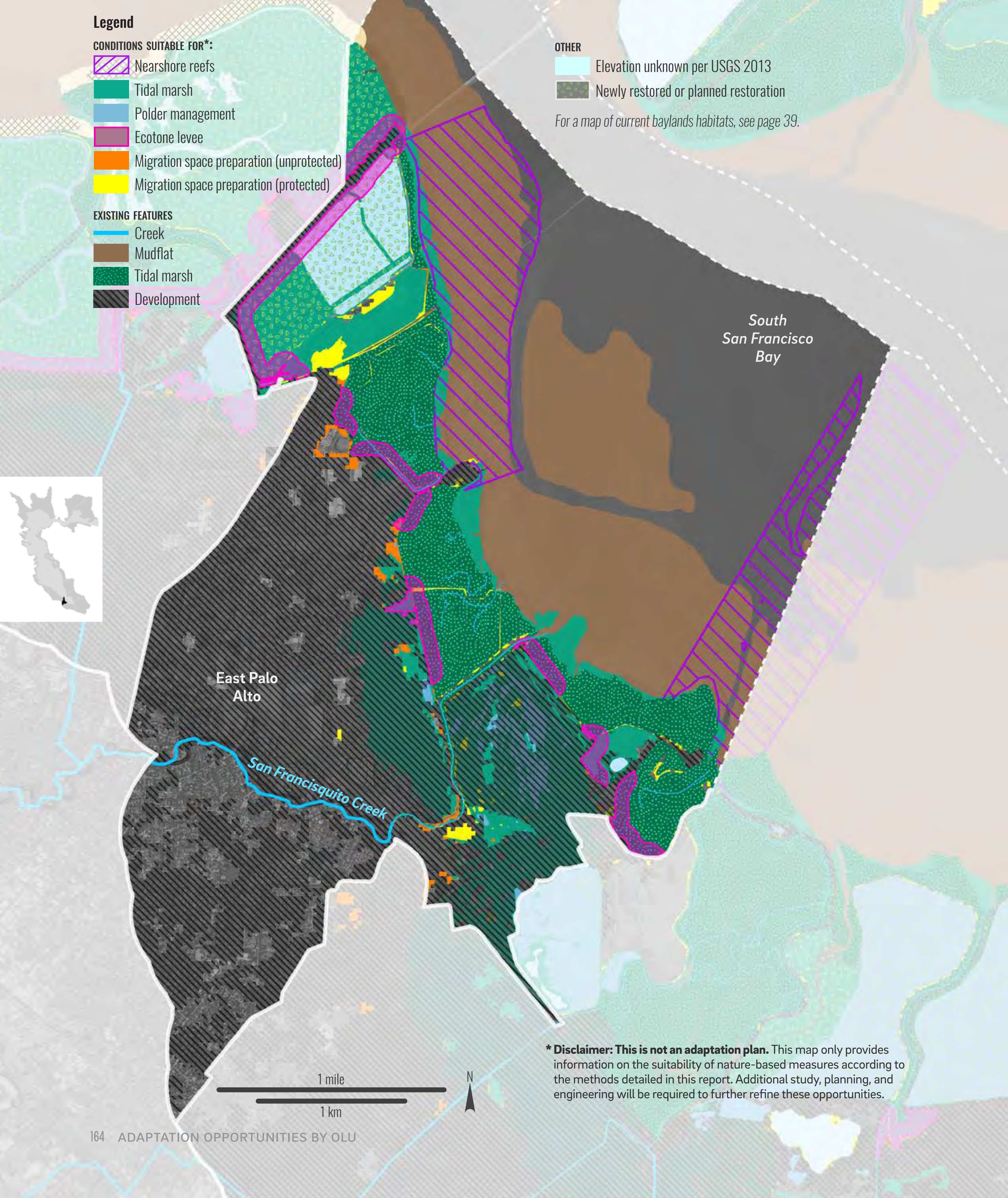
Stevens has a high percentage of land devoted to low-density office parks, industrial and infrastructure uses, and suburban job centers. Adaptation opportunities here include retrofitting the built environment through building codes that require flood-proofing, including flood-proofing from groundwater. Floodable spaces and green infrastructure, especially in inland areas, are good options for parks and public places to reduce risks posed by watershed or fluvial flooding. Some grey or hybrid infrastructure options, such as elevating transportation infrastructure onto protective levees, may be used further inland to "hold the line." Pumping may continue to be needed in areas with high groundwater tables and sunny-day flooding risks.

Place Types Map



24 NATURE-BASED ADAPTATION OPPORTUNITIES MAP

San Francisquito



* **Disclaimer: This is not an adaptation plan.** This map only provides information on the suitability of nature-based measures according to the methods detailed in this report. Additional study, planning, and engineering will be required to further refine these opportunities.

Nature-based Adaptation Measures

The San Francisquito OLU has large areas of critical existing marsh buffering communities and the Bay. These marshes should be enhanced by strategic placement of sediment to ensure that they can maintain elevations over time. One key to maintaining the marshes in the long term will be enhancing the delivery of watershed-derived sediment to the baylands. Where the baylands abut development, ecotone levees are suitable to provide flood protection to low-lying communities and also provide high-tide refugia and limited migration space for marshes with sea level rise. Ecotone levees are currently slated for implementation as part of the SAFER Bay project and the South Bay Salt Ponds Restoration Project Phase 2. Projects to reconnect San Francisquito Creek to its marshes have been implemented. Green stormwater infrastructure could continue to be implemented in the upper watershed to reduce fluvial flooding in the developed areas.

Selected Measures

	Selected Measures	Suitability
NATURE-BASED	Nearshore reefs	High suitability
	Submerged aquatic vegetation	Limited suitability
	Beaches	Limited suitability
	Tidal marshes	High suitability
	Polder management	Some suitability
	Ecotone levees	High suitability
	Migration space preparation	Some suitability

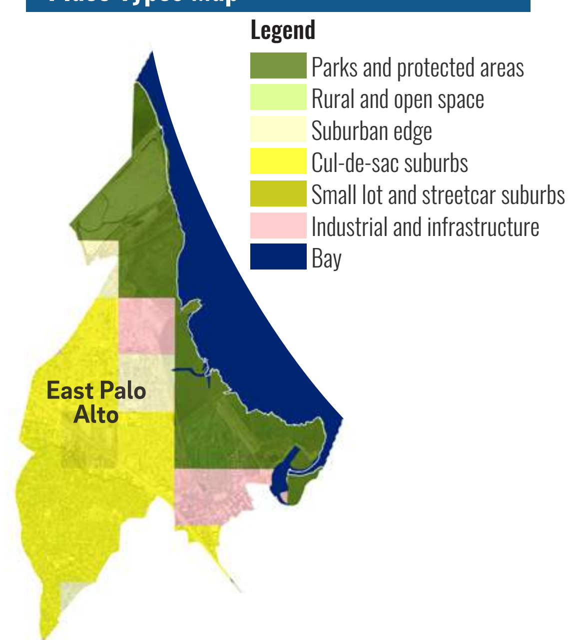
Limited suitability · Some suitability · High suitability

Aerial view of residential and industrial lands in East Palo Alto, fronted by tidal marsh (Photo by Craig Howell, CC BY 2.0)

Other Adaptation Opportunities

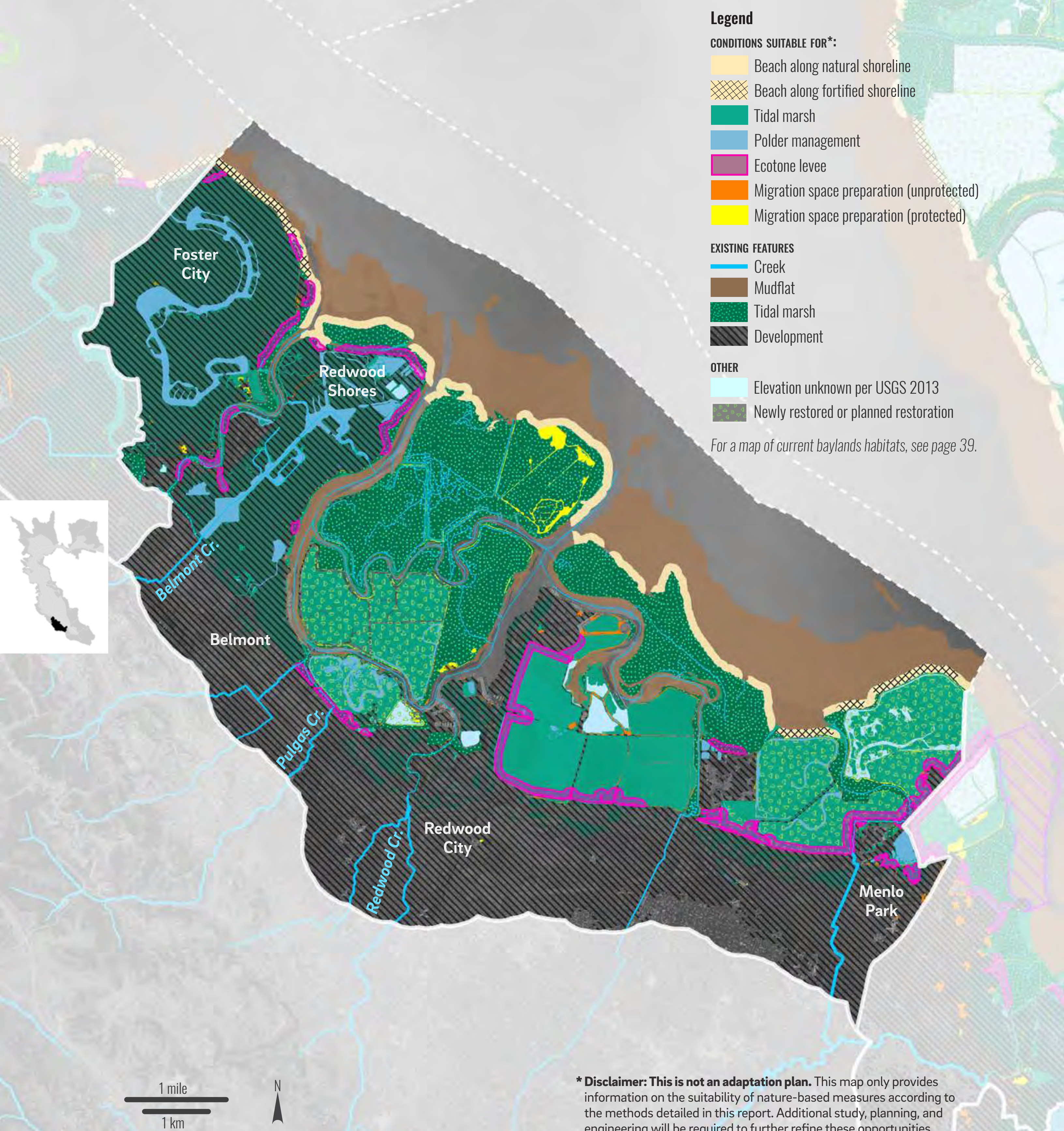
San Francisquito is a small OLU that is unique in being over 50% comprised of low-density residential suburbs, with a small amount of commercial and industrial uses potentially at risk of near-term sea level rise. Like other South Bay OLUs, San Francisquito has a lot of protected open space to work with between the Bay and these neighborhoods, representing an opportunity for leveraging nature-based solutions and providing flood control and protection benefits for adjacent neighborhoods. In this area, options could include elevating streets, constructing inland flood walls and berms, implementing overlay zoning, and requiring building retrofits to adapt to future sea level rise. Green infrastructure and floodable spaces in the San Francisquito Creek watershed are key opportunities to minimize combined flooding and manage the impacts of rising groundwater. Some businesses or industrial areas with repeat-flood issues in the future may be supported in moving to higher ground through a TDR program or tax incentives; residential neighborhoods could establish a GHAD to finance needed protections.

Place Types Map



NATURE-BASED ADAPTATION OPPORTUNITIES MAP

25 Belmont-Redwood



***Disclaimer: This is not an adaptation plan.** This map only provides information on the suitability of nature-based measures according to the methods detailed in this report. Additional study, planning, and engineering will be required to further refine these opportunities.

Nature-based Adaptation Measures

The Belmont-Redwood OLU is characterized by wide baylands and significant urban development on top of historical baylands. Large areas of tidal marshes, such as Inner and Outer Bair Island, have been restored, and more areas such as the Ravenswood Ponds are in planning stages. While there are no existing opportunities for natural marsh migration in this OLU, hybrid solutions such as ecotone levees may be suitable for helping manage flood risk for low-lying communities. These may also provide high-tide refuge for marsh wildlife in certain locations where marshes of sufficient width are next to developed areas. Mudflats in this OLU are critical for buffering waves, reducing marsh scarp erosion, and supplying coarse materials to the existing beaches. Shell hash beaches and other coarse grained beach faces, which already exist along much of this OLU shoreline, should also be considered as part of the suite of hybrid options suitable in this OLU; beaches may be necessary as the height of traditional flood infrastructure is limited due to geotechnical constraints. Management of these beaches would have to take into account the significant longshore transport of shell and coarse material into the Bay in the nearshore areas. Polders, and in particular retention basins, will need to be managed carefully as groundwater and sea levels rise. Green stormwater infrastructure could continue to be implemented in the upper watershed to reduce fluvial flooding in the developed areas.

Selected Measures

	Selected Measures	Suitability
NATURE-BASED	Nearshore reefs	○
	Submerged aquatic vegetation	○
	Beaches	●
	Tidal marshes	●
	Polder management	●
	Ecotone levees	●
	Migration space preparation	○

○ Limited suitability ◐ Some suitability ● High suitability

Aerial view of marsh and salt ponds fronting development in the Belmont-Redwood OLU (Photo by Doc Searls, CC BY 2.0)

Other Adaptation Opportunities

This OLU has a very long and complex shoreline, fronting a diverse and dense mix of residential and commercial uses, much of which is at risk of near-term sea level rise without further modifications to the shoreline and the land behind it. Parts of Foster City and Redwood Shores are especially at risk, along with other suburban “cul-de-sac” neighborhoods, industrial and infrastructure land, and medium-density job centers. The Belmont-Redwood OLU has some significant areas of open space and protected areas (e.g., Bair Island, Bedwell Bayfront Park) which can be leveraged to provide flood protection. In developed areas, adaptation opportunities include creating a sea level rise overlay zone that would apply flood resilience policies—including building retrofit requirements—to new development and redevelopment, and potentially prohibiting densification or siting of critical new infrastructure in unprotectable low-lying areas. Constructing inland flood walls and berms, raising roads onto protective levees, and creating floodable spaces with green infrastructure are also opportunities for certain areas within this OLU. Neighborhoods could pool resources via a GHAD to pay for protective infrastructure. In 2018, Foster City voters overwhelming approved a bond supported by property tax increases to pay for raising the city’s shoreline levees. Facing worsening sea level rise and shoreline flooding risks, the community’s flood insurance rates were set to spike if the levees were not improved.

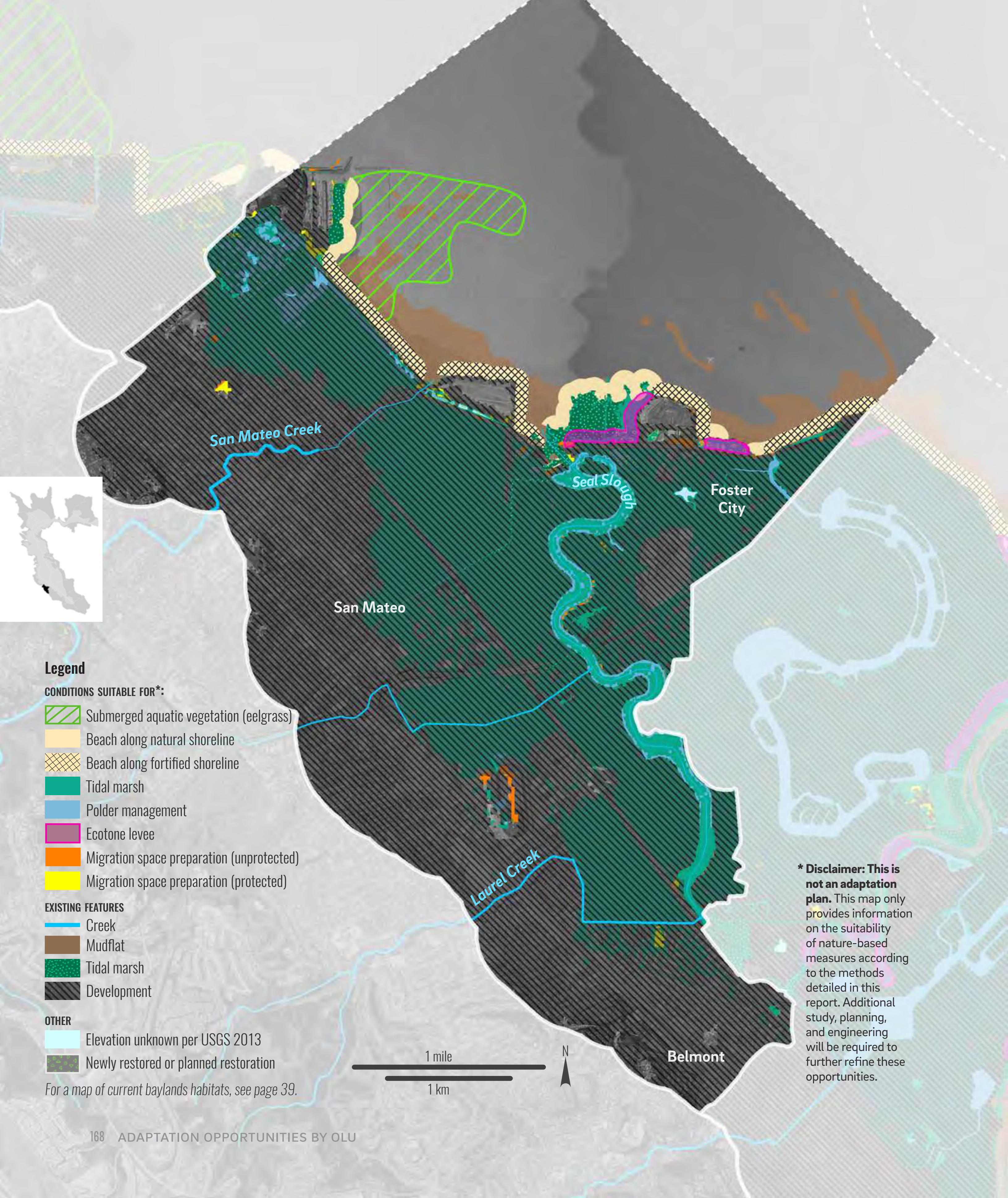
Place Types Map

Legend

- Parks and protected areas
- Rural and open space
- Suburban edge
- Cul-de-sac suburbs
- Small lot and streetcar suburbs
- Industrial and infrastructure
- Office parks
- Job centers
- Bay

NATURE-BASED ADAPTATION OPPORTUNITIES MAP

San Mateo



For a map of current baylands habitats, see page 39.

* **Disclaimer: This is not an adaptation plan.** This map only provides information on the suitability of nature-based measures according to the methods detailed in this report. Additional study, planning, and engineering will be required to further refine these opportunities.

Nature-based Adaptation Measures

The San Mateo OLU is very urbanized, with development taking over most of the baylands and extended into the Bay by filling. There are few opportunities to restore marshes without significant realignments of levees, besides at the mouth of Seal Slough and within Burlingame Lagoon. No areas exist for natural marsh migration in this OLU, as all of the rising upland adjacent to marshes has been developed. Limited space for ecotone levees exist. However coarse beaches present an opportunity to soften the shoreline, limit marsh edge erosion, and dampen wave energy as well as provide recreation benefits, and could be developed as part of a hybrid green-grey strategy. Management of these beaches would have to take into account the significant longshore transport of coarse material. There are some opportunities for eelgrass beds which could be an addition to a hybrid living shorelines strategy. Opportunities to reconnect disconnected creeks to the shoreline are limited as there is not much room to restore their floodplains. Green stormwater infrastructure could continue to be implemented in the upper watershed to reduce fluvial flooding in the developed areas.

	Selected Measures	Suitability
NATURE-BASED	Nearshore reefs	○
	Submerged aquatic vegetation	●
	Beaches	●
	Tidal marshes	◑
	Polder management	◑
	Ecotone levees	◑
	Migration space preparation	○

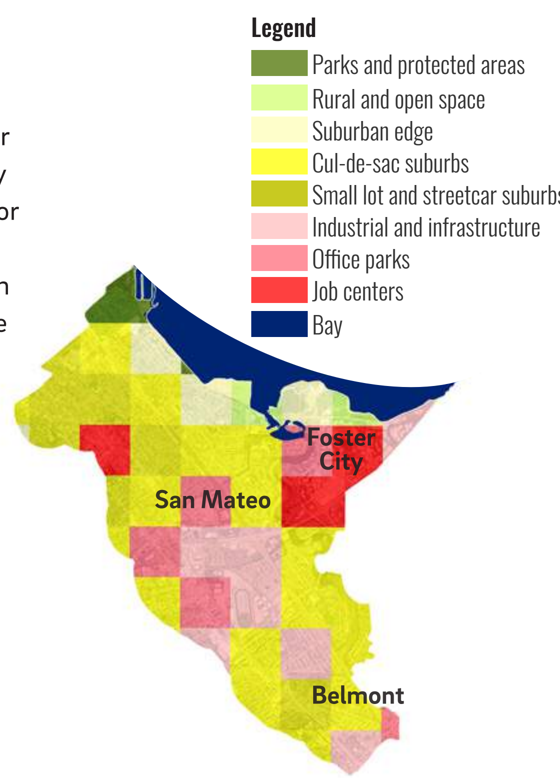
○ Limited suitability ◑ Some suitability ● High suitability

(right) View looking across San Mateo towards Coyote Point Recreation Area (Photo by Craig Howell, CC BY 2.0)

Other Adaptation Opportunities

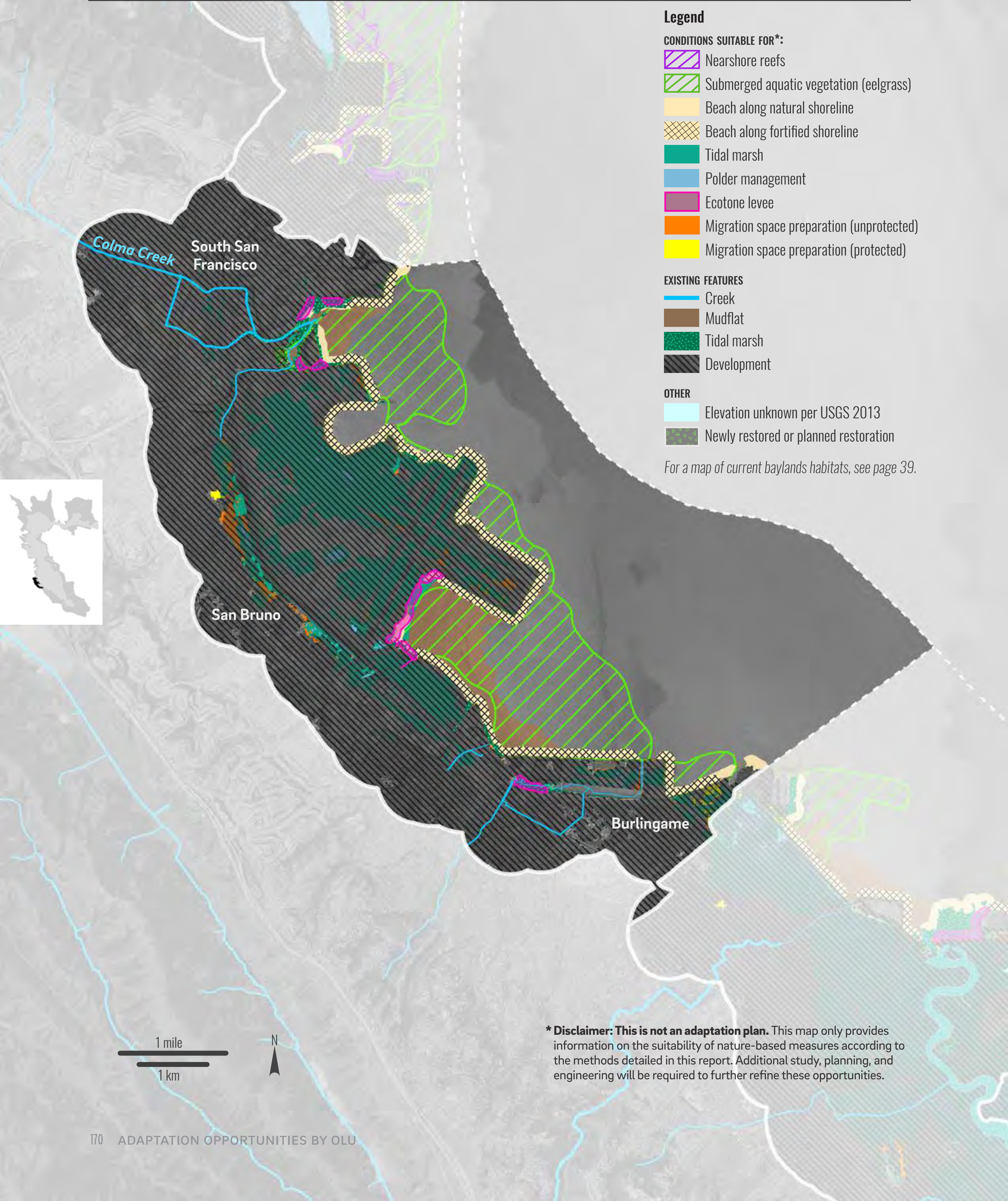
San Mateo, like its neighbor San Bruno, has one of the lowest percentages of open space and protected area place types of any OLU. Developed right up to the shoreline, San Mateo is home to dense job centers, moderate-density "cul-de-sac" suburbs, and older mixed-use and "streetcar" suburbs that are all nearly as imperiled by near-term as by long-term sea level rise. Adaptation opportunities for San Mateo include perimeter protection through raising roads onto levees, inland protection such as flood walls and berms, and creation of floodable areas to retain stormwater, especially near the shoreline and in the floodplains of creeks and sloughs. Some commercial buildings or businesses in this OLU may find it a better investment to move out rather than protect in place; a TDR program or tax incentives could help with moving businesses to higher and safer ground. Neighborhoods may choose to support financing of flood protection or property buyouts in repeat-flood areas through the establishment of one or more GHADs. A sea level rise overlay zone in this OLU could help specify adaptation policies, redevelopment rules, and building codes that would apply by neighborhood or city, depending on local resilience goals.

Place Types Map



27 NATURE-BASED ADAPTATION OPPORTUNITIES MAP

Colma-San Bruno



* **Disclaimer: This is not an adaptation plan.** This map only provides information on the suitability of nature-based measures according to the methods detailed in this report. Additional study, planning, and engineering will be required to further refine these opportunities.

Nature-based Adaptation Measures

The Colma-San Bruno OLU is dominated by the San Francisco International Airport, and by a shoreline that covers the historical marshes and extends into the shallow Bay. At the mouth of Colma Creek, there are opportunities for marsh restoration and ecotone levees if it is possible to transfer less appropriate land uses that are close to the Bay and more vulnerable. Coarse beaches provide possibly the most extensive opportunity to soften rip-rapped shorelines and help reduce wave runup and erosion on levees and seawalls. Eelgrass beds and mudflat augmentation may help attenuate waves and provide important subtidal habitat. Green stormwater infrastructure could continue to be implemented in the upper watershed to reduce fluvial flooding in the developed areas.

Selected Measures

	Selected Measures	Suitability
NATURE-BASED	Nearshore reefs	Limited suitability
	Submerged aquatic vegetation	High suitability
	Beaches	High suitability
	Tidal marshes	Some suitability
	Polder management	Limited suitability
	Ecotone levees	Some suitability
	Migration space preparation	Limited suitability

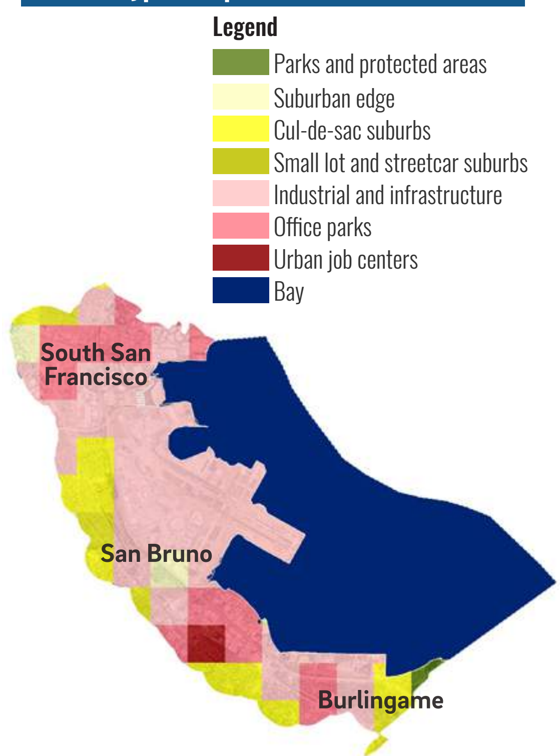
○ Limited suitability ◐ Some suitability ● High suitability

View of South San Francisco looking south towards San Francisco International Airport in the Colma-San Bruno OLU (Photo by Craig Howell, CC BY 2.0)

Other Adaptation Opportunities

Colma-San Bruno is a unique OLU that stands out in several ways: it has the least percentage of open space (0%) and parks/protected areas (1%), the highest percentage of industrial and infrastructure land uses (55%) due to the influence of San Francisco International Airport and its surrounding uses, and the highest percentage of office parks (21%). It has very little residential area at risk of near-term sea level rise—such place types all adjoin the upland boundary of the OLU. Adaptation opportunities for Colma-San Bruno suggest two pathways: 1) Densify, flood-proof, and protect existing development by fixing drainage, raising levees/seawalls (and placing roads atop them) for perimeter protection, adding green infrastructure and floodable spaces in creek floodplains upland to reduce combined flooding problems, and elevating new redevelopment areas (or runways); or 2) Relocating commercial activities to higher ground through a TDR program, tax incentives to relocate, and a new sea level rise overlay zone. The decision about which pathway to take should be made through a planning process that takes into account the nature of hazards, future protectability, historic significance, the complexity of retreat (e.g., high parcelization, many owners), social and economic values, and the feasibility of relocating jobs and employers to higher ground.

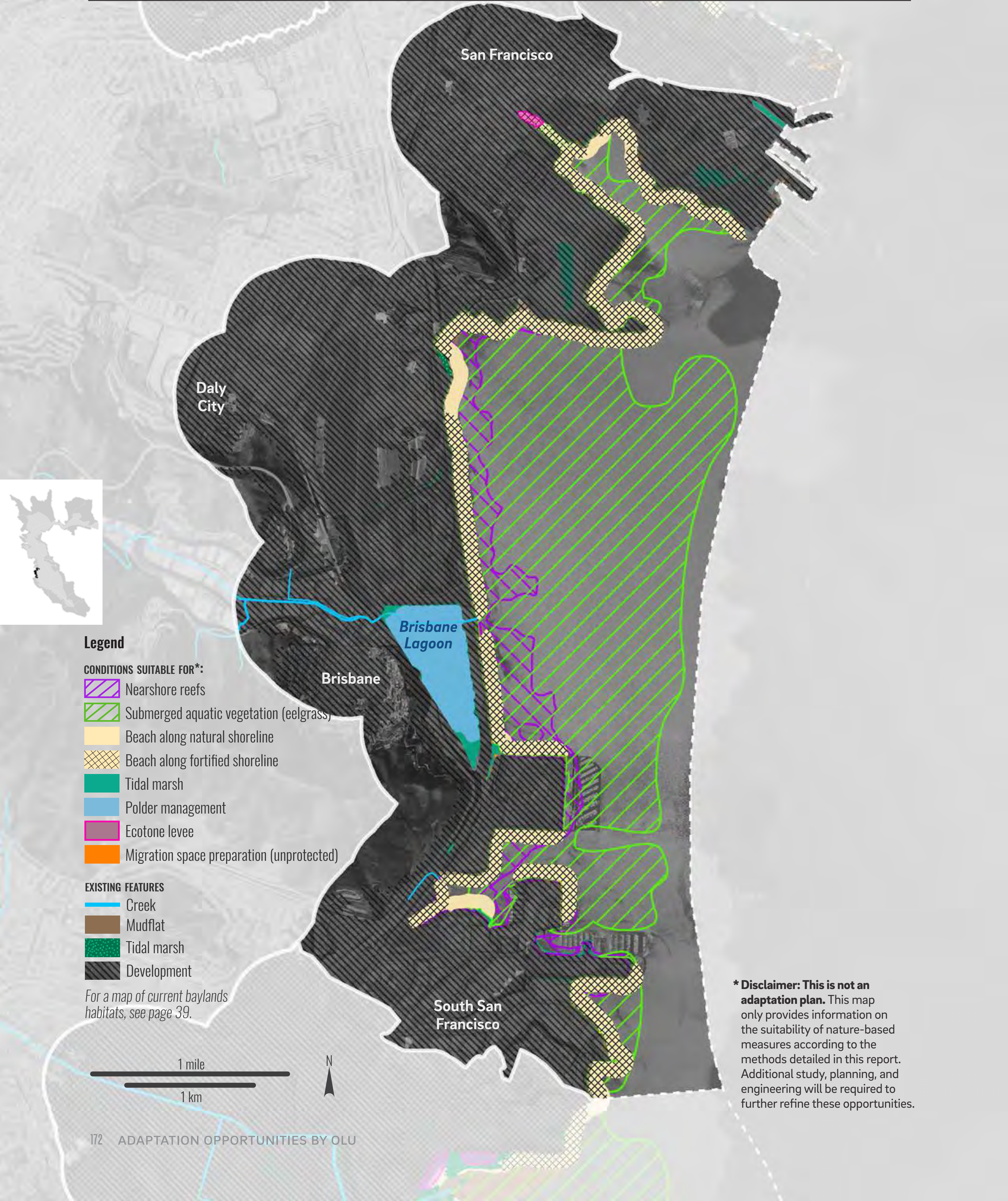
Place Types Map



28

NATURE-BASED ADAPTATION OPPORTUNITIES MAP

Yosemite-Visitacion



For a map of current baylands habitats, see page 39.

* **Disclaimer: This is not an adaptation plan.** This map only provides information on the suitability of nature-based measures according to the methods detailed in this report. Additional study, planning, and engineering will be required to further refine these opportunities.

Nature-based Adaptation Measures

The Yosemite-Visitacion OLU is characterized by a hardened shoreline extended into the Bay by filling. As such there are few opportunities for marsh restoration, and most adaptation opportunities relate to the low-tide terrace (where it exists), and to shallow subtidal areas. Both eelgrass beds and nearshore reefs may be suitable in this OLU. A coarse composite beach along Highway 101 could be an alternative to riprap to provide a more natural shoreline, and would necessitate hybrid features such as groins or artificial headlands. Brisbane Lagoon itself is characterized as a polder, and tidal action could be restored by improving the culverts under Highway 101, creating opportunities for mudflats, marshes, and ecotone levees within the lagoon. Green stormwater infrastructure could continue to be implemented in the upper watershed to reduce fluvial flooding in the developed areas.

Selected Measures

	Selected Measures	Suitability
NATURE-BASED	Nearshore reefs	●
	Submerged aquatic vegetation	●
	Beaches	●
	Tidal marshes	○
	Polder management	◐
	Ecotone levees	○
	Migration space preparation	○

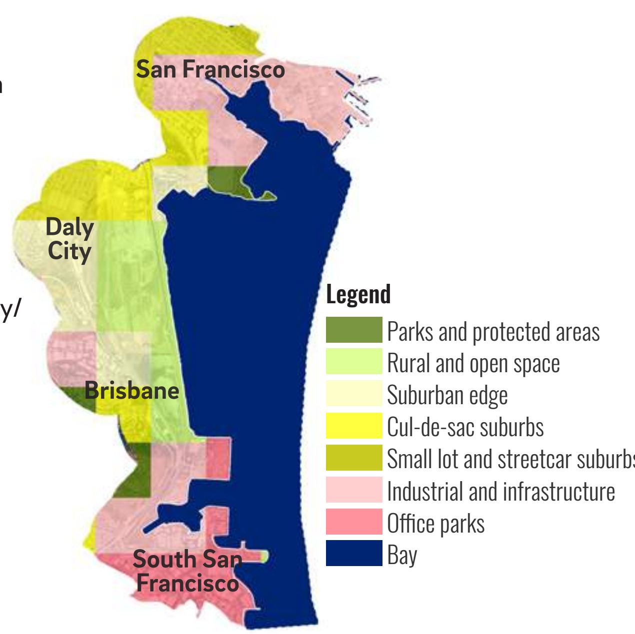
○ Limited suitability ◐ Some suitability ● High suitability

Office parks and industrial buildings located along South San Francisco and Brisbane's shoreline, looking northwest towards Brisbane Lagoon (Photo by Doc Searls, CC BY 2.0)

Other Adaptation Opportunities

This OLU has a diverse mix of place types including office parks, industrial and infrastructure, undeveloped open space, and low- to moderate-density residential neighborhoods. Most of the near-term sea level rise risk is confined to small areas on the north (Hunters Point) and south (Oyster Point) sides of the OLU, which are home to office parks and commercial redevelopment areas. Adaptation opportunities for Yosemite-Visitacion include densifying and flood-proofing developed or planned-development sites through building retrofits, perimeter protection with grey infrastructure or hybrid grey/green measures, and land and road elevation.

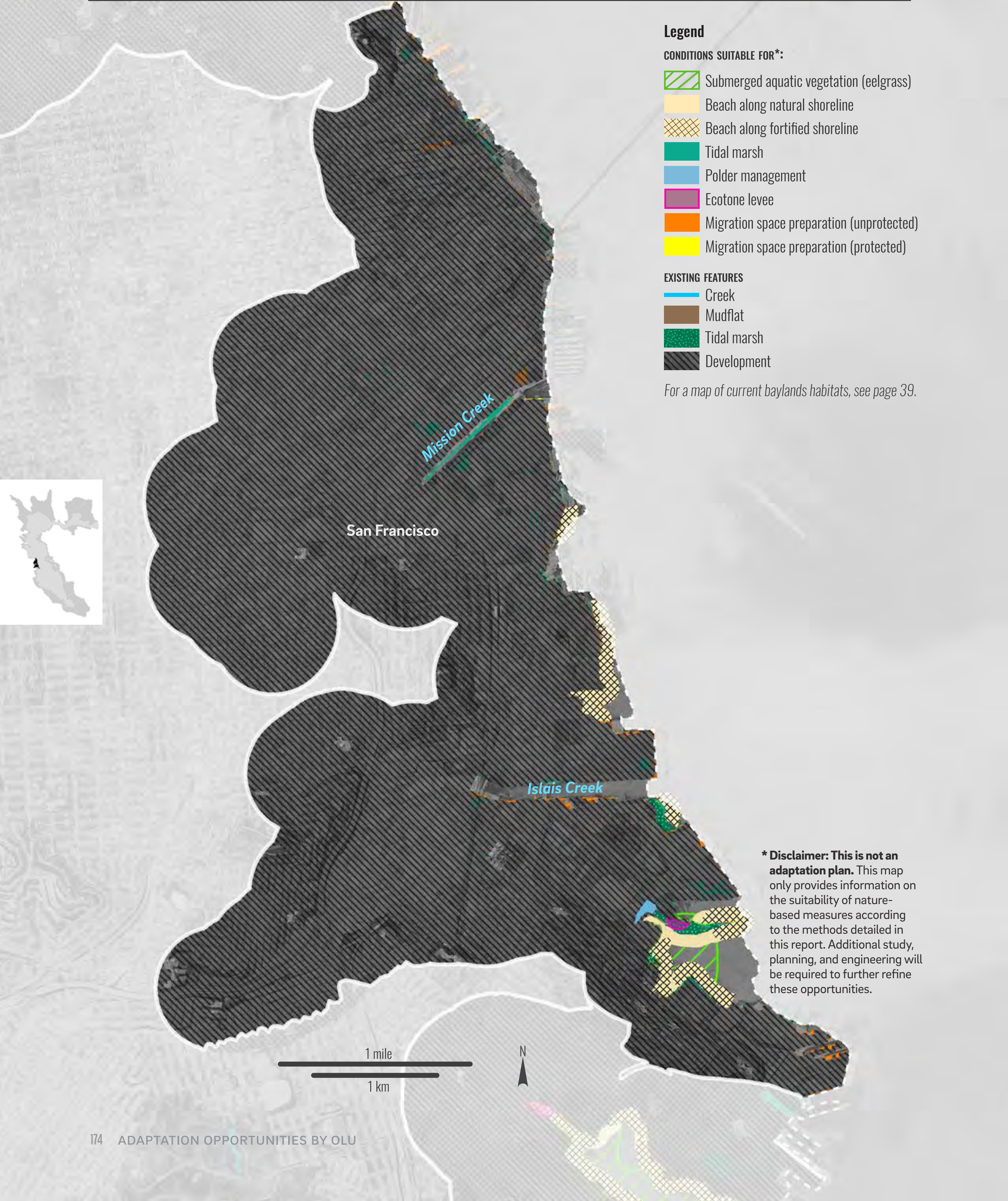
Place Types Map



29

NATURE-BASED ADAPTATION OPPORTUNITIES MAP

Mission-Islais



Legend

CONDITIONS SUITABLE FOR*:

- Submerged aquatic vegetation (eelgrass)
- Beach along natural shoreline
- Beach along fortified shoreline
- Tidal marsh
- Polder management
- Ecotone levee
- Migration space preparation (unprotected)
- Migration space preparation (protected)

EXISTING FEATURES

- Creek
- Mudflat
- Tidal marsh
- Development

For a map of current baylands habitats, see page 39.

* **Disclaimer: This is not an adaptation plan.** This map only provides information on the suitability of nature-based measures according to the methods detailed in this report. Additional study, planning, and engineering will be required to further refine these opportunities.

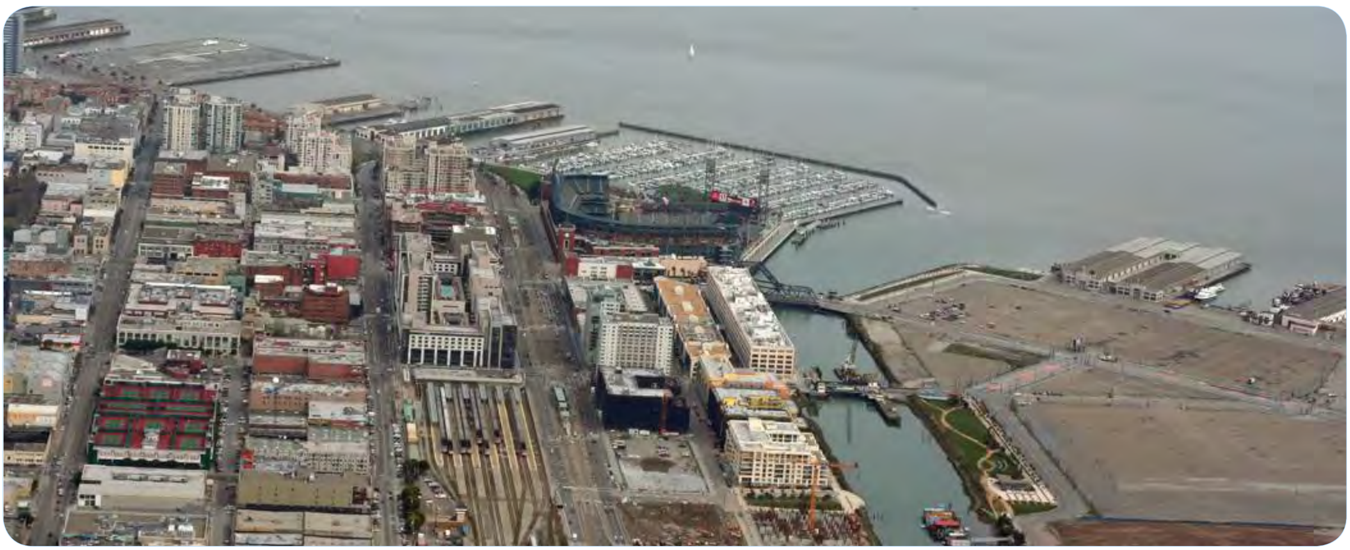
Nature-based Adaptation Measures

The Mission-Islais OLU is a shoreline that mostly covers the historical extent of marshes, and in places extends into the shallow Bay. As a result, the water is too deep along much of the shoreline of this OLU for the creation of marshes or beaches. In some areas in the south of the OLU, such as India Basin and Pier 94, beaches and eelgrass beds could be created to protect remaining marshes such as Heron's Head Marsh. Efforts to encourage plant species with more vertical structure, such as *Suaeda californica*, could be appropriate in this constrained environment.

Selected Measures / Suitability

	Selected Measures	Suitability
NATURE-BASED	Nearshore reefs	○
	Submerged aquatic vegetation	●
	Beaches	●
	Tidal marshes	○
	Polder management	○
	Ecotone levees	○
	Migration space preparation	○

○ Limited suitability ◐ Some suitability ● High suitability

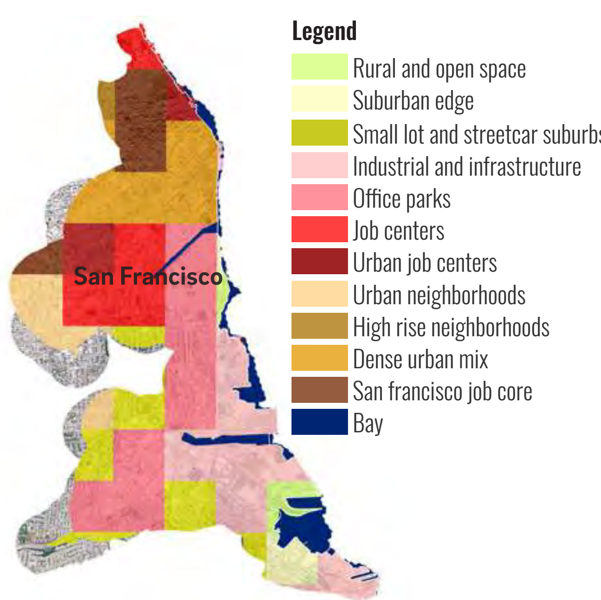


2006 aerial photo of industrial lands and infrastructure located along the urbanized edge of Mission Creek and San Francisco's southern shoreline (Photo by Niall Kennedy, CC 2.0)

Other Adaptation Opportunities

Mission-Islais is the most intensely developed of all OLUs. It is home to high-density mixed-use place types not found in any other OLU, including downtown San Francisco, SOMA, and Mission Bay. It also has the lowest amount of parks or protected areas (0%) among all OLUs. Mission-Islais is an economic center with extensive infrastructure investments. Adaptation opportunities include constructing seawalls, constructing inland berms and flood walls in some locations, and retrofitting the built environment to require flood-proofing (including flood-proofing from groundwater). Floodable spaces and green infrastructure can help to reduce the risk of fluvial and combined flooding, especially in the upland areas of urban watersheds.

Place Types Map



Golden Gate

For a map of current baylands habitats, see page 39.

*** Disclaimer: This is not an adaptation plan.** This map only provides information on the suitability of nature-based measures according to the methods detailed in this report. Additional study, planning, and engineering will be required to further refine these opportunities.

Nature-based Adaptation Measures

The Golden Gate OLU has seen significant beach and marsh restoration in a lagoonal setting at Crissy Field, which could be extended along the Bay shore, as originally planned. However, the deep water offshore, and the dense development landward leave limited opportunity for other nature-based adaptation measures. Beaches could be located in other areas along the hardened shoreline, and could be a habitat-friendly alternative to riprap while also providing wave attenuation. Management of these beaches would have to take into account the significant longshore transport of sand into the Bay in the nearshore areas. Rocky intertidal adaptation measures could be explored at Fort Point. Green stormwater infrastructure could continue to be implemented in the upper watershed to reduce fluvial flooding and enhance the connection between Tennessee Hollow and Crissy Field.

Selected Measures / Suitability

	Selected Measures	Suitability
NATURE-BASED	Nearshore reefs	Limited suitability
	Submerged aquatic vegetation	Limited suitability
	Beaches	High suitability
	Tidal marshes	Limited suitability
	Polder management	Limited suitability
	Ecotone levees	Limited suitability
	Migration space preparation	Limited suitability

Limited suitability · Some suitability · High suitability

(Left) Existing beach at Crissy Field, located inside the Golden Gate OLU along San Francisco's shoreline (Photo by Shira Bezalel, SFEI)
(Right) Aerial view of the deep water piers and dense buildings that comprise the Embarcadero, San Francisco (Photo by Craig Howell, CC BY 2.0)

Other Adaptation Opportunities

Golden Gate is the second-smallest of all OLUs. Almost all of its near-term flood risk is confined to parks and protected areas—specifically the Crissy Field and Crissy Marsh area of the Golden Gate National Recreation Area. Among all OLUs, Golden Gate has by far the highest percentage of urban, high-rise neighborhood place types (44%), though this area within the OLU is at a higher elevation and is not especially vulnerable to near term flooding. Over the long run, some combination of seawalls or bulkheads, street elevation, flood-proofing of ground floors, and inland flood walls could be used. Some commercial and industrial land along the north side of the Port of San Francisco, especially pier sheds and parking lots, are at risk and could be protected by elevating the Embarcadero seawall and piers, retrofitting piers to float, and/or using perimeter protection—a combination of grey or hybrid measures—around their edges to prevent wave overtopping. Other commercial and retail uses may either choose to flood-proof sites or to relocate. The neighborhoods affected by long-term sea level rise could create a GHAD to help finance flood protection measures.

Place Types Map

Legend
- Parks and protected areas
- Industrial and infrastructure
- Office parks
- Job centers
- Urban neighborhoods
- High rise neighborhoods
- Bay

AERIAL VIEW OF COAST GUARD ISLAND AND INNER HARBOR IN ALAMEDA • PHOTO BY CRAIG HOWELL (CC BY 2.0)

6 NEXT STEPS
for the OLU framework: uses and additional research

We hope this work can further local and regional discussions around sea level rise adaptation and climate change in several ways:

The OLU framework encourages communities to work together on long-term shoreline adaptation strategies. OLUs cut across traditional jurisdictional boundaries, allowing stakeholders who experience similar hazards and share similar physical and ecological settings to come together to develop effective adaptation solutions.

This report offers a first cut at determining the suitability of nature-based measures for different parts of the San Francisco Bay shoreline. The simple and robust criteria can be used to help site and size several nature-based shoreline protection features within different physical and ecological settings. Detailed maps show which adaptation measures can work together in a particular place.

OLUs integrate across the land-water divide to connect bayside and landside adaptation strategies. Combining measures suitable for shallow parts of the Bay, the wetlands along the Bay shore, and the land above the shoreline will help create synergistic and locally appropriate strategies. Local and regional priorities will guide the selection and integration of these strategies into a pathway or vision for a particular area over time.

Climate adaptation action is urgently needed now, and will only become more pressing as sea level rise impacts accelerate in the coming decades. The intent of this report and the OLU framework is to foster and inform a collaborative, data-driven vision for resilience to sea level rise that can be implemented at multiple scales. Building on and supporting the many innovative projects already underway, this report intends to provide guidance for the regulatory community, regional governments, planners, and members of local communities on how to proactively integrate nature-based adaptation measures into adaptation plans.

How to use this information in adaptation planning

Here, we suggest a step-wise framework for integrating this information into stakeholder processes; many of these steps are already underway in the region. The OLU framework can help at the outset of a stakeholder planning process to identify the geographic area of focus, which may help to identify which individuals and organizations should be included in the stakeholder group. An OLU stakeholder group would ideally encompass the range of interests represented within that

STEP 1

Assess vulnerabilities, exposure, and risk to sea level rise by OLU

- This step is underway in parts of the region as part of the Adapting to Rising Tides (ART) Bay Area project, a regional sea level rise vulnerability and adaptation planning project being led by BCDC. The goal of the vulnerability assessment is to understand which assets are vulnerable to flooding in different sea level rise scenarios.
- It is harder, although critical, to assess the root sources of vulnerabilities in order to identify the most effective possible adaptation options.

STEP 2

Filter adaptation options, focus on nature-based strategies in each OLU

- Identify adaptation options that are suitable within each OLU.
- Understand which vulnerabilities different adaptation options address.
- Determine what physical configuration would maximize the effectiveness of a particular adaptation option.
- Estimate how long they will last, how much they cost, and what are potential adverse impacts of each measure.

STEP 3

Consider desired futures and goals

- Define the resilience outcomes desired by communities within the OLU.
- Determine what the OLU strategy needs to achieve on behalf of stakeholders. E.g., Maintain function or service X and Y at location Z up to 2070.
- Identify a vision or themes to guide development of the adaptation strategy.

OLU, including community members, advocates, local government, businesses, and regulatory agencies. The OLU framework also filters down the range of nature-based strategies suitable in an OLU, which can streamline discussions of goals, scenarios, and eventually adaptation pathways. This approach has been piloted in both San Mateo and Marin counties in partnership with the Natural Capital Project and Point Blue Conservation Science.

STEP 4

Create scenarios composed of adaptation measures

- Develop a scenario, or combination of measures, for each desired future.
- Determine what combination of measures could be used where and when to achieve the goals. Discuss the co-benefits of each scenario or combination.

STEP 5

Evaluate trade-offs and prioritize strategies and scenarios

- Identify benefits/services and assess trade-offs between strategies.
- Once scenarios have been drafted, they can be compared or evaluated for trade-offs, including cost and ecosystem services. These can include benefits to people and wildlife, such as carbon storage, wave attenuation, recreation, and impacts to regional transportation.

STEP 6

Develop adaptation pathways to achieve desired outcome/scenario

- Once stakeholders have identified their desired future, develop an adaptation pathway needed to achieve it.
- A strategy will be implemented by individual projects over time. Each project has it's own cycle. E.g., alternatives, feasibility, permitting, design, construction.
- Adaptation pathways can help mitigate uncertainty around future scenarios and provide feedback loops for re-evaluating decisions.*

*Adaptation pathways are an ideal way to implement strategies to achieve goals or visions. To reach this step, communities must be involved in the planning process from the beginning, and decisions should emerge from a community-driven perspective. A stakeholder group (made up of community members and leaders, elected officials, municipal managers, scientists, engineers, and others) organized by OLU should work together to set goals, assess exposure and risk, combine measures into strategies, and evaluate trade-offs. The adaptation pathway can become the mechanism to achieve the goals decided by the group and allows the plan to adjust as the climate changes. For more information on adaptation pathways, see page 63.

VIEW FROM COYOTE HILLS • PHOTO BY SHIRA BEZALEL (SFEI)

Future phases of research and application

This effort represents the first phase of the development of shoreline Operational Landscape Units. This new concept invites governments and planners to look outside traditional boundaries to address the shared challenge of sea level rise adaptation planning. As a next step, SFEI and SPUR will address critical data gaps and facilitate use of the OLU framework by providing input to local and regional planning processes.

Advancing the science and addressing data gaps

Given considerable ongoing research in the Bay, baylands, and local watersheds that could be incorporated into the OLU framework, we have focused this chapter on information that could increase the specificity of the measures mapped in this report.

An analysis of potential sediment supply to and demand from the baylands under different future scenarios will help elucidate the ability of the Bay's wetlands to keep pace with sea level rise. Furthermore, more detailed mudflat mapping, including characterization of mudflat shape and change over time, would help with assessing the suitability of marsh restoration. Also, a comprehensive survey of patterns and rates of shoreline erosion is critical for adaptation planning.

Integrating tools for improved watershed management, including urban greening and stormwater management, with shoreline adaptation planning is important to further cross the land-water divide and connect the estuary to its watersheds. Connecting planning processes in the watersheds to OLUs will help coordinate adaptation to other climate change impacts, including increased fire risk, heat island effects, and flooding from creeks.

Information about the current elevation or depth of areas near the shoreline is one of the most basic needs for sea level rise adaptation planning. Many physical processes, including wetland accretion, tectonic movement, erosion, and of course sea level rise, cause elevations and depths to change constantly. Therefore, elevation datasets need regular updating. For example, the analysis of marsh potential and other measures in this report will need to be updated when new LiDAR elevation data is produced for the region (expected to be released in 2019). Also, the analysis of polders is hampered by the lack of recent bathymetric data for many former salt ponds.

Many of these data gaps and monitoring needs point to the importance of a regional wetlands monitoring program (under development), as well as a regional data center to house and update data and make it easily accessible to stakeholders, including the public.

Several specific issues related to particular kinds of infrastructure and to certain land uses that are vulnerable to sea level rise were not addressed in this report and will be the focus of ongoing efforts. Features not explicitly addressed in this report include landfills, contaminated sites, wastewater treatment plants, and power transmission infrastructure. In addition, future work on the OLU framework will continue to integrate natural and nature-based adaptation measures more directly with the transportation infrastructure that rings much of the San Francisco Bay shoreline.

The next phase of OLU planning will incorporate more information on water quality. Many of the adaptation measures described here have a close linkage with water quality. As indicated in Chapter 4 (Adaptation Measures) , many measures (e.g., tidal marsh restoration) have the potential to improve Bay water quality, either by serving as traps for contaminated sediment or through enhanced biogeochemical processing of contaminants such as nitrogen. On the other hand, some adaptation measures could have negative water quality impacts. Over the long-term, the filtration function of some adaptation measures may lead to the gradual accumulation of contaminants, such as mercury, to levels that pose unacceptable risks to wildlife (including species such as Ridgway's Rail in tidal marshes). When combined with certain adaptation measures, contamination in watersheds or in sediment on the Bay margins may pose health risks to humans or aquatic life. Some OLUs, such as San Leandro and East Bay Crescent, for example, have areas with relatively high concentrations of contaminants that could constrain the implementation of certain adaptation measures. As another example, placing beaches near stormwater sources that are contaminated with bacteria could create new public health risks. These potential water quality concerns should be anticipated and factored into the process of prioritizing adaptation measures.

Understanding trade-offs between adaptation options

Key to adaptation planning is the integration of cost-benefit information (in dollars) and other metrics quantifying ecosystem services such as recreation, flood risk reduction, habitat for wildlife, carbon sequestration, and others. This type of quantification of adaptation options will allow communities to weigh the trade-offs between potential adaptation scenarios. Several efforts currently underway are aimed at quantifying the ecosystem service benefits of various strategies, both at the regional scale and within OLUs. These efforts will help decision makers analyze the trade-offs and long-term economic performance of measures. Hydrodynamic modeling of adaptation strategies between OLUs and across sub-embayments is another important next step. This will help identify the impacts and trade-offs of choices made within OLUs on other areas of the Bay.

Applications to local and regional government

Some local and regional governments in the Bay Area are already using OLUs as an organizing principle for vulnerability assessments and adaptation planning. BCDC's ART Bay Area program has begun to assess vulnerabilities in the context of OLUs. San Mateo and Marin county governments are using OLUs as a way to assess options for adaptation throughout their baylands, to bring stakeholders together around a common physical unit, and to begin to test potential adaptation strategies. At the city and special district level, this information can continue to be integrated into adaptation plans. Moving forward, the OLU framework could be a potential basis for a regional sea level rise adaptation strategy. In the long run, stakeholders such as cities, counties, flood control districts, and others could develop shared agreements or memorandums of understanding (MOUs) around adaptation planning within each OLU, as a way to formalize the planning process and assign responsibilities.

Supporting pilot projects

Natural and nature-based measures are generally poorly understood in comparison with conventional physical infrastructure. One way to spread awareness is by investing in nature-based pilot projects, particularly hybrids designed to integrate with existing or future infrastructure. We hope the OLU framework can help to catalyze new adaptation projects that the community can monitor and learn from, and to support projects already underway.

Engaging communities and lifting up equitable solutions

The engagement of people living and working in OLUs will be critically important in any adaptation planning effort, especially around something as long-term and potentially threatening as sea level rise and associated storm and tidal flooding. Without intentional community engagement early on in the process, we will certainly miss opportunities for creative solutions and might cause more significant problems. For example, the histories of many large engineering projects, and of urban planning, are rife with examples of "modernization" or "improvements" that have imposed unfair and egregious harm to some communities in favor of bettering others. While negative impacts may have been unintentional, harms have often occurred disproportionately within low-income communities and communities of color. We believe that no OLU planning process should take place without the intentional engagement of community-based stakeholders, and that equity and environmental justice are important principles to hold up in any sea level rise planning activities. This way we can avoid replicating past actions that have led to today's inequities, and we can better assure environmental justice through both outcome and process.

Expanding and improving communication tools

The accessibility of this information to the Bay community is critical for it to be useful and effective in adaptation planning. SFEI is developing a robust data-driven interactive map, and will be tracking and updating components. Further work needs to be done to translate this effort into usable tools for community-driven resilience planning by including social factors such as social equity, income disparity, and barriers to self-determination in planning processes. A prototype of the interactive map with data from this report can be found at *adaptationatlas.sfei.org*.

In conclusion

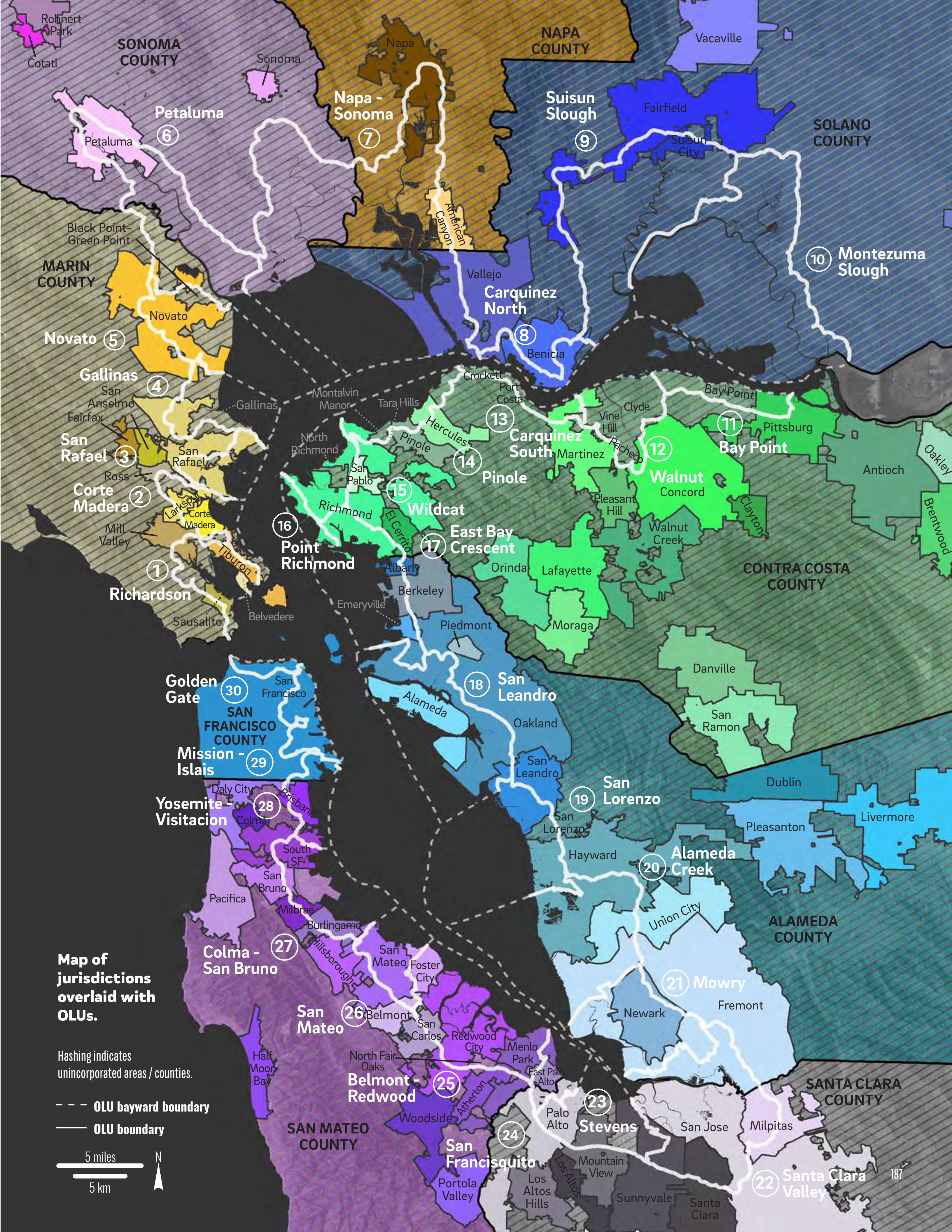
With climate change and sea level rise already impacting Bay Area communities and expected to accelerate over the next few decades, the need for shoreline adaptation is urgent. The intent of this report and the OLU framework is to foster and inform a collaborative, data-driven vision for regional resilience to sea level rise that can be implemented at multiple scales. Building on and supporting the many important projects already underway, this framework can provide guidance for the regulatory community, regional governments, planners, and members of local communities on how to proactively integrate nature-based adaptation measures into adaptation plans.

This report, and future updates to these datasets, maps, and OLU-based projects around the region, will be available online at ***adaptationatlas.sfei.org.***

Appendix 1: Jurisdictions grouped by OLUs

OLU	County	Water and Flood Control Districts	City or Census-designated Places
1. Richardson	Marin	Marin County Flood Control And Water Conservation District (Zones 3 and 4)	Mill Valley, Tiburon*, Belvedere, Sausalito, Alto, Marin City, Strawberry, Tamalpais-Homestead Valley
2. Corte Madera	Marin	Marin County Flood Control And Water Conservation District (Zone 9)	Corte Madera, Ross, Tiburon*, Larkspur, Kentfield
3. San Rafael	Marin	Marin County Flood Control And Water Conservation District (Zone 9)	San Rafael*
4. Galinas	Marin	Marin County Flood Control And Water Conservation District (Zones 6 and 7)	San Rafael*, Lucas Valley, Santa Venetia
5. Novato	Marin	Marin County Flood Control And Water Conservation District (Zone 1)	Novato, Black Point-Green Point*
6. Petaluma	Marin	Marin County Flood Control And Water Conservation District (No specified zone)	Black Point-Green Point*
	Sonoma	Sonoma Water (Zone 9a)	Petaluma
7. Napa-Sonoma	Napa	Sonoma Water (Zone 9A)	Napa, American Canyon
	Solano	Napa County Flood Control and Water Conservation District	Vallejo*
8. Carquinez North	Solano	Solano County Water Agency	Vallejo*, Benicia
9. Suisun Slough	Solano	Solano County Water Agency	Suisun City, Fairfield
10. Montezuma Slough	Solano	Solano County Water Agency	-
11. Bay Point	Contra Costa	Contra Costa County Flood Control and Water Conservation District	Pittsburgh, Bay Point
12. Walnut	Contra Costa	Contra Costa County Flood Control and Water Conservation District (Walnut Creek, Mt. Diablo Creek)	Concord, Martinez*, Pleasant Hill, Pacheco, Vine Hill, Clyde
13. Carquinez South	Contra Costa	Contra Costa County Flood Control and Water Conservation District (Alhambra Creek)	Martinez*, Port Costa, Crockett*
14. Pinole	Contra Costa	Contra Costa County Flood Control and Water Conservation District (Pinole Creek, Rodeo Creek)	Hercules, Pinole, Richmond*, Crockett*, Montalvin Manor, Tara Hills
15. Wildcat	Contra Costa	Contra Costa County Flood Control and Water Conservation District (Wildcat Creek, San Pablo Creek, and Rheem Creek)	Richmond*, San Pablo, North Richmond
16. Point Richmond	Contra Costa	Contra Costa County Flood Control and Water Conservation District	Richmond*
17. East Bay Crescent	Contra Costa	Contra Costa County Flood Control and Water Conservation District	El Cerrito, Richmond*
	Alameda	Alameda County Flood Control And Water Conservation District (Zone 12)	Albany, Berkeley, Emeryville, Oakland*
18. San Leandro	Alameda	Alameda County Flood Control And Water Conservation District (Zones 12 and 13)	Oakland*, Alameda, San Leandro*
19. San Lorenzo	Alameda	Alameda County Flood Control And Water Conservation District (Zones 9, 2A, 2, and 4)	Hayward*, San Leandro*, San Lorenzo
20. Alameda Creek	Alameda	Alameda County Flood Control And Water Conservation District (Zones 3A and 5)	Hayward*, Union City, Fremont*
21. Mowry	Alameda	Alameda County Flood Control And Water Conservation District (Zones 5 and 6)	Newark, Fremont*
22. Santa Clara Valley	Alameda	Alameda County Flood Control And Water Conservation District (Zone 6)	Fremont*
	Santa Clara	Santa Clara Valley Water District	San Jose, Sunnyvale*, Santa Clara, Milpitas
23. Stevens	Santa Clara	Santa Clara Valley Water District	Palo Alto*, Sunnyvale*, Mountain View
24. San Francisquito	Santa Clara	Santa Clara Valley Water District	Palo Alto*
	San Mateo	San Mateo Flood Control District (San Francisquito Creek)	East Palo Alto*, Menlo Park*
25. Belmont-Redwood	San Mateo	San Mateo Flood Control District	Atherton, Foster City*, Menlo Park*, San Carlos, Redwood City, North Fair Oaks, East Palo Alto*, Belmont*
26. San Mateo	San Mateo	San Mateo Flood Control District	Foster City*, San Mateo*, Belmont*
27. Colma-San Bruno	San Mateo	San Mateo Flood Control District (San Bruno Creek)	San Bruno, Milbrae, Burlingame, South San Francisco*, San Mateo*
28. Yosemite-Visitacion	San Mateo	San Mateo Flood Control District (Colma Creek)	Daly City, South San Francisco*, Brisbane
	San Francisco	San Francisco Public Utilities Commission	San Francisco
29. Mission-Islais	San Francisco	San Francisco Public Utilities Commission	San Francisco
30. Golden Gate	San Francisco	San Francisco Public Utilities Commission	San Francisco

**Indicates that a city or census-designated place falls within more than one OLU.*



Map of jurisdictions overlaid with OLUs.

Appendix 2: Notes on naming and identifying the boundaries between OLUs

Naming OLUs

To reflect the delineation of OLUs based on physical features and conditions, we intentionally avoided naming OLUs after cultural features. Instead, the OLUs were named after the dominant creek or creeks within their boundaries. OLUs without major creeks were instead named after another physical landform. Since many of these creeks and landforms share names with cities, towns, and other municipalities, many of the OLUs do conveniently share names with familiar cultural features. The physical features the OLUs are named after, and related cultural features, are summarized in the table below.

OLU #	OLU name	Feature/s OLU is named after	Notes
1	Richardson	Richardson Bay	
2	Corte Madera	Corte Madera Creek (also: Town of Corte Madera)	
3	San Rafael	San Rafael Creek (also: City of San Rafael)	
4	Gallinas	Gallinas Creek	
5	Novato	Novato Creek (also: City of Novato)	
6	Petaluma	Petaluma River (also: Petaluma Valley, City of Petaluma)	
7	Napa-Sonoma	Napa River, Sonoma Creek (also: Napa Valley, Sonoma Valley, City of Napa, City of Sonoma)	
8	Carquinez North	Northern shoreline of Carquinez Strait	
9	Suisun Slough	Suisun Slough	
10	Montezuma Slough	Montezuma Slough	
11	Bay Point	Census-designated place of Bay Point	Without any major creeks or another commonly-used name for a defining physical land form, this OLU was instead named after a major cultural feature.
12	Walnut	Walnut Creek	
13	Carquinez South	Southern shoreline of Carquinez Strait	The dominant creek here is Alhambra Creek, but we named the OLU Carquinez South for consistency with Carquinez North, which lacks a major creek.
14	Pinole	Pinole Creek (also: City of Pinole)	
15	Wildcat	Wildcat Creek	
16	Point Richmond	Point Richmond headlands/geologic feature (also: Town of Point Richmond)	

OLU #	OLU name	Feature/s OLU is named after	Notes
17	East Bay Crescent	The Eastshore shoreline, which forms a general crescent-moon shape between Richmond and Oakland	
18	San Leandro	San Leandro Creek	
19	San Lorenzo	San Lorenzo Creek	
20	Alameda Creek	Alameda Creek	By default, we did not include the word “creek” in OLUs named after creeks. “Creek” was retained here to distinguish the OLU from the island of Alameda.
21	Mowry	Mowry Slough	
22	Santa Clara Valley	Santa Clara Valley (also: City of Santa Clara)	Named after the valley instead of the dominant creek (Coyote Creek).
23	Stevens	Stevens Creek	
24	San Francisquito	San Francisquito Creek	
25	Belmont-Redwood	Belmont Creek, Redwood Creek (also: City of Belmont, Redwood City)	
26	San Mateo	San Mateo Creek (also: City of San Mateo)	
27	Colma-San Bruno	Colma Creek, San Bruno Creek (also: City of San Bruno)	
28	Yosemite-Visitacion	Yosemite Creek, Visitacion Valley Creek	
29	Mission-Islais	Mission Creek, Islais Creek	
30	Golden Gate	Golden Gate strait connecting San Francisco Bay to the Pacific Ocean	

Identifying boundaries between OLUs

On page 22, we describe the process of defining geomorphic units and then subdividing these units into individual OLUs, using different methods for each geomorphic unit type. Here we provide additional details related to this process.

Within geomorphic units classified as headlands and small valleys, OLU boundaries were located along the shoreline at the apex of major points or promontories, using the distance from the shoreline to deep water as a guide. To identify “major” promontories, we first used GIS to divide the shoreline into 100 meter segments and to calculate for each segment the minimum distance to deep water. For this calculation we used the shoreline mapped through SFEI’s Bay Shore Inventory project (SFEI 2016), which defined the shoreline as the line of features that would provide the ‘first line of defense’ against coastal flooding. This included vegetated wetlands, where present, at the approximate elevation of mean higher high water (MHHW). When calculating the distance from the shoreline to deep water, we used the historical extent of “deep bay” mapped by SFEI-ASC (1997), modified slightly to remove very small and isolated areas of deep water (we were attempting to measure approximate distance to the natural position of the primary deep water channel of the Bay). The distance of each shoreline segment to deep water was then plotted on a single chart and smoothed using a 5 km moving average filter, with the local minima of the resulting curve corresponding to promontories that jut into the Bay towards deep water. Major promontories were then distinguished from minor ones by selecting points that were, on average, more than 500 m closer to deep water than the two neighboring local maxima. When using the major promontories to define the boundaries between OLUs, we disregarded one major promontory in Marin County associated with the Paradise Cay bay fill. We also elevated the minor promontory at Pier 27 (near Telegraph Hill) to a major promontory based on swell conditions (the location marks the transition from high and medium exposure to swell along the northern shoreline of San Francisco to low exposure on its bayward side). Finally, we added an OLU break at Long Point at the boundary of the Miller Creek watershed. This point was not identified as a major promontory using the methods described above, but historically separated the Novato Creek baylands from the Miller and Gallinas creek baylands.

Within geomorphic units characterized as alluvial fans and alluvial plains, OLU boundaries were located along the shoreline at the apex of the major alluvials fans mapped by Knudsen et al. (2000). The one exception to this rule is the additional OLU break we included at Foster City at the San Mateo Bridge landing. Though the break is located at the apex of an alluvial fan formed by Laurel Creek, this feature is significantly smaller than the other fans used to demarcate OLUs. The primary reason to include an OLU break at this location was to distinguish between the swash-aligned vs. drift-aligned shoreline orientation on either side of the bridge.

Within geomorphic units characterized as wide alluvial valleys, we relied on major tidal watershed boundaries to determine the boundaries between individual OLUs. In the North Bay, the Napa Valley and Sonoma Valley baylands are connected via Napa Slough and were thus considered one OLU. They were separated from the Petaluma OLU based on the drainage divide below Sears Point. In Suisun Bay, the OLUs were demarcated based on whether the baylands are drained by Montezuma Slough or Suisun Slough. In Santa Clara Valley the baylands that drain to Coyote Creek were considered part of the Santa Clara Valley OLU, while those that drain directly to the Bay were included in the Stevens OLU.

When necessary, tidal watershed boundaries were identified by drawing a line around the first order channels that drain to the high-order channel/s of interest. These lines were positioned equidistant to the two tidal channel networks being divided.

Appendix 3: Place types development

Overview

Place types are a classification of every quarter-square-mile of the Bay Area into major categories of land use and physical form. This approach, developed by SPUR, classifies the entirety of the nine-county Bay Area according to its present day physical characteristics, such as building and road patterns. This comprehensive snapshot offers a baseline against which various proposed changes to land use can be evaluated, or current growth trends analyzed or extrapolated. This report is a prime example of how place types can be used to plan for changes in land use. The existing land use conditions summarized by the place type typology, such as job and housing unit density, are critical in pairing adaptation strategies to each Operational Land Unit (OLU). For example, in areas with intense economic and population development, more defensive walls or other investments may make sense to combat rising seas. In areas with less development, marshland restoration to accommodate regular flooding may be more appropriate.

The idea of creating a typology of existing land uses is not new. In particular, SPUR's place types were inspired by a similar classification done by the Regional Plan Association (RPA) in New York (Montemayor and Calvin 2015). Montemayor and Calvin's methodology largely served as the blueprint for SPUR's place types, although SPUR did tailor some steps for the context of the Bay Area and the policies SPUR anticipates analyzing with place types.

The main steps taken in creating SPUR's place types were 1) making a grid, 2) cross-walking spatial data to the grid, 3) performing k-means cluster analysis, 4) performing an overlay analysis and 5) ground-truthing the results. Each step is described in more detail below.

Making a grid

Creating a grid serves to standardize the geographic unit for place types across the nine Bay Area counties. In other words, each grid cell can be used to directly compare quarter-square-mile (0.65 km^2) areas across the Bay. While it is possible to specify and make a grid with cells of any size, SPUR chose grid cells that are square in shape and a half-mile on each side (or the area of a quarter square mile). A smaller or multi-sided cell geometry (such as a hexagon) can offer a more fine grained specificity for place types. However, there are two downsides to using smaller and/or multi-sided geometries. First, they make geoprocessing much more costly and time consuming. Second, since many datasets are made available at coarser geographies, such as US Census blocks, a smaller grid cell size requires a greater confidence in the assumption that people, housing units, or other variables are spread uniformly across blocks. There is no way of knowing to what degree this assumption holds for each grid cell, but larger grid cells generally reduce the margin of error associated with this uniform distribution assumption. The goal in choosing grid cell size is to draw the maximum size that still captures the small-scale variability of different land uses.

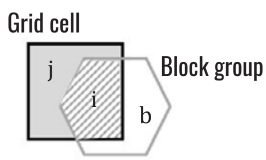
After the grid was created, the area of actual land in each cell was also calculated. In other words, the area of bay and ocean were subtracted from each grid cell. This would prove important in density calculations below.

Cross-walking data to grid cells

Data used to determine place types were largely taken from the list of variables used by the RPA. These are: housing unit density, job density, intersection density, land-use entropy (or how mixed the land use is), and pavement permeability.

Many other variables could be used to describe the physical characteristics of building patterns and land use. However, using the fewest variables in cluster analysis often yields the most robust and interpretable results. SPUR ran cluster analyses with other variables, such as the year housing was built, but found that the place types generated by the five variables above yielded the closest match to our understanding of the Bay Area. Below is a description of how each of these variables were cross-walked to the grid and prepared for cluster analysis.

Housing unit density was calculated using US Census American Community Survey 5-year estimates for 2012–2016 (table B25001; U.S. Census Bureau 2017a). These data are available by the census block group. The ultimate goal of cross-walking the data to the grid is to end up with area-weighted counts of housing units by grid cell. This process involved first taking the area of each polygon in the block group shapefile (the area of hexagon 'b' in the figure below). Next, the block group polygons were intersected with the SPUR grid to form shapes like 'i' below. Using the ratio of 'i' over 'b', all the counts of housing units were area weighted (all 'x' in 'b'). The weighted housing unit counts (WHU) were then summed for all intersections 'i' in each grid cell 'j'.



$$WHU_j = \sum_i \left(\frac{Area_{\ ij}}{Area_b}\right) * x_b$$

Geospatial cross-walking and area-weighting *count data*

In determining the density of the area-weighted housing unit count, the area of land within each grid cell was used, as areas of bay and the ocean were subtracted from each grid cell:

$$HU\ Density_j = \frac{WHU_j}{Land\ area_j}$$

Job density was calculated using 2015 US Census Longitudinal Employer-Household Dynamics (LEHD) Origin-Destination Employment Statistics Data for Workplace Area Characteristics (U.S. Census Bureau 2017b). These are available by census block, the finest census geography. The steps taken to weight jobs data were the same as those taken to weight housing units (described above). From there, a job density variable was similarly constructed.

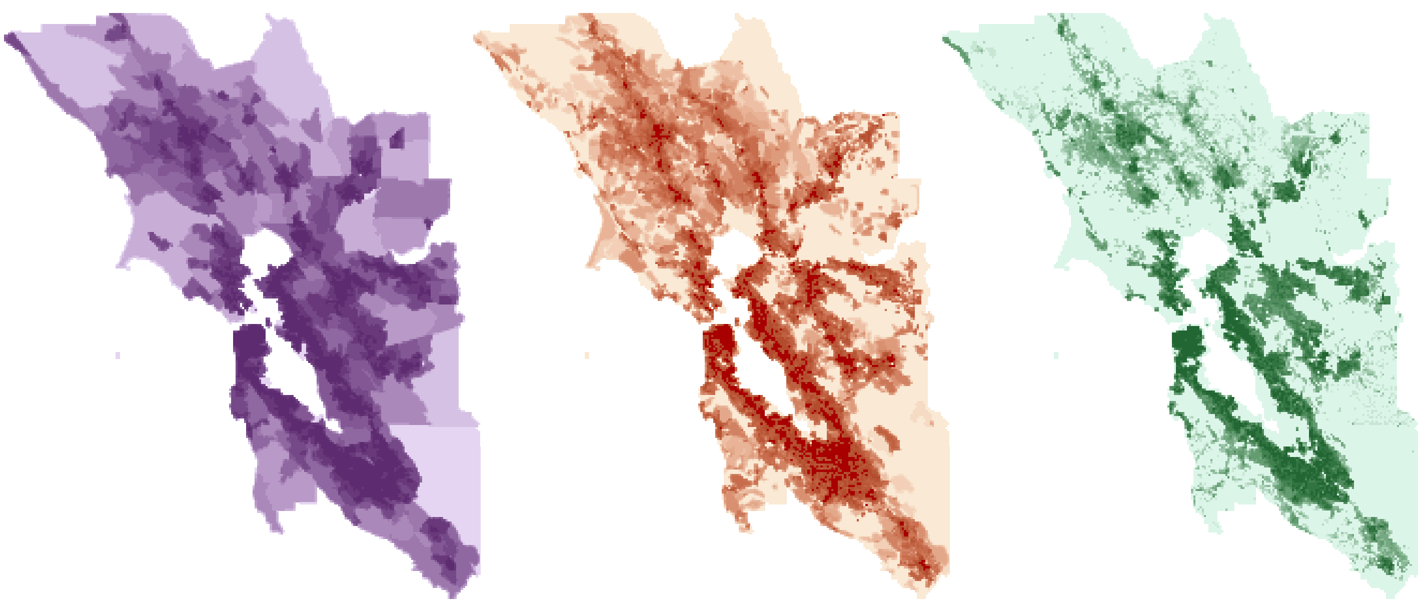
Intersection density was calculated using US Census Bureau TIGER/Line road centerlines available by US county (U.S. Census Bureau 2017c). The road centerlines were first subset to exclude freeways, off ramps, and rights-of-way in parking lots. What remained were centerlines for the street network. Next, the longitude and latitude for each node or intersection of the road polylines was calculated. SPUR kept all points where three or more points shared the same coordinates, representing at least three-way intersections. SPUR then applied a spatial command to identify the grid cells in which each three-way intersection fell. Upon inspection, some intersections were double counted because some large roads (Market Street in San Francisco for example) have a center line for each direction of travel. To overcome this, a distance matrix between all intersections was created and a radius around each intersection drawn. Intersections within 28 m of each other were considered duplicates. This radius size fully captured double counting in tighter street networks like downtown San Francisco, but did not capture every single duplicate on wider streets like those in the South Bay. No one size could fully capture all duplicates without also dropping intersections that were not duplicates. The choice of 28 m was chosen so that even when erring on the side of double counting larger streets, the tighter networks still show up with the highest intersection density in the region.

Land-use entropy, or the degree to which land uses are mixed in each grid cell, was calculated using simplified parcel data provided to SPUR from the Metropolitan Transportation Commission (MTC). These data showed whether or not the building on a parcel of land had square footage with residential, non-residential, or a mix of both uses. Similar to the area weighting done for census blocks and block groups, these steps were repeated for parcels.

Once the parcel-level data were cross-walked, the equation below served as a model to calculate a score for land-use entropy. In this equation, 'P' represents percentage of land use 'i' in each grid cell 'j'. 'N' represents the number of land uses in each grid cell. In the resulting land-use entropy scores, 0 denotes areas with one homogenous land use, while 1 denotes an equal mix of land uses. The idea of an entropy score to rank heterogeneity is found sprinkled throughout the land use and transportation literature (Cervero and Kockelman 1997, Manaugh and Kreider 2013, Bordoloi et al. 2013, Spears et al. 2014).

$$Entropy_j = \left(\frac{-\sum_i P_{ij} * \ln(P_{ij})}{\ln(N_j)} \right) (1 - P_{ij}) + P_{ij}$$

Pavement permeability was calculated using the National Land Cover Database (NLCD; Homer et al. 2015) made available by the U.S. Geological Survey and supported by a consortium of federal agencies. The NLCD dataset is generated from Landsat satellite imagery and classified into various ground cover categories at a 30 m resolution. Ground cover classifications range from different types of marsh to cropland to four categories of developed space, each with increasing degrees of pavement impermeability. SPUR cross-walked the NLCD raster to the SPUR grid and calculated the percent of developed / impermeable space in each grid cell.



***Variables cross-walked to the SPUR grid**, from left to right: area-weighted housing unit density, area-weighted job density, and land-use entropy*

As a check on each cross-walking step, SPUR rendered and inspected maps of the distributions of cross-walked variables. A sample of these is shown below.

Cluster analysis

SPUR used cluster analysis to sort each grid cell into a unique category or place type. Each grid cell was evaluated by an algorithm according to the five defining variables listed above. SPUR used a k-means algorithm, a foundational form of unsupervised machine learning (University of Cincinnati. 2018). The algorithm takes the defining variables, the desired number of clusters, the number of random starting positions, and maximum number of iterations as inputs. In the end, the algorithm finds the mean of distinct clusters of grid cells within the five-dimensional space of all variables. Grid cells are classified into the cluster whose mean is closest. The algorithm uses Euclidean distances by default and minimizes distance through sum-of-least squares.

SPUR tested the number of clusters to use, choosing as few as seven and as many as 14. The random start was set to 25 and the algorithm set to iterate no more than 50 times to best minimize the distance between clusters' means and grid cells. To choose the cluster number that resulted in the highest quality results, SPUR tested each iteration of k clusters with the average silhouette method, which measures how well any grid cell fits inside a cluster (Rousseeuw 1987). The closer the silhouette score to 1, the stronger the classification. SPUR's classifications never went below 0.82 and never went above 0.88, showing a strong score regardless of the number of clusters chosen. Iterations that resulted in clusters made up of only one grid cell were rejected, and the final number of clusters was chosen based on inspection of the cluster classifications in GIS. In the end, SPUR chose k=12 because it showed enough and appropriate variation against satellite imagery.

Overlay analysis

With twelve distinct clusters, SPUR sought to overlay some land-uses that are determined not by a mix of physical attributes but by the presence of a single type of land use, including protected areas and cultivated cropland.

Protected areas were cross-walked to the grid using the California Protected Areas Database, made available by GreenInfo Network (CPAD 2017). Their shapefile combines open spaces ranging from national wildlife refuges to neighborhood pocket parks. Cultivated lands were designated using the NLCD data. If over 50% of a grid cell was comprised of either protected area or cultivated land, it was reclassified as such. This increased the number of place types from 12 to 14.

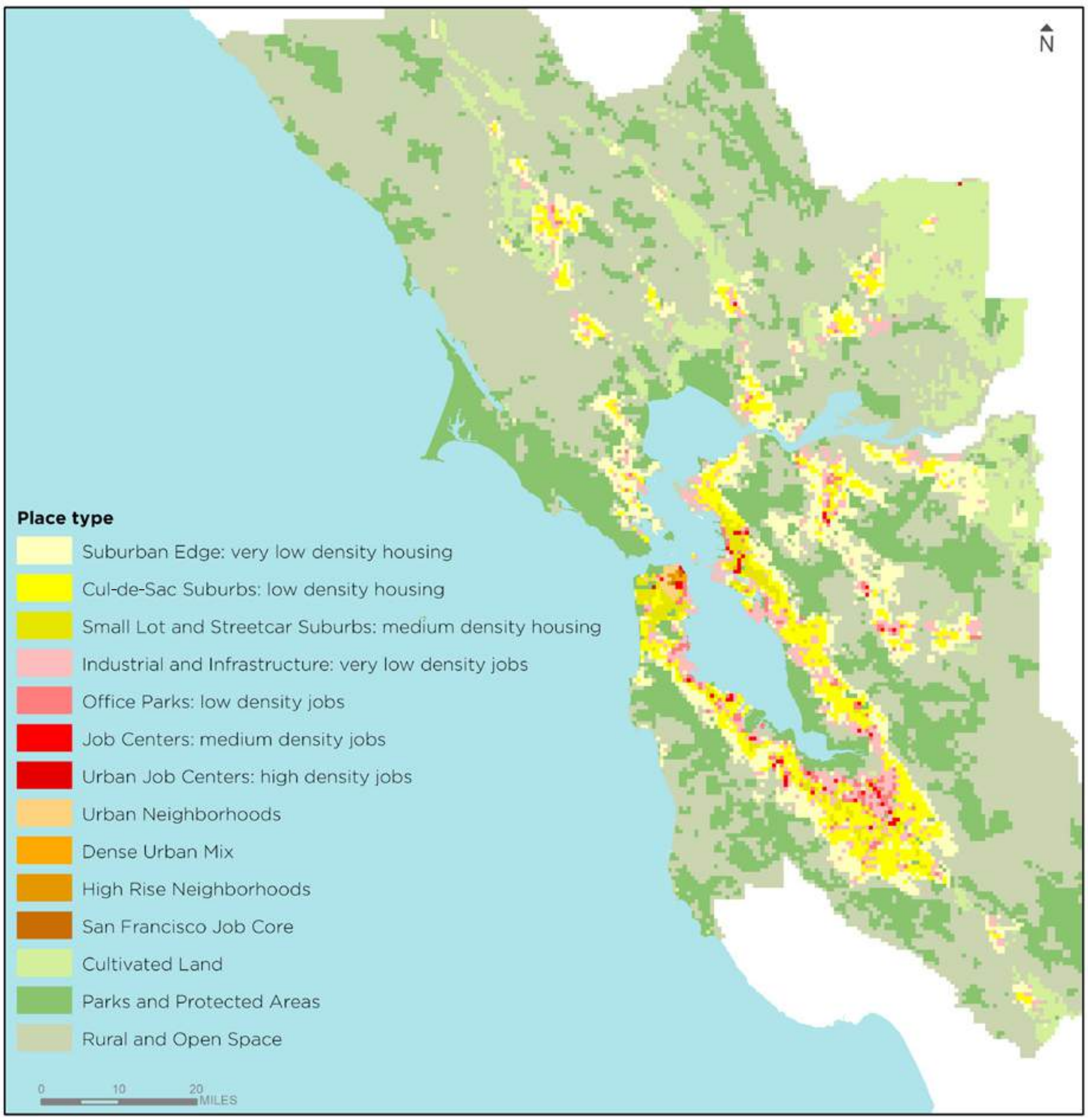
Ground-truthing

A shapefile was generated with the 14 place types and inspected against satellite imagery in GIS and Google Earth. The algorithm seemed weakest on areas where sparse housing met open space and in areas where two distinct land uses met in one grid cell, such as where warehouses met tract homes. SPUR inspected and reclassified some of these, ultimately choosing the classification that corresponded to 50% or more of one land use. In addition, due to their large patches of dirt and grasses, the algorithm classified many airports, military bases, sea ports and other public infrastructure lands into the cluster comprised of rural and open space. SPUR reclassified the airports and other uses into the place type comprised of mostly jobs at the lowest job density. In the end, roughly 4% of the nine-county area was reclassified through ground-truthing.

Results

From the cluster analysis, twelve place types were generated and in the overlay analysis two more were distilled, for a total of 14. These 14 place types fall under four broad categories: primarily housing, primarily jobs, a mix of housing and jobs, and open space. The table on page 197 lists the names SPUR assigned each place type, as well as their dominant characteristics. The map below shows the nine-county Bay Area as seen through place types.

In future applications of machine learning to classify large, continuous areas by physical land uses, grid cells of a circular or more multi-sided shape could be an improvement. Applications of supervised machine learning to identify particular physical patterns across a geography could also prove worthwhile.



SPUR place types *across the nine-county Bay Area*

***Summary of place type** by defining variables.*

	Place type	Square miles	Average housing units per acre	Average intersections per square mile	Average jobs per acre	Land-use entropy score	Pavement permeability
Open Space	Rural and Open Space	3,847	< 1	4	< 1	0.01	Almost completely permeable
	Cultivated Lands	608	< 1	2	< 1	0.01	Almost completely permeable
	Parks and Protected Areas	1,591	< 1	2	< 1	0.00	Almost completely permeable
Primarily Housing	Suburban Edge: very low density housing	500	2	82	1	0.09	Ranging from low to medium impermeability
	Cul-de-sac Suburbs: low density housing	291	5	134	2	0.21	Mostly medium impermeability
	Small Lot and Streetcar Suburbs: medium density housing	64	10	156	5	0.45	Mostly medium to high impermeability
Primarily Jobs	Industrial and Infrastructure: very low job density	204	2	58	7	0.19	Mostly medium to high impermeability
	Office Parks: low job density	42	3	72	21	0.22	Mostly medium to high impermeability
	Job Centers: medium job density	11	5	102	43	0.36	Mostly medium to high impermeability
	Urban Job Centers: high job density	4	9	132	91	0.45	Mostly medium to high impermeability
Mixed	Urban Neighborhoods	7	26	209	18	0.65	Mostly high impermeability
	High Rise Neighborhoods	1	50	285	57	0.76	Almost completely high impermeability
	Dense Urban Mix	2	31	218	161	0.65	Almost completely high impermeability
	San Francisco Job Core	1	18	343	484	0.61	Almost completely high impermeability

SAN FRANCISCO BAY BY RICHMOND-SAN RAFAEL BRIDGE • PHOTO BY SHIRA BEZALEL (SFEI)

Appendix 4: OLU Typology

With 30 individual OLUs defined, we created a typology as a hypothesis to describe and group fundamental similarities shared between OLUs that might be useful for regulators, policy-makers, and planners to apply lessons learned in one OLU to other OLUs that share a similar landscape setting. Since municipalities, counties, and regulatory agencies rarely operate within geomorphic boundaries, categorizing OLUs by type could catalyze collaborations beyond traditional jurisdictions and groups of decision-makers.

Using the previously described data sets, we categorized the 30 OLUs into 12 types. There are many ways to group OLUs depending on the question being asked and the variables most likely to influence the outcome to the question. For example, OLUs could be paired based on marsh resilience to sea level rise, which may involve sorting OLUs based on variables like shoreline change, sediment availability, salinity levels, and elevation capital. A different approach could be taken to pair OLUs by social resilience to sea level rise, which could focus on variables like job density, housing density, and land ownership types. The typology discussed here aims to aggregate OLUs based on where similar types of nature-based adaptation measures could occur, and a recurring criteria throughout the process of mapping each nature-based adaptation measure described in Chapter 4 was *accommodation space*—where sufficient room exists to implement nature-based adaptation measures. While space is not the only requirement to consider when determining whether a measure is appropriate in a certain place, it was found to be one of the most limiting factors. As such, the methodology behind the OLU typology described here stems from categorizing OLUs by their natural and built setting based on the degree to which accommodation space exists. This process relied heavily on best professional judgment to determine both the typology criteria as well as the sorting of OLUs into types.

To create the OLU typology we followed three basic steps:

Step 1. We grouped OLUs based on the three major **geomorphic units** described in Chapter 2: headlands and small valleys, alluvial fans and alluvial plains, and wide alluvial valleys. The geomorphic unit was used as the first criteria to distinguish between major differences in landscape setting as it relates to space, with headlands and small valleys being the most space-limited setting and wide alluvial valleys being the most spacious setting.

Step 2. Each geomorphic unit was split into two categories of **geomorphic form**, based on the historical baylands extent: wide baylands and narrow baylands, distinguishing those areas with more space or opportunity for nature-based adaptation measures from those with less space. Breaks between wide and narrow baylands were determined by calculating average historical baylands width within each OLU and then using best professional judgment to sort OLUs into wide verses narrow baylands categories. We used a series of maps including bathymetry, topography, and historical ecology of the baylands (ca. 1800) to help classify the historical landscape into these categories. Wide baylands were those greater than 500 m for OLUs within headlands and small valleys, and those greater than 1,200 m for OLUs within alluvial fans and alluvial plains, and wide alluvial valleys. The only exception to this rule was Colma-San Bruno OLU, which has an average baylands width around the 1,200 m threshold; given the lack of space due to extensive development, this OLU was categorized as narrow.

Step 3. We then divided these categories into sub-groups based on **current land use patterns** (i.e., modern condition), using data such as modern extent of the baylands, sea level rise projections and flood risk, land use and density patterns, and characterization of the shoreline. The flow charts in this appendix describe the major differences in land use patterns between each OLU type. Interpretations are based on the map layers used and best professional judgement.

This appendix is organized by typology groups (i.e., geomorphic unit) and sub-groups (i.e., OLU type), and can be used to identify similarities in physical and land use settings. This section is not intended to guide site-specific strategies within an OLU, but rather to compare and contrast geomorphic setting and current land uses within OLUs on a regional scale. For more detailed information on suitability of adaptation measures within a specific OLU, see *Chapter 4: Adaptation Measures* and *Chapter 5: Adaptation Opportunities by OLU.*

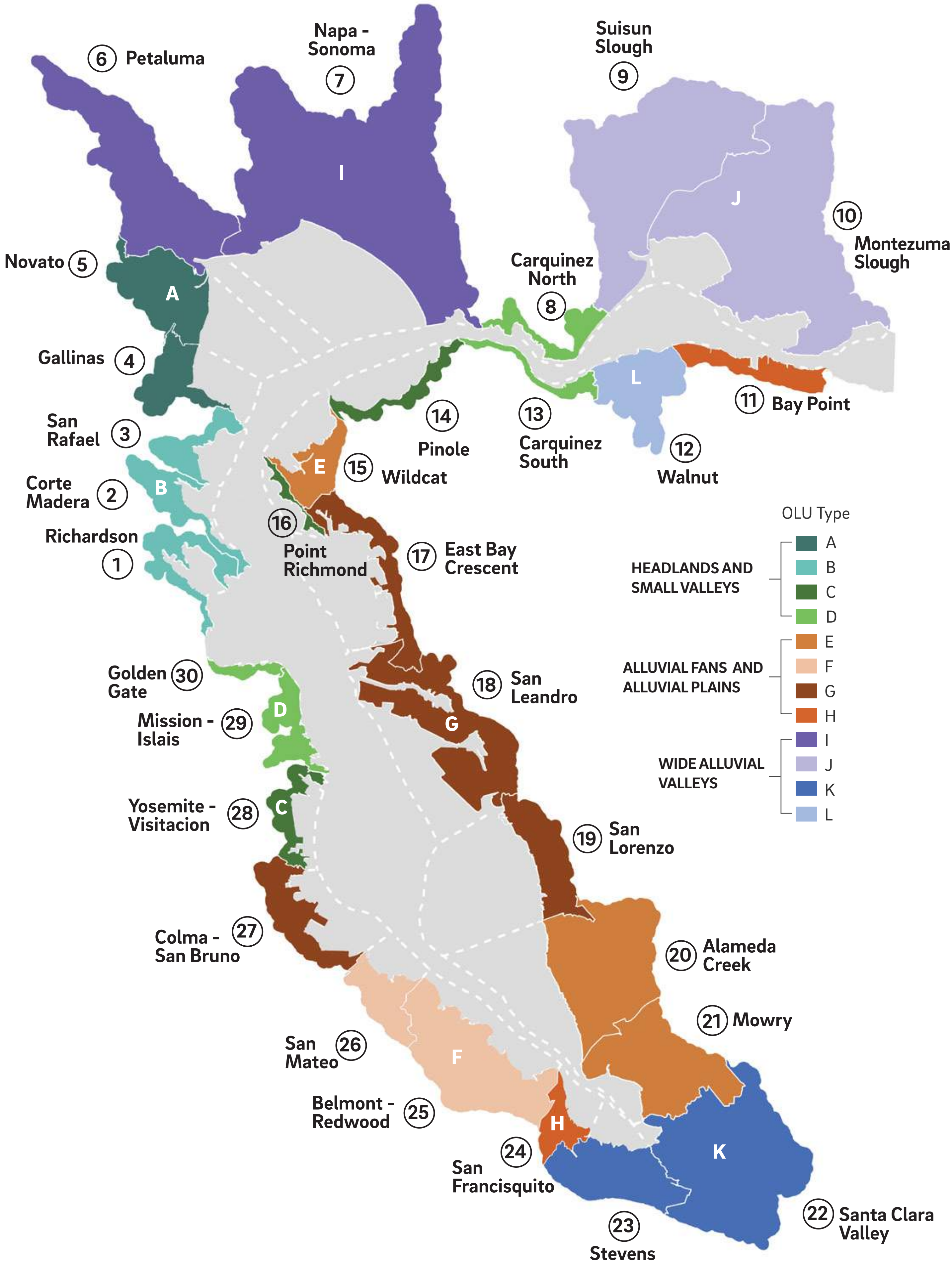
Data gaps, uncertainties, and next steps:

- This is a first attempt at characterizing and matching broad similarities between OLU landscape setting as it relates to accommodation space. The information outlined in this section relied heavily on best professional judgement, leaving room for interpretation and bias. This analysis should be further tested and refined using statistical analyses to separate OLU types in addition to a more robust review from technical advisors before integrating this information into planning processes.
- Many approaches exist for identifying similarities and differences between OLUs, and a different series of types would likely result from considering different variables.
- Several data sets that were unavailable at the time of this report would be useful to further refine this approach, including: tidal flat grain size, tidal flat and tidal marsh morphology, and shoreline change over time.
- Average annual sediment loads described throughout this section are taken from Schoellhamer et al. (2018), which provides watershed-specific sediment loads based on local measurements where available, and regional flow-sediment relationships where measured sediment data is not available; thus, watersheds with no active gauges and no sediment load measurements likely have the highest uncertainty.

Mission-Islais and Golden Gate OLUs (Type D) have little to no accommodation space along their shorelines due to extensive development that has been built out into the Bay, adjacent to deep water (Photo by Craig Howell, CC BY 2.0)

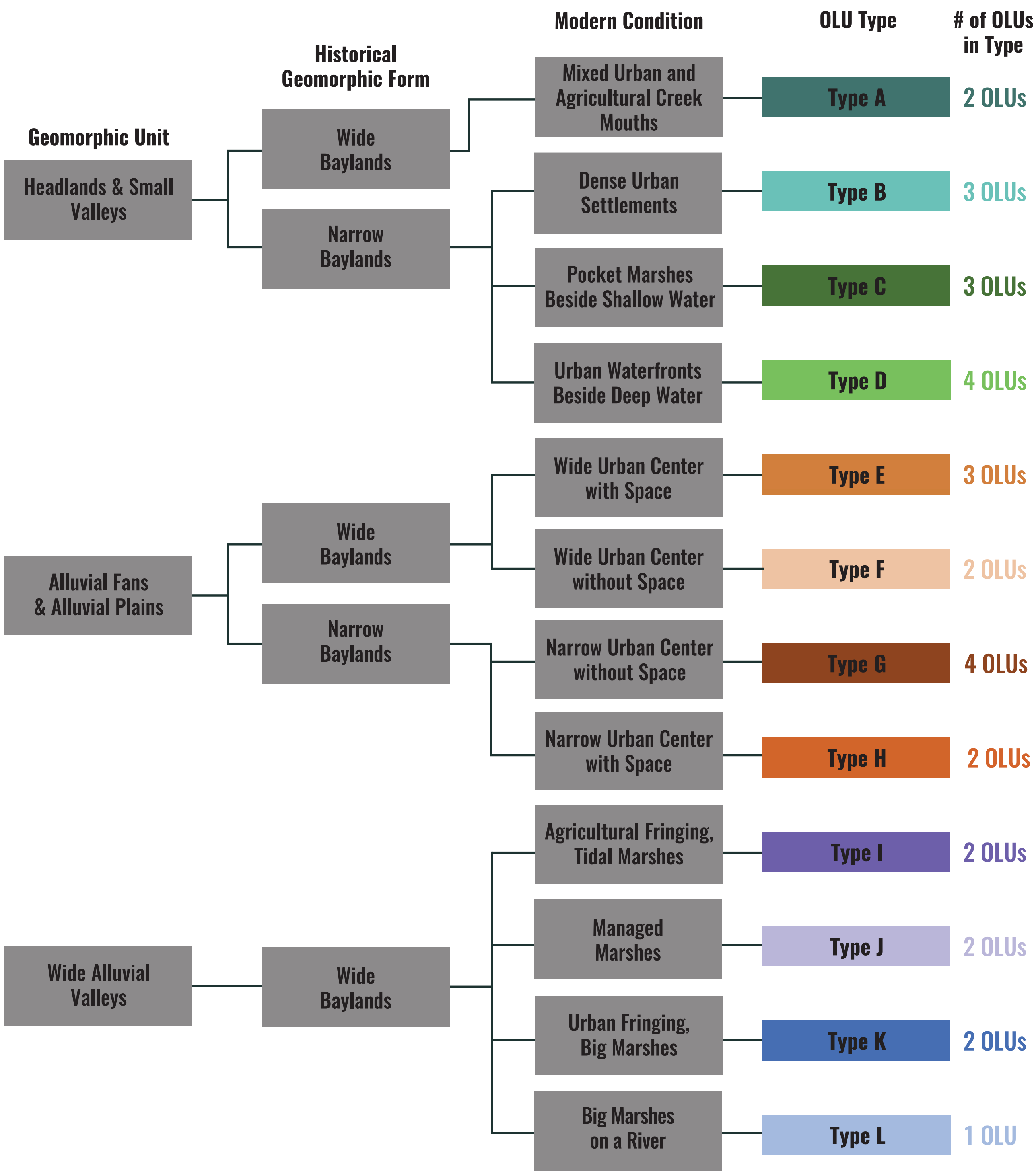
East Bay Crescent OLU (Type G) has little accommodation space along its shoreline due to extensive development and transportation infrastructure built on top of historical baylands; however, some marsh and shallow areas exist, allowing for more nature-based adaptation options compared to Type D (Photo by Jay Huang Photography, CC BY 2.0)

Petaluma OLU (Type I) has much more accommodation space along its shoreline, compared to Types D and G above, due to the large expanse of tidal marsh that has been left intact in this OLU (Photo by Phliar, CC BY-SA 2.0)



6 Petaluma
Napa - Sonoma
7
Suisun Slough
9
I
J
10
Montezuma Slough
Novato 5
A
Carquinez North
8
Gallinas 4
L
11 Bay Point
San Rafael 3
14
Pinole
13
Carquinez South
12
Walnut
Corte Madera 2
B
E
15 Wildcat
16
Point Richmond
Richardson
1
17 East Bay Crescent
OLU Type
HEADLANDS AND SMALL VALLEYS
A
B
C
D
ALLUVIAL FANS AND ALLUVIAL PLAINS
E
F
G
H
WIDE ALLUVIAL VALLEYS
I
J
K
L
Golden Gate 30
18 San Leandro
Mission - Islais 29
D
G
Yosemite - Visitacion 28
C
19 San Lorenzo
Colma - San Bruno 27
20 Alameda Creek
21 Mowry
San Mateo 26
F
Belmont - Redwood 25
H
24
San Francisquito
K
22 Santa Clara Valley
23
Stevens

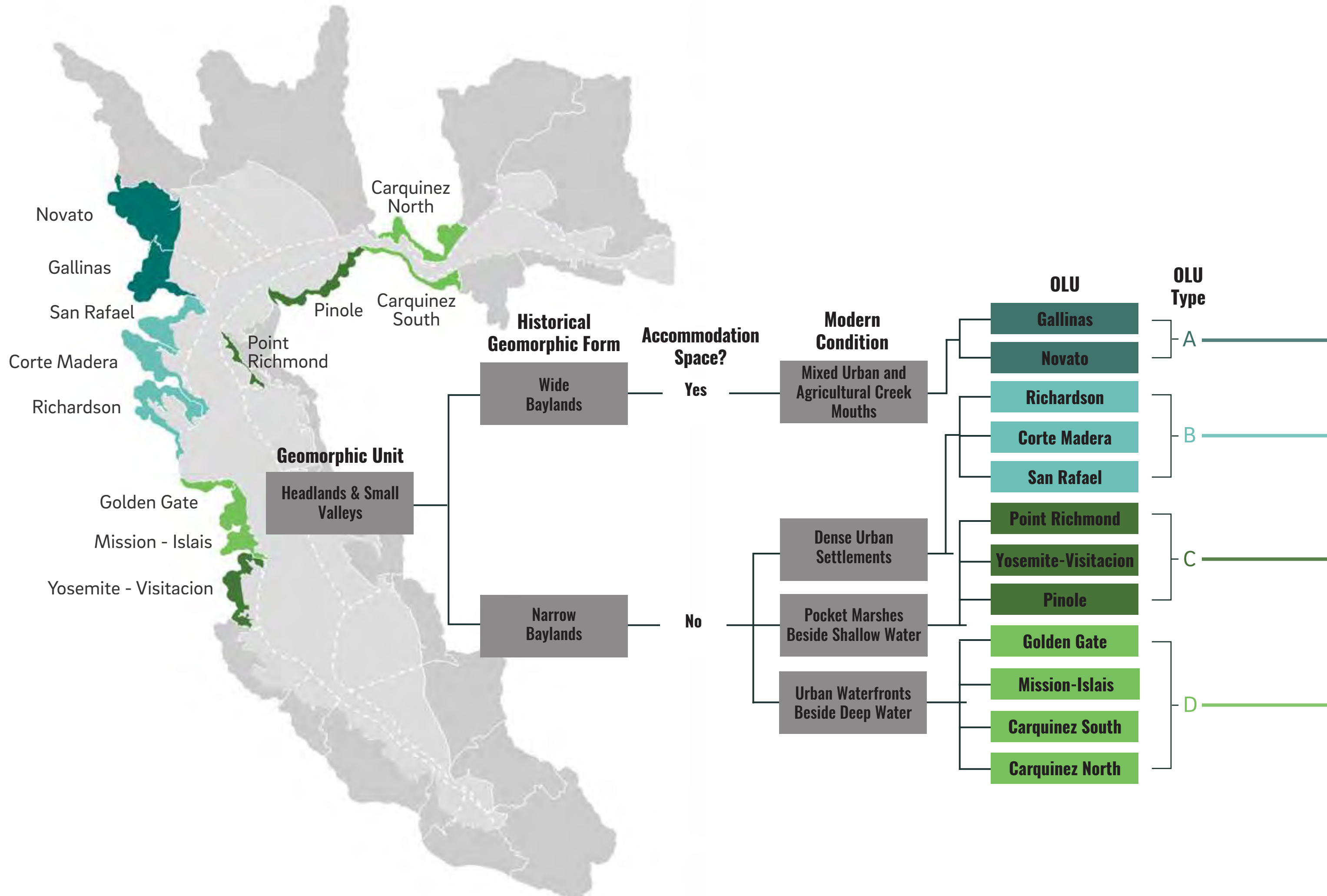
Flow chart showing criteria used to categorize OLUs into similar Bay shore types (based on best professional judgment) for the purpose of understanding similarities in landscape settings throughout San Francisco Bay.

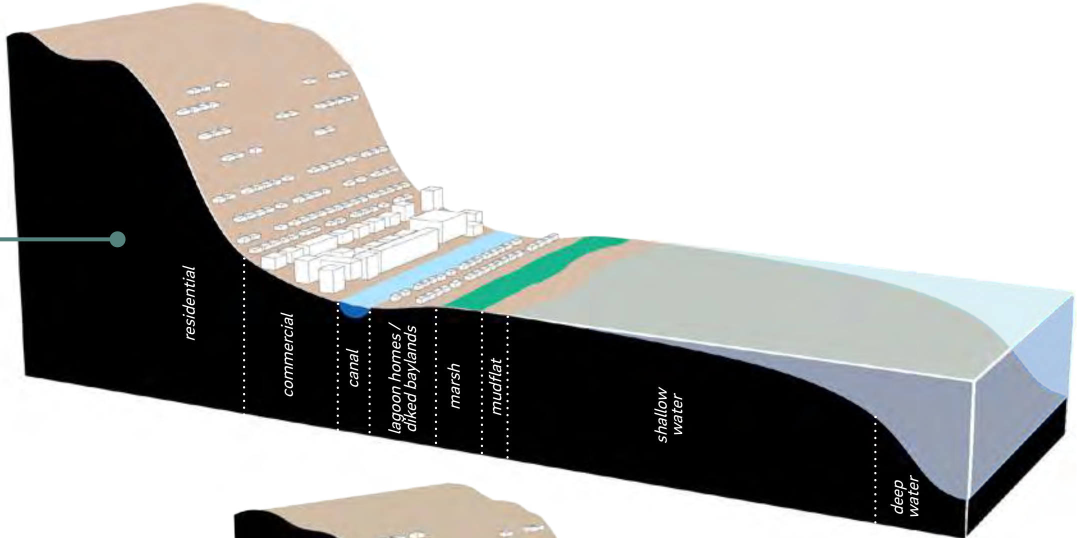


Headlands and small valleys

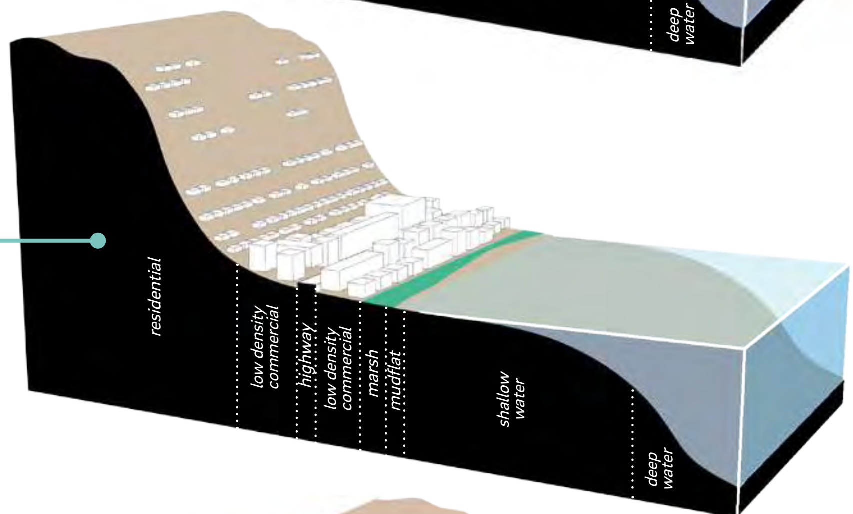
Headlands and small valleys are generally located where older, uplifted pre-Quaternary rock formations lie directly adjacent to the Bay. These steep sections of shoreline (headlands) are often interrupted by small valleys filled with younger, Quaternary alluvium. Pocket marshes—small marshes located between two headlands—are common in sheltered stretches away from wind waves and farther from the Bay's deep channels; in some places, steep headlands plunge into the Bay's deeper waters, leaving little room for intertidal habitats.

Relative to the other types, the headlands and small valleys geomorphic unit type is characterized by small watersheds, steep slopes, narrow baylands, a short distance from the shoreline to deep water, and insufficient accommodation space for tidal habitats to migrate with sea level rise, making them more susceptible to future "coastal squeeze."

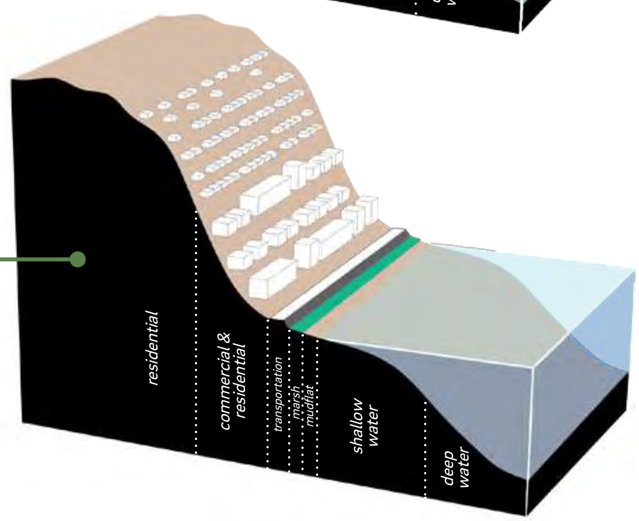




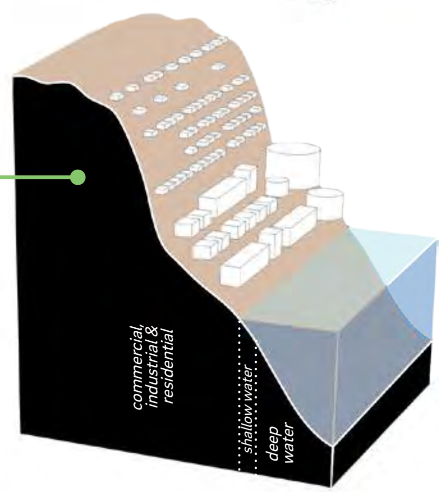
TYPE A: Wide Baylands, Confined Bays and Promontories with More Space



TYPE B: Narrow Baylands, Confined Bays, and Promontories with Less Space



TYPE C: Narrow Baylands, Pocket Marshes, and Beaches Beside Shallow Water with Less Space



TYPE D: Narrow Baylands, Urban Waterfronts Beside Deep Water with Less Space

Conceptual drawings of generalized transects of each OLU type in the headlands & small valleys geomorphic unit.

Headlands and small valleys

TYPE A: WIDE BAYLANDS, CONFINED BAYS & PROMONTORIES WITH MORE SPACE

Mixed urban and agricultural creek mouths

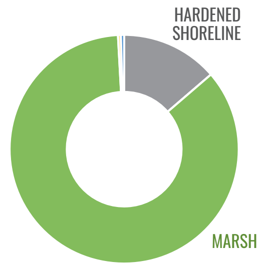
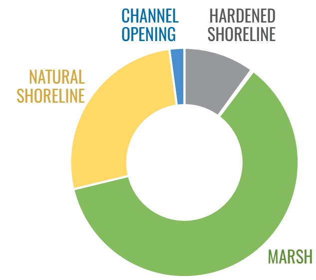
This type, seen only in the San Pablo Bay region, consists of larger watersheds with less confined mouths/deltas. Promontories flank these creek mouths, but they are located further inland, with marsh built up around them. This type features large areas of marsh with mudflats in front and a marsh-dominated shoreline. Sediment deposition from historical hydraulic mining led to progradation of marshes and mudflats which were then reclaimed, thus pushing land uses into the shallow muddy waters of San Pablo Bay (Salomon et al. 2015). Dominant land uses in this type are open space, agriculture, and low-density residential development, notably in the form of man-made "lagoon" communities in Santa Venetia and Bel Marin Keys. This type does not have major development directly on the shoreline.

Key similarities and differences

Gallinas and Novato OLUs vary significantly in their vulnerabilities to sea level rise largely because of the proximity of houses and communities to the shoreline, the degree of baylands subsidence, and the size and sediment loads of their contributing watersheds. The Novato baylands are deeply subsided (extending below mean lower low water in some areas), and surround the Bel Marin Keys community, which is perched at sea level. The northern undeveloped parts of the Gallinas OLU are slightly subsided, but much of their vulnerability is due to combined flooding hazards from Gallinas Creek, which threatens areas in Santa Venetia. Novato has a much larger watershed size, and sediment supply and delivery vary between these two OLUs. Differences in lateral shoreline change also exist. While the marsh edge in Gallinas has been the degree of stable for the last 20 years, about two-thirds of the marsh scarp in the Novato OLU, along the edge of the Hamilton Marsh Restoration project, has eroded at an average of 2 m per year between 1993 and 2010 (Beagle et al. 2015).

(Left) View looking towards Pacheco Pond and the Bel Marin Keys community in the Novato OLU (Photo by Sharon Hahn Darlin, CC BY 2.0)

(Right) King tides at China Camp State Park in San Rafael, Gallinas OLU (Photo by Stephen Sarhad, CC BY 2.0)

HISTORICAL BAYLANDS	MODERN BAYLANDS	CURRENT SHORELINE COMPOSITION*	
			Novato
			Gallinas

LEGEND & SCALE

Baylands ca. 1800

- Deep bay / channel
- Salt pond
- Shallow bay / channel
- Lagoon
- Tidal flat
- Tidal marsh
- Shellflat / shellmound
- Dune / beach

Baylands 2009

- Deep bay / channel
- Salt pond
- Shallow bay / channel
- Managed pond**
- Tidal flat**
- Tidal marsh**
- Diked wetland**
- Agriculture / other undeveloped area
- Developed areas

*For more information on shoreline composition categories, see page 234.

**Hashing on Baylands 2009 maps indicates where restoration activities have occurred or are planned based on 1998 and 2009 data. For managed ponds this includes habitat enhancement. Habitats shown represent projected restoration endpoints.

FOR ALL MAPS ON THIS PAGE

1 mile

1 km

N

Headlands and small valleys

TYPE B: NARROW BAYLANDS, CONFINED BAYS & PROMONTORIES WITH LESS SPACE

Coves with dense urban centers

This type consists of small narrow valleys between steep promontories jutting into the Bay, creating protected coves, or small embayments, where marshes formed historically. Wind-wave energy is high along headlands adjacent to deep water, and lower within coves, though long fetches exist. Historically, marshes existed at the deltas of the creeks draining these watersheds, with large mudflats on the bayward side. These small valleys have been densely developed, mainly for residential use in the hills, and for mixed-use commercial developments, town centers, and light industry in the baylands, and many have subsided. Shorelines in this typology have been built out to or beyond the historical extent of marshes, and often into the historical mudflat extent. Each shoreline is over 50% hardened—often with a road right along the water's edge—with areas of remnant marsh still present in Corte Madera and Richardson OLUs. Development in historical marshes, typically mixed-use commercial and light industry, is particularly vulnerable to sea level rise in these settings.

Key similarities and differences

These three OLUs might be considered similar for their relative vulnerabilities and possible appropriate strategies. However it is important to recognize their differences. Richardson poses its own specific set of flood risk challenges along low-lying sections of transportation, such as Highway 101, Highway 1, and Miller Avenue. Many low-lying communities are also at risk, including Almonte, Marin City, and the Marinship area in Sausalito (BayWAVE 2017). Corte Madera and San Rafael OLUs were historically more similar in the orientation of their shorelines, with creek deltas fronted by wide mudflats. A critically important, though eroding, marsh complex remains along the Corte Madera shoreline, though the San Rafael equivalent has been filled completely, leaving little opportunity for marsh restoration on the outboard side of San Rafael's levee, except at Tiscornia Marsh. Corte Madera has a relatively large, sediment-rich contributing watershed, while San Rafael is smaller.

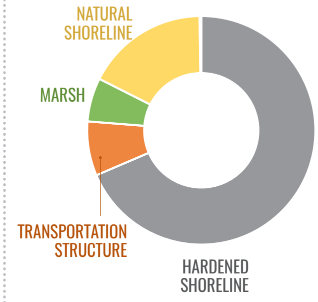
(Left) View of Richardson Bay's shoreline in Richardson OLU from Angel Island towards Mount Tamalpais (Photo by Phoca2004, CC BY 2.0)

(Right) Shoreline at San Quentin in Corte Madera OLU (Photo by Shira Bezalel, SFEI)

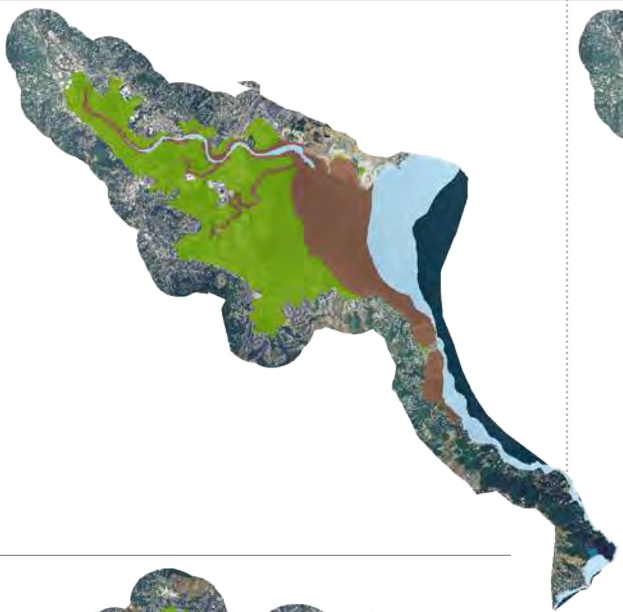
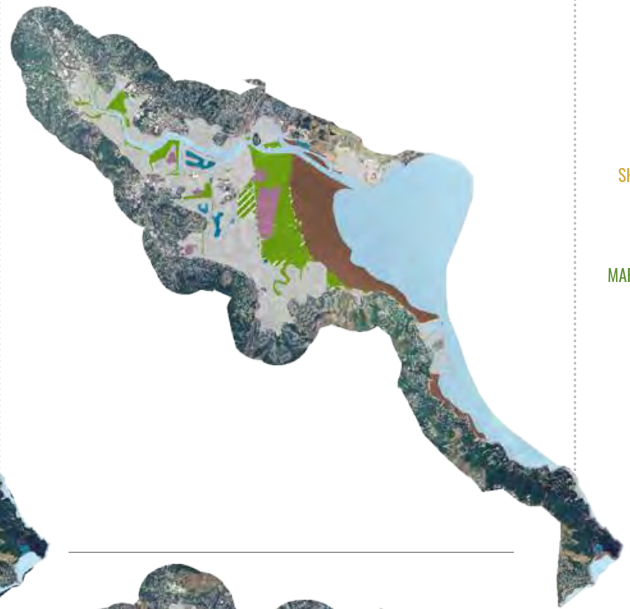
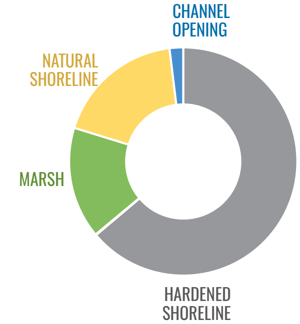
HISTORICAL BAYLANDS	MODERN BAYLANDS	CURRENT SHORELINE COMPOSITION*

San Rafael



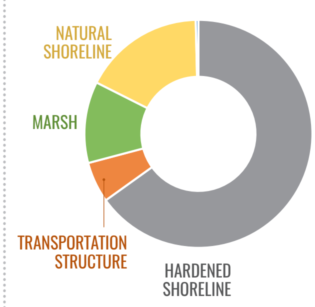


Corte Madera

Richardson





LEGEND & SCALE

Baylands ca. 1800

- Deep bay / channel
- Salt pond
- Shallow bay / channel
- Lagoon
- Tidal flat
- Tidal marsh
- Shellflat / shellmound
- Dune / beach

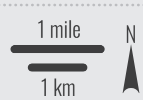
Baylands 2009

- Deep bay / channel
- Salt pond
- Shallow bay / channel
- Managed pond**
- Tidal flat**
- Tidal marsh**
- Diked wetland**
- Agriculture / other undeveloped area
- Developed areas

*For more information on shoreline composition categories, see page 234.

**Hashing on Baylands 2009 maps indicates where restoration activities have occurred or are planned based on 1998 and 2009 data. For managed ponds this includes habitat enhancement. Habitats shown represent projected restoration endpoints.

FOR ALL MAPS ON THIS PAGE



Headlands and small valleys

TYPE C: NARROW BAYLANDS, SHALLOW WATER WITH LESS SPACE

Pocket marshes and beaches with shallow water

This type is characterized by steep bluffs, with some pocket marshes, small creeks, small mudflats, and areas of shallow water protected in a cove-like orientation in a high-wave environment. These areas tend to have major transit (e.g., roads or rail) near the water that cross or bisect open space. The nearest development is typically low-density residential, mixed use, or heavy industry with a smaller area at risk of near-term sea level rise.

Key similarities and differences

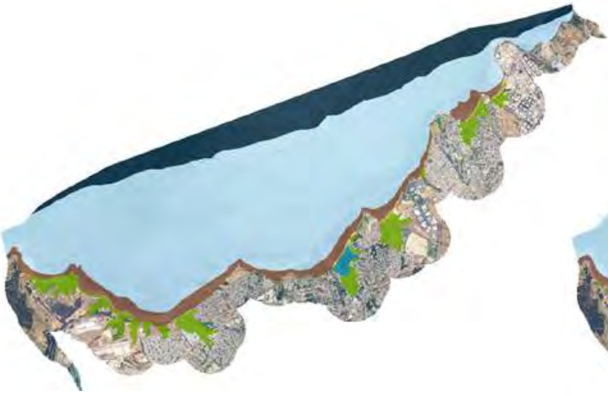
While these three OLUs have a similar form and slope, and similar relative vulnerabilities, their orientation and relative importance to regional connectivity varies greatly. Highway 101 is the "first line of defense" in the Yosemite-Visitacion OLU, and is the major transportation corridor between San Francisco and Silicon Valley. The Pinole OLU shoreline is similarly fronted by a critical rail line connecting the Bay Area with the State Capitol. Point Richmond is home to several oil refineries which are generally not at risk of flooding from sea level rise in the near term but are vulnerable to other climate change impacts (e.g., increased frequency and intensity of wildfires). Both Point Richmond and Pinole are naturally occurring bluffs and, through bluff erosion, can provide a natural source of coarse material that supports pocket beaches except when infrastructure prevents sediment delivery. Although pocket beaches exist, they are less common in Yosemite-Visitacion since much of it's shoreline has been built out with artificial fill beyond its historical mudflat extent.

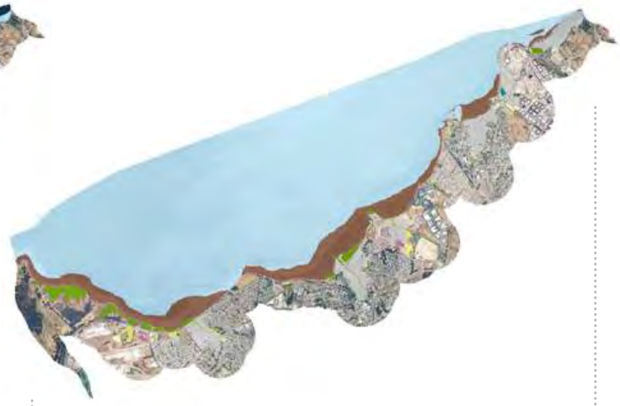
(Left) View of the Bay Trail in Point Pinole Regional Shoreline, East Bay Regional Park District in the Pinole OLU (Photo by Shira Bezalel, SFEI)

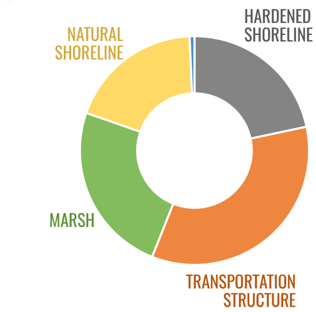
(Right) Winehaven, a historical building at Point Molate located on the Point Richmond OLU shoreline (Photo by Jeff, CC BY 2.0)

HISTORICAL BAYLANDS	MODERN BAYLANDS	CURRENT SHORELINE COMPOSITION*

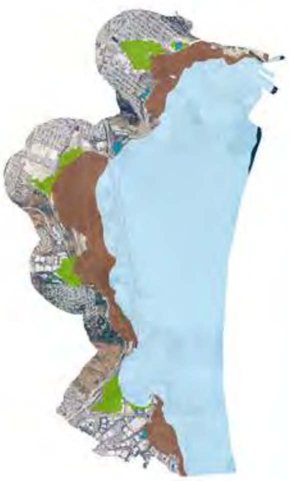
Pinole

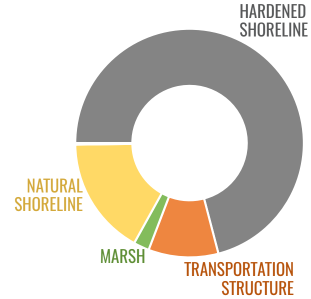




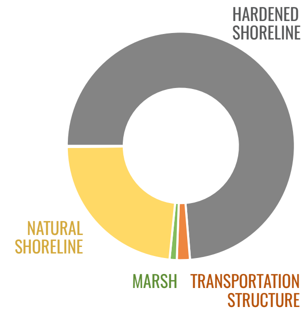


Yosemite-Visitacion





Point Richmond



LEGEND & SCALE

Baylands ca. 1800

- Deep bay / channel
- Salt pond
- Shallow bay / channel
- Lagoon
- Tidal flat
- Tidal marsh
- Shellflat / shellmound
- Dune / beach

Baylands 2009

- Deep bay / channel
- Salt pond
- Shallow bay / channel
- Managed pond**
- Tidal flat**
- Tidal marsh**
- Diked wetland**
- Agriculture / other undeveloped area
- Developed areas

*For more information on shoreline composition categories, see page 234.

**Hashing on Baylands 2009 maps indicates where restoration activities have occurred or are planned based on 1998 and 2009 data. For managed ponds this includes habitat enhancement. Habitats shown represent projected restoration endpoints.

FOR ALL MAPS ON THIS PAGE

1 mile

1 km

N

Headlands and small valleys

TYPE D: NARROW BAYLANDS, DEEP WATER WITH LESS SPACE

Urban waterfronts

This type is characterized by a shoreline that drops quickly into deep water, adjacent to either steep headlands or a fully developed area with steep, engineered topography. This type is subject to higher wave energy and naturally supports rocky or sandy shorelines. In these settings there were historically small areas of pocket or backbarrier marsh and a very narrow intertidal area. In some settings the shoreline has been built out significantly with dense urban development (e.g., downtown San Francisco in Golden Gate OLU) or heavy industry (e.g., Mission-Islais OLU). Transportation structures often front this type of shoreline, reflecting these areas' development history of filling baylands to create a deep-water offshore port accessible by road or rail. Land use in these settings is intensely urban and may include a mix of industrial, commercial, and high-density residential.

Pocket beach at Benecia State Recreation Area in the Carquinez North OLU (Photo by Shira Bezalel, SFEI)

Key similarities and differences

This type is characterized by a generally steep land slope and abrupt interface to deep water. This limits the feasibility of marsh restoration or other adaptation measures that require a lot of space. However there are key differences between the shoreline of San Francisco, where Bay fill has pushed the shoreline unnaturally out into deep, high-energy water highly subject to swell, and the Carquinez Strait, where a river naturally narrows between bedrock and the current dominates over swell- or wind-waves. These two groups of OLUs (the San Francisco and the Carquinez) also fall on opposite ends of the salinity gradient, with often saline environments in the more marine-dominated mouth of the Bay compared to the brackish environments towards the Sacramento-San Joaquin Delta. Because of this, these two groups of OLUs support different types of marsh vegetation communities which have different abilities to keep pace with sea level rise based on bulk density requirements. Even between the Golden Gate and the Mission-Islais OLUs there are major differences in wave environments. The Golden Gate OLU is subject to swell, while the Mission-Islais OLU (i.e., the eastern shoreline of San Francisco) is slightly more protected, though still a high wave-energy environment.

LEGEND

Baylands ca. 1800

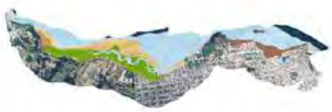
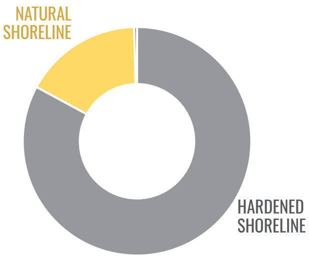
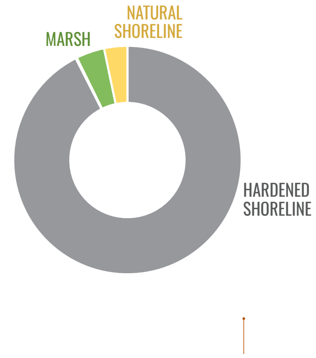
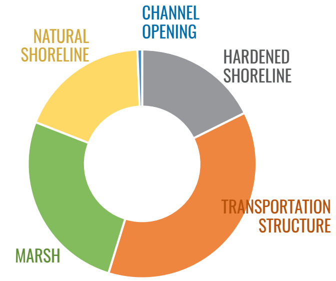
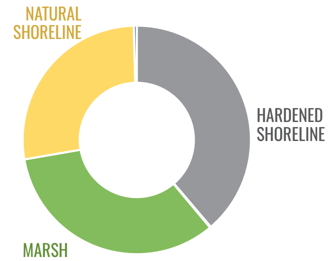
- Deep bay / channel
- Salt pond
- Shallow bay / channel
- Lagoon
- Tidal flat
- Tidal marsh
- Shellflat / shellmound
- Dune / beach

Baylands 2009

- Deep bay / channel
- Salt pond
- Shallow bay / channel
- Managed pond**
- Tidal flat**
- Tidal marsh**
- Diked wetland**
- Agriculture / other undeveloped area
- Developed areas

*For more information on shoreline composition categories, see page 234.

**Hashing on Baylands 2009 maps indicates where restoration activities have occurred or are planned based on 1998 and 2009 data. For managed ponds this includes habitat enhancement. Habitats shown represent projected restoration endpoints.

HISTORICAL BAYLANDS	MODERN BAYLANDS	CURRENT SHORELINE COMPOSITION*	
			**Golden Gate**
			**Mission-Islais**
			**Carquinez South**
			**Carquinez North**

SEE PREVIOUS PAGE FOR LEGEND

FOR ALL MAPS ON THIS PAGE

1 mile

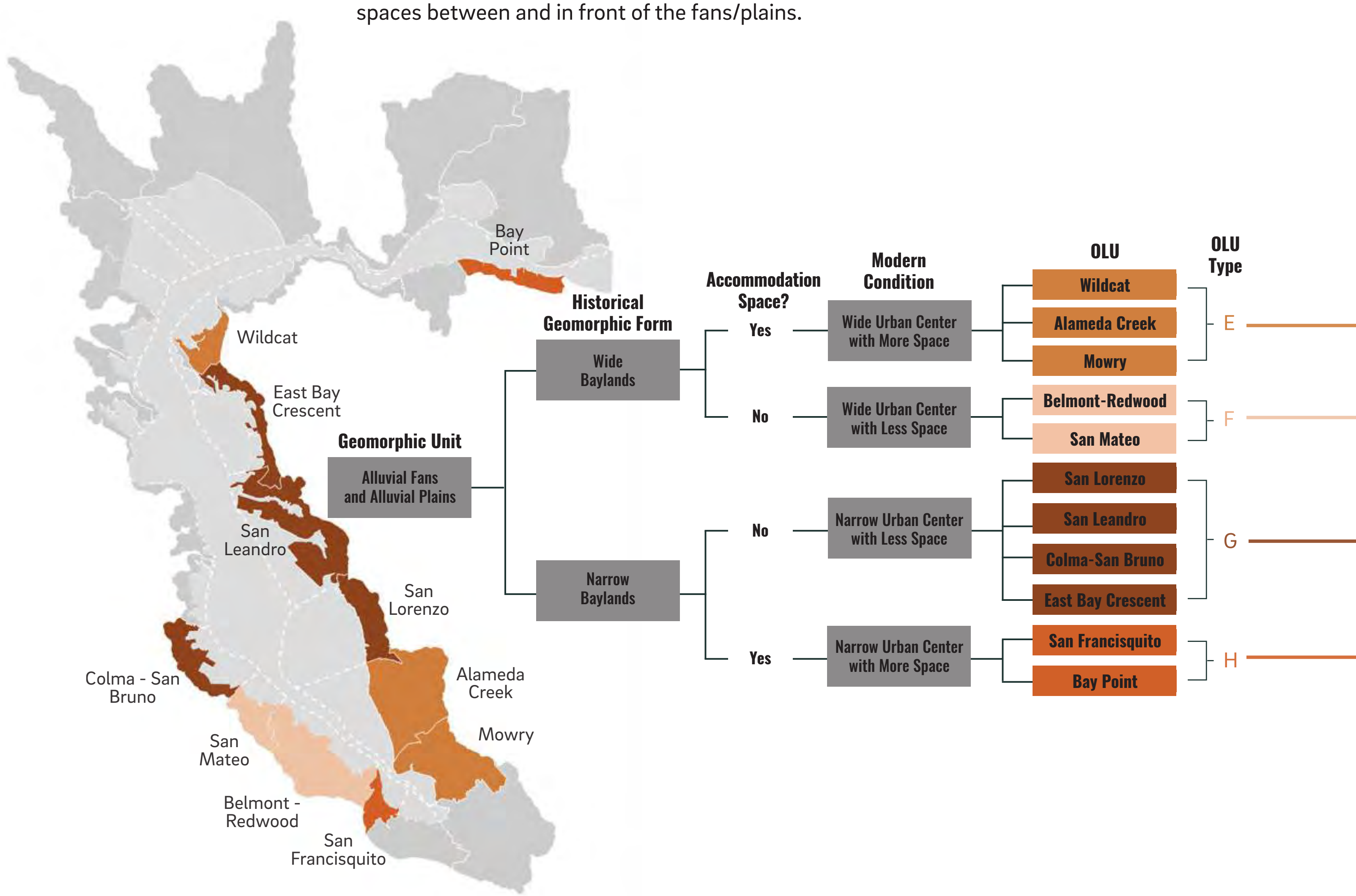
1 km

N

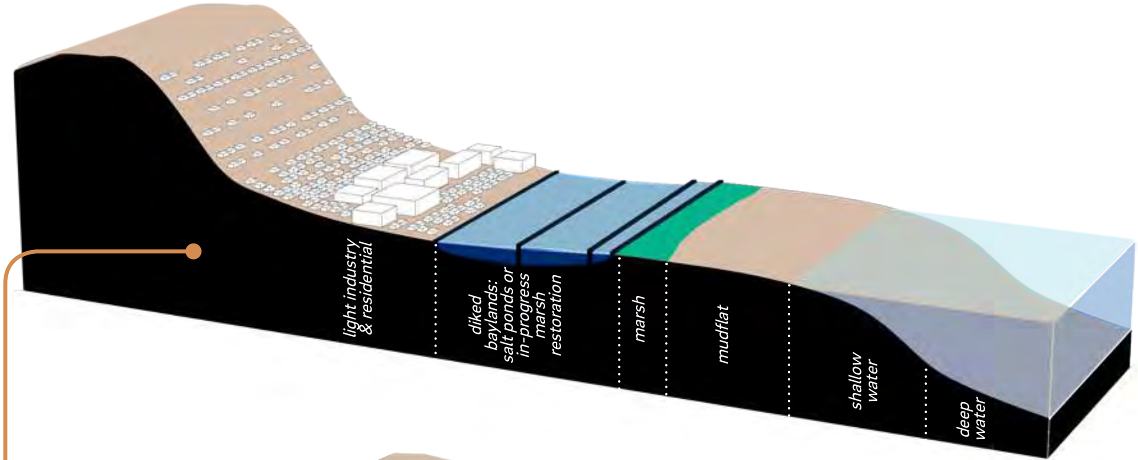
SCALE

Alluvial fans and alluvial plains

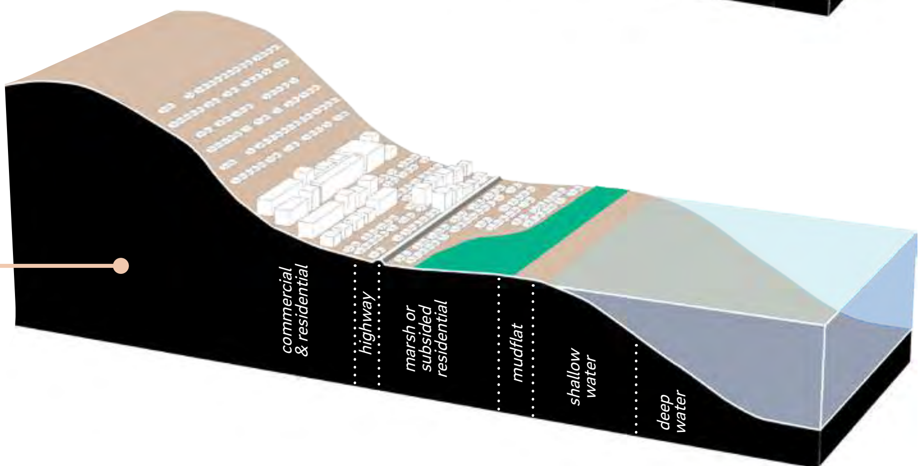
Alluvial fans and alluvial plains are the areas built up over thousands of millennia with sand and gravel eroded from the Coast Range hills and deposited on the floor of the valley that currently contains San Francisco Bay (Sloan 2006). These areas include the distinct fans formed by San Mateo, San Francisquito, Alameda, San Lorenzo, San Leandro, and Wildcat creeks, and less-pronounced plains formed by many smaller creeks, such as the East Bay flats between Oakland and El Cerrito and the flats northeast of the Diablo Range between Port Chicago and Oakley (Knudsen et al. 2000, Sloan 2006). The location and shape of the fans and plains influences the shape of the baylands, which generally have filled in the spaces between and in front of the fans/plains.



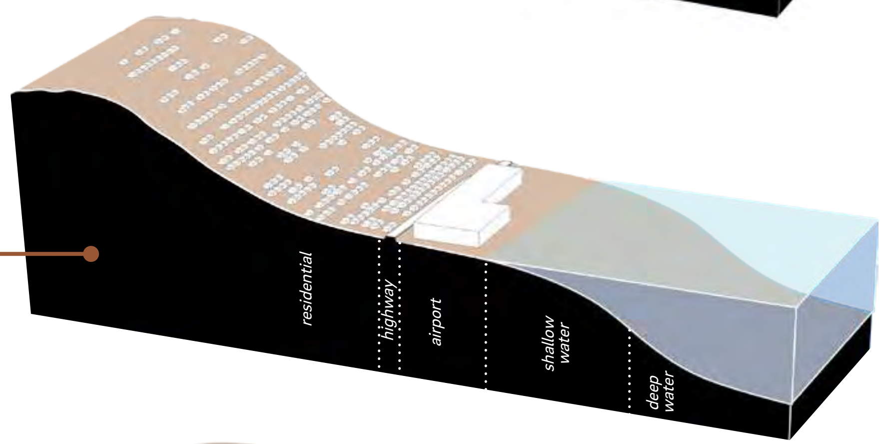
Along with OLU Types A and B, where development has settled around low-lying creek mouths, OLUs in this geomorphic unit type have the greatest amount of high-density developments most threatened by near-term sea level rise.



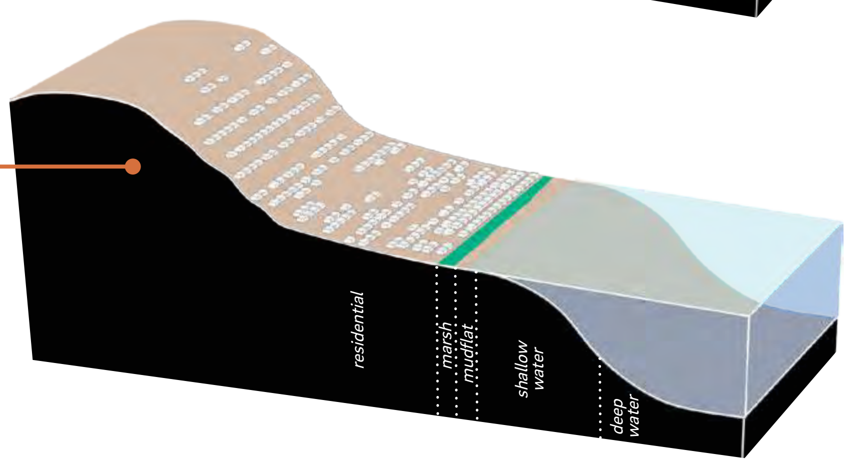
TYPE E: Wide Baylands, Urban Centers With More Space



TYPE F: Wide Baylands, Urban Centers With Less Space



TYPE G: Narrow Baylands, Urban Centers With Less Space



TYPE H: Narrow Baylands, Urban Centers With More Space

Conceptual drawings of generalized transects of each OLU type in the alluvial fans & alluvial plains geomorphic unit.

Alluvial fans and alluvial plains

TYPE E: WIDE BAYLANDS, URBAN CENTERS WITH MORE SPACE

Wide, developed baylands

This type is characterized by historically wide marshes and mudflats in between the apexes of fans. These areas have gradual slopes and a long gradient between the subtidal and supratidal zones. Because of the wide expanse of baylands and mudflats, development (e.g., transportation, residential, town centers) tends to be further from the shoreline. The shorelines in this type are mainly composed of fringing marshes, backed by unengineered berms and subsided salt ponds or diked marsh. Low-density light industry and commercial land uses such as big box stores (i.e., large commercial buildings with big surrounding parking lots) occupy the locations of historical wet meadow along the backshore.

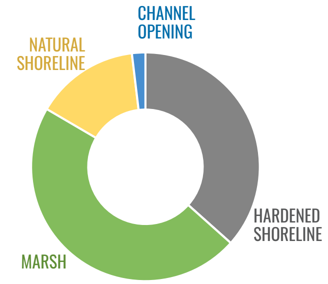
Key similarities and differences

While the vast majority of the historical tidal marshlands in Alameda Creek and Mowry OLUs were converted to diked salt ponds, Wildcat OLU's marshlands were filled, in large part to create land for heavy industry, though some areas were diked to create storage and treatment ponds (Collins et al. 2001). Although the scale of the current mouth of Wildcat Creek is smaller than the Alameda Creek and Mowry OLUs, these three OLUs are unique in that space exists adjacent to vulnerable development to employ marshes as flood protection and implement other adaptation measures that require a certain amount of space. While Wildcat and Alameda Creek OLUs are fed directly by large watersheds, the Mowry OLU is characterized by very little fluvial input or watershed connections, making combined flooding less of a concern. Alameda Creek OLU has an average annual sediment load that is estimated to be an order of magnitude higher than Mowry and Wildcat OLUs (Schoellhamer et al. 2018), but it drains a much larger area—at approximately 1,800 km^2 (700 mi^2), Alameda Creek has the largest contributing watershed area of all San Francisco Baylands OLUs.

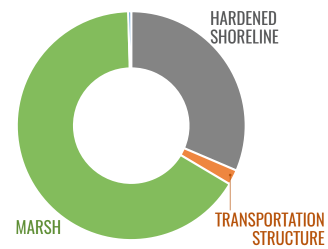
View of the baylands from Coyote Hills Regional Park in the Alameda Creek OLU (Photo by Shira Bezalel, SFEI)

HISTORICAL BAYLANDS	MODERN BAYLANDS	CURRENT SHORELINE COMPOSITION*

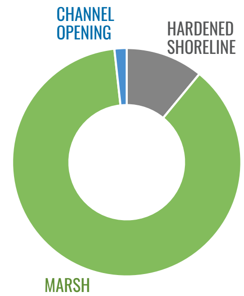
Wildcat



Alameda Creek



Mowry



LEGEND & SCALE

Baylands ca. 1800

- Deep bay / channel
- Salt pond
- Shallow bay / channel
- Lagoon
- Tidal flat
- Tidal marsh
- Shellflat / shellmound
- Dune / beach

Baylands 2009

- Deep bay / channel
- Salt pond
- Shallow bay / channel
- Managed pond**
- Tidal flat**
- Tidal marsh**
- Diked wetland**
- Agriculture / other undeveloped area
- Developed areas

*For more information on shoreline composition categories, see page 234.

**Hashing on Baylands 2009 maps indicates where restoration activities have occurred or are planned based on 1998 and 2009 data. For managed ponds this includes habitat enhancement. Habitats shown represent projected restoration endpoints.

FOR ALL MAPS ON THIS PAGE

1 mile

1 km

N

Alluvial fans and alluvial plains

TYPE F: WIDE BAYLANDS, URBAN CENTERS WITH LESS SPACE

Wide, developed baylands

This type also has historically wide marshes and mudflats in between the apexes of fans, and a long, low gradient between subtidal and supratidal zones. However this subgroup is distinct from Type E because in many places development has encroached all the way out onto historical mudflats, leaving the shoreline closer to deep water than it naturally would be, especially in areas like Foster City and Redwood Shores. This creates significant drainage challenges, along with a higher risk of near-term inundation from sea level rise. Highway 101 also forms a hard boundary along the historical extent of baylands in this type.

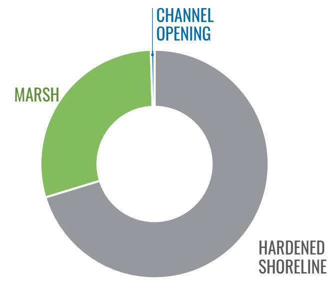
Key similarities and differences

The key difference between the two OLUs in Type E is seen in development patterns. Development in the San Mateo OLU has left no natural marshes, and only a narrow mudflat (though it does have some open space in the form of parks and landfills along the shoreline), while development in the Belmont-Redwood OLU has left some natural marshes and mudflats intact. While the northernmost portion of the Belmont-Redwood OLU around Foster City resembles the San Mateo OLU development patterns, the rest of the OLU has preserved large portions of its historical tidal marsh and tidal flats. These development patterns have resulted in different ecological implications: the portions of shoreline fronted by Bair Island and Greco Island in the Belmont-Redwood OLU remain some of the largest stretches of tidal marsh dominated shoreline in this section of the Bay, making it critical as a stepping stone for marsh birds and wildlife.

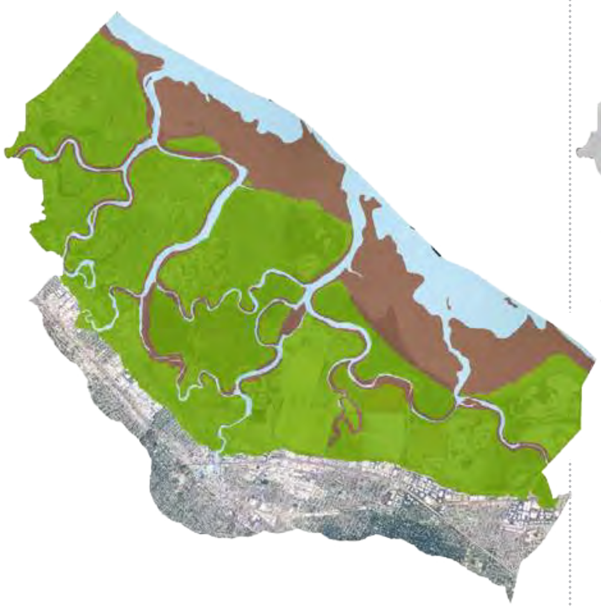
Examples of development in the Belmont-Redwood OLU that have been built to the shoreline, leaving little space for nature-based sea level rise adaptation measures. However, large islands like Bair Island, pictured below, remain undeveloped and protected as tidal marsh restoration projects (Photo by Mark Doliner, CC BY 2.0)

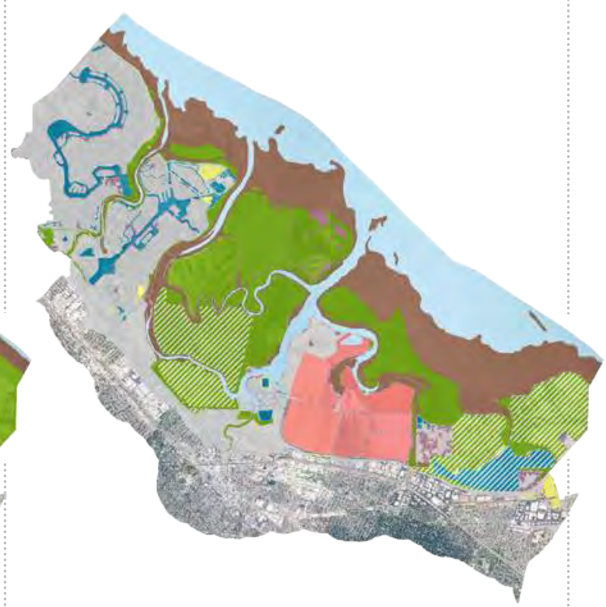
HISTORICAL BAYLANDS	MODERN BAYLANDS	CURRENT SHORELINE COMPOSITION*

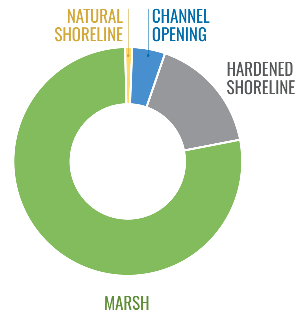
San Mateo



Belmont-Redwood







LEGEND & SCALE

Baylands ca. 1800

- Deep bay / channel
- Salt pond
- Shallow bay / channel
- Lagoon
- Tidal flat
- Tidal marsh
- Shellflat / shellmound
- Dune / beach

Baylands 2009

- Deep bay / channel
- Salt pond
- Shallow bay / channel
- Managed pond**
- Tidal flat**
- Tidal marsh**
- Diked wetland**
- Agriculture / other undeveloped area
- Developed areas

*For more information on shoreline composition categories, see page 234.

**Hashing on Baylands 2009 maps indicates where restoration activities have occurred or are planned based on 1998 and 2009 data. For managed ponds this includes habitat enhancement. Habitats shown represent projected restoration endpoints.

FOR ALL MAPS ON THIS PAGE

1 mile

1 km

N

Alluvial fans and alluvial plains

TYPE G: NARROW BAYLANDS, URBAN CENTERS WITH LESS SPACE

Industrial shorelines

Like type H, this type is characterized by historically narrow baylands in higher sloped areas where fans or plains pushed into the Bay. Type G historically had less marsh than types E and F, making it easier for development to occur close to the shoreline or into the Bay by way of artificial fill. These OLUs are located in the high wave-energy central part of the Bay, where there is a concentration of heavy industry, ports, and airports, including Oakland International Airport and San Francisco International Airport. This OLU type is characterized by a largely hardened shoreline fronting mixed-use developments that host a large number of jobs and residences at risk of near-term sea level rise.

Key similarities and differences

While it shares many of the same characteristics as other OLUs in this type, the San Lorenzo OLU differs in having relatively high potential for marsh restoration in the narrow buffer between development and the Bay. Light industry, wastewater treatment plants, and other infrastructure occupy this area. Alameda Island in the San Leandro OLU also has residential land uses directly adjacent to the Bay, posing increased risk with sea level rise.

(Left) Major highway infrastructure located along the Bay shore in the East Bay Crescent OLU (Photo by Katie McKnight, SFEI)

(Right) Aerial view of the Port of Oakland and Oakland International Airport, located along the Bay shore in the San Leandro OLU (Photo by Craig Howell, CC BY 2.0)

LEGEND

Baylands ca. 1800

- Deep bay / channel
- Salt pond
- Shallow bay / channel
- Lagoon
- Tidal flat
- Tidal marsh
- Shellflat / shellmound
- Dune / beach

Baylands 2009

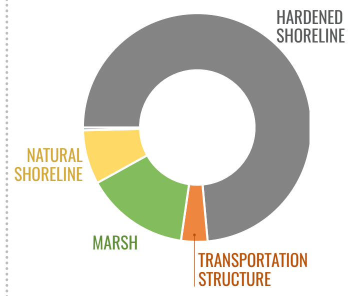
- Deep bay / channel
- Salt pond
- Shallow bay / channel
- Managed pond**
- Tidal flat**
- Tidal marsh**
- Diked wetland**
- Agriculture / other undeveloped area
- Developed areas

*For more information on shoreline composition categories, see page 234.

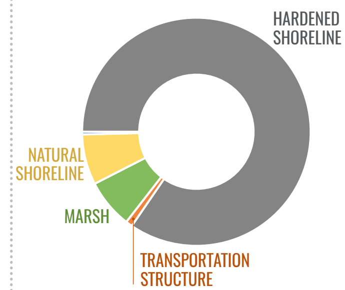
**Hashing on Baylands 2009 maps indicates where restoration activities have occurred or are planned based on 1998 and 2009 data. For managed ponds this includes habitat enhancement. Habitats shown represent projected restoration endpoints.

HISTORICAL BAYLANDS	MODERN BAYLANDS	CURRENT SHORELINE COMPOSITION*	

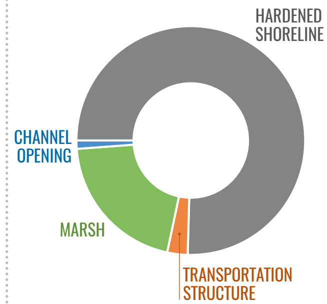
East Bay Crescent



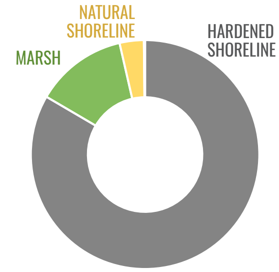
San Leandro



San Lorenzo



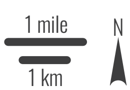
Colma-San Bruno



SCALE

SEE PREVIOUS PAGE FOR LEGEND

FOR ALL MAPS ON THIS PAGE



Alluvial fans & alluvial plains

TYPE H: NARROW BAYLANDS, URBAN CENTERS WITH MORE SPACE

Marshes and mixed uses

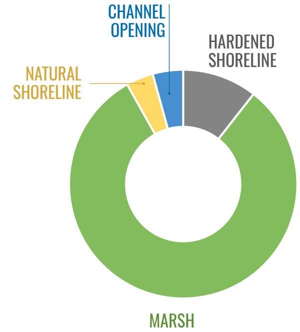
This OLU type is characterized by historically narrower baylands, where fans pushed into the Bay, but that still sustain remnant marshes and other open spaces between the Bay and urban development. Industrial and medium-density mixed uses are the primary development types upland of the marshes and open space. Both OLUs in this type have centers of frontline communities predicted to be vulnerable to rising seas, and both have stretches of ecologically valuable marshes separating residential communities from the Bay.

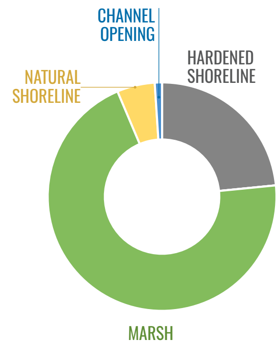
Key similarities and differences

While both of the OLUs in this type have shorelines predominately fronted by tidal marsh, the San Francisquito OLU shoreline is characterized by high waves, a high tidal range, and shallow water offshore, while the Bay Point OLU is adjacent to the Sacramento-San Joaquin River and is characterized by deep water, low waves, and a low tidal range. Salinity levels between Suisun Bay and the lower South Bay are very different, impacting the type of marsh vegetation communities supported within each OLU, with more saline marsh in San Francisquito and more brackish marsh in Bay Point. These marsh vegetation types have inherent bulk density differences that translate to varying abilities to keep pace with sea level rise (Schile 2012). San Francisquito also has over four times the amount of average annual total sediment load and double the contributing watershed area compared to Bay Point (building upon data created by Schoellhamer et al. [2018]). San Francisquito Creek is the main watershed draining the San Francisquito OLU, while Bay Point's contributing watershed area is more evenly divided among approximately eight smaller watersheds.

Residential and industrial land uses fronted by tidal marsh in East Palo Alto, San Francisquito OLU (Photo by Craig Howell, CC BY 2.0).

HISTORICAL BAYLANDS	MODERN BAYLANDS	CURRENT SHORELINE COMPOSITION*





Baylands ca. 1800

- Deep bay / channel
- Salt pond
- Shallow bay / channel
- Lagoon
- Tidal flat
- Tidal marsh
- Shellflat / shellmound
- Dune / beach

Baylands 2009

- Deep bay / channel
- Salt pond
- Shallow bay / channel
- Managed pond**
- Tidal flat**
- Tidal marsh**
- Diked wetland**
- Agriculture / other undeveloped area
- Developed areas

*For more information on shoreline composition categories, see page 234.

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FOR ALL MAPS ON THIS PAGE

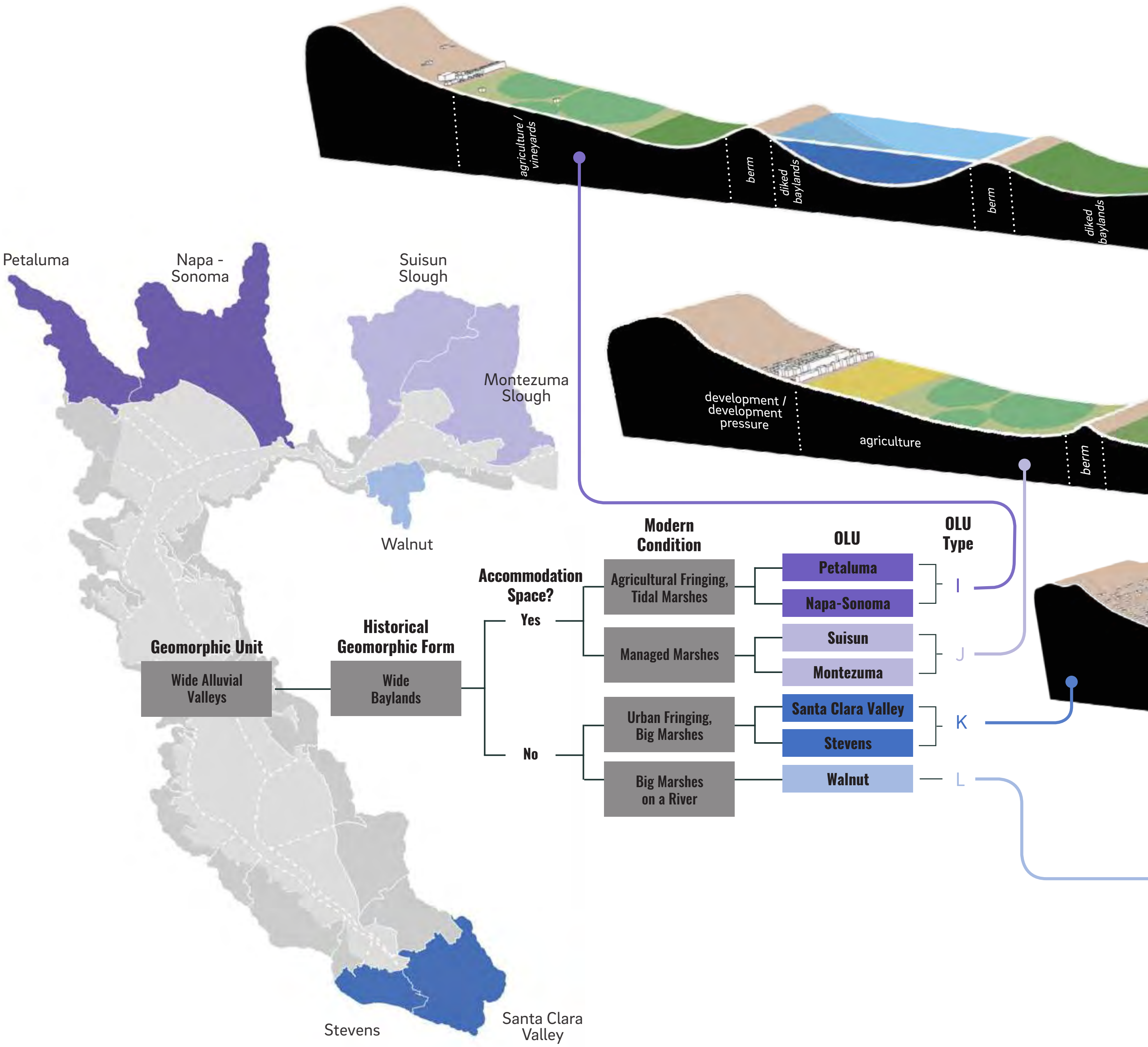
1 mile

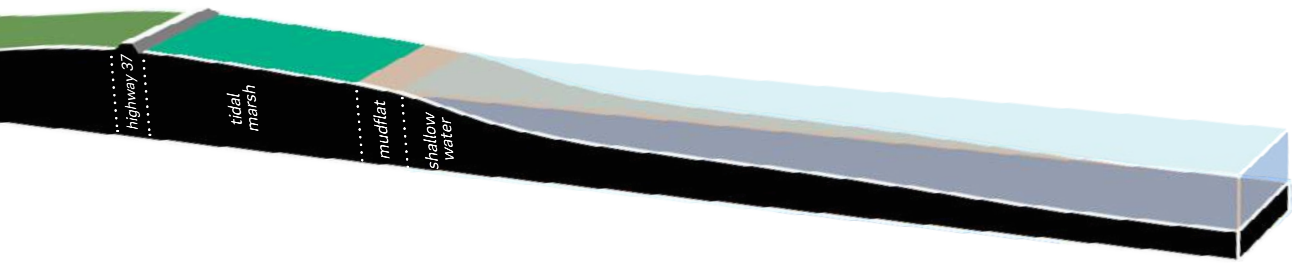
1 km

N

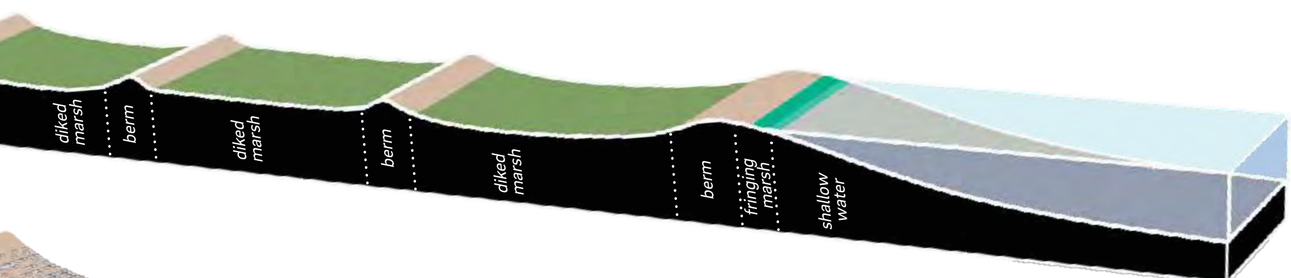
Wide alluvial valleys

Wide alluvial valleys are tectonic valleys that formed between the parallel ridges of the Coast Ranges. Relative to the other geomorphic unit types, the wide alluvial valleys are characterized by large watersheds, gradual slopes, wide baylands, and a great distance from the shoreline to deep water. Largely because of the lack of access to the deep bay, and the wide stretches of baylands to cross, these areas were not often the locations of ports or major bayside cities. Instead, land uses remained focused on high-value agriculture, and more recently, low-density tech campuses. Wide alluvial valleys also will experience the greatest extent of inundation under future sea level rise scenarios, given their low elevation.

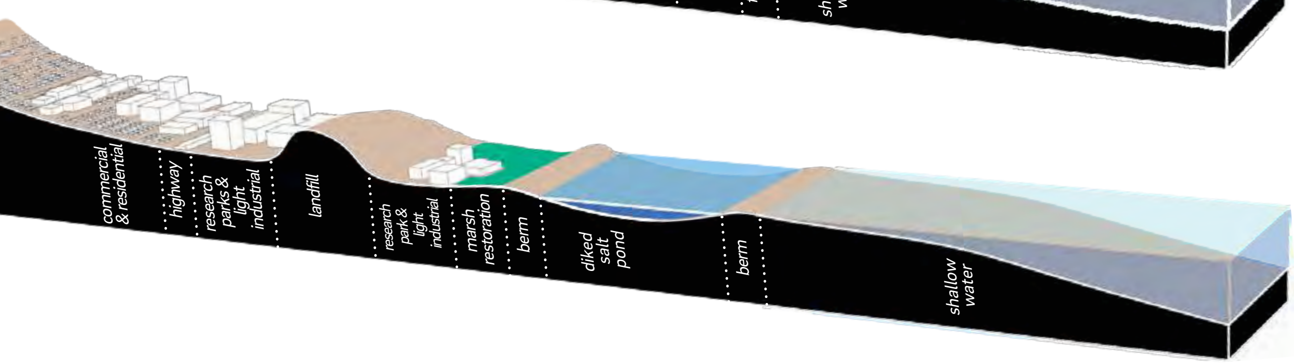




TYPE I: Wide Baylands, Agricultural Fringing Tidal Marshes with More Space

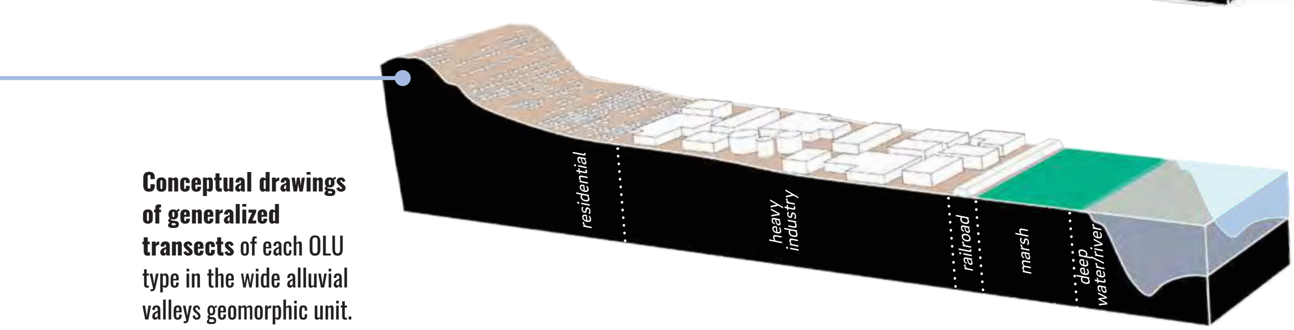


TYPE J: Wide Baylands, Managed Marshes with More Space



TYPE K: Wide Baylands, Urban Fringing Big Marshes with Less Space

Conceptual drawings of generalized transects of each OLU type in the wide alluvial valleys geomorphic unit.



TYPE L: Wide Baylands, Big Marshes on a River with Less Space

Wide alluvial valleys

TYPE I: WIDE BAYLANDS, TIDAL MARSHES WITH MORE SPACE

Agricultural fringing, tidal marshes

This type includes large expanses of open space including freshwater wetlands, tidal marsh, and agriculture, and has very little urbanized area compared to other OLUs within the wide alluvial valley type. Petaluma and Napa-Sonoma have large watersheds with high sediment loads available from the large rivers that run through them. These areas support high value agriculture, and some urban development at their upstream ends. They are characterized by subsided baylands, and also share the common problem of vulnerable road and rail infrastructure, including Highway 37, which crosses both of these OLUs.

Key similarities and differences

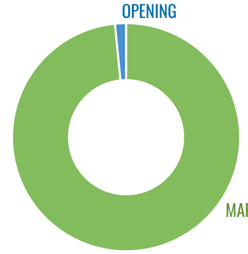
Petaluma and Napa-Sonoma have experienced parallel development patterns since major Euro-American modifications (ca. 1800) due to a similar yet divergent agricultural history. The Petaluma Valley was known as the "Egg Basket of the World" in the early 20th century while the Napa Valley was internationally known, and still is, for its wine (Grossinger 2012; Baumgarten et al. 2018). Both OLUs experienced sharp declines in the extent of tidal and non-tidal wetlands since the 1800s, in part to create more lands for agricultural cultivation. Today, the type of agriculture within each OLU varies and likely has implications for land value differences between them. In Napa-Sonoma, high-value viticulture still dominates the agricultural fields while a mixture of cultivated and fallow cropland, dairy farms, and pastureland dominate in Petaluma (Grossinger 2012; Baumgarten et al. 2018). Over the last decade, however, there has been an increase in viticulture within Petaluma.

Aerial view looking west from Skaggs Island towards a former naval facility in the Napa-Sonoma OLU (Photo by Todd Lappin, CC 2.0).

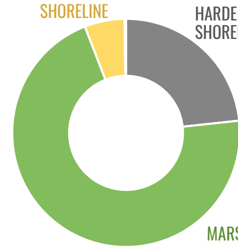
While both OLUs have very large sediment loads compared to other Bay OLUs, Napa-Sonoma OLU's contributing watershed is approximately four times as large as the Petaluma OLU. The majority of both shorelines have experienced short-term progradation between 1993 to 2010 (Beagle et al. 2015). These OLUs also have regionally significant tidal marsh habitats: the Petaluma OLU supports one of the oldest, most intact tidal marshes in the San Francisco Estuary (Baumgarten et al. 2018) and Napa-Sonoma supports the largest continuous marsh patch in the Bay (Goals Project 2015). Both OLUs face the challenge of baylands subsidence from historical draining and diking. However, while Petaluma has a large amount of diked subsiding areas, most of the salt ponds in Napa-Sonoma have been bought for restoration. Elevations of the ponds vary from shallow subtidal to intertidal elevations that could support marsh vegetation, with active restoration in progress. Because of the undeveloped nature of these OLUs, large potential exists to restore transition zone habitats through land acquisition and to create marsh migration space for sea level rise. However, the existing extent of and increasing conversion to high-value viticulture presents significant constraints for tidal marsh transgression in both OLUs. Unlike most other OLU types, Petaluma and Napa-Sonoma have high potential to support the restoration of interconnected and functioning marsh, the long-term maintenance of tidal marsh, and the planning/creation of areas for transgression with sea level rise.

HISTORICAL BAYLANDS	MODERN BAYLANDS	CURRENT SHORELINE COMPOSITION*

Petaluma



Napa-Sonoma



LEGEND & SCALE

Baylands ca. 1800

- Deep bay / channel
- Salt pond
- Shallow bay / channel
- Lagoon
- Tidal flat
- Tidal marsh
- Shellflat / shellmound
- Dune / beach

Baylands 2009

- Deep bay / channel
- Salt pond
- Shallow bay / channel
- Managed pond**
- Tidal flat**
- Tidal marsh**
- Diked wetland**
- Agriculture / other undeveloped area
- Developed areas

*For more information on shoreline composition categories, see page 234.

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FOR ALL MAPS ON THIS PAGE 1 mile 1 km N

Wide alluvial valleys

TYPE J: WIDE BAYLANDS, MANAGED MARSHES WITH MORE SPACE

Managed marshes

Suisun and Montezuma OLUs have lower sediment supply per square mile compared to Type I OLUs, and have large areas of tidal sloughs. These OLUs are characterized by brackish marsh and support many important species. Land in this OLU type is almost entirely dominated by agriculture and recreational open space, such as duck clubs, with fewer residents and jobs by an order of magnitude than in any other OLU type. The hydrology of these marshes and sloughs is managed to a large degree to provide low-salinity water for duck club operations (Goals Project 2015), one of the main factors setting these OLUs apart from Type I OLUs.

Key similarities and differences

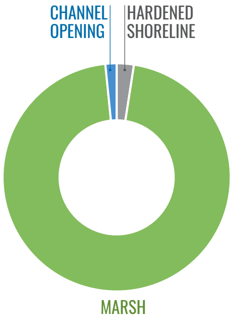
Historically, Montezuma and Suisun OLUs supported fully tidal, wide, fresh and brackish marshlands bordered by extensive areas of moist grasslands interspersed with vernal pools (Goals Project 2015). Because of the undeveloped nature of these OLUs, large potential exists to restore transition zone habitats through land acquisition and to create marsh migration space for sea level rise. However, both OLUs have the added challenge of subsidence due to the network of levees that cuts off the baylands from tidal action. Natural gas pipelines and rail lines run through low-lying portions of both OLUs, posing additional challenges with sea level rise. While the entire Suisun region (both OLUs together) should be considered as one landscape, Montezuma, with the shorelines of Suisun Bay and Grizzly Bay, has different opportunities than the Suisun OLU, which has less shoreline. Suisun OLU also has much more shoreline development, such as housing and infrastructure in Suisun City and Fairfield, compared to Montezuma OLU, which has almost no development.

(Left) Aerial view of Suisun Bay Reserve Fleet looking southeast towards Roe Island (Photo by George Grinsted, CC 2.0).

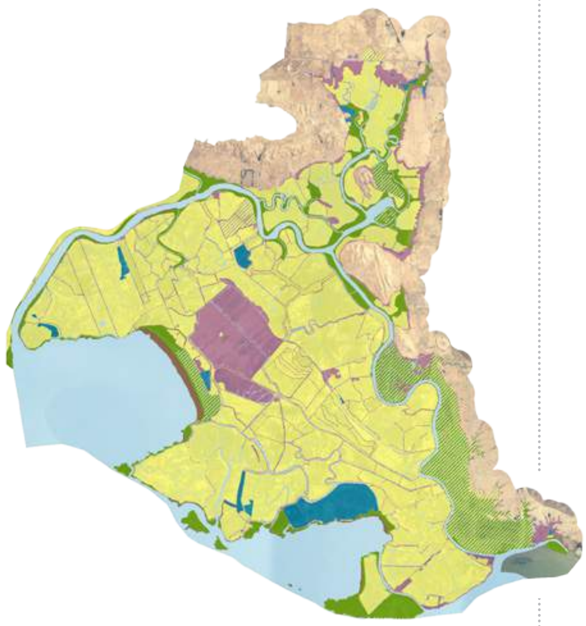
(Right) View of marsh in the Suisun OLU near Fairfield, CA (Photo by Ken Lund, CC BY-SA 2.0)

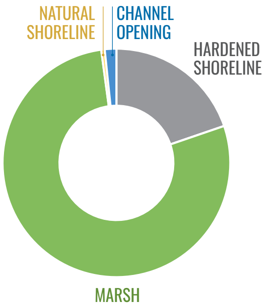
HISTORICAL BAYLANDS	MODERN BAYLANDS	CURRENT SHORELINE COMPOSITION*

Suisun



Montezuma





LEGEND & SCALE

Baylands ca. 1800

- Deep bay / channel
- Salt pond
- Shallow bay / channel
- Lagoon
- Tidal flat
- Tidal marsh
- Shellflat / shellmound
- Dune / beach

Baylands 2009

- Deep bay / channel
- Salt pond
- Shallow bay / channel
- Managed pond**
- Tidal flat**
- Tidal marsh**
- Diked wetland**
- Agriculture / other undeveloped area
- Developed areas

*For more information on shoreline composition categories, see page 234.

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FOR ALL MAPS ON THIS PAGE

1 mile

1 km

N

Wide alluvial valleys

TYPE K: WIDE BAYLANDS, URBAN FRINGING MARSHES WITH LESS SPACE

Urban fringing, big marshes

Stevens and Santa Clara Valley OLUs are located in South San Francisco Bay's Santa Clara Valley, which looked quite similar to the Napa-Sonoma OLU before major Euro-American modifications (ca. 1800), with oak savannas and wet meadows bordering broad low-lying marshlands. The Santa Clara Valley, historically nicknamed "the Garden of Heart's Delight," was known in the 19th and early 20th centuries for its fertile soils (Beller et al. 2010, Grossinger 2012). However, instead of continuing in agricultural production like OLU types I and J, development pressures from nearby population centers transformed the Santa Clara Valley into the high-density land uses that support today's booming Silicon Valley tech industry (Grossinger 2012).

The majority of the historical tidal marsh in these OLUs was converted to salt ponds between 1897 and 1960 (Grossinger and Askevold 2005), and today these areas comprise a part of one of the largest salt marsh restoration projects in the country (SBSPRP 2018). Although the conversion to salt ponds inadvertently preserved a wide area of open space at the edge of the Bay in these OLUs, many of these leveed areas are significantly subsided and surrounded by dense urban development.

Key similarities and differences

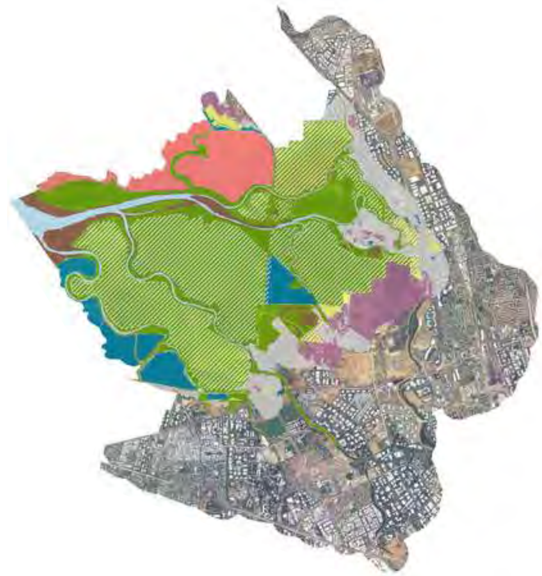
Santa Clara Valley and Stevens OLUs are experiencing development pressure around their edges due to the nature of Silicon Valley, and both share problems related to groundwater flooding and pressures from sea level rise. Throughout the first half of the 20th century, both OLUs experienced widespread land subsidence due to over-extraction of groundwater to meet increasing local demand (SCVWD 2016). Efforts to manage groundwater extraction by the Santa Clara Valley Water District resulted in the halting of further subsidence in 1969, but the lowering of the Valley that occurred up to that point increased the risk of flooding from creeks and sea level rise in both OLUs. In addition, both OLUs have numerous landfills and contaminated sites along their shorelines which will need to be protected from erosion and inundation. The Santa Clara Valley OLU drains two of the biggest watersheds in the region, Coyote Creek and Guadalupe Creek, bringing hazards, such as combined flooding and contamination, but also providing opportunities for creek and watershed management and the possibility of increased sediment supply to the baylands. Stevens OLU drains smaller, historically less connected watersheds, and the threat of combined flooding may be lower in comparison to Santa Clara Valley OLU.

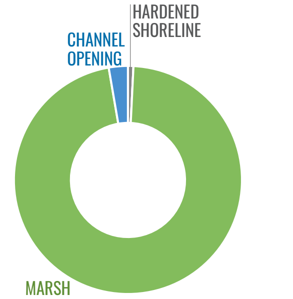
(Left) Aerial view of office parks and golf courses fronted by managed ponds in the Stevens OLU (Photo by Craig Howell, CC 2.0).

(Right) View from above of Silicon Valley in the Santa Clara Valley OLU (Photo by Patrick Nouhailler, CC BY-SA 2.0)

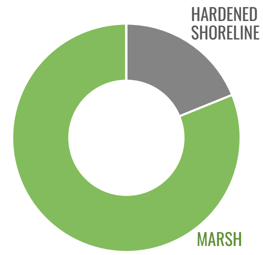
HISTORICAL BAYLANDS	MODERN BAYLANDS	CURRENT SHORELINE COMPOSITION*

Santa Clara Valley





Stevens



LEGEND & SCALE

Baylands ca. 1800

- Deep bay / channel
- Salt pond
- Shallow bay / channel
- Lagoon
- Tidal flat
- Tidal marsh
- Shellflat / shellmound
- Dune / beach

Baylands 2009

- Deep bay / channel
- Salt pond
- Shallow bay / channel
- Managed pond**
- Tidal flat**
- Tidal marsh**
- Diked wetland**
- Agriculture / other undeveloped area
- Developed areas

*For more information on shoreline composition categories, see page 234.

**Hashing on Baylands 2009 maps indicates where restoration activities have occurred or are planned based on 1998 and 2009 data. For managed ponds this includes habitat enhancement. Habitats shown represent projected restoration endpoints.

FOR ALL MAPS ON THIS PAGE

1 mile

1 km

N

Wide alluvial valleys

TYPE L: WIDE BAYLANDS, BIG MARSHES ALONG A RIVER WITH LESS SPACE

Big marshes along a river

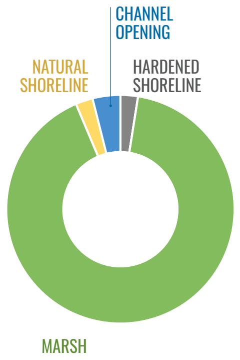
The Walnut OLU is unlike any of the other OLUs within the wide alluvial valley type because of its unique combination of watershed, shoreline, intertidal, and land use characteristics. Walnut has one of the highest average annual total sediment loads in the Bay Area, second only to Napa-Sonoma (Schoellhamer et al. 2018). The high annual sediment yield likely results from a combination of drivers, including its location on moderately erosive bedrock, relatively fast uplift rates in the portions of the contributing watershed near Mt. Diablo, and historical grazing and logging practices in the upper watersheds (SFEI-ASC 2016).

The wide historical baylands in this OLU were comprised of approximately 5,000 acres of tidal marsh, pannes, and channels which drained to a broad intertidal mudflat. The historical baylands were bordered by steep hills to the east and west and an 800-acre (320 ha) freshwater marsh complex to the south (SFEI-ASC 2016). Walnut's close proximity to the deep channel draining the Sacramento-San Joaquin River subjects it to a high degree of freshwater influence and fast-moving flows, resulting in brackish marsh vegetation communities with little to no mudflat or shallow water, in contrast to its historical setting. Over the last 150 years, Walnut's shoreline has prograded by up to half a mile, pushing its marsh edge even closer to the Bay's deep channel and leaving little to no space for subtidal habitats. Approximately 40% of Walnut's historical tidal marsh extent was converted to industrial and urban developments in the 19th and 20th centuries, and the marsh that remains has been fragmented by industrial facilities, roads, and other infrastructure (SFEI-ASC 2016). Walnut has been uniquely dominated by heavy industry, with several industrial plants, a military facility, deep water ports, and major roads and rail lines constructed along or near the shoreline. Several landfills and a Superfund site located along the shoreline will need to be protected from erosion as sea level rises. With the exception of communities in Pacheco, people generally live further back from the shoreline and outside of the floodplain in this OLU, a major difference compared to Type K OLUs (i.e., Santa Clara Valley and Stevens).

(Left) Aerial view of Walnut OLU, looking down onto heavy industry located along the lower reaches of Walnut Creek, facing east (Photo by Charles Kremenak, CC BY 2.0)

(Right) View from McNabney Marsh, Waterbird Regional Preserve, of the industrial facilities in the Walnut OLU (Photo by Shira Bezalel, SFEI)

HISTORICAL BAYLANDS	MODERN BAYLANDS	CURRENT SHORELINE COMPOSITION*



Baylands ca. 1800

- Deep bay / channel
- Salt pond
- Shallow bay / channel
- Lagoon
- Tidal flat
- Tidal marsh
- Shellflat / shellmound
- Dune / beach

Baylands 2009

- Deep bay / channel
- Salt pond
- Shallow bay / channel
- Managed pond**
- Tidal flat**
- Tidal marsh**
- Diked wetland**
- Agriculture / other undeveloped area
- Developed areas

*For more information on shoreline composition categories, see page 234.

**Hashing on Baylands 2009 maps indicates where restoration activities have occurred or are planned based on 1998 and 2009 data. For managed ponds this includes habitat enhancement. Habitats shown represent projected restoration endpoints.

FOR ALL MAPS ON THIS PAGE

1 mile

1 km

N

Current shoreline composition category definitions

Natural shoreline: The edge of predominantly natural land (e.g., cliffs, bluffs) were mapped as natural shoreline at the first major slope break along the Bay shoreline (natural shoreline was not mapped inland of the Bay shoreline), as specified in the SF Bay Shore Inventory report (SFEI 2016).

Transportation structure: Transportation structures were mapped on the edge (or centerline of narrower structures) of a railroad track or a major road, as described in the SF Bay Shore Inventory report (SFEI 2016). All railroads and a subset of major roads were classified as transportation structures regardless of the feature shape (e.g., one and two slopes). Smaller roads (e.g., private property access roads) were not attributed separately within the dataset, but instead were determined by referencing aerial imagery and existing GIS road layers. Only roads that were elevated from the surrounding landscape were mapped. Therefore, the dataset does not constitute a comprehensive layer of all roads within the mapped extent. If a road was part of an engineered levee, then the feature was mapped as an engineered levee.

Channel opening: This class mainly identifies breaks in mapped features where openings were not apparent in the DEM analyzed in the SF Bay Shore Inventory report (SFEI 2016), and are generally culverts running under levees or berm features. This class was also used to map some passive water control structures and tidal channels. This class was not mapped comprehensively, and is not intended to be used as a complete map of channel openings or penetration points within levees.

Hardened shoreline: Shorelines with berms, embankments, engineered levees, flood walls, shoreline protection structures, or water control structures were considered hardened shoreline. Details on how each of these Bay shore features was mapped is detailed in the SF Bay Shore Inventory report (SFEI 2016).

Marsh: Marshes (referred to as “wetland” in the SF Bay Shore Inventory report) were mapped along the Bay shoreline and along major slough channels and tributaries to the Bay. The edge of marshes were mapped corresponding to the marsh edge scarp in the DEM analyzed in the SF Bay Shore Inventory report (SFEI 2016).

Appendix 5: Methods for mapping suitable areas for natural and nature-based measures

Calculating relative elevations (z*)

Elevation is a critical driver of which adaptation measures are appropriate in any given area. Of particular importance in adaptation planning is an understanding of a site's elevation relative to the elevation of the tides. To facilitate the mapping of suitable areas for different adaptation measures, we calculated and mapped the relative elevation of the land surface (including the bathymetric elevation of areas submerged by water) within the tidal frame—a dimensionless elevation value referred to as *z**, calculated by dividing a location's absolute elevation relative to mean sea level (MSL) by the difference between the elevation of mean higher high water (MHHW) and MSL . By definition, *z** is equal to 0 when the land surface elevation is equal to the elevation of MSL and *z** is equal to = 1 when the land surface elevation is equal to the elevation of MHHW. A *z** value of -1 would be approximately equal to mean lower low water (MLLW).

Local *z** values were calculated using absolute elevation data from the Coastal National Elevation Database (CoNED) topobathymetric model of San Francisco Bay (USGS 2013). This DEM has a cell size of 2 m, and utilizes input data collected between 2004 and 2011. *z** values were calculated for every raster grid cell using the following equation (derived from Swanson et al. 2014; see the table below for a summary of the sources and parameters we used):

$$Z^* = \frac{Z_{local} - Z_{MSL}}{Z_{MHHW} - Z_{MSL}}$$

Variable/ Parameter	Definition	Value used in calculations	Source and notes
z^*	relative elevation within the tidal frame	n/a	n/a
z_{local}	absolute land surface elevation (in meters NAVD88)	Local absolute land surface elevation	Coastal National Elevation Database (CoNED) topobathymetric model of San Francisco Bay (USGS 2013)
z_{MSL}	local mean sea level (MSL) elevation (in meters NAVD88)	average MSL elevations were calculated for each OLU (see table on page 237)	AECOM 2016
z_{MHHW}	average local mean higher high water elevation (in meters NAVD88)	average MHHW elevations were calculated for each OLU (see table on page 237)	AECOM 2016

Tidal datums for each OLU used to calculate *z** were determined by taking the average MSL or MHHW values of each of the sites modeled by AECOM (2016) located within the OLU (see table on page 237). Sites associated with islands were not included when calculating the average tidal datum values for each OLU. Four OLUs (Alameda Creek, Santa Clara Valley, Stevens, and San Francisquito) did not intersect any sites with MSL data; MSL values for these OLUs were calculated by taking the average MSL value of the nearest bordering OLUs with MSL data (e.g., the Alameda Creek MSL value was determined by taking the average MSL value of San Lorenzo to the north and Mowry to the south).

z^* values were an input to the analyses of areas potentially appropriate for tidal marshes, polder management, ecotone levees, and migration space preparation (see below).

OLU	MHHW (meters NAVD88)	MSL (meters NAVD88)	OLU	MHHW (meters NAVD88)	MSL (meters NAVD88)
1- Richardson	1.83	1.00	16- Point Richmond	1.86	1.01
2- Corte Madera	1.84	1.01	17- East Bay Crescent	1.89	1.01
3- San Rafael	1.85	1.01	18- San Leandro	1.98	1.01
4- Gallinas	1.88	1.02	19- San Lorenzo	2.12	1.02
5- Novato	1.90	1.03	20- Alameda Creek	2.18	1.01
6- Petaluma	1.91	1.04	21- Mowry	2.24	1.00
7- Napa - Sonoma	1.90	1.06	22- Santa Clara Valley	2.28	1.00
8- Carquinez North	1.84	1.07	23- Stevens	2.25	1.00
9- Suisun Slough	1.88	1.10	24- San Francisquito	2.23	1.00
10- Montezuma Slough	1.89	1.13	25- Belmont - Redwood	2.16	1.00
11- Bay Point	1.88	1.14	26- San Mateo	2.10	1.01
12- Walnut	1.87	1.10	27- Colma - San Bruno	2.07	1.01
13- Carquinez South	1.84	1.07	28- Yosemite - Visitacion	2.03	1.01
14- Pinole	1.90	1.05	29- Mission - Islais	1.95	1.01
15- Wildcat	1.88	1.02	30- Golden Gate	1.84	0.99

Accurate z^* values could not be calculated in areas where the lidar-derived DEM (USGS 2013) denoted the elevation of the water surface elevation (instead of the bathymetric elevation of the land surface beneath the water). We identified these areas by using a neighborhood filter to extract flat portions of the DEM and labeled them as "Elevation unknown per USGS 2013" on the map of z^* values (p. 41). These areas also needed to be addressed when mapping areas potentially appropriate for adaptation measures derived from z^*. These "data gaps" should be addressed in future versions of this work by incorporating other sources of elevation data and expert knowledge of specific locations. It would also be improved by utilizing a lidar-derived DEM that has been corrected for vertical bias due to vegetation (e.g., Buffington and Thorne 2019).

Nearshore reefs

Subtidal areas with conditions that could support oysters and would be suitable for restoration projects were identified by the San Francisco Bay Subtidal Habitat Goals Project (Subtidal Goals 2010). Specifically, the areas mapped on page 67 are those that were identified through the Subtidal Goals Project as "potential restoration sites" based on the best professional judgment of scientists considering water depth (sites were only mapped where depth is <2 m), salinity, substrate type, oyster recruitment potential, and site access.

This analysis could be improved in the future by utilizing a more repeatable, transparent, and comprehensive habitat suitability analysis for mapping potential sites.

Submerged aquatic vegetation

Areas mapped as appropriate for submerged aquatic vegetation restoration were derived from a predictive model developed by Merkel & Associates (Merkel 2005), which identified potentially suitable eelgrass habitat based on water residence time, salinity, and hours of light saturation. Specifically, the areas shown as suitable on page 69 are those with a modeled habitat suitability index greater than zero. These areas were digitized from a low-resolution georeferenced copy of the suitability map.

This analysis could be improved in the future by:

- utilizing the original, high-resolution data (instead of the low-resolution georeferenced map) ;
- utilizing improved bathymetry data collected since 2003 in the habitat suitability analysis;
- incorporating other species of submerged aquatic vegetation into the map of suitable areas for SAV restoration.

Mudflat augmentation

We were unable to identify specific areas of mudflat in need of augmentation. Instead, we simply mapped the current extent of mudflats using the Bay Area Aquatic Resource Inventory (SFEI-ASC 2017a; selected areas mapped as "Bay Tidal Flat"). A critical next step towards identifying areas where augmentation might be beneficial is to identify which mudflats are actually eroding or are otherwise most at risk of loss with sea level rise.

With this in mind, the analysis presented here could potentially be improved in the future by:

- analyzing mudflat profiles, since mudflats with concave profiles (vs. convex profiles) are expected to be characterized by seaward sediment transport, net erosion, and ongoing landward retreat (Friedrichs 2011), and might therefore be good candidates for augmentation;
- utilizing hydrodynamic models to determine sites where sediment disposed into the water column would be most effectively transported to mudflats in need of augmentation (e.g., Bever et al. 2014);
- utilizing updated maps of mudflat extent (e.g., Murray et al. 2019).

Beaches

Areas mapped as suitable for beaches were identified by selecting shoreline reaches that are fronted by existing beaches or wetlands, or are currently fortified by rip rap, sea walls, or other structures indicative of high wave energy environments. Results were refined by removing buffers that overlap channel openings, marinas, and ports, which assumes beaches would not be appropriate in these areas based on current land use. Existing beaches, wetlands, fortified areas, and channel openings were mapped using SFEI's Bay Shore Inventory dataset (SFEI 2016). Marina and port locations were digitized based on photo interpretation of 2018 aerial imagery from Google Earth. Areas suitable for beaches were only mapped within historical beach provinces (e.g., where evidence of beaches exist circa 1800) based on historical beach locations as mapped by EcoAtlas (SFEI-ASC 1997) and expert opinion (Peter Baye, personal communication). Areas that fell outside of the historical beach province boundary include the north shore of San Pablo Bay, Carquinez Strait, Suisun Bay, and the far South Bay demarcated by Dumbarton Bridge. Beach crest elevations were calculated for each 100 m shoreline segment based on the runup of the 100-year significant wave height (DHI 2011, 2013). The low-tide terrace elevation was set at MLLW. Beach slope was assumed to be 30:1 (horizontal:vertical) and representative of a mixture of sand, shell, cobble, and gravel.

This analysis could be improved in the future by:

- utilizing data on wind direction and shoreline orientation to identify whether shoreline reaches are "drift-aligned" or "swash-aligned." Drift-aligned reaches (where waves approach at an oblique angle) are more likely than swash-aligned reaches (where wave-thrust is orthogonal to the shoreline) to require microgroins or other structures to retain beach material;
- quantifying the amount of fill required to construct the needed beach profile, based on local bathymetry, which will influence the feasibility of beach creation.

Tidal marshes

Areas mapped as suitable for tidal marsh restoration were identified by selecting areas between the approximate elevation of MSL and highest astronomical tide (HAT) (with a z^* value between -0.14 and 1.38), which is the range determined by Thorne et al. (2018) as supporting tidal marshes at Petaluma Marsh in San Francisco Bay (the range corresponds to the area between the lowest extent of tidal marsh vegetation and the highest extent flooded on average at least once per year). To assess the appropriateness of defining potential marsh across the whole Bay using a relative marsh elevation (z^*) range from only Petaluma Marsh, we calculated the elevation range of 11 other marshes with tidal datum and marsh elevation data from USGS (Takekawa et al. 2013). Finding that the mean relative elevation (z^*) range of these sites was comparable to the relative elevation range of Petaluma Marsh determined by Thorne et al. (2018), we felt comfortable using the Petaluma Marsh values to identify areas at the right elevation for tidal marshes across the Bay. Future iterations of this work could incorporate data from additional sites (particularly Suisun Marsh) to define different elevation ranges for each OLU.

Although the DEM utilized to calculate z^* values and determine areas suitable for tidal marshes is topobathymetric (containing elevation for both dry and submerged parts of the study extent), there are submerged areas (including some lakes, marinas, and current/former salt ponds) without true bathymetric data. In these areas the DEM reports the elevation of the water surface, which would be expected to lead to false positives (areas that seem to be at the right elevation for marsh vegetation but are in fact too low) and false negatives (areas that seem too high for marsh vegetation but are in fact at the correct elevation). To identify these areas, we first identified portions of the DEM likely quantifying the elevation of the water surface (instead of the land surface) by using a neighborhood filter to identify flat areas. Flat areas with an z^* value that is suitable for marsh vegetation were flagged as potential false positives. Flat areas with a z^* value above the range suitable for marsh vegetation were flagged as potential false negatives. The potential false positives and negatives were then merged and are shown on the map of suitable areas for tidal marshes as data gaps (areas that may or may not be at the right elevation for marsh).

To supplement the mapping, we also calculated how wide marshes need to be in each OLU in order to provide high levels of shoreline protection. Specifically, we calculated the minimum width of marsh needed to attenuate 100-year incident waves down to 0.3 m (1 ft) in height before they reach the back edge of the marsh (and the built shoreline behind it). This width threshold was calculated for every 100 m segment of the Bay's shoreline using the following equation (derived from Bouma et al. 2014; see the table below for the sources and parameters we used):

$$L = -\ln\left(\frac{H_L}{\min\{H_{maxdepth}, H_{maxfetch}\}}\right) \div \left(k_{habitat} \times \frac{B}{B_{max}} \times e^{-dh}\right)$$

Variable/ Parameter	Definition	Value used in calculations	Source and notes
L	cross-shore length of the marsh (marsh width needed to attenuate waves down to H_L)	n/a	n/a
H_L	wave height (in meters) after attenuation by the marsh	0.3	for the purposes of this report, 0.3 m waves (~1 ft) are assumed not to cause significant erosion of levees
$H_{maxdepth}$	maximum wave height (in meters) that can exist assuming fetch is long enough (depth-limited wave height over marsh)	0.6 X h, where h is the maximum depth of water over the marsh at MHHW with a 100-year storm surge (see below)	multiplying the water depth by 0.6 is a standard method to estimate breaking wave conditions and so the depth-limited wave heights
h	maximum depth of water over the marsh (in meters) at MHHW with a 100-year storm surge	h was set equal to 5% of the local tidal range (z_{MHHW}-z_{MLLW}) plus the height of the local 100-year storm surge (z_{surge}-z_{MHHW})	• 5% is the typical height of high marshes in the intertidal frame as a percentage of the submersion period (Bouma et al. 2014) • local values for z_{MHHW} and z_{MLLW} were derived from AECOM 2016 • local values for z_{surge} were derived from AECOM 2016 (100-year "extreme tide" water levels)
$H_{maxfetch}$	maximum wave height (in meters) that can exist over marsh given local fetch	local modeled 100-year wave heights	DHI 2011, 2013
$k_{habitat}$	habitat dependent decay constant	0.05	maximum value for marshes reported by Bouma et al. 2014
B	percent coverage of marsh vegetation along the cross-shore length of the marsh	100%	assume maximum coverage of salt marsh vegetation
B_{max}	maximum percent coverage of marsh vegetation along the cross-shore length of the marsh	100%	assume salt marsh vegetation is capable of covering the entire cross-shore length of marsh
d	decay coefficient for the loss of friction with water depth	1.5	Ysebaert et al. 2011, as reported in Bouma et al. 2014

This analysis could be improved in the future by:

- classifying potential marshes as wide enough or not wide enough to provide high levels of shoreline protection;
- filling elevation data gaps to determine which of the flagged areas are actually at the right elevation for tidal marshes;
- utilizing a lidar-derived DEM that has been corrected for vertical bias due to vegetation (e.g., Buffington and Thorne 2019).

Polder management

Areas mapped as suitable for polder management were identified by selecting any contiguous areas with elevations below MSL and disconnected from tidal inundation by dikes—i.e., areas that would be inundated on most tides if dikes were not present. This was accomplished in a GIS by isolating all areas with a z^* value <0 and then deselecting the portions of this area that are contiguous with (i.e., connected to) the Golden Gate. In a few areas we were required to add or subtract connections to reflect known landscape modifications that have occurred since the underlying DEM was generated (e.g., adding the Hamilton Wetlands breach). In the final map we only show polders with surface areas greater than 0.3 ha.

Although the DEM utilized to calculate z^* values and determine areas suitable for polder management is topobathymetric (containing elevation for both dry and submerged parts of the study extent), there are submerged areas (including some lakes, marinas, and current/former salt ponds) without true bathymetric data. In these areas the DEM reports the elevation of the water surface, which would be expected to lead to some false negatives (areas that—because of the water surface elevation—seem to be above MSL and not polders, but where the land is actually below MSL and qualifies as a polder). To identify these areas, we first identified portions of the DEM likely quantifying the elevation of the water surface (instead of the land surface) by using a neighborhood filter to identify flat areas. Flat areas with an z^* value >0 were then flagged as potential false negatives and shown on the suitable areas map as data gaps (areas that may or may not be polders). It is likely that most of these flagged areas are, in fact, polders and suitable for polder management.

This analysis could be improved in the future by:

- filling elevation data gaps to determine which of the flagged areas are or are not actually polders;
- classifying polders based on appropriate management strategies (e.g., which polders should be filled vs. flooded);
- utilizing a lidar-derived DEM that has been corrected for vertical bias due to vegetation (e.g., Buffington and Thorne 2019).

Ecotone levees

Areas mapped as suitable for ecotone levees were identified by selecting areas at the proper elevation for tidal marsh (see above) that are both adjacent to developed areas and wide enough to support a levee with a 1:30 slope, assuming a crest height equal to the height of the 100-year storm surge plus 2.1 m of sea level rise. Specifically, we mapped these sites by buffering developed areas by the necessary ecotone levee width (see below) to generate potential ecotone levee footprints, then selecting those footprints (split at regular intervals of approximately 100 m) that mostly (>85%) overlap areas mapped as suitable for tidal marsh restoration (see above). From this selection, we manually identified the potential ecotone levees that fronted meaningful development (potential ecotone levees were not mapped fronting isolated berms, isolated roads, or in undeveloped areas entirely surrounded development without connection to the baylands). The developed areas used in this analysis were derived from a modified version of the 2011 National Land Cover Database (NLCD; Homer et al. 2015). Specifically, we extracted all areas classified in the NLCD as "Developed- Low Intensity," "Developed- Medium Intensity," or "Developed- High Intensity" and then corrected developed feature edges by erasing any wetland or aquatic features mapped in the higher-resolution Bay Area Aquatic Resources Inventory (SFEI-ASC 2017a; see Goals Project 2015). Necessary ecotone levee widths were calculated on an OLU-by-OLU basis as follows:

$$W = \frac{1}{m}(Z_{surge} - Z_{marsh} + H_{SLR})$$

Variable/ Parameter	Definition	Value used in calculations	Source and notes
W	ecotone levee width	n/a	n/a
m	ecotone levee slope (rise over run)	0.033	a slope of at least 0.033 (1:30 or 30x wider than tall) is thought to be gradual enough to balance width of marsh migration zone and habitat patch size and limit wave-driven erosion of the levee
z_{surge}	storm surge elevation (meters NAVD88)	average local 100-year storm surge elevations	AECOM 2016 (100-year "extreme tide" water levels)
z_{marsh}	marsh plain elevation (meters NAVD88)	for these calculations we assumed the marsh plain elevation was equal to the average local MHHW elevation	local values for were derived from AECOM 2016
H_{SLR}	height of projected sea level rise (in meters)	2.1	OPC 2018 (projected height of sea level rise with a 1-in-200 chance of occurring under the high-emission scenario by 2100)

This analysis could be improved in the future by:

- identifying sites that have the space to support both an ecotone levee and a wide marsh;
- refining the necessary ecotone levee width and mapping suitable areas with other levee slopes (both steeper and less steep than 1:30);
- refining the elevational criteria (i.e., showing additional areas where ecotone levees might make sense if polders were filled);
- refining our treatment of the developed areas in need of protection (i.e., showing where ecotone levees might makes sense if you allow for shoreline realignment in certain areas);
- utilizing a lidar-derived DEM that has been corrected for vertical bias due to vegetation (e.g., Buffington and Thorne 2019).

Migration space preparation

Locations mapped as suitable for migration space preparation were identified by selecting undeveloped areas expected to be inundated with 2.0 m of sea level rise (CoSMoS Model SF Bay Product Suite, Barnard et al. 2014) that are above today's highest astronomical tide ($z^* > 1.34$). Results were refined by removing areas of existing tidal marsh by using SFEI-ASC (2017a) data to map tidal ditch, tidal marsh flat, tidal panne, and tidal vegetation classification types. We then distinguished protected migration space from unprotected migration space using the California Protected Areas Database (CPAD 2017). Note that the 2.0 m sea level rise scenario utilized in the analysis is slightly less severe than the 2.1 m assigned 0.5% probability of occurring by 2100 under high emissions scenarios by OPC (2018). Undeveloped areas were distinguished from developed areas using the 2011 National Land Cover Database (Homer et al. 2015) using the crosswalk developed by Collins (2015).

This analysis could be improved in the future by:

- assessing migration space connectivity—i.e., distinguishing which areas mapped as undeveloped migration space are actually connected to existing or potential marshes (some areas at the right elevation for migration space are disconnected from existing/potential marshes because of development patterns, but this is not addressed in the current analysis);
- determining where the migration space is wide enough to provide an ecologically-significant transition zone over time;
- refining our treatment of developed areas (i.e., showing where migration space preparation might make sense if we allow for shoreline realignment in certain areas);
- utilizing a lidar-derived DEM that has been corrected for vertical bias due to vegetation (e.g., Buffington and Thorne 2019).

Creek-to-baylands reconnection

Locations to consider reconnecting creeks to baylands were derived from the contemporary fluvial-tidal (F-T) interface database developed by SFEI-ASC (2017b), which maps and categorizes the locations where creeks meet the tidal environment of the Bay. The table below lists which interface types we considered "disconnected" and included on the map and which we considered "connected" and did not map. Creek data and the extent of the baylands were derived from SFEI-ASC (2017a).

Category	Description	GIS identifier
F-T interface types considered "disconnected" (mapped)		
Connected to a tidal channel through diked baylands	Channels enter areas where baylands have been diked (i.e., are isolated from the tides by dikes or levees) and flow into a tidal channel	Tidal channel through diked baylands
Connected to a tidal channel through bay fill	Channels flow through bay fill (i.e., fine sediment placed on baylands to increase elevation and allow for development) before reaching the Bay	Tidal channel through bayfill
Drains onto bay fill	Channels enter baylands that are now covered in bay fill but dissipate without connecting to a tidal channel	Bayfill
F-T interface types considered "connected" or otherwise deemed less appropriate for re-connection (not mapped)		
Connected to the Bay	Channels entered directly into the Bay without passing through baylands (i.e., mudflats, tidal marshes, tidal-terrestrial transition zones)	Bay
Connected to a tidal marsh channel	Channels reach the baylands and merge into a tidal channel network	Tidal marsh channel
Drains onto diked baylands	Channels enter baylands that are now diked (e.g., salt ponds, managed marsh) but dissipate without connecting to a tidal channel	Diked baylands
Channel has become a tributary channel	Channels that historically reached the baylands but have been re-routed inland to flow into another channel	Tributary channel
Channel no longer present on the landscape	Channels have been routed into underground culverts or have been filled in completely	Channel no longer present

This exercise admittedly oversimplifies where reconnecting creeks to baylands is or is not possible. Additional work is needed to evaluate opportunities on a stream-by-stream basis. Some good starting places for improving the analyses in the future would be :

- assessing whether any interfaces classified as "Channel has become a tributary channel" (which were not included on the map) might actually present good opportunities for re-connection. Some of these tributaries could potentially be re-routed and re-connected to the baylands;
- assessing whether any interfaces classified as "Channel no longer present on the landscape" (which were not included on the map) might actually present good opportunities for re-connection. Channels included in this category that have been routed into underground culverts could potentially be daylighted and re-connected to the baylands.

Green stormwater infrastructure

Areas shown as suitable for green stormwater infrastructure (GSI) were derived from the work of Kass et al. (2011), who mapped where various landscape integrated design treatments are suitable in the Bay Area based on the slope of the land, depth to water table, soil hydrologic type, land use, liquefaction risk, and prevalence of impervious surfaces. We only included areas mapped by Kass et al. as suitable for permeable pavement, vegetated swales, or bioretention. Other kinds of green stormwater infrastructure might be suitable in other areas.

This analysis could be improved in the future by:

- incorporating areas suitable for additional types of GSI;
- distinguishing which areas are suitable for which types of GSI;
- utilizing available tools to map fine-scale opportunities for implementing GSI (e.g., Wu et al. 2019).

Defining ecosystem services

We characterized each natural or nature-based adaptation measure by ecosystem services derived from the United Nation's assessment of the services provided by wetlands (MEA 2005). The table on the next page details the four ecosystem service groups identified, as well as the individual ecosystem services we assign to each measure detailed in *Chapter 4: Adaptation Measures*.

Ecosystem services provided by San Francisco Baylands OLUs *(and their relationship to the services provided by wetlands defined by the UN's Millennium Ecosystem Assessment [MEA 2005]).*

Ecosystem services provided by wetlands (MEA 2005)	Ecosystem services adapted for San Francisco Baylands OLUs	Description, comments, and examples
Provisioning		
Food	Food supply	fishing (e.g., Pacific herring, Chinook salmon, rockfish, shrimp), shellfish harvesting and aquaculture (e.g., crustaceans, mollusks), hunting (e.g., waterfowl, snipe, elk, rabbit), plant and seaweed foraging
Freshwater	*Not considered for San Francisco Baylands OLUs*	storage and retention of fresh water; provision of water for irrigation and for drinking
Fibre and fuel (Raw materials)	*Not considered for San Francisco Baylands OLUs*	salt production, oyster shell mining, sand mining
Biochemical products	*Not considered for San Francisco Baylands OLUs*	provision of medicines, biocides, food additives, and biological materials from biota
Genetic materials	*Not considered for San Francisco Baylands OLUs*	genes and genetic information used for animal and plant breeding and biotechnology
Regulating		
Climate regulation	Climate regulation	carbon sequestration, local temperature regulation (urban cooling)
Water purification and waste treatment	Water quality improvement	retention, recovery, and removal of excess nutrients and pollutants
Water regulation (hydrological flows)	Coastal flood control and shoreline protection	see page 64 for "Coastal risks managed" section
Erosion regulation		
Natural hazard regulation		
Pollination	*Not considered for San Francisco Baylands OLUs*	
Cultural		
Recreational	Recreation	outdoor recreation, wildlife viewing, eco-tourism, park space
Spiritual and inspirational	Other cultural services	cultural heritage; religious, spiritual, artistic, and aesthetic values; opportunities for formal and informal education
Aesthetic		
Educational		
Supporting		
Biodiversity	Biodiversity	provides habitat for resident or transient species (also see page 64 for "Ecosystem functions" section)
Soil formation	*Not considered for San Francisco Baylands OLUs*	sediment retention and accumulation of organic matter
Nutrient cycling	*Not considered for San Francisco Baylands OLUs*	storage, recycling, processing, and acquisition of nutrients

Appendix 6: Determining ranked adaptation measure suitability by OLU

Natural and nature-based measure suitability ratings

Based on the mapping explained in *Chapter 4: Adaptation Measures*, the suitable area of each natural or nature-based adaptation measure in each OLU was summed using GIS software. For each measure, the suitable areas within each OLU were divided by the total suitable area across all OLUs to yield the proportion of the total suitable area present in each OLU. A proportion close to 1 indicates that a high percentage of the total area suitable for the measure in question exists within the OLU, whereas a proportion close to 0 means the OLU has a very small fraction of the total suitable area. In order to arrive at suitability ratings that are normalized for the size of an OLU (all else being equal, large OLUs would be expected to have more total area suitable for a given adaptation measure), the proportion of a measure's suitable area in each OLU was divided by the OLU's size as a proportion of the total area of all OLUs (see table on page 247). Subtidal measures (e.g., nearshore reefs, submerged aquatic vegetation, and beaches) were normalized by the proportion of an OLU's subtidal area relative to the total subtidal area of all OLUs. Land-based measures (i.e., measures found inland of the OLU shoreline such as tidal marshes, polder management, ecotone levees, and migration space preparation) were normalized by the proportion of an OLU's upland area (as delineated from the shoreline to the back of the OLU boundary) relative to the total upland area of all OLUs.

For each measure in each OLU, suitability ratings (*x*) were calculated as follows:

$$x = (A_S / A_T) / (A_O / A_C)$$

Where:

A_S = area suitable for measure in OLU

A_T = total area suitable for measure across all OLUs

*A_O = area of OLU**

*A_C = area of all OLUs combined**

For subtidal measures, OLU area was based on the subtidal area only, from the shoreline to the depth of closure; for land-based measures, OLU area was based on the upland area only, from the shoreline to the back of the OLU boundary.

Final suitability ratings were binned into one of three categories: (1) limited suitability; (2) some suitability; and (3) high suitability. The threshold suitability values between each category, listed in the table on the next page, vary by measure and were determined by analyzing data distributions. Best professional knowledge was used to determine where the threshold values between categories fell, and in some cases OLUs were moved from one category to another, also based on best professional judgement. These exceptions are documented in the table on the next page.

Values used to categorize the suitability *of each nature-based measure.*

<table>
<tr><th rowspan="2">Nature-based measure</th><th colspan="3">Suitability rating (proportion of measure opportunity area / proportion of OLU area)</th><th rowspan="2">Exceptions based on best professional judgment</th><th rowspan="2">Notes</th></tr>
<tr><th>Limited suitability</th><th>Some suitability</th><th>High suitability</th></tr>
<tr><td>Nearshore reefs</td><td>x ≤ 0.01</td><td>0.01 < x ≤ 0.04</td><td>x > 0.04</td><td>Stevens (moved from high suitability to some suitability)</td><td rowspan="3">Suitability ratings for subtidal measures were normalized by proportion of subtidal area to total subtidal area of all OLUs.</td></tr>
<tr><td>Submerged aquatic vegetation (eelgrass)</td><td>x ≤ 0.01</td><td>0.01 < x ≤ 0.10</td><td>x > 0.10</td><td>n/a</td></tr>
<tr><td>Beaches</td><td>x ≤ 0.03</td><td>0.03 < x ≤ 0.40</td><td>x > 0.40</td><td>n/a</td></tr>
<tr><td>Tidal marsh</td><td>x ≤ 0.10</td><td>0.10 < x ≤ 0.40</td><td>x > 0.40</td><td>n/a</td><td rowspan="4">Suitability ratings for measures inland of the shoreline were normalized by proportion of upland area to total upland area of all OLUs.</td></tr>
<tr><td>Polder management</td><td>x ≤ 0.05</td><td>0.05 < x ≤ 0.20</td><td>x > 0.20</td><td>n/a</td></tr>
<tr><td>Ecotone levee</td><td>x ≤ 0.20</td><td>0.20 < x ≤ 1.30</td><td>x > 1.30</td><td>Golden Gate (moved from some suitability to limited suitability); San Leandro (moved from some suitability to limited suitability)</td></tr>
<tr><td>Migration space preparation</td><td>x ≤ 0.31</td><td>0.31 < x ≤ 0.50</td><td>x > 0.50</td><td>Santa Clara Valley (moved from some suitability to high suitability);
San Leandro (moved from some suitability to limited suitability)</td></tr>
</table>

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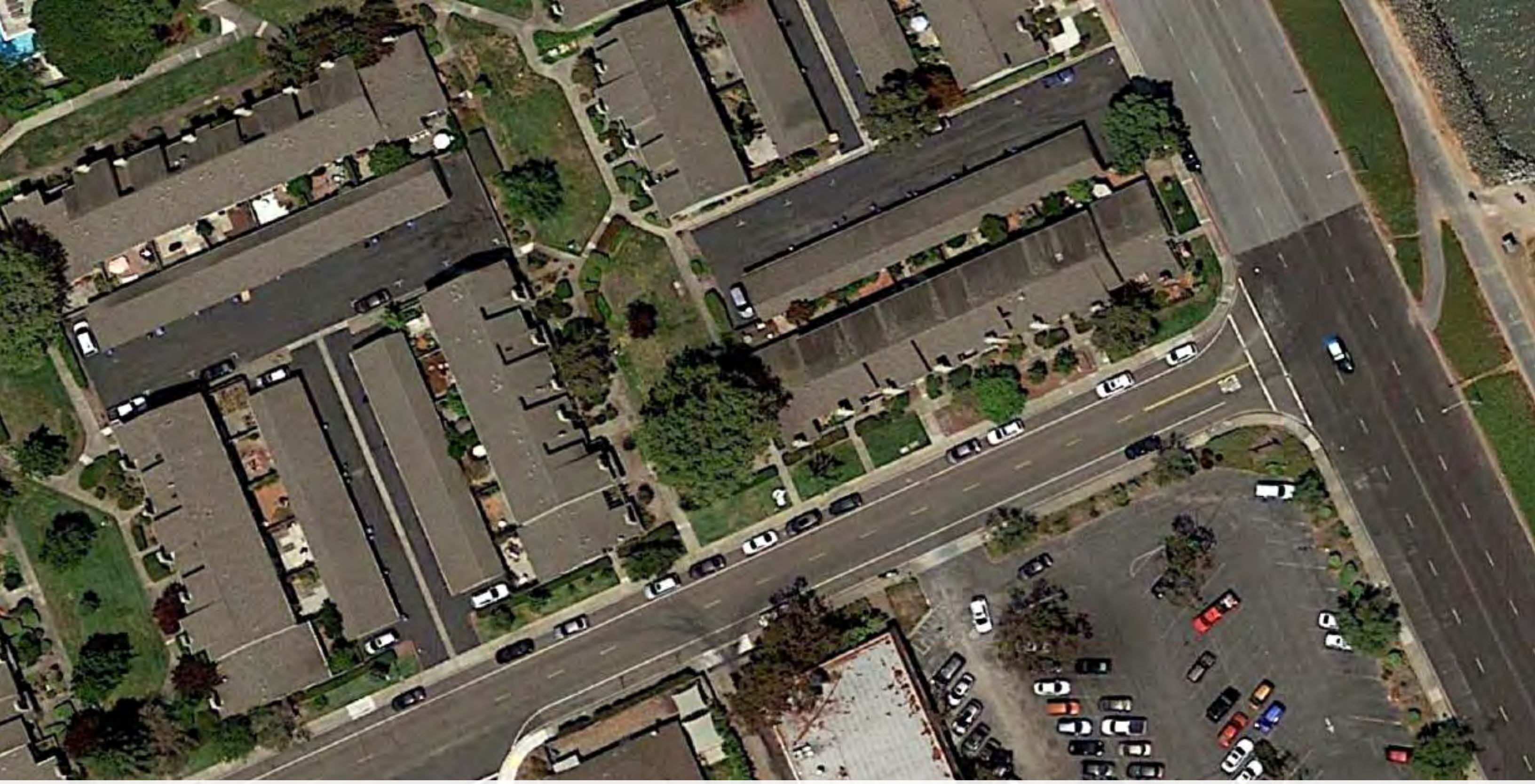

As the climate continues to change, San Francisco Bay shoreline communities will need to adapt in order to build social and ecological resilience to rising sea levels. Given the complex and varied nature of the Bay shore, a science-based framework is essential to identify effective adaptation strategies that are appropriate for their particular settings and that take advantage of natural processes. This report proposes such a framework—*Operational Landscape Units* for San Francisco Bay.

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