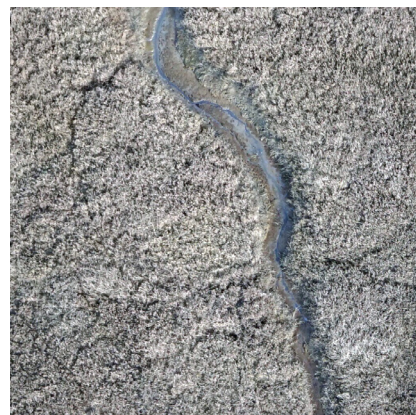
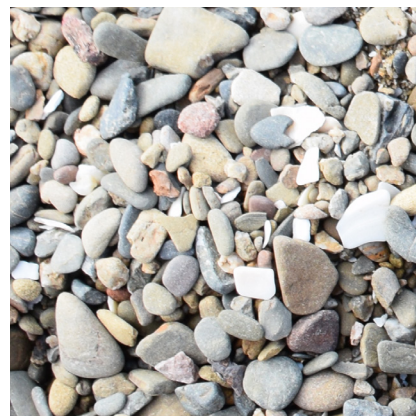


SEA LEVEL RISE

Adaptation Framework

.....
A user guide to planning with nature,
as demonstrated in Marin County



SEA LEVEL RISE

Adaptation Framework

.....
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as demonstrated in Marin County

Prepared by

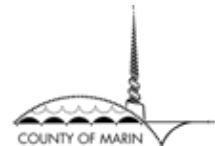
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COVER and FRONT MATTER CREDITS

(Right, top to bottom) Drone imagery of Corte Madera Marsh channel (Photo by Pete Kauhanen, SFEI); China Camp beach (Photo by Katie McKnight, SFEI); Drone imagery of mudflats in Corte Madera Marsh (Photo by Pete Kauhanen, SFEI); Oysters (Photo by Marco Verch Professional Photographer and Speaker, CC BY 2.0); Eelgrass (Photo by CA Sea Grant, CC BY 2.0); (Left) Paradise Drive along Corte Madera's shoreline (courtesy of Google Earth)

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TABLE OF CONTENTS

INTRODUCTION	1
About the user guide.....	4
Broader context	5
A human process: engaging stakeholders.....	6
OVERVIEW OF THE ADAPTATION FRAMEWORK.....	8
APPLYING THE FRAMEWORK IN FIVE STEPS	10
Step 1: Assess vulnerability to sea level rise by OLU	10
Step 2: Identify adaptation approaches with a focus on natural and nature-based measures.....	12
Step 3: Envision desired futures	16
Step 4: Develop adaptation strategies.....	17
Step 5: Evaluate tradeoffs and prioritize strategies	18
APPLYING THE FRAMEWORK IN MARIN COUNTY: CASE STUDY EXAMPLES.....	20
Novato OLU case study	22
Corte Madera OLU case study	34
NEXT STEPS.....	44
APPENDICES	46
Appendix 1: Physical processes & vulnerability maps.....	46
Appendix 2: Nature-based adaptation opportunities maps	60
Appendix 3: Strategy maps.....	66
Appendix 4: Understanding how sea level rise may affect adaptation measures and objectives over time.....	72
REFERENCES.....	82

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GLOSSARY

Adaptation measures: specific interventions or actions to manage the shoreline in response to, or in anticipation of climate change. Measures can be structural (e.g., seawalls or tidal marshes), or non-structural (e.g., policy, regulatory, or financial incentives), and allow for protection, accommodation, or retreat from coastal climate hazards.

Adaptation pathway: the implementation of strategies using a series of planned phases that identify “what to do and when” based on particular environmental thresholds (e.g., future water levels), which can serve as a way to address uncertainty in future projections of climate change and allow for flexibility and adjustment over time.

Adaptation strategy: a combination of appropriately-sited adaptation measures that work together to achieve an adaptation goal. In our framework approach, a strategy would be created by combining suitable measures at the Operational Landscape Unit scale, though it would be implemented in phases as individual projects over time. A strategy might include a map of selected measures and a timeline for their implementation and useful life.

Ecotone levee: see definition and examples on page 14.

Migration space preparation: see definition and examples on page 14.

Natural and nature-based measures: physical landscape features that can evolve over time through the actions of environmental processes, such as the flow of water and sediment. They can be naturally occurring, or engineered to mimic natural processes. They can reduce the vulnerability of communities to flood hazards related to climate change while also providing a wide array of additional benefits that most traditional hard armoring solutions lack (e.g., fish and wildlife habitat, recreational opportunities, and carbon sequestration). Examples include nearshore oyster reefs, submerged aquatic vegetation, beaches, and wetlands. They are also referred to as living shorelines, green infrastructure, or natural infrastructure.

Nearshore reef: see definition and examples on page 13.

Polder: see definition and examples on page 14.

Submerged aquatic vegetation: see definition and examples on page 13.

Tidal prism: the volume of water between low and high tide in a particular estuary or inlet.

Vision: a description and/or illustration of a desired future shoreline, based on stakeholder priorities for physical, biological, social, and economic outcomes of adaptation. A vision provides a set of desired outcomes necessary to build an adaptation strategy, as it will guide decisions on which measures to use where, and for what purpose. Each vision needs specific goals and a planning horizon.



View of Sausalito looking towards downtown San Francisco (photo by Shira Bezael, SFEI)

INTRODUCTION

As sea levels continue to rise, coastal communities will need to adapt their shorelines in order to manage risk and create greater social and ecological resilience to a changing landscape. Adapting to sea level rise will be challenging; coastal planners typically have limited resources, and they will need to deploy these as effectively and efficiently as possible. Many communities are in the process of or have completed assessing their vulnerability to sea level rise and other climate impacts. What can communities do to address their vulnerabilities, how do those options change over time, and how can they reflect the values and goals of the local place? Given the natural variety of coastal zones, adaptation will ultimately require a coordinated, place-based, cross-jurisdictional, and landscape-scale approach. A critical tool for this process is a science-based framework for developing shoreline adaptation strategies that are locally appropriate, reflect the values and priorities of the community, and work with natural coastal processes (i.e. Adaptation Framework).

Natural and nature-based measures are often less-understood options for adaptation, but they can meet many of these objectives. They can reduce the vulnerability of communities to flood hazards related to climate change while also providing a wide array of additional benefits that most traditional hard armoring solutions lack, and that communities often value, such as fish and wildlife habitat, recreational opportunities, and carbon sequestration. In addition, because natural and nature-based measures work with rather than against coastal processes of sediment and water movement, they tend to enhance rather than degrade adjacent coastal ecosystems and are inherently designed to change and adapt as seas rise. Natural and nature-based adaptation measures can take many forms, including restored oyster reefs and seagrass beds, marshes, beaches, and ecotone levees. They will likely be implemented in concert with more traditional grey engineering as hybrid strategies. They are also often referred to as living shorelines, green infrastructure, or natural infrastructure.

Despite these multiple benefits, natural and nature-based measures have primarily been implemented only as pilot projects in California and face several challenges before they can become mainstream and widespread. These challenges include (1) a lack of familiarity with the options and their efficacy, (2) a lack of technical guidance to understand where and under what conditions different options may be suitable or appropriate, and (3) how long natural and nature-based measures last and what levels of flood protection and other services they provide. The Adaptation Framework, case studies, and resources presented in this user guide are intended as one step toward addressing these challenges. While the emphasis in this user guide is focused on natural and nature-based measures, we note that the Adaptation Framework approach will be likely applied to developing strategies that mix grey, natural, and nature-based solutions.

The business-as-usual scale for planning for sea level rise often follows ownership or jurisdictional divides. However, changes to the shoreline in one location may have unintended consequences in other locations, as the rising water levels will not necessarily follow jurisdictional boundaries. Instead, the scale of sea level rise planning should reflect the scale at which natural processes, such as tides, waves, and sediment movement, affect shorelines. An example of such an alternative planning scale is referred to as an Operational Landscape Unit (OLU) (Verhoeven et al. 2008).

OLUs are geographic areas that share certain physical characteristics that control the production and flow of coastal ecosystem functions and services (Verhoeven et al. 2008, SFEI and SPUR 2019). Defining and mapping shoreline planning areas such as OLU provides communities with a way to develop coherent, geographically-appropriate adaptation strategies. Baylands OLU, as defined by SFEI and SPUR (2019), share similar environmental variables—including topography, bathymetry, elevation, wave climate, shoreline characteristics, sediment supply, and adjacent land use—that influence their vulnerability and adaptability. OLU often cross traditional jurisdictional boundaries of cities and counties, adhering instead to the boundaries of natural processes. Shoreline adaptation projects implemented within an OLU are likely to influence and be influenced by neighboring projects and natural biophysical conditions within the OLU boundary.

Defining and delineating Baylands OLU involved connecting watershed processes to the shoreline and into the Bay. Topography forms boundaries between watersheds, directing 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 OLU. In some places the boundaries may be easily identifiable headlands, and in other places the boundary may be a fuzzy transition zone between adjacent creeks or tidal sloughs.

Baylands OLU 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 OLU are important—altering the movement of sediment or water in one part of an OLU is likely to have an impact

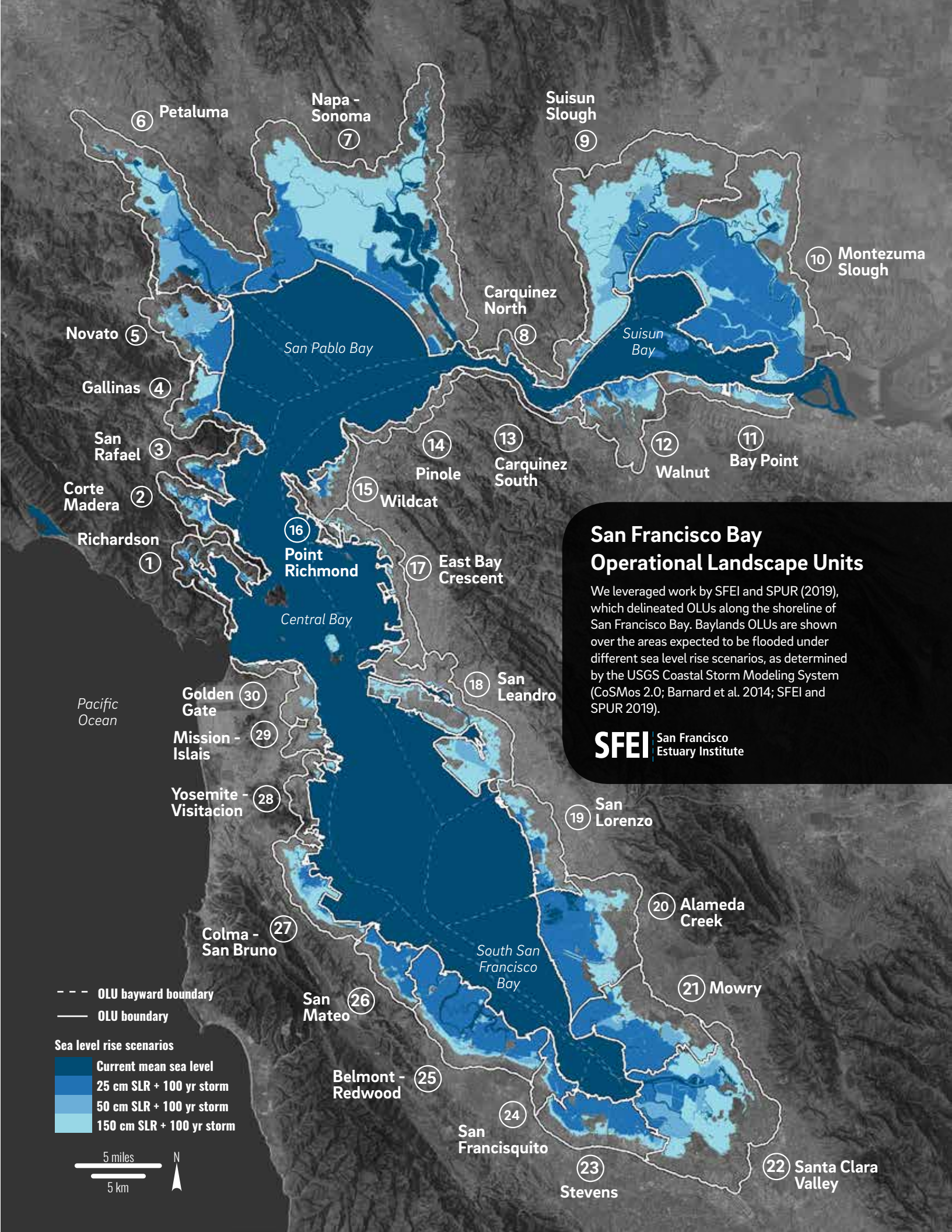
elsewhere in the OLU. For example, within a single OLU, detaining water and sediment behind dams in the upper watershed will likely have an effect on the wetland accretion downstream. Likewise, opening a diked area to tidal action could affect the sediment supply to other parcels along the same tidal channel. Because of these close connections, effective management of one feature within the OLU requires the consideration and management of the other connected features within the OLU. OLU boundaries may be adjusted in the future as new understanding is gained about controlling processes, their effects on adaptation measures, and interactions between measures within and among OLU.

With a better understanding of the likely biophysical interactions within any given OLU, we can begin to identify suitable adaptation measures, and consider how they may be used in combination to address specific vulnerabilities, manage risk, and achieve a desired set of



USEFUL RESOURCE:

For more information on how OLU were delineated for San Francisco Bay, see Chapter 2 (page 21) of the [San Francisco Bay Shoreline Adaptation Atlas](#) (SFEI and SPUR 2019).



San Francisco Bay Operational Landscape Units

We leveraged work by SFEI and SPUR (2019), which delineated OLU along the shoreline of San Francisco Bay. Baylands OLU are shown over the areas expected to be flooded under different sea level rise scenarios, as determined by the USGS Coastal Storm Modeling System (CoSMos 2.0; Barnard et al. 2014; SFEI and SPUR 2019).

SFEI | San Francisco Estuary Institute

--- 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

adaptation outcomes. For example, tidal marshes can help manage risk on the shoreline by buffering waves and protecting the built environment behind it, as well as providing many other co-benefits, but they are only sustainable in areas with the right elevations and wave environments, and with sufficient supplies of sediment. This OLU-scale approach can also be used to help identify adverse and unintended consequences—certain actions might have a short-term resilience benefit for some communities but worsen outcomes for others over the long term. For example, seawalls can worsen erosion on neighboring shorelines by reflecting wave energy and interrupting sediment supply.

About the user guide

The goal of this Adaptation Framework is to enable planners and other coastal decision makers to identify, evaluate, and prioritize adaptation strategies to manage risk in a way that transparently considers multiple benefits. The resources that have been developed to support the framework are intended to help coastal decision-makers to efficiently identify a range of natural and nature-based, landscape-scale adaptation strategies that can address coastal climate change vulnerabilities. The framework also provides guidance enabling coastal decision makers to evaluate how well these adaptation strategies achieve coastal community objectives and prioritize their implementation. We demonstrate the application of the user guide by illustrating the decision-making process with examples from two regions of the Marin County shoreline: Novato and Corte Madera OLUs.

The Framework is organized in five main steps which, while linear on paper, will ultimately be an iterative process. Step one assesses the vulnerability of the place focusing on the sources of the vulnerability. Step two identifies nature-based adaptation measures that are suitable to the place and also addresses the vulnerabilities identified in step one. Step three asks the user to articulate goals and desired future scenarios and step four asks users to organize the available measures into configurations that meet those desired future goals. Step five evaluates the trade-offs between the different strategies. We provide general guidance on each of the five main steps of the Adaptation Framework process and point to key resources. Some of these resources were developed for all OLUs of Marin County, and are included in Appendices. Next, we provide examples of how one might walk through the Adaptation Framework steps for two specific OLUs—Novato and Corte Madera.

View from Bel Marin Keys, a waterfront community in Marin County (photo by Shira Bezalel, SFEI)



Broader context

A multitude of frameworks and guidance documents to organize the adaptation planning process exist or are under development at the federal, state, regional, and local levels. All of these efforts are variations on a theme aimed to support local governments as they begin to tackle the question of how to adapt in the face of climate change. They are intended to integrate with existing planning processes, such as general plans, local hazard mitigation plans, local coastal programs, and climate action plans. Our Adaptation Framework described in this user guide was informed by existing guidance and aligns with many efforts under development in California. It is a more detailed resource to support the transition between assessing vulnerability and developing an adaptation plan, with a particular emphasis on (1) considering an alternative scale for planning (i.e., the OLU scale), (2) prioritizing use of natural and nature-based adaptation measures where suitable, and (3) transparently considering multiple benefits (beyond construction cost) in evaluating trade-offs among strategies. It can and should be used in conjunction with and as a complement to broader planning guidance.

For example, the California Governor's Office of Emergency Services (Cal OES) is leading an effort to update the state's Adaptation Planning Guide (APG). A public review draft of "APG 2.0" is expected in Fall 2019, and will be finalized by March 2020. It will detail a four-step process, of which Phase 3 (define adaptation framework and strategies) is likely to be where our more detailed Adaptation Framework will be most relevant. In the San Francisco Bay Area, adaptation strategies and broader planning guidance are being developed through county-led efforts (e.g., Marin County BayWAVE, Sea Change San Mateo County), and by the San Francisco Bay Conservation and Development Commission's Adapting to Rising Tides (ART) program.

As of the date of this user guide, the ART program was in the process of refining its "Plan" step, which is the transition from understanding vulnerability to identifying and implementing adaptation solutions. The ART process plans to leverage our Sea Level Rise Adaptation Framework resources for guidance on natural and nature-based measures, and will also include non-structural measures related to capacity-building, policies, operations, and funding. The high level guidance developed by the ART program team will be applied and tested in case study locations as part of the ART Bay Area project (expected Fall 2019). While the ART effort was actively evolving as of the date of this user guide, initial discussions indicated general alignment between this Adaptation Framework approach and ART's expanded "Plan" step guidance. Both of our adaptation processes guide the selection of measures (termed "actions" by BCD) that can be combined to create adaptation strategies to support a desired future, and both processes support the evaluation of trade-offs and benefits among different strategies. Where we provide an overview on developing adaptation pathways to support sequencing measures over time, the ART process will provide more detailed guidance. Coordination will continue to effectively communicate and leverage all of these developing resources.

A human process: engaging stakeholders

We believe that no adaptation planning process should take place without the intentional engagement and leadership of community-based stakeholders, more specifically of communities impacted by sea level rise, and that equity and environmental justice are critical to both outcome and process. The engagement of people managing, living in, working in, or benefiting from the coastal zone is key to the success of any coastal adaptation planning effort, especially around issues as long-term and far-reaching as sea level rise and associated storm and tidal flooding. In this document, we define “stakeholders” as government agencies and organizations with shoreline interests as well as members of the community living or working within the coastal zone. Without transparency and intentional community engagement throughout the planning process, we will certainly miss opportunities for creative solutions and might create new problems or exacerbate existing ones disproportionately felt by low-income communities and communities of color.

There are some general best practices that should be employed to achieve meaningful engagement with disadvantaged communities. Most importantly, meaningful engagement requires trust between all parties. It takes time to build trust, so partnering with trusted community organizations can expedite engagement. Be prepared to communicate in multiple languages and using common terminology that is easily understood. Hold meetings in public venues that are accessible to the whole community and schedule meetings at times when community members are most likely to attend. Be prepared to offer travel assistance or child care to encourage participation.

We expect stakeholder engagement to be a vital part of each step within the Adaptation Framework process. While we provide some basic guidance to indicate what type of stakeholder input is particularly critical for each step of the Framework, further details on how to engage and develop a stakeholder process are beyond the scope of this user guide. Many excellent resources on this topic already exist, particularly in the San Francisco Bay Area (e.g., *Adapting to Rising Tides*, Marin County C-SMART and BayWAVE, Alameda County Climate Change Adaptation Workshop Planning Guide, the National Association of Climate Resilience Planners’ Community-driven Climate Resilience Planning framework).



USEFUL RESOURCE:

For more information on community-driven climate resilience planning, see the *National Association of Climate Resilience Planners’ framework report* available at www.nacrp.org.



The Bay Trail
along Richmond's
shoreline (photo by
Shira Bezalel, SFEI)



**Flooding along
Alameda's
shoreline** during
a king tide event
(photo by Shira
Bezalel, SFEI)

OVERVIEW OF THE ADAPTATION FRAMEWORK

The Adaptation Framework is an iterative process intended to support planners and other coastal decision makers in identifying, evaluating, and prioritizing adaptation strategies in a way that transparently considers multiple benefits. The five steps are summarized here, elaborated on in the following pages, and illustrated with two case study examples located in Marin County.

This chapter walks through the steps linearly to demonstrate how the framework could be applied to a real place, but the order of the steps can be adapted to fit the needs of the users or incorporate lessons learned. In particular, we acknowledge that practitioners could implement Step 3 before Step 2, resulting in a filter that narrows the number of measures that need to be considered. Individual steps may also need to be revisited with the availability of new data, changes in stakeholder goals, or other considerations that change the inputs driving the outcomes.



STEP 1

Assess vulnerability to sea level rise by OLU

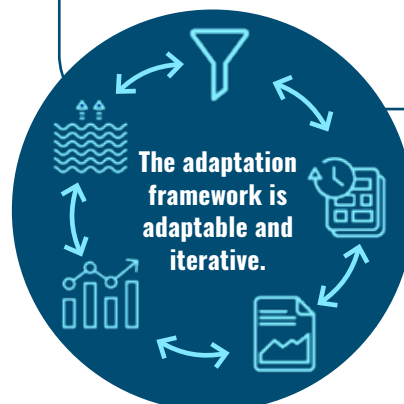
- In this step, stakeholders determine what assets are vulnerable by assessing exposure and risk, documenting where assets are located, and identifying hazards (e.g., coastal flooding, riverine flooding, erosion from waves)
- The goal of the vulnerability assessment is to understand which assets are vulnerable to flooding in different sea level rise scenarios.
- It is difficult, although critical, to assess the root cause of vulnerability (e.g., coastal vs. riverine flooding, combined flooding, erosion from waves) in order to identify the most effective adaptation options.



STEP 2

Identify adaptation approaches with a focus on natural and nature-based measures

- Identify adaptation measures that are suitable within each OLU.
- Understand which vulnerabilities are addressed by different adaptation measures.
- Determine what physical configuration would maximize the effectiveness of a particular adaptation approach.





STEP 3

Envision desired futures

- Define a vision or alternate visions, goals, and the outcomes desired by communities within the OLU to guide development of adaptation strategies.
- Determine what the OLU strategy needs to achieve based on the needs and desires of the communities and stakeholders projected to be impacted by sea level rise and future flooding (e.g., maintain function or service X and Y at location Z up to 2070).



STEP 4

Develop adaptation strategies

- Develop a strategy for each vision. There may be one or more strategies for each vision.
- Determine what combination of measures could be used where and when to achieve the goals of each vision.
- Discuss the co-benefits of each strategy.



STEP 5

Evaluate trade-offs and prioritize strategies

- Once strategies 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.
- Estimate how long the strategy will last, how much it costs, and what are potential adverse impacts of each measure within a strategy.
- The process is iterative. Once there is a sense of benefits and trade-offs among strategies, elements of strategies may be combined into a final strategy, or the goals and visions revisited and the strategies redefined.

Framework steps to plan adaptation efforts (modified from SFEI and SPUR 2019)

APPLYING THE FRAMEWORK IN FIVE STEPS

Step 1 **Assess vulnerability to sea level rise by OLU: Determine what assets are vulnerable, assess exposure and risk, and identify the source of vulnerability.**

The goal of the vulnerability assessment is to understand which assets are vulnerable to flooding or erosion under different sea level rise scenarios, and to understand where and what the near-term and long-term risks are. Several such assessments have been completed around the Bay. The County of Marin completed the BayWave Vulnerability Assessment, which can be found at marinslr.org, in 2017. We refer the reader to this document for details on working through this step of the process and provide only some highlights and additional considerations here. In Step 1 it is critical to assess the root causes of vulnerabilities in order to effectively match appropriate adaptation measures with hazards. The box on the next page illustrates different ways to reduce risk and how to share risk.



- ***Our Coast Our Future's*** interactive web map and downloadable flooding scenarios
- ***BCDC'S Adapting to Rising Tides Bay Shoreline Flood Explorer*** interactive web map
- ***Marin Bay Waterfront Adaptation Vulnerability Evaluation*** (BayWAVE) for Marin County

Key questions to address with stakeholders:

- What is the environmental setting and land use context (e.g., topography, bathymetry, waves/tides, land use setting, land use history, subsidence map)?
- What assets are exposed at different future water levels?
- Where are their vulnerabilities, and what is the relative importance of the affected assets?
- Are there pre-existing conditions, such as income/wealth disparity, that exacerbate a community's vulnerabilities?
- What is the source of the hazards to which assets are exposed (e.g., inundation from the Bay, flooding from creeks, combined flooding, inability to drain by gravity, wave exposure/shoreline erosion, groundwater regime change)?
- Is the area directly vulnerable or dependent upon a vulnerability in another area (e.g., an access road)?
- What is the magnitude of change that needs to be achieved to achieve the desired level of protection?

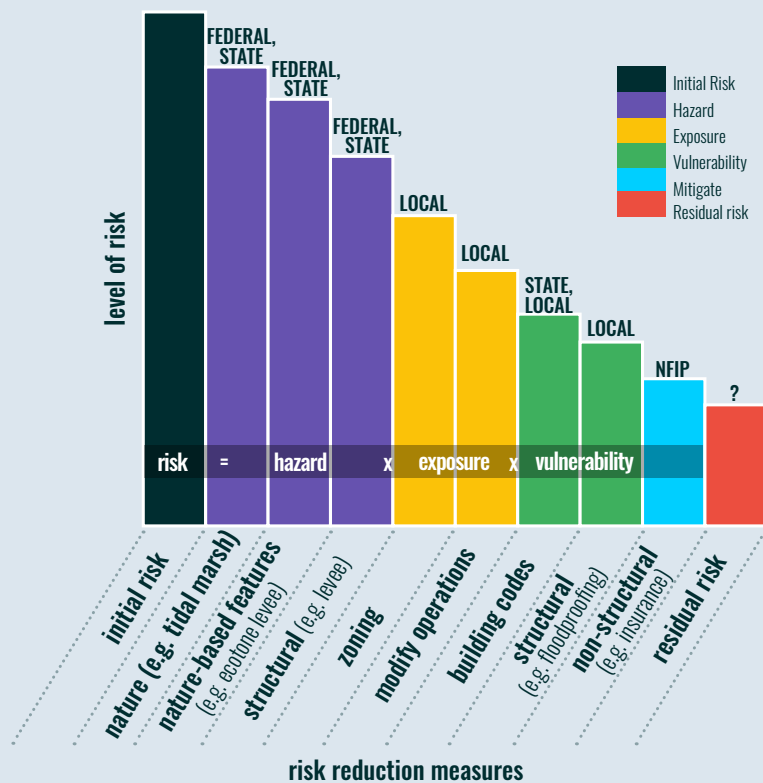
Risk management

The first step to risk management is to analyze the risk of damage from flooding and erosion of both man-made and natural assets. For a specified hazard, such as flooding, the assessment should identify the consequences of damage to an asset. Flooding can occur from a number of different sources, such as from coastal storm surges, from high runoff events in creeks, or both in combination (flooding in creeks due to backwater effects of high coastal water levels). Hazards are specified in terms of probability of a certain magnitude event per year (e.g. 1% water level, referred to as the 100-year event). Consequences are the product of the vulnerability of the asset to damage by the hazard and the proportion of the asset exposed to the hazard. Consequences are specified in dollars per event. Multiplying the cost per event by the number of events per year gives the risk in terms of cost per year.

The figure below shows how the initial risk can be managed using different adaptation measures, often implemented by different stakeholders. For example, the flood hazard may be reduced by natural features such as marshes, or by levees and seawalls; exposure to flooding may be reduced by changing land-use zonation or operations, and the vulnerability to flooding may be reduced by floodproofing. Combinations of adaptation measures can reduce risk to a tolerable level of residual risk. In the past we have generally focused on structural measures, such as levees, but in the future hybrid strategies using multiple adaptation measures and sharing risk may be more appropriate, with different stakeholders working in collaboration, and provide multiple benefits. The figure below is illustrative only and does not indicate the efficacy of individual measures.

$$\text{Risk} = \text{Hazard} \times \text{Exposure} \times \text{Vulnerability}$$

(\$/yr) (events/yr) x (% exposed) x (\$/event)



Step 2

Identify adaptation approaches with a focus on natural and nature-based measures: Identify adaptation measures that could work well in a given place and use nature as much as you can.

Adaptation measures are specific interventions or ways to manage the shoreline in response to or in anticipation of climate change. Natural and nature-based measures are physical landscape features designed to evolve over time through the actions of environmental processes, such as the flow of water and sediment. They can provide coastal protection and many other ecosystem services. They can include measures that are engineered to mimic characteristics of natural features. They can also be used in combination with conventional hard infrastructure (e.g. levees and seawalls) to develop hybrid, large-scale, multi-objective shoreline adaptation strategies.

The *San Francisco Bay Shoreline Adaptation Atlas* defines and describes more than two dozen adaptation measures that are potentially appropriate to the Baylands OLU (SFEI and SPUR 2019). This user guide evaluates the natural and nature-based measures mapped by SFEI and SPUR (2019) within Marin County's OLU to determine potential future strategies to address sea level rise. We used the best available information to take a first pass at mapping suitability of natural and nature-based measures. We encourage the refinement or improvement of criteria and mapping as current data gaps are filled and the resolution of existing data (e.g., bathymetry) is improved in the future. We also note that site-specific feasibility and engineering designs will require local studies.





When mapping suitable areas for each nature-based measure and determining the dimensions (e.g., width and height) necessary to provide coastal flood control and shoreline protection, we worked with a standard set of planning assumptions:

- **2.1m of sea level rise by 2100:** when required for mapping and calculations, we assumed 2.1 m of sea level rise by 2100 under a high emissions scenario, which is recommended by the State of California for use when making decisions requiring a medium to high level of risk aversion (OPC 2018).
- **100-year 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 (AECOM 2016).
- **100-year 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) (DHI 2011 and 2013).

Definitions and descriptions of the seven natural and nature-based measures considered in this report are listed in the table below and continue onto the following page. For a full description on landscape configuration, design, and process guidelines, ecosystem functions, and policy considerations, as well as mapping methods and other details see Chapter 4 and Appendix 5 of the *San Francisco Bay Shoreline Adaptation Atlas* (SFEI and SPUR 2019).

USEFUL RESOURCES:

San Francisco Bay Shoreline Adaptation Atlas
[interactive web map](#)
 and [report](#)

Adaptation Measure	Definition	Landscape configuration, design, & process guidelines
<p>Nearshore reefs</p> 	<p>Nearshore (lower intertidal/subtidal) reefs made of structures such as bags of oyster shell and reef balls made of baycrete (a cement mixture composed mostly of Bay sand and shells) that provide hard substrate for shellfish including native Olympia oysters (<i>Ostrea lurida</i>) and other aquatic plants and animals. Nearshore reefs can reduce wave transmission at lower tidal elevations and stabilize areas in their lee (Latta and Boyer 2015).</p>	<ul style="list-style-type: none"> • Best suited to shallow water in areas of low wave action, at the low end of mudflats • Generally need to be located relatively close to shore in order to create a wave shadow in their lee, trapping sediment and reducing marsh edge erosion • 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)
<p>Submerged aquatic vegetation (eelgrass)</p> 	<p>“Submerged aquatic vegetation” (SAV) refers to all underwater flowering plants, and can contribute to trapping sediment and slowing shoreline erosion. Eelgrass (<i>Zostera marina</i>) is the main species in the lower parts of the San Francisco Estuary, but other submerged vegetation species exist throughout the Bay as well.</p>	<ul style="list-style-type: none"> • Salinity and light are limiting factors for eelgrass beds • Eelgrass can grow in sand, silt, or clays, and do best where current speeds and wave energy are not excessive • Potential exists to establish eelgrass beds at depths less than about 2 m in broad swaths along the shores of San Pablo Bay, Central Bay, and South Bay (Merkel 2005)
<p>Beaches</p> 	<p>Coarse or composite estuarine beaches are dynamic features that can consist of a mixture of sand, shell, gravel, or cobble. Coarser gravel and cobble beaches can dissipate wave energy over shorter distances and therefore may be more suitable within an urbanized and constrained estuary.</p>	<ul style="list-style-type: none"> • Beaches are effective at dissipating and reflecting wave energy • Beaches can be placed in front of levees, roads or other infrastructure vulnerable to wave overtopping, or in front of marshes vulnerable to erosion • Groins or other retention structures should be considered for beaches implemented along shorelines where the dominant waves tend to transport sediment down the shoreline (i.e. high drift), but are not necessary for naturally constrained areas (e.g., beaches between headlands)
<p>Tidal marshes</p> 	<p>Protecting, maintaining, and restoring tidal marshes and their associated tidal flats is critical for sustaining their flood risk management services with 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.</p>	<ul style="list-style-type: none"> • The topography of the marsh and its associated mudflat plays a significant role in wave refraction, shoaling, and breaking • Marsh width is one important factor that influences the degree to which a tidal marsh is able to attenuate waves • Vegetation type, elevation within the tidal frame, and salinity levels are important considerations when designing marshes for sea level rise adaptation

(photo by Marilyn Latta)

(photo by Ronald Phillips, CC BY 2.0)

(photo by Peter Baye)

(image courtesy of Google Earth)

(photo by Nate Kauffman)

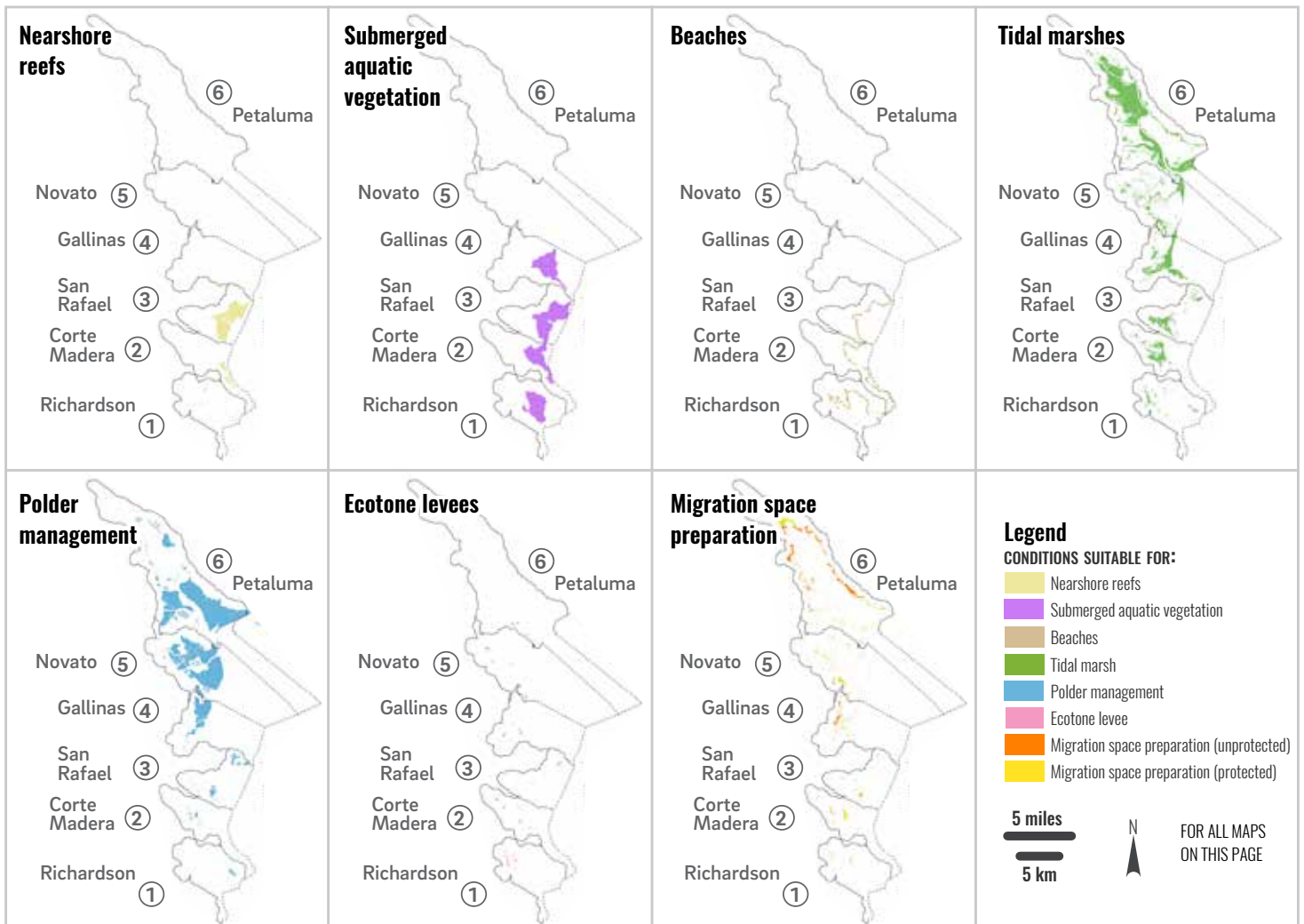
Adaptation Measure	Definition	Landscape configuration, design, & process guidelines
<p>Polder management</p> 	<p>Polders are low-lying areas of land that would normally be inundated by regular tides if they were not protected by dikes. Polders are the diked, ditched, and drained historical marshes and 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, hayfields 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. Polder management refers to the active decision making and specific management approaches to protect, raise, and/or tidally reconnect polders as sea levels rise.</p>	<ul style="list-style-type: none"> • If a polder is intentionally or accidentally returned to tidal action, the additional tidal prism will need to be analyzed as it will increase the demand for sediment within the polder • The location of polders relative to structures is important as the large increase in tidal prism may lead to widening of downstream channels, undermining levees, bridge abutments, and other structures • In a planned restoration, the topography may be graded before breaching and dredged sediment may be placed to raise elevations • Methods such as warping (managing water to allow sediment to settle to the bottom) and levee lowering may allow the more gradual introduction of sediment into polders, by natural means, to reduce the impacts of catastrophic dike failures
<p>Ecotone levees</p> 	<p>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 (Nur et al. 2018). They can attenuate waves, provide high-tide refuge for marsh wildlife, and allow room for marshes to migrate upslope with sea level rise.</p>	<ul style="list-style-type: none"> • Slopes are designed to stretch down from the crest of the flood risk management levee to tidal marsh elevation with a gradient between 20:1 and 30:1 • Subsurface irrigation on the ecotone levee (i.e. a “horizontal levee”) can be incorporated to support fresh to brackish wetlands on the levee at the upland edge of the tidal marsh • Levees wider than 25 m, planted with dense vegetation between 50–100 cm tall, can provide measurable benefits to tidal marsh dependent birds, both in the short- and long-term (www.pointblue.org/tbirds).
<p>Migration space preparation</p> 	<p>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 adjacent to developed lands.</p>	<ul style="list-style-type: none"> • Acquiring and protecting areas that are currently undeveloped and at proper elevations for marsh migration will be critical for long-term adaptation of tidal marshes • 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 • Management is often necessary to establish desired native plant communities • 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

Suitability ratings were determined 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). Final ratings were binned into three categories: (1) limited suitability; (2) some suitability; and (3) high suitability. For more information on how suitability ratings were calculated, see pages 246 and 247 of the *Adaptation Atlas*.

	Nearshore reefs	Submerged aquatic vegetation (eelgrass)	Beaches	Tidal marshes	Polder management	Ecotone levees	Migration space preparation
1. Richardson	●	●	●	◐	○	◐	○
2. Corte Madera	●	●	●	◐	◐	◐	◐
3. San Rafael	●	●	●	◐	◐	◐	○
4. Gallinas	◐	●	○	●	●	◐	●
5. Novato	○	○	○	●	●	◐	●
6. Petaluma	○	○	○	●	●	○	●

(Left) Suitability ratings for each measure for Marin County OLUs (courtesy of SFEI and SPUR 2019)

(Below) Maps of each nature-based measure considered in this report (see Appendix 2 for more detailed maps)



Step 3

Envision desired futures: What are the desired outcomes? Develop visions to identify desired future(s).

There are many ways to combine individual adaptation measures into a comprehensive adaptation strategy. To make decisions on which measures to use where, and for what purpose, a guiding vision and set of desired outcomes is necessary to achieve a particular desired future.

Managing the shoreline within an OLU entails more than managing the risk to key assets. There are other benefits, such as wildlife support, water quality, recreation, or carbon sequestration, that need to be maintained or that could be further enhanced. The different parts of the OLU are connected by physical, biological, and social processes. It is therefore important to work with stakeholders to express desired futures as a series of goals articulated and illustrated in visions of the future landscape.

Each vision needs specific goals and a planning horizon. A goal may be to “protect the wastewater plant from an 100-year flood event up to 2070” or “to allow the existing marshes to accrete and migrate with 3 feet of sea level rise” or “to reduce wave heights reaching the levees to less than 1 foot.” The planning horizon could be set by the working life of major assets or by thresholds of the amount of sea level rise. The vision could be described with text and sketched maps or illustrations that show what the landscape would look like.

There may be a number of visions that get developed around priorities such as “equitable access to nature”, “realign levees where possible”, “minimize risk to critical facilities”, or “keep the present shoreline alignment”. Visions can be used as bookends, or extreme examples, to help illustrate choices and trade-offs to stakeholders, and an iterative process can then occur where elements of different strategies may ultimately get combined into a final selected strategy.

Questions to consider with stakeholders:

- What do stakeholders value about the existing shoreline (i.e., aspects to maintain into the future)? What aspects could be improved? Are there elements of historical shoreline functions (biophysical or social) that might be restored?
- What are the desired outcomes of an adaptation strategy (economic, social, ecological)?
- How might these outcomes be grouped into 2-3 alternative visions for strategy development?
- What are key assumptions or criteria for each vision (e.g., all current development will be protected in place, marsh habitat will be allowed to migrate inland)?
- Is the present level of flood risk management sufficient? Is there a common standard of protection to consider across the entire OLU shoreline (e.g., FEMA 100-yr floodplain) or will it vary by asset (e.g., residential, industrial, open space)?
- Is the default to maintain the present level of protection under future sea level rise, or is there a need to bring all protection up to some common standard?

Step 4

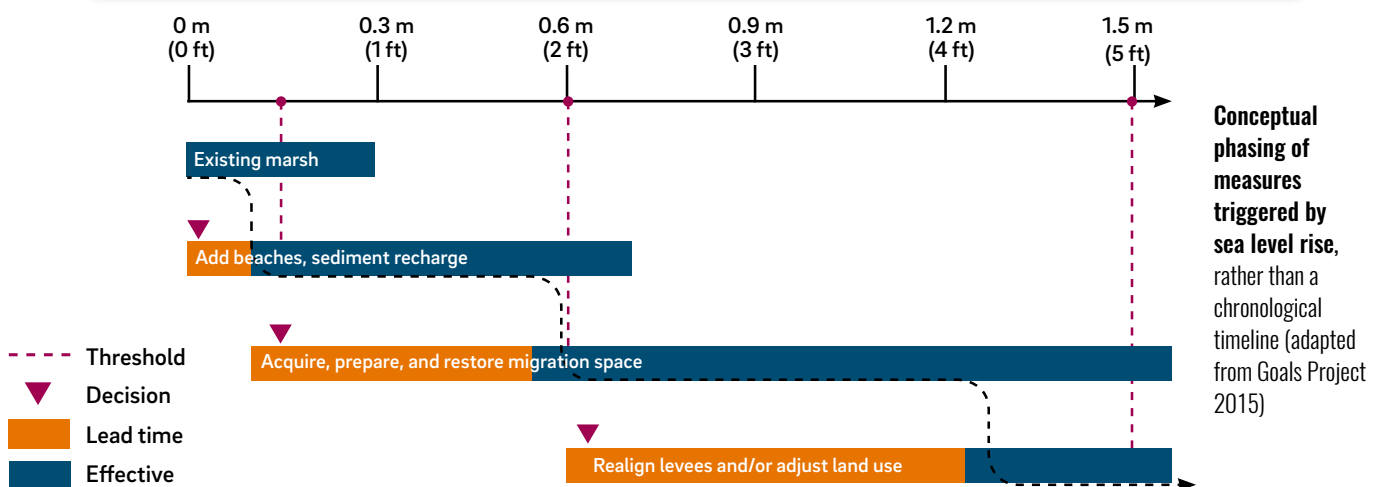
Develop adaptation strategies: A strategy is a combination of adaptation “measures.” Develop an adaptation strategy for each vision.

A strategy is a combination of appropriately-sited adaptation measures (identified in Step 2) that addresses the criteria and realizes the vision and goals identified in Step 3. It includes a map of selected measures and a timeline for their implementation and useful life. While the strategy is created for the whole OLU it would be implemented as individual projects over time. Each project has its own project cycle, e.g. alternatives, feasibility, permitting, design, implementation, monitoring and maintenance. Over time, the completion of individual projects as part of the strategy would realize the vision. Projects can be combined and implemented in phases over time in a planned sequence or “pathway” that is appropriate to the landscape setting and helps to manage and reduce various coastal hazards, including erosion, sea level rise, riverine flooding, and combined (riverine and tidal) flooding (Reeder and Ranger 2011, Haasnoot et al. 2013).

Each measure will accommodate differing amounts or rates of sea level rise. A strategy may therefore need to consider different measures at different times, allowing the landscape to evolve as sea level rise accelerates and other drivers change (such as sediment supply and desired assets to protect). The timeline for a strategy can therefore be triggered by the amount or rate of sea level rise rather than by calendar year, as shown in the figure below. However the individual projects are likely to be implemented through capital improvement projects that generally follow a chronological timeline.

Questions to consider when combining suitable adaptation measures into “strategies”:

- What vulnerabilities do you need to address (from Step 1)?
- Which measures address identified vulnerabilities, where do they need to be located, and how large do they need to be in order to effectively achieve the desired outcomes?
- What are specific success criteria for each vision?
- When would the individual measures start providing desired benefits? When do they stop working?
- Each measure needs to consider their whole-life cost



Step 5

Evaluate tradeoffs and prioritize strategies: Assess benefits and trade-offs among the strategies identified.

The final step of this framework is to assess benefits and trade-offs among the different strategies. Coastal protection benefits, such as reducing losses or preventing future flood damages, are benefits associated with traditional benefit-cost assessments (e.g., FEMA, USACE). However, unlike traditional hard armoring, natural and nature-based measures continue to provide a host of benefits beyond coastal protection, including public access, recreation opportunities, carbon sequestration, water filtration, and biodiversity support (Barbier et al. 2011). It is important to adequately account for the breadth of benefits derived from natural and nature-based strategies in order to improve the ability of communities to develop adaptation responses that can achieve multiple objectives and to accurately assess trade-offs when weighing adaptation options (Arkema et al. 2015, Sutton-Grier 2015). Accounting for multiple benefits can also open doors to a wider range of potential funding sources, including those related to flood control, public access, and habitat restoration.

We take a broad view of “benefits” derived from natural and nature-based strategies as being inclusive of benefits to people (termed ecosystem services) as well as the intrinsic value or existence value of nature (conserving nature for nature’s sake). As an example, a recent ecosystem service conceptual model developed for salt marsh restoration (Mason et al. 2018) explicitly includes species and habitat persistence as “services,” along with more typical human-centric benefits of shoreline protection and recreation. Our framework is intended to be driven by a broad group of stakeholders, and as such is flexible to allow for inclusion of a diversity of voices, values, and priorities.

There is a wealth of literature and guidance on developing and measuring ecosystem benefits (e.g., Brown et al. 2014, National Ecosystem Services Partnership). The main point we emphasize is that assessments of benefits work best when co-developed with stakeholders so that they reflect the shared values and priorities of the community. In addition to practical considerations of cost for implementation and maintenance, we find it helpful to organize benefits based on functional categories of ecosystem services defined by the Millenium Ecosystem Assessment (2005):

- **Provisioning services** are products obtained from ecosystems, such as food, fiber, and fuel
- **Regulating services** are benefits obtained from the regulation of ecosystem processes, such as flood and erosion control
- **Cultural services** include nonmaterial benefits such as spiritual, recreational, and cultural values
- **Supporting services** are necessary for the production of all other ecosystem services and that maintain the conditions for life on Earth, such as soil formation, nutrient cycling, and support of habitat

Example benefits within each category are provided in the table below, which can be used as a starting point to engage with stakeholders in brainstorming and prioritizing benefits (Millenium Ecosystem Assessment 2005, Liqueete et al. 2013). The next decision is how and what can be measured to represent a priority benefit, known as a benefit-relevant indicator (Olander et al. 2018). There is much existing guidance on developing appropriate indicators (e.g., Brown et al. 2014). The indicators can be derived from a variety of data sources, including GIS-based information (e.g., total miles of trails), models (e.g., projected changes in habitat or recreation use), or surveys (e.g., ranking by stakeholders or a particular focus group).

Indicators do not always need to boil down to dollars (Guerry et al. 2015). The purpose of assessing benefits in this framework is to understand and compare **relative** differences among strategies. Thus, it may be enough to know that Strategy A would create 2 miles of new trails, whereas Strategy B would create 10 miles of new trails, without having to translate to a dollar value for recreation. In other cases, there may be a minimum/maximum value of a metric that needs to be attained for a strategy to work (e.g., must cost less than “x” dollars, or must have a minimum of “y” acres of a particular habitat). The objective of this step is to explicitly define the benefits, and to seek alignment among stakeholders on which benefits to prioritize so that they can be appropriately measured and compared among strategies.

(Below) Example benefits to consider
for evaluating and prioritizing strategies

Cost considerations
Low-cost construction
Low-cost maintenance
Ease of permitting
Political/community acceptability
Regulating services
Coastal hazard reduction
Reduced storm surge
Reduced erosion
Reduced combined flooding
Reduced impacts from short-term sea level rise
Reduced impacts from long-term sea level rise
Carbon sequestration and storage (i.e., climate regulation)
Water filtration (improved water quality)
Pest and disease regulation
Supporting services
Biodiversity support (habitat, species, genetic diversity)
Nutrient cycling
Cultural/social services
Recreation and tourism
Educational values
Aesthetic values
Spiritual and religious values
Cultural heritage values
Services to disadvantaged communities/vulnerable populations
Provisioning services
Food (e.g., sportfish)
Raw materials (e.g., shells, fiber)



USEFUL RESOURCES:

- [Future San Francisco Bay Tidal Marshes](#) interactive web map
- [San Mateo County Wetlands Vulnerability Study](#) technical report

Approach to evaluate and prioritize strategies

- Identify benefits important to stakeholders
- Identify benefit-relevant indicators that can be measured
- Quantify indicators based on key input assumptions from Step 4, and determine any additional assumptions (e.g., timing of implementation, rate of sea level rise, sediment availability)
- Decide with stakeholders whether to weight certain benefits and associated indicators more than others. This may be particularly important to address issues of equity.
- Compare and assess trade-offs among strategies
- Determine importance of key uncertainties in input assumption to the ultimate ranking of strategies (e.g., sensitivity analysis)

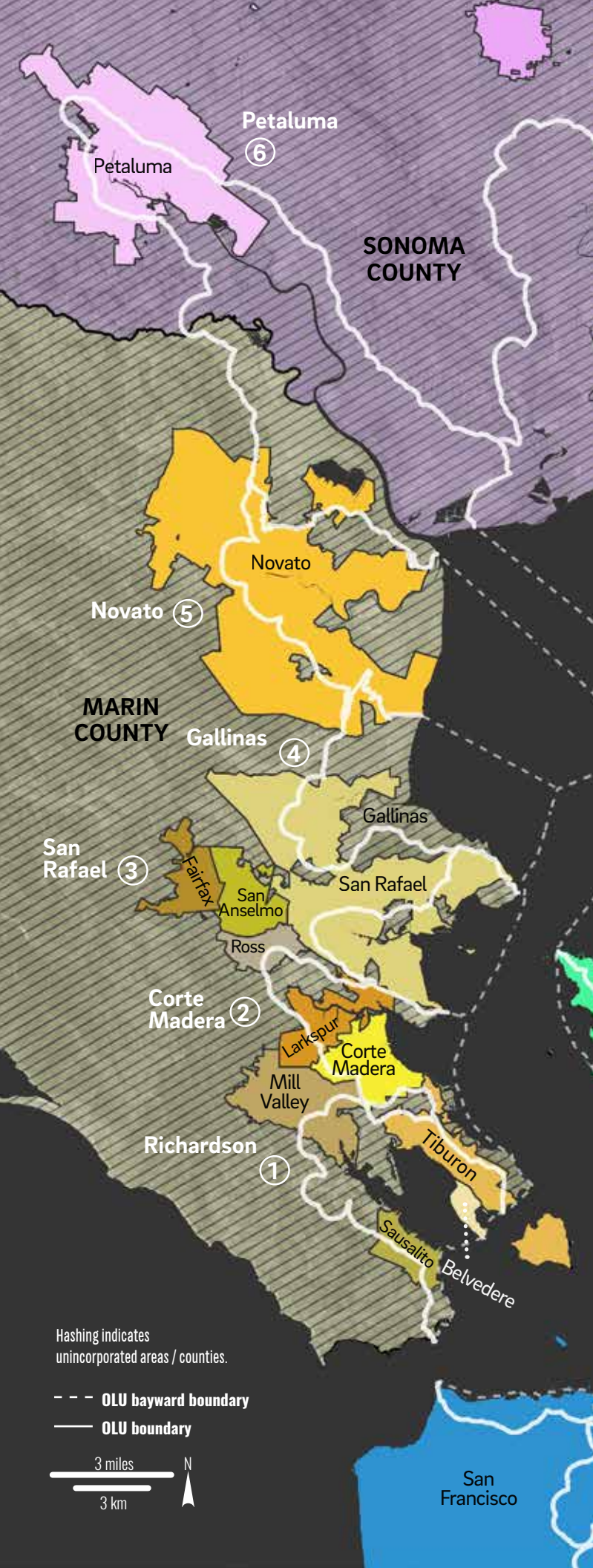
APPLYING THE FRAMEWORK IN MARIN COUNTY: CASE STUDY EXAMPLES

We refined and demonstrated the framework approach in Marin County as a way to illustrate the process of bringing stakeholders together around a common planning unit (the OLU), assess options for adaptation, and begin to develop and evaluate potential adaptation strategies. Six Baylands OLUs fall within Marin County, encompassing over a dozen cities and unincorporated areas. This section uses Novato and Corte Madera OLUs as case studies to demonstrate how to apply the five-step adaptation framework to real places.

The case studies discussed here build on the County's existing efforts to prepare for climate change, including the BayWAVE project that has already undertaken extensive stakeholder and community outreach. It is important to note that the case studies described in this section are intended only as examples to illustrate the framework process. The visions, strategies, and evaluation criteria do not reflect stakeholder or County priorities, they do not address all vulnerabilities, there has been no engineering design, and they do not include details of project phasing or adaptation pathways.

(Left, facing page)
Jurisdictions grouped by OLUs in Marin County, many of which are responsible for actions and permitting activities along the shoreline.

(Right, facing page) OLUs overlaid with 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.



Hashing indicates unincorporated areas / counties.

--- OLU bayward boundary
 — OLU boundary

3 miles
 3 km

N

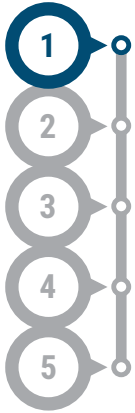
Sea level rise scenarios

- Dark blue: Current mean high water
- Medium blue: 25 cm SLR + 100 yr storm
- Light blue: 50 cm SLR + 100 yr storm
- Very light blue: 150 cm SLR + 100 yr storm

--- OLU bayward boundary
 — OLU boundary

3 miles
 3 km

N



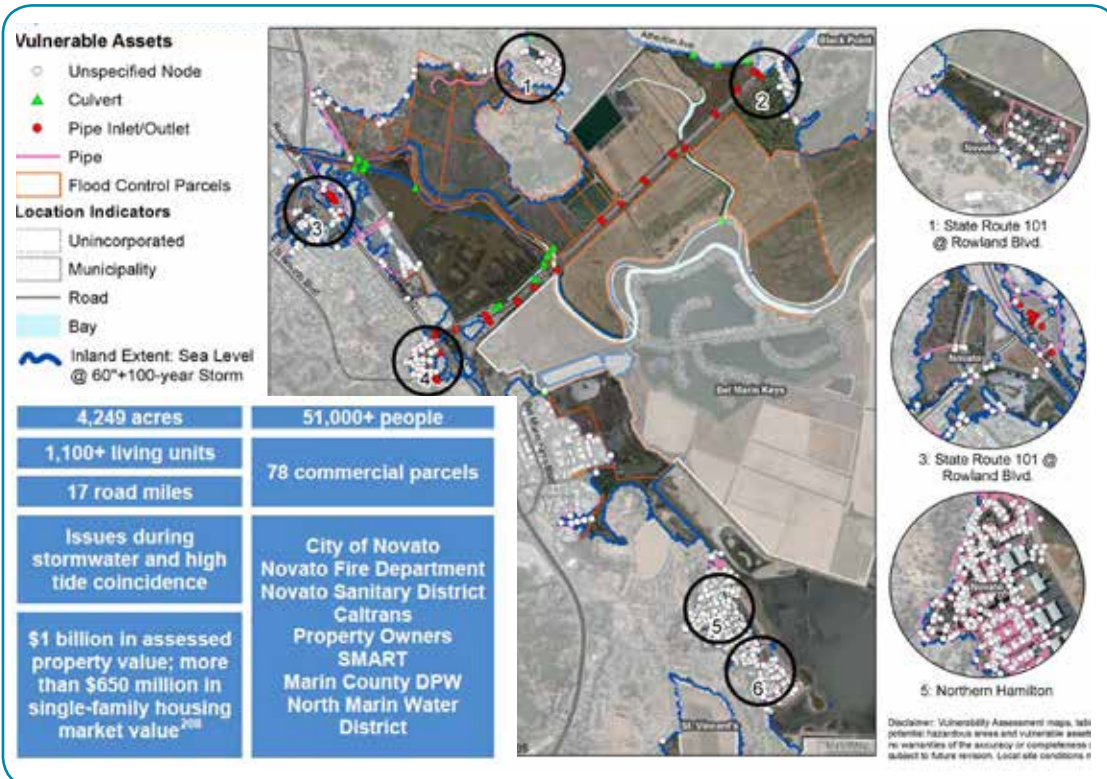
Novato OLU case study

Step 1: Assess vulnerability

The Novato OLU is characterized by subsided diked baylands (polders) at the mouth of Novato Creek. Novato has the highest proportion of polders by area of the Baylands OLU, and the deepest in San Pablo Bay. If breached, these polders could create long fetches (i.e. wind-generated waves over a long distance) which could result in significant wind waves being generated, leading to more erosion and overtopping.

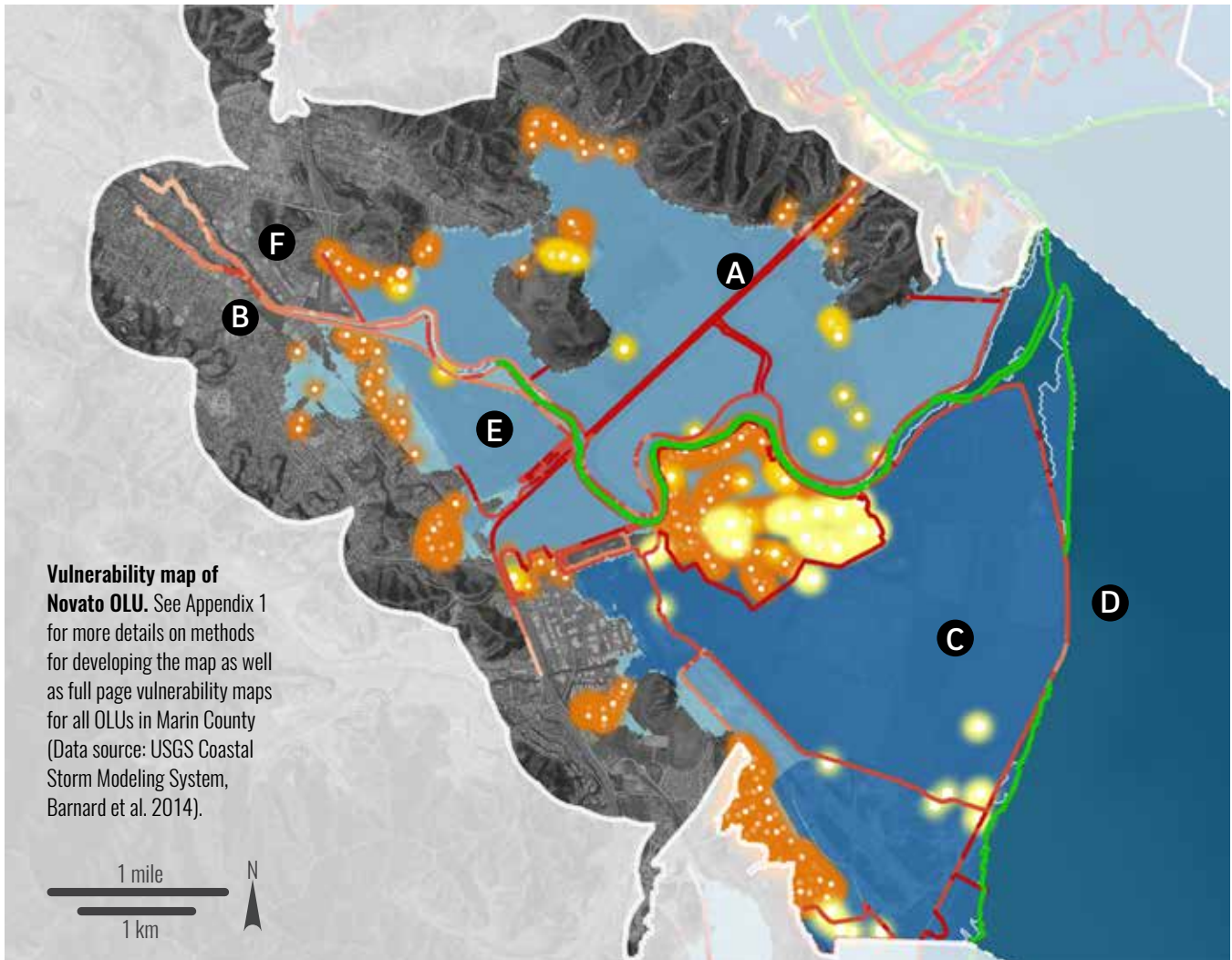
Developed areas within the Novato OLU were built out on former marshes and mudflats. Earthen berms and levees were built up along Novato Creek and at the shoreline. Former baylands currently behind berms and levees have subsided, resulting in large polder areas that require pumping to keep them dry. The levee system that serves as the first line of shoreline defense is long and will require significant maintenance and improvements to continue to provide protection with rising seas. Additionally, if the outboard levee breaks, there are few internal berms dividing the area and many of the former baylands and existing roads will flood. The outboard levee is protected from bay waves in many locations by existing marshes and mudflats, which reduce levee maintenance, but these outboard marshes are eroding, particularly to the south of Novato Creek.

Another vulnerability within the OLU comes from combined flooding from the creek, which results from a combination of high riverine discharges, high bay water levels, and lack of floodplain that has led to the confinement and shallowing of the channel.



Stormwater assets vulnerable to sea level rise in the Novato OLU, from the Marin Shoreline Sea Level Rise Vulnerability Assessment (BayWAVE 2017)

VULNERABILITY MAP NOVATO OLU



Sources of vulnerability in Novato OLU include:

- A** Low-lying infrastructure including Highway 37, rail lines, and a wastewater treatment plant, and vulnerable neighborhoods (e.g. Bel Marin Keys)
- B** Combined flooding from Novato Creek and other tributaries, rising groundwater, and sea level rise
- C** Subsided lands behind levees (i.e. polders) large enough to result in significant wind waves being generated internally
- D** Erosion on fringing marshes that protect the bayside of existing levees.

Assets in the Novato OLU include:

- E** Large areas of land that are used for agriculture and spray fields, undeveloped and in public ownership
- F** Topographically confined, local sediment sources

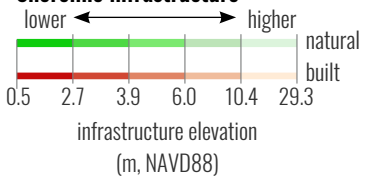
Vulnerable buildings

- 25 cm SLR + 100 year storm
- 50 cm SLR + 100 year storm
- 150 cm SLR + 100 year storm

Flood hazard

- existing (0 cm SLR, no storm)
- 25 cm SLR + 100 year storm
- 50 cm SLR + 100 year storm
- 150 cm SLR + 100 year storm

Shoreline infrastructure





Step 2: Identify adaptation measures

The opportunity map to the right illustrates suitable locations for a number of natural and nature-based adaptation measures. These maps were created based on the existing shoreline. New opportunities may be created by modifying the shoreline through realigning levees, adding fill or regrading. It is unlikely that a single measure on its own will reduce risk to a manageable level. Most nature-based measures must be used together with other natural and engineered features in order to be most effective (e.g. a marsh needs a mudflat, an ecotone levee needs a fronting marsh and a flood risk management levee). Below, we provide a brief discussion of the suitability of measures in the context of ongoing adaptation and restoration projects and regional ecological goals such as those set by the Goals Project (2015) and the Subtidal Goals (2010) project. For a full description on mapping methods, suitability ranking, and combining measures into strategies, see chapter 4 and Appendix 5 of the San Francisco Bay Shoreline Adaptation Atlas (SFEI and SPUR 2019).

NOVATO OLU

Nature-based Adaptation Measures

Adaptation strategies for the Novato OLU will need to address how to maintain the extensive existing levee system or accelerate the build up of sediment to fill the large polders to marsh elevation and manage the additional tidal prism. With such deeply subsided polders, elevations may be raised by lowering or breaching levees adjacent to Novato Creek to allow sediment-laden water to spill over, by placing clean dredged sediment, or by geomorphic dredging. All have been used to raise elevations of subsided baylands in the restoration of Hamilton Wetlands. 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 because Novato OLU is not within the historical extent of beaches, they are not included on the opportunity map yet should be considered.

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 flood risk management 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 inland edges of polders. Green stormwater infrastructure should continue to be implemented in the upper watershed to reduce riverine 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

Suitability

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

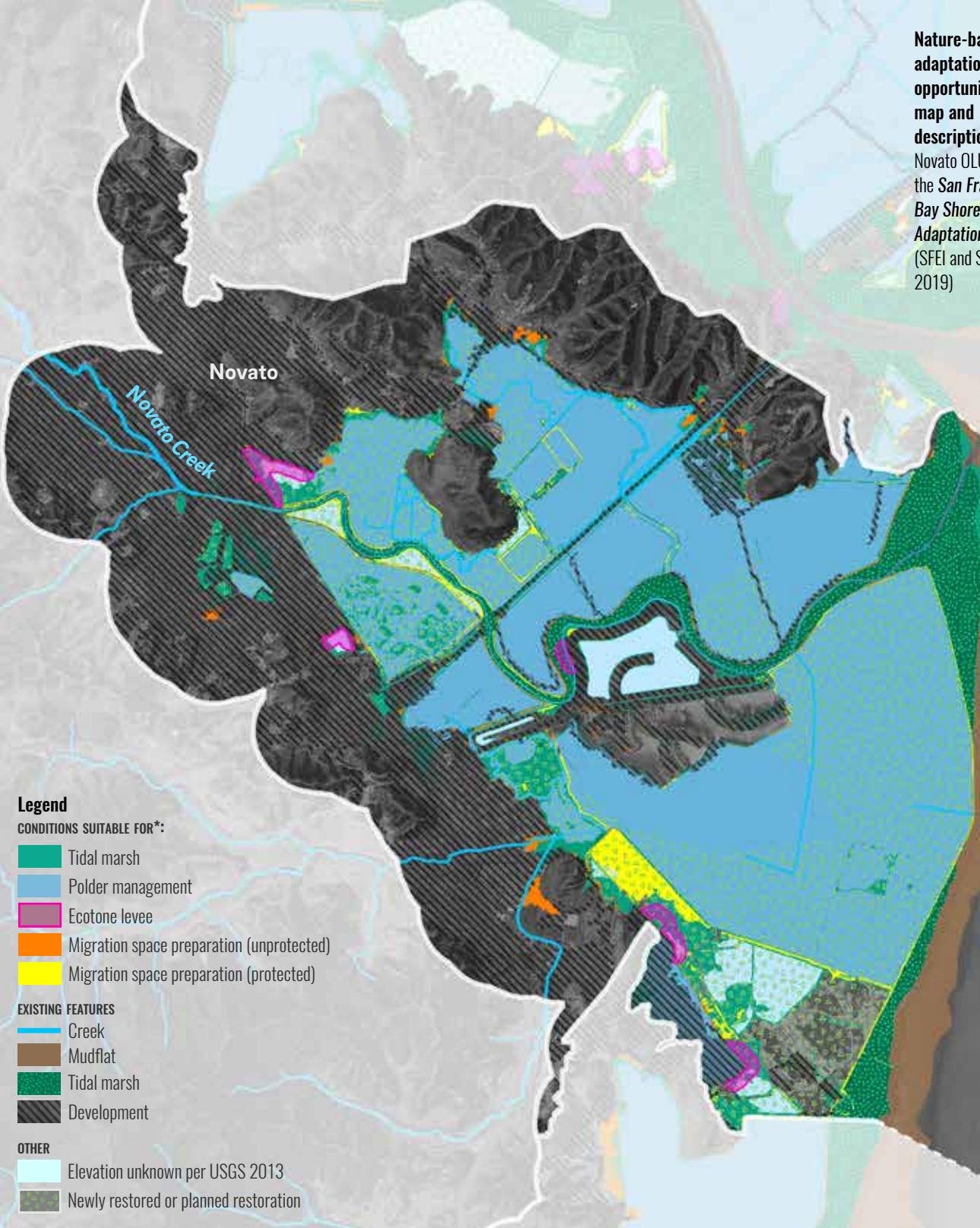
○ Limited suitability ◐ Some suitability ● High suitability



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

NATURE-BASED ADAPTATION OPPORTUNITIES MAP NOVATO OLU

Nature-based adaptation opportunities map and description for Novato OLU, from the *San Francisco Bay Shoreline Adaptation Atlas* (SFEI and SPUR 2019)



Legend

CONDITIONS SUITABLE FOR*:

- 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



***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.



Step 3: Envision desired futures. What are plausible and/or desired future visions for the area?

For the purposes of illustrating the framework process, the project team developed three hypothetical visions that represent different priorities. We considered societal and ecological values, and also tried to develop visions that would result in relatively distinct strategies that might span the range of options from “do nothing” to implementing every suitable nature-based adaptation measure.

Vision 1: “Hold the Line”

The “Hold the Line” vision assumes maintaining and defending the current shoreline configuration such that currently dry areas remain dry into the future (including the polders). This assumes maintaining the existing shoreline protection infrastructure (e.g., levees), continuing to pump, and limiting use of natural and nature-based adaptation measures to opportunities that are bayward of the existing first line of defense.

Vision 2: “Buffer with Public Open Space”

This vision considers opportunities to move the existing first line of shoreline defense by taking advantage of public open space where additional habitat can be restored with minimal reconfiguration of existing vulnerable infrastructure and with strategic realignment of existing levees. This vision allows protected public open space to get wet, but keeps existing developed areas dry. Nature-based adaptation measures can be implemented in protected public open space as necessary to ameliorate identified vulnerabilities.

Vision 3: “Maximize Habitat/Minimize Risk”

This vision expands on the previous buffering concept, and allows for reconfiguration of larger vulnerable infrastructure or levee realignment as necessary to maximize opportunities for nature-based features. Existing development continues to be defended. This vision seeks to maximize the ecological functions and benefits of nature-based measures by restoring or enhancing connectivity of natural processes, from creeks to baylands to the bay itself.



A flood wall adjacent to the Bay Trail near Hamilton Wetlands in Marin County (photo by Shira Bezalel, SFEI)



The Bay Trail along Marin County's shoreline (photo by Shira Bezalel, SFEI)



Step 4. Combine suitable adaptation measures into “strategies” for each desired future

Example strategy to achieve vision 1: “Hold the Line”

Nature-based strategies would focus on maintaining the remnant marsh and mudflat outboard of the existing Bay levee that fronts the Novato Baylands, Bel Marin Keys and the Hamilton Airfield restoration. A marsh in front of this levee would attenuate waves and reduce erosion and overtopping of the levee. In some places, particularly in front of Bel Marin Keys Unit V, the remnant marsh is very narrow and a coarse beach or berm in front of the levee may serve a similar purpose. Where there is marsh, a coarse beach at the marsh scarp could help reduce marsh erosion. This strategy would require significant improvements to the existing creek and outboard levee system in order to address overtopping.

Example strategy to achieve vision 2: “Buffer with Public Open Space”

This strategy assumes that the construction of the Bel Marin Keys Unit V levee and tidal restoration is completed. The existing developments at Bel Marin Keys and Hamilton Airfield continue to be protected by levees. It is assumed that Highway 37 and the railroad are raised on to an embankment, that also serves as a levee, and that the bridge across Novato Creek is also raised and lengthened. Raising the road and railroad allows the hayfields and spray fields north of Novato Creek and east of Highway 37 to be restored to tidal action. Novato creek and its floodplain would be enlarged to improve conveyance of storm water.

Example strategy to achieve vision 3: “Maximize Habitat/Minimize Risk”

This strategy expands on the previous buffering strategy. The existing developments at Bel Marin Keys and Hamilton Airfield continue to be protected by levees. In this strategy it is assumed that Highway 37 and the railroad are elevated onto a piled causeway or an embankment with wide tidal crossings, allowing greater tidal reconnection on the western side of Highway 37 adjacent to Simmons Slough. The road and railroad bridge across Novato Creek is raised and lengthened as before. These actions would allow tidal restoration of the hayfields and spray fields north of Novato Creek and to the west of Highway 37. New setback levees would be needed along Atherton Avenue and adjacent to Deer Island but much of the area is gently sloping open space that could allow for a broad wetland-upland transition zone.

Legend (for all maps on facing page):

..... Existing berm or levee	Mid marsh
— Ecotone levees	Low marsh
Area behind existing levees	Mudflat
Upland	Subtidal
High marsh	Area restored to tidal action

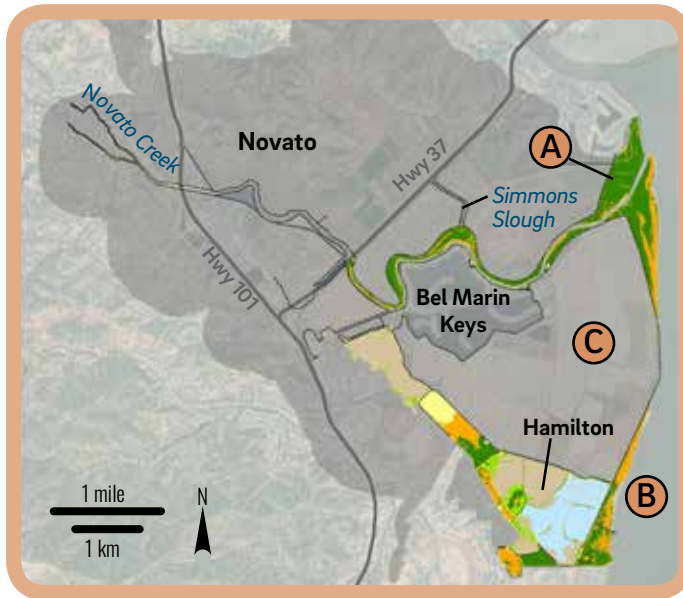
Full-page maps of each strategy are provided in Appendix 3.

STRATEGY MAPS
Novato OLU

Opportunities to “hold the line”:

- A** Maintain and enhance existing marsh and mudflat
- B** Place coarse beaches in front of eroding marsh scarps*
- C** Improve and maintain existing levee alignment

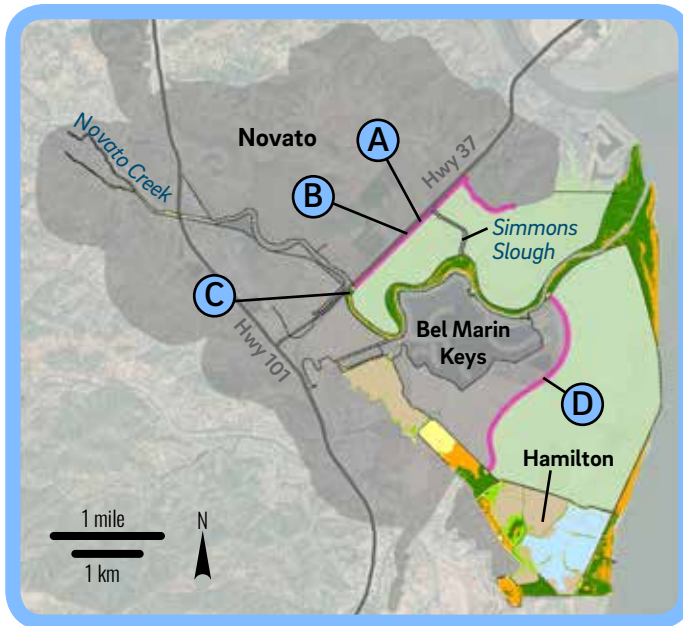
*not pictured on map



Hold the line strategy for Novato OLU

Opportunities to “buffer with public open space”:

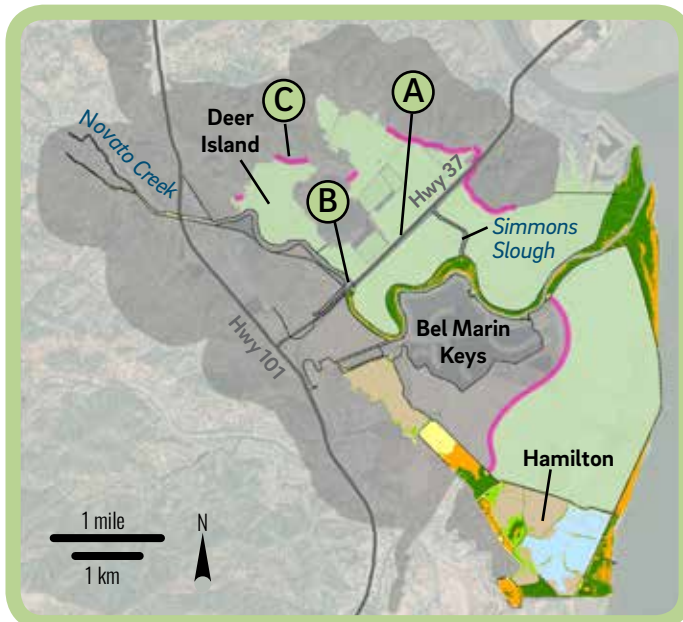
- A** Build wide, gently sloped ecotone levees in front of Highway 37, the new line of defense
- B** Raise Highway 37 berm to keep pace with sea level rise
- C** Lengthen and raise Highway 37 bridge over Novato Creek
- D** Assumes the construction of the Bel Marin Keys Unit V levee and tidal restoration is completed



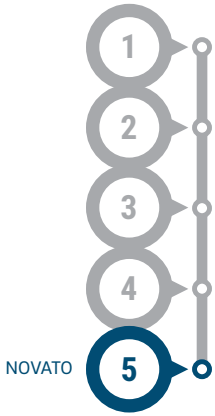
Buffer with public open space strategy for Novato OLU

Opportunities to “maximize habitat/minimize risk”:

- A** Reconnect baylands to tidal action by elevating Highway 37 onto a causeway
- B** Lengthen and raise Highway 37 bridge over Novato Creek
- C** Build ecotone levees between development and areas newly restored to tidal action



Maximize habitat/minimize risk strategy for Novato OLU



Step 5. Evaluate and prioritize strategies

To illustrate different approaches for comparing among strategies, we selected four indicators that covered a range of benefits and that could be readily measured with existing GIS-based data. We modeled how tidally-influenced elevations may change through time with rising seas for all case study strategies (Appendix 4) in order to understand how long adaptation measures might last and how adaptation objectives or outcomes change with sea level rise (e.g., “Timing Matters” on page 32). Our goal was to illustrate a few examples of how this type of quantitative modeling could be used to inform development of and comparisons among adaptation strategies (see Appendix 4 for details). For a more comprehensive list of benefits to consider, see page 19.

Below and on the facing page are two formats that allow for comparison among strategies. A tabular format (below) can include raw indicator values, scaled indicator values (i.e., a scale from 0-1 based on the minimum and maximum raw values across an indicator), or even a simplified representation of scaled values (e.g., the dark filled,

Benefit	Indicator	Units	Strategies		
			Hold the line	Buffer with open space	Maximize habitat
Cost considerations					
Low cost construction	Fill volume for ecotone levees ¹	million cubic yards	● 0.00	○ 2.22	○ 2.25
Low cost maintenance	Linear distance of existing shoreline protection that would need to be raised or maintained ²	miles	○ 21	● 11	● 9
Supporting services					
Biodiversity support (habitat, species)	Projected area of marsh in 2030	acres	○ 980	◐ 1,136	● 1,276
Cultural/social services					
Recreation	Length of new trails ³	miles	○ 0	◐ 3.2	● 4.2

¹ Sediment is expensive, so lower fill volume results in lower cost and more “benefit” from a low cost construction consideration

² The shorter the distance, the more cost-savings in terms of less improvements or maintenance

³ Trail length only reflects new distance of trail added to the top of an ecotone levee and does not account for any potential loss of existing trails.

Comparison table showing quantification of example benefits for Novato OLU. Raw values are included, along with a visual representation of the relative benefit (low, moderate, high) among strategies for each indicator.

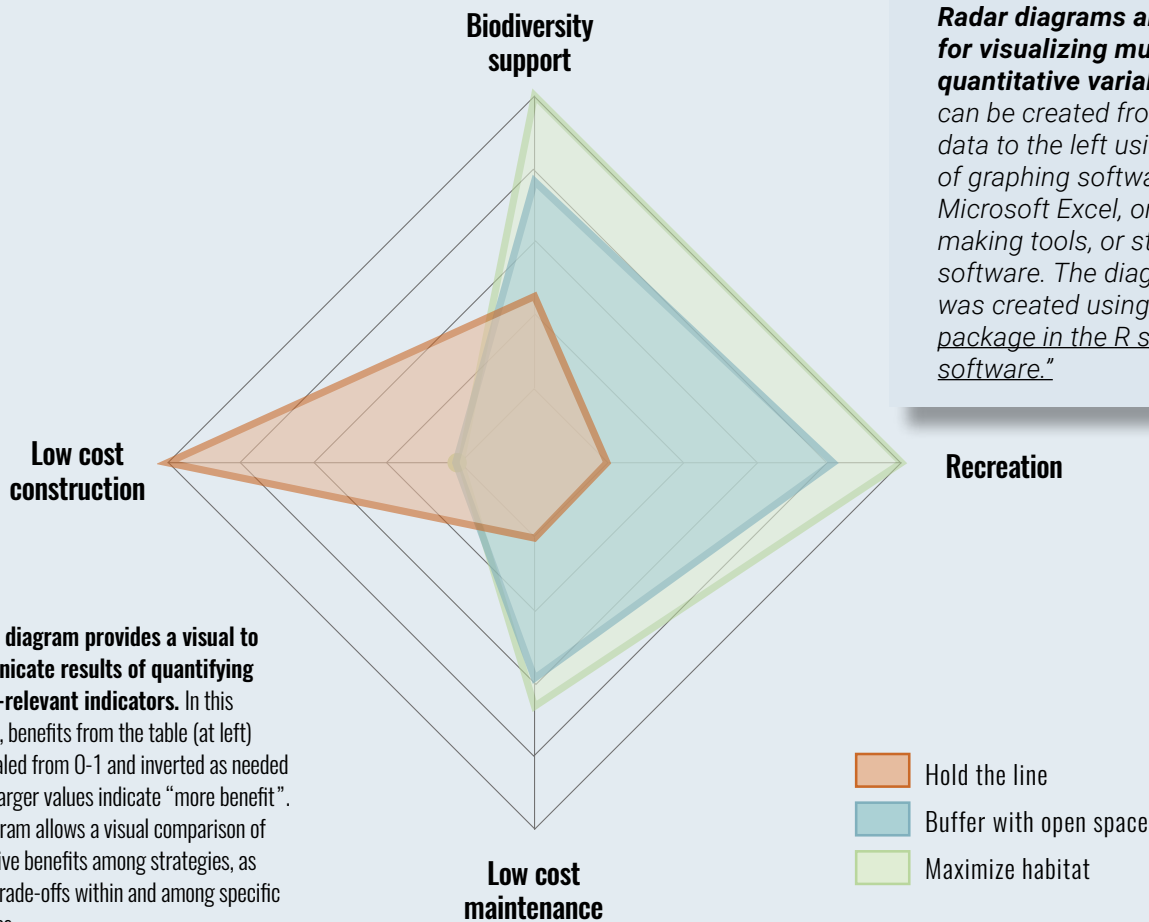
half-filled, open circle symbols) to visually indicate which strategy provides the highest to lowest benefits. One can then quickly scan down the column to see, for example, that the “Hold the Line” strategy for the Novato OLU requires the least amount of fill (a benefit from construction-cost perspective), but provides few additional benefits. The other two strategies require similar amounts of fill and similarly high additional benefits.

The tabular information can also be translated into visuals such as the radar diagram (below). This type of diagram allows comparison of trade-offs among strategies (1) as a whole by looking at total polygon areas relative to each other, while (2) still being able to see trade-offs among individual benefits. For ease of communication, in this example all benefits were scaled from 0-1 and inverted as needed so that larger values indicate “more benefit”. We can then see that the “Maximize Habitat” strategy has the most cumulative benefits (largest polygon), but there is a trade-off in terms of construction cost (low value indicates high cost of construction associated with larger fill volume necessary to build ecotone levees).



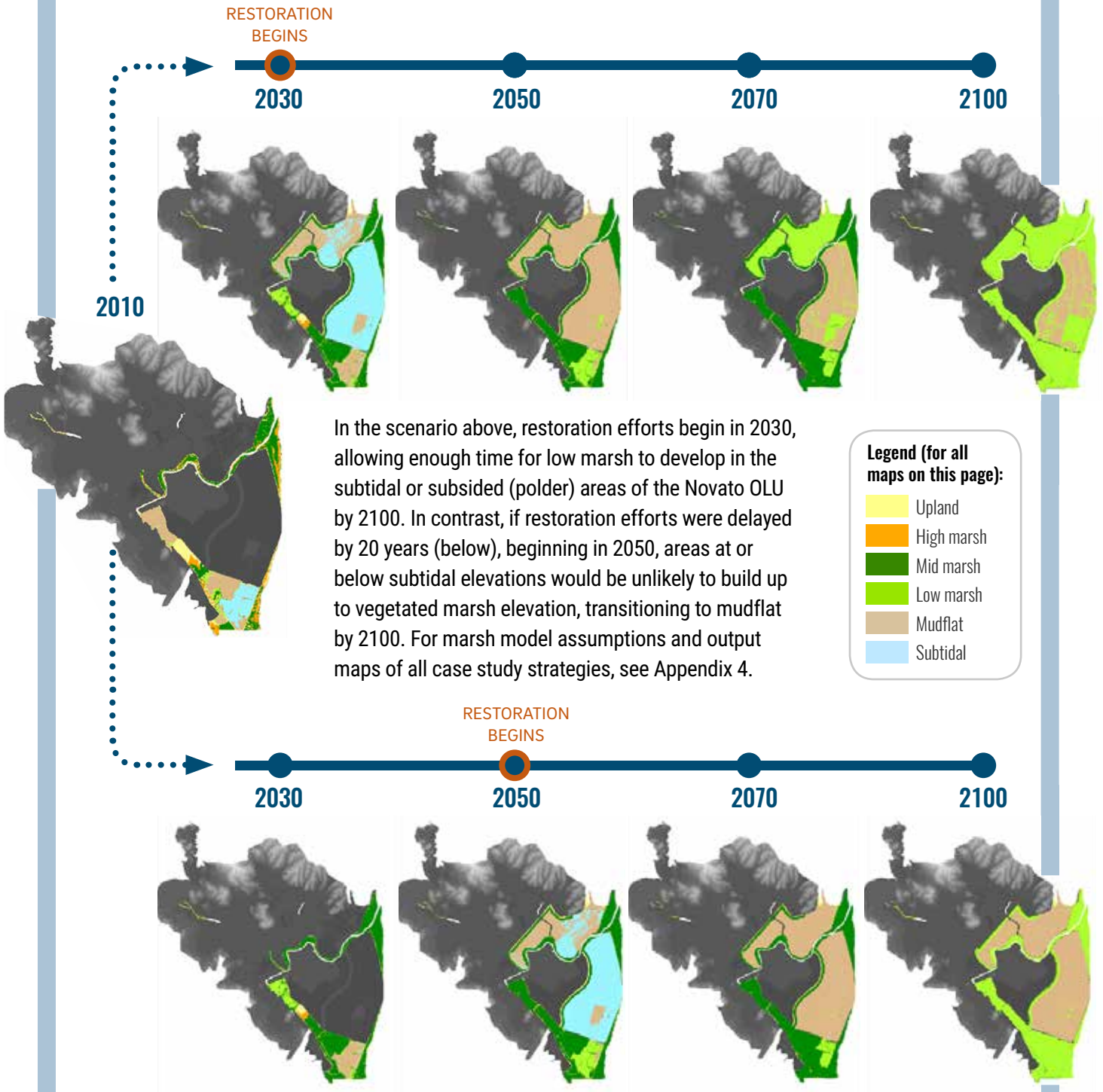
USEFUL RESOURCE:

Radar diagrams are useful for visualizing multiple quantitative variables. They can be created from the tabular data to the left using a variety of graphing software, from Microsoft Excel, online chart making tools, or statistical software. The diagram here was created using the [*fmsb*](#) package in the R statistical software.”



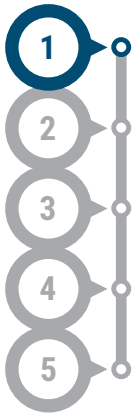
Timing matters: a note on spatial and temporal variability

We modeled marsh accretion for all case study strategies to understand how timing of restoration affects long-term habitat outcomes, and to ask the questions: how long do these features last? how do you compare among strategies if your goal is to use nature-based measures to achieve multiple benefits? how might objectives change with sea level rise?





View of Tiburon from Old St. Hilary's Open Space Preserve (photo by Shira Bezalel, SFEI)

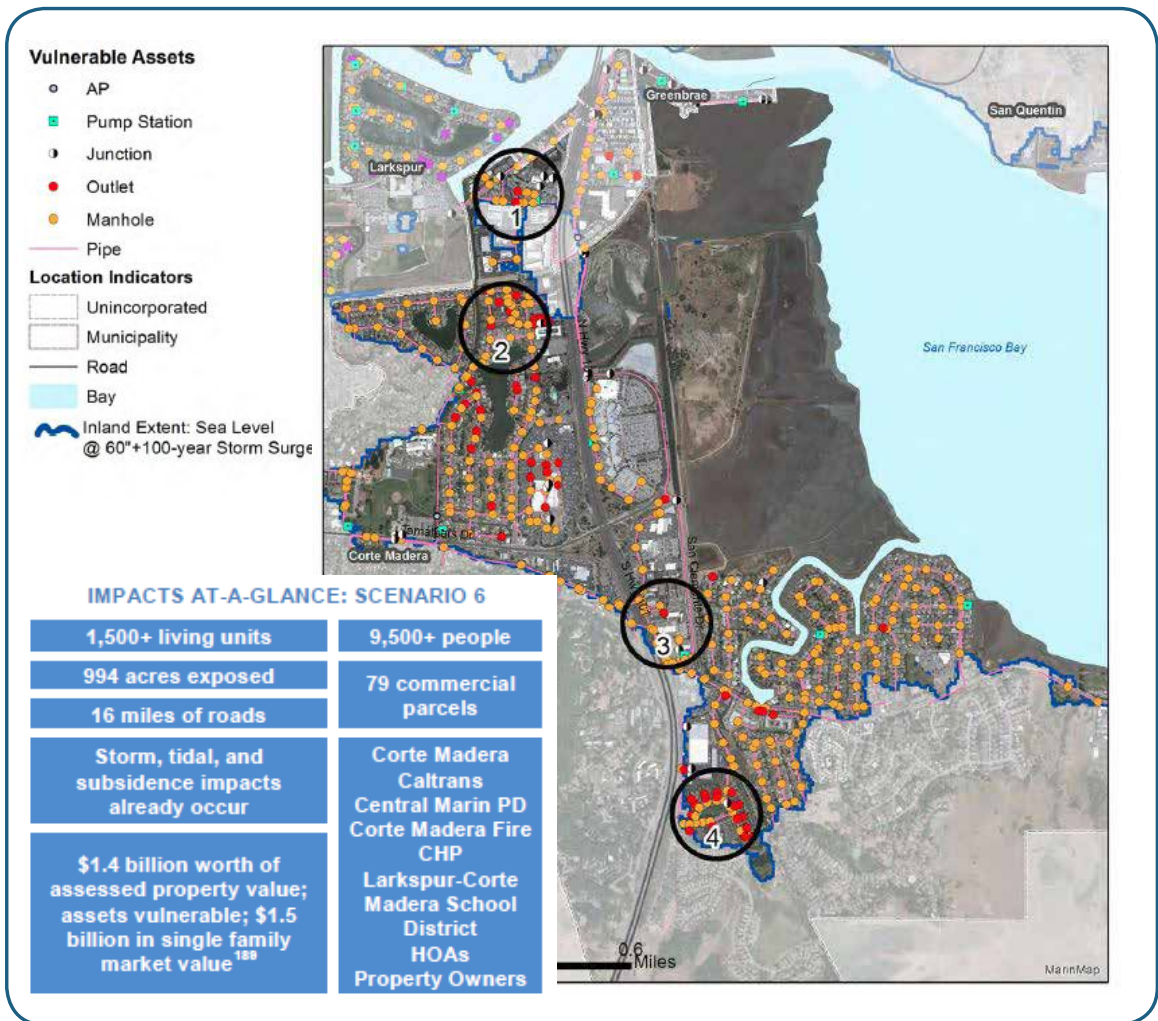


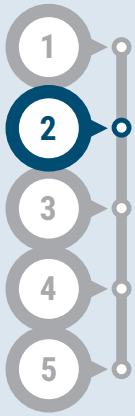
Corte Madera OLU case study

Step 1: Assess vulnerability

The Corte Madera OLU is a relatively narrow valley between steep promontories jutting into the Bay that create a protected cove, or small embayment, where marshes formed historically. Wind-wave energy is high along headlands adjacent to deep water, and lower within the embayment. Ferries also play a role in generating wakes within the Bay. Historically, extensive marshes existed at the mouth of Corte Madera Creek, with large mudflats on the bayward side. This small valley has been densely developed, mainly for residential use in the hills, and for residential, mixed-use commercial developments, shopping malls, and light industry in the baylands. Many of the developed baylands have subsided. Muzzi and Heerdt marshes constitute the largest contiguous marsh in Southern Marin, although with the continuing erosion of the outboard levee edge, the edge of Muzzi marsh is rapidly retreating. Combined riverine and tidal flooding will continue to be a key vulnerability.

Corte Madera vulnerable wastewater utility assets mapped in the Marin Shoreline Sea Level Rise Vulnerability Assessment (BayWAVE 2017)





Step 2: Identify adaptation measures

As described for the Novato case study, the purpose of the opportunity map to the right is to illustrate, within the case study OLU, the general location and size of a number of natural and nature-based adaptation measures that are suitable for the given environmental context. These maps have been created based on the existing shoreline. New opportunities may be created by modifying the shoreline through realigning levees, adding fill or regrading. It is unlikely that a single measure on its own will reduce risk to a manageable level. Most nature-based measures must be used together with other natural and engineered features (e.g. a marsh needs a mudflat, an ecotone levee needs a fronting marsh and a flood risk management levee). Below we provide a brief discussion of the suitability of measures in the context of ongoing adaptation and restoration projects and regional ecological goals such as those set by the Goals Project (2015) and the Subtidal Goals (2010) project. For a full description on mapping methods, suitability ranking, and combining measures into strategies, see chapter 4 and Appendix 5 of the San Francisco Bay Shoreline Adaptation Atlas (SFEI and SPUR 2019).

CORTE MADERA OLU

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 Heerdts marshes constitute the largest contiguous marsh in southern Marin, although with the continuing erosion of the outboard levee edge, the Muzzi marsh edge is rapidly retreating. Enhancing the existing marsh by reusing sediments dredged from the nearby ferry terminal, placing coarse beaches in front of the marsh edges, 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 riverine flooding along Corte Madera Creek. Submerged aquatic vegetation and nearshore reefs are also suitable in this OLU, and could help reduce wave energy reaching the marsh edge.

Selected Measures Suitability

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

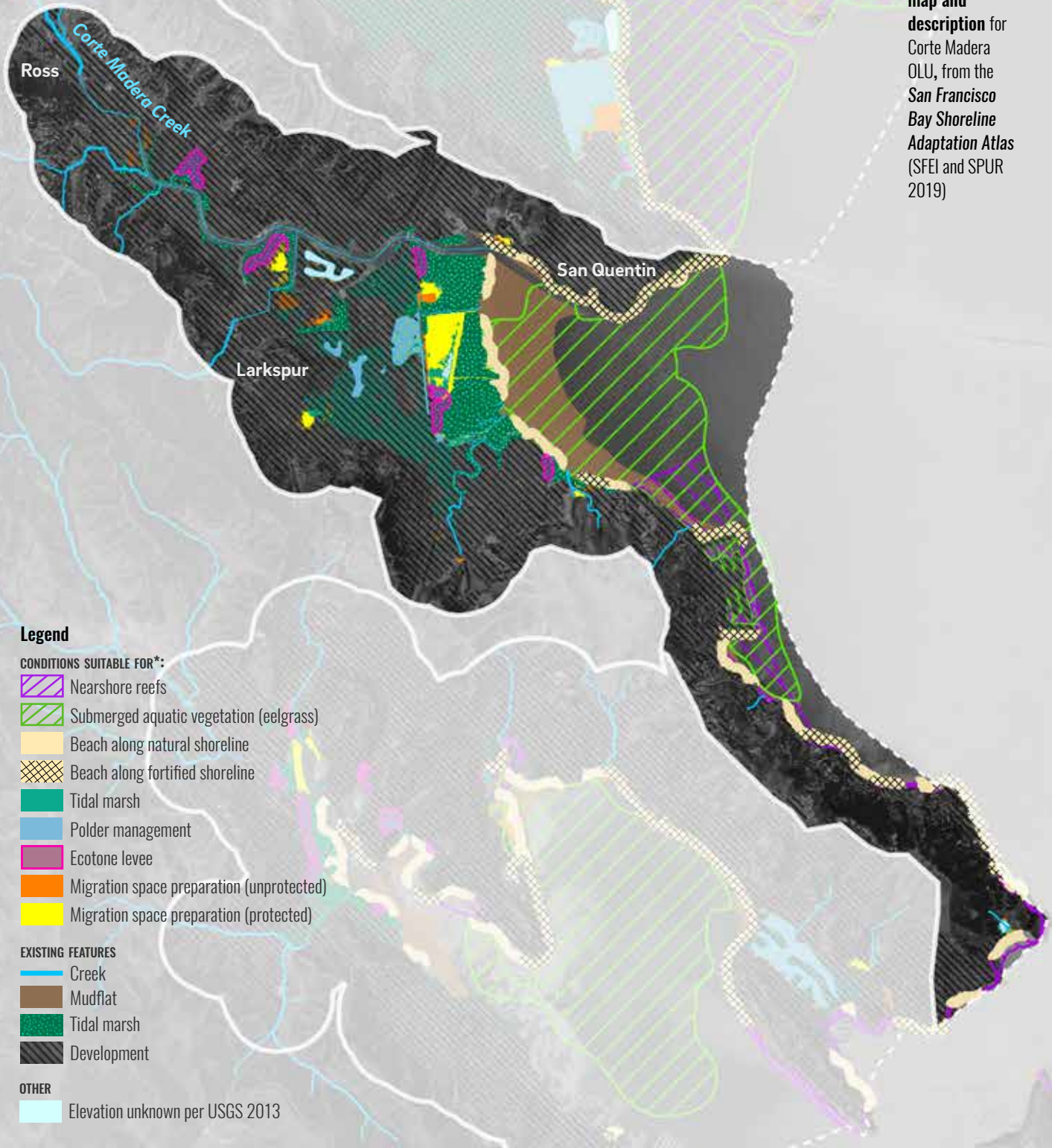
○ Limited suitability ◐ Some suitability ● High suitability



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

NATURE-BASED ADAPTATION OPPORTUNITIES MAP CORTE MADERA OLU

Nature-based adaptation opportunities map and description for Corte Madera OLU, from the *San Francisco Bay Shoreline Adaptation Atlas* (SFEI and SPUR 2019)



Legend


CONDITIONS SUITABLE FOR*:

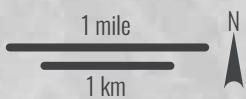
-  Nearshore reefs
-  Submerged aquatic vegetation (eelgrass)
-  Beach along natural shoreline
-  Beach along fortified shoreline
-  Tidal marsh
-  Polder management
-  Ecotone levee
-  Migration space preparation (unprotected)
-  Migration space preparation (protected)

EXISTING FEATURES

-  Creek
-  Mudflat
-  Tidal marsh
-  Development

OTHER

-  Elevation unknown per USGS 2013



***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.



Step 3: Envision desired futures. What are plausible and/or desired future visions for the area?

For the purposes of illustrating the framework process, the project team developed two hypothetical visions that represent different priorities. We considered societal and ecological values, and also tried to develop visions that would result in relatively distinct strategies that might span the range of options from “do nothing” to implementing every suitable nature-based adaptation measure. For the Corte Madera OLU case study, strategies for only two of the three visions were developed because topographic and development constraints limit options for realigning levees (see page 26 for a description of the third vision).

Vision 1: “Hold the Line”

The “Hold the Line” vision assumes maintaining and defending the current shoreline configuration such that currently dry areas remain dry into the future (including the polders). This assumes maintaining the existing shoreline protection infrastructure (e.g., levees), continuing to pump, and limiting use of natural and nature-based adaptation measures to opportunities that are suitable bayward of the existing first line of defense.

Vision 2: “Buffer with Public Open Space”

This vision considers opportunities to move the existing first line of shoreline defense by taking advantage of public open space where buffering habitat can be restored with minimal reconfiguration of existing vulnerable infrastructure and with strategic realignment of existing levees. This vision allows protected public open space to get wet, but keeps existing developed areas dry. Nature-based adaptation measures can be implemented in protected public open space as necessary to ameliorate identified vulnerabilities.



View of San Quentin Beach located along the Corte Madera OLU shoreline (photo by Shira Bezael, SFEI)



Step 4. Combine suitable adaptation measures into “strategies” for each desired future

■ Example strategy to achieve vision 1: “Hold the Line”

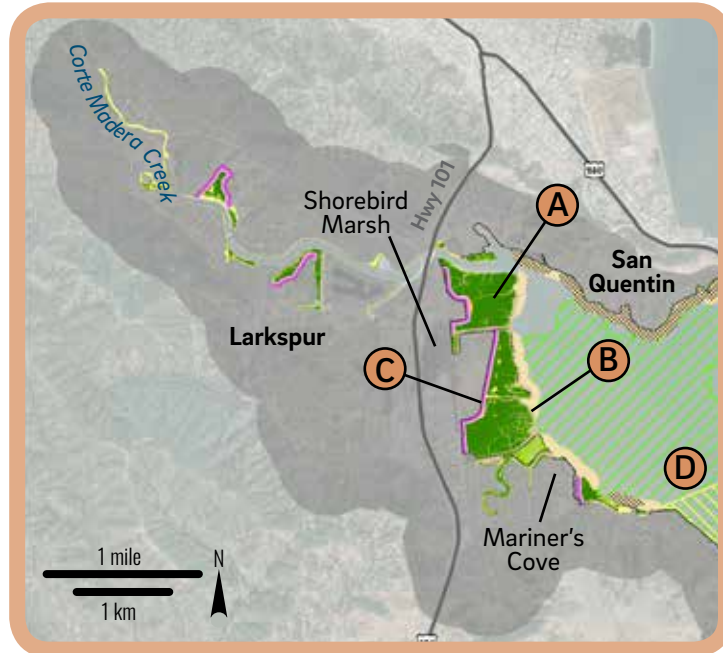
Nature-based strategies bayward of existing shoreline protection would focus on maintaining the existing marsh and mudflat in front of the outer-most levee, with the option to add a coarse beach at the marsh edge to help protect against erosion. In areas where there is no outboard marsh, such as along Mariner’s Cove, it might be possible to raise mudflat elevation and encourage marsh development by strategic placement of dredged fine sediment. Alternatively, the placement of coarse beach material to protect houses might be appropriate. To reduce the impacts of flooding due to runoff, retention basins such as Shorebird Marsh have been constructed. With the restoration of tidal marshes to the east of the railroad berm, these retention basins (always wet to some degree) could be rerouted to pass water and sediment into the backs of the marshes, rather than straight out to the Bay as they do at the moment. This strategy would require significant improvements to the existing levee system in order to address all vulnerabilities.

■ Example strategy to achieve vision 2: “Buffer with Public Open Space”

Corte Madera OLU is constrained by headlands flanking developed baylands, resulting in limited opportunities for retreat using public open space. The main opportunity is to reduce the length of the existing levee system by realigning it against the old railroad with an ecotone levee. Much of the area is currently higher elevation and would allow transition zone space for the marshes to move upslope with sea level rise. Upstream in Corte Madera Creek there is the opportunity to use Piper Park for additional space. There may also be opportunities to use existing open space for detention basins (usually dry except during storms) to alleviate flooding due to runoff during storms.

Nature-based opportunities to “hold the line”:

- A** Use local sediment to enhance existing marsh
- B** Place coarse beaches in front of eroding marsh edges
- C** Build wide, gently sloped ecotone levees behind marsh
- D** Create beds of submerged aquatic vegetation (eelgrass) and/or oyster reefs

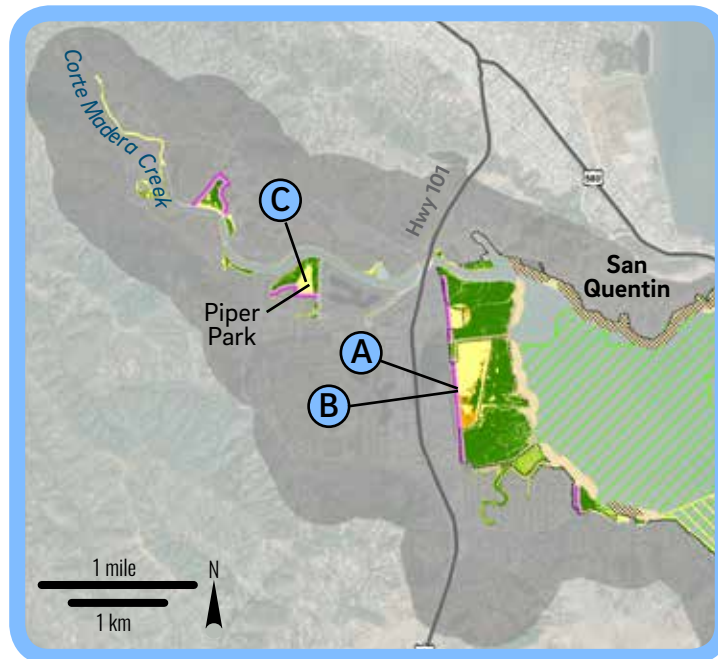


Hold the line strategy for the Cortez Madera OLU

Nature-based opportunities to “buffer with public open space”:

- A** Realign existing levee system along the old railroad
- B** Build a wide, gently sloped ecotone levee in front of the realigned levee
- C** Protect and prepare marsh migration space
- D** Grade open spaces (e.g., parks) to act as detention basins during storms*

*not pictured on map

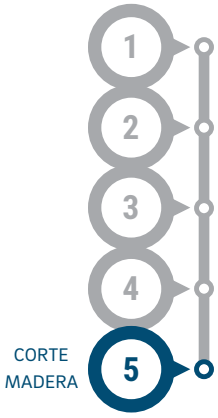


Buffer with public open space strategy for Cortez Madera OLU

Legend (for all maps on this page):

..... Existing berm or levee	High marsh	Nearshore reefs
Ecotone levees	Mid marsh	Submerged aquatic vegetation (eelgrass)
Beach along natural shoreline	Low marsh	
Beach along fortified shoreline	Mudflat	
Area behind existing levees	Subtidal	
Upland	Area restored to tidal action	

Full-page maps of each strategy are provided in Appendix 3.



Step 5: Evaluate and prioritize strategies

To illustrate different approaches for comparing among strategies, we selected four indicators that covered a range of benefits and that could be readily measured with existing GIS-based data. We modeled how tidally-influenced elevations may change through time with rising seas for all case study strategies (Appendix 4), in order to understand how long adaptation measures might last and how adaptation objectives or outcomes change with sea level rise (e.g., “Timing Matters” on page 32). Our goal was to illustrate a few examples of how this type of quantitative modeling could be used to inform development of and comparisons among adaptation strategies (see Appendix 4 for details). For a more comprehensive list of benefits to consider, see page 19.

Below and on the facing page are two formats that allow for comparison among strategies. A tabular format (below) can include raw indicator values, scaled indicator values (i.e., a scale from 0-1 based on the minimum and maximum raw values across

Benefit	Indicator (metric)	Units	Strategies	
			Hold the line	Buffer with open space
Cost considerations				
Low cost construction	Fill volume for ecotone levees ¹	cubic yards	○ 179,036	● 115,176
Low cost maintenance	Linear distance of existing shoreline protection that would need to be raised or maintained ²	miles	○ 15.3	● 14.7
Supporting services				
Biodiversity support (habitat, species)	Projected area of marsh in 2030	acres	● 268	● 304
Cultural/social services				
Recreation	Length of new trails ³	miles	● 2.5	● 2.1

¹ Sediment is expensive, so lower fill volume results in lower cost and more “benefit” from a low cost construction consideration

² The shorter the distance, the more cost-savings in terms of less improvements or maintenance

³ Trail length only reflects new distance of trail added to the top of an ecotone levee and does not account for any potential loss of existing trails.

Comparison table showing quantification of example benefits for Corte Madera OLU. Raw values are included, along with a visual representation of the relative benefit (low, medium, high) among strategies for each metric.

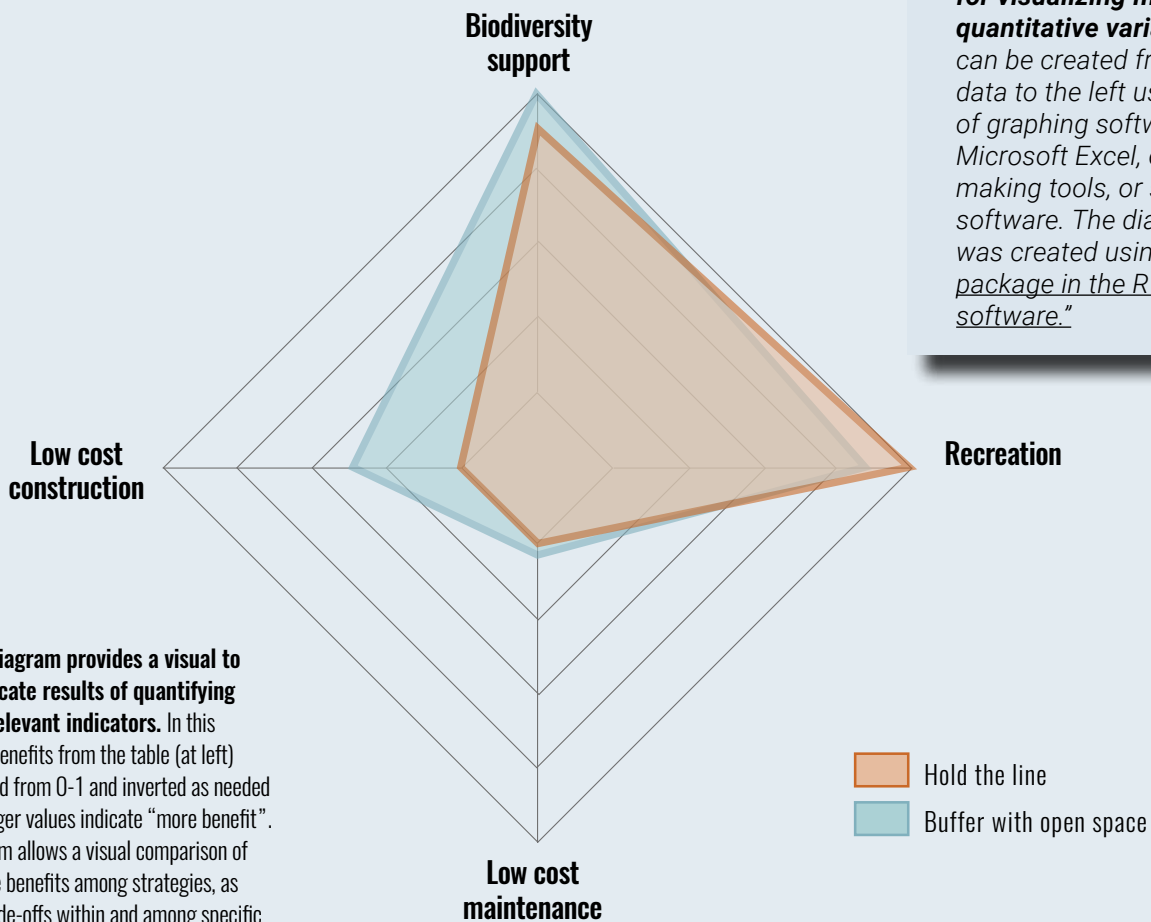
an indicator), or even a simplified representation of scaled values (e.g., the dark filled, half-filled, open circle symbols) to visually indicate which strategy provides the highest to lowest benefits.

The tabular information can also be translated into visuals such as the radar diagram (below). This type of diagram allows comparison of trade-offs among strategies (1) as a whole by looking at total polygon areas relative to each other, while (2) still being able to see trade-offs among individual benefits. For ease of communication, in this example all benefits were scaled from 0-1 and inverted as needed so that larger values indicate “more benefit”. We can then see that the “Buffer with Public Open Space” strategy has slightly higher cumulative benefits (larger polygon area) relative to the “Hold the Line” strategy, with a trade-off primarily between benefits related to low-cost construction (less fill volume necessary to build ecotone levees), and recreation (fewer miles of new trails).

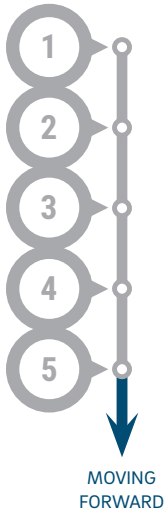


USEFUL RESOURCE:

Radar diagrams are useful for visualizing multiple quantitative variables. They can be created from the tabular data to the left using a variety of graphing software, from Microsoft Excel, online chart making tools, or statistical software. The diagram here was created using the [*“fmsb” package in the R statistical software.*](#)



A radar diagram provides a visual to communicate results of quantifying benefit-relevant indicators. In this example, benefits from the table (at left) were scaled from 0-1 and inverted as needed so that larger values indicate “more benefit”. The diagram allows a visual comparison of cumulative benefits among strategies, as well as trade-offs within and among specific strategies.



NEXT STEPS

Climate adaptation action is urgently needed, and will only become more pressing as sea level rise impacts accelerate in the coming decades. The intent of this framework is to continue 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 framework intends to provide guidance for regional governments, planners, and members of local communities on how to proactively integrate nature-based adaptation measures into adaptation plans.

This sea level rise adaptation framework encourages communities to work together on long-term shoreline adaptation strategies. Operational Landscape Units 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 cross-jurisdictional collaboration is necessary because the hazards associated with climate change will not adhere to political boundaries. However, this presents a critical governance challenge, as we currently do not have the regional governance structure to motivate, support, permit, or incentivize cross-jurisdictional planning.

There are examples of locally-driven cross-jurisdictional governance occurring in the San Francisco Bay Area. The San Francisquito Creek Joint Powers Authority formally brings together five local agencies from two counties—the cities of Palo Alto, Menlo Park, and East Palo Alto, the County of San Mateo, and the Santa Clara Valley Water District—to plan and implement environmental, flood protection, and recreational projects throughout the watershed. Other examples include the Strategy to Advance Flood protection, Ecosystems and Recreation along San Francisco Bay (SAFER Bay) Project and the Hayward Area Shoreline Protection Agency (HASPA). The Marin BayWAVE Vulnerability Assessment was structured specifically to promote inter-jurisdictional coordination and collaboration. In addition to the County of Marin, it includes key infrastructure special districts, and all the cities, even those inland who recognize their common reliance on bayside infrastructure. The San Francisco Estuary Invasive Spartina Project and the San Francisco Bay Joint Venture are two other examples of a coordinated regional effort among local, state and federal organizations working toward a common purpose. Most recently, San Mateo County is beginning a step towards inter-jurisdictional planning by creating the “San Mateo County Sea Level Rise Resiliency Agency.” This agency will help facilitate meaningful progress towards new governance shaped to the dimensions of the problem. However, more examples

and more leadership is needed to manage the challenges of sea level rise and climate change adaptation in an equitable and science-informed way.

It must be emphasized that the engagement of people living and working in OLUs will be critically important in any adaptation planning effort, especially around an issue as long-term and potentially threatening as sea level rise and associated storm and tidal flooding. 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. Through meaningful engagement 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.

The framework proposes methods meant to support the needs of communities in understanding the trade-offs within and between choices necessary to prioritize resources, funding, and ensure an adaptive future. Key to adaptation planning is the integration of cost-benefit information (in dollars) and other indicators quantifying the many additional benefits of natural and nature-based adaptation measures, such as recreation, flood risk reduction, habitat for wildlife, and carbon sequestration. Adequately accounting for the breadth of benefits derived from natural and nature-based strategies is important for communities to be able to develop adaptation responses that can achieve multiple objectives and to transparently weigh trade-offs and the whole-life costs of different adaptation strategies.

Thus far, we have tested the framework process and developed specific resources for the estuarine environment of the San Francisco Bay, focusing on sea level rise adaptation. However, the OLU concept and general framework process can be translated for application to any coastal environment, from a sheltered estuary to a high wave energy outer coast setting. The OLU concept can also be used to draw manageable planning boundaries around other climate risks, such as riverine flooding in upland urban environments. The OLU concept is scalable and nested and we are in the process of piloting this approach in other locations and for other risks associated with climate change.

APPENDICES

Appendix 1: PHYSICAL PROCESSES & VULNERABILITY MAPS

Inputs to physical processes & drivers maps

To create the physical processes and drivers maps, we combined four layers of spatial data to understand the main forces shaping the baylands, shoreline, and upland areas within each OLU: wind-wave heights, elevation capital, topobathymetry, and sea level rise projections.

The variables and data sources used to create these maps are described in the table below.

Physical process and drivers maps are shown on pages 48, 50, 52, 54, 56, and 58.

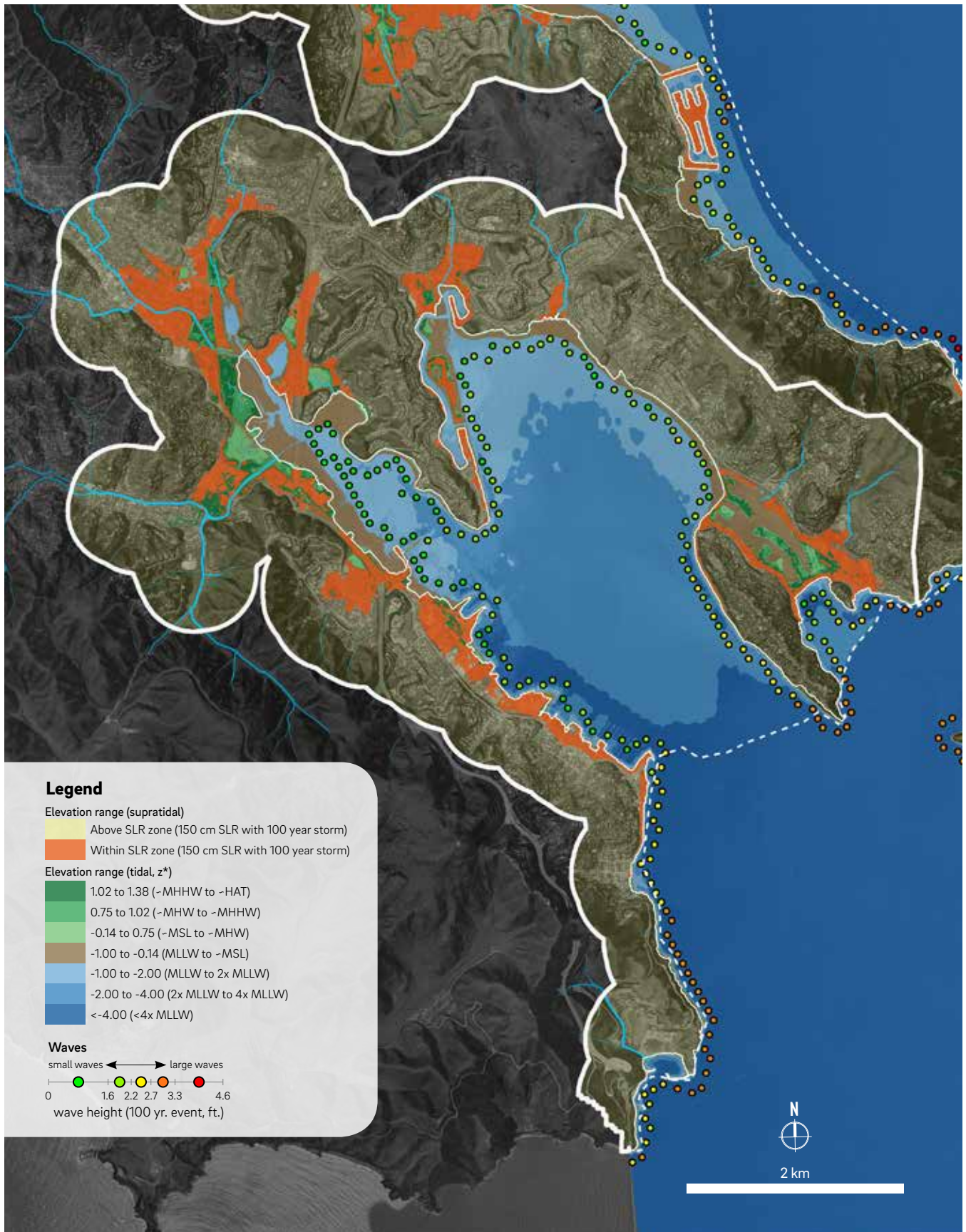
Variable	Description	Data Sources
Wind-wave heights	Wind-waves are locally generated waves in the Bay which can cause erosion of marsh edges and overtopping of levees. The height of a wind wave is dependent on the fetch length, depth of water, wind speed, and duration. The direction of waves will be dependent upon the prevailing wind and can therefore vary at any one location over time.	Wind-wave heights are based on DHI Coastal Hazard Models' 1% Significant Wave Height from AECOM's 2016 "San Francisco Bay Tidal Datums and Extreme Tides Study" (AECOM 2016)
Elevation capital (z* elevation range)	Elevation capital is determined by comparing the absolute elevation of a marsh with the local water levels and tide range (Cahoon and Guntenspergen, 2010). Swanson et al (2013) presents a dimensionless indicator (z*) of elevation capital based on mean sea level and tide range. This non dimensional parameter is simple to calculate using existing data (marsh elevation, e.g., from LiDAR and a nearby tidal datum) and makes it possible to compare marshes with different elevations and tide regimes. It also helps indicate areas of the Baylands that are subsided below MSL (>1).	Elevation capital was calculated using 2m topobathymetric digital elevation model from USGS's Coastal National Elevation Database (CoNED) Project and tidal data from AECOM's 2016 "San Francisco Bay Tidal Datums and Extreme Tides Study" (USGS 2013, AECOM 2016)
Sea level rise	Flood risks along creeks from storm events may increase due to more frequent extreme high sea level events 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. Transition zone space will be critical to allow marsh migration and provide high tide refugia for resident wildlife. To determine a supratidal boundary (i.e. transition zone extent), the 150cm SLR + 100-year storm event scenario was used.	150cm SLR + 100-year storm event scenario was adapted from Our Coast Our Future / USGS Coastal Modeling System (CoSMoS) study (Barnard et al. 2014)
Topobathymetry	A 2m-topobathymetric layer was used to assess subtidal environments, water depths, and subtidal boundaries.	Topographic LiDAR data and bathymetric data (USGS 2013)

Inputs to vulnerability maps

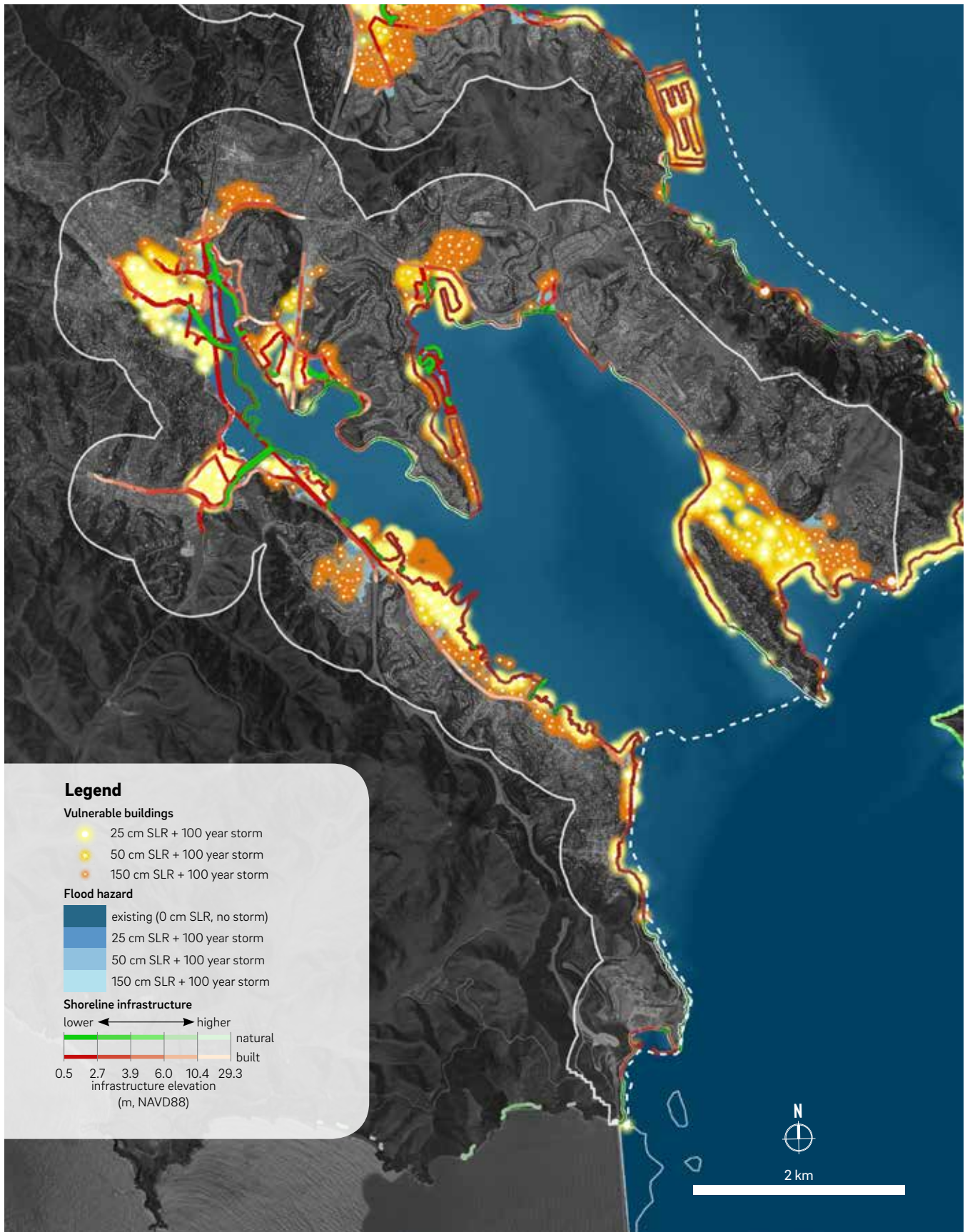
Vulnerability maps were created by combining the findings of Marin County’s BayWAVE vulnerability study with shoreline infrastructure types (e.g., natural vs. built) and elevations. These vulnerability maps can be used to evaluate buildings in low-lying areas with little to no flood protection, thus pinpointing the areas most vulnerable to sea level rise. The variables and data sources used to create these maps are described in the table below. Vulnerability maps are shown on pages 49, 51, 53, 55, 57, and 59.

Variable	Description	Data Sources
Vulnerable buildings	BayWAVE is a focused vulnerability assessment of the eastern Marin shoreline from the Golden Gate Bridge to the northern end of Novato. BayWAVE evaluated the extent of impacted assets using multiple sea level rise and flooding scenarios. For the purpose of this study, modeling results from 0cm, 25cm, 50cm, and 150cm SLR scenarios combined with a modeled 100-year storm event were used to evaluate vulnerable buildings.	Marin County BayWAVE vulnerability assessment (BayWAVE 2017)
Flood hazards	BayWAVE evaluated the extent of impacted assets using multiple sea level rise and flooding scenarios. For the purpose of this study, modeling results from 0cm, 25cm, 50cm, and 150cm SLR scenarios combined with a modeled 100-year storm event were used to evaluate future flood-prone areas.	Based on flood extent projections from the USGS Coastal Storm Modeling System Marin County BayWAVE vulnerability assessment (BayWAVE 2017)
Shoreline infrastructure	SF Bay shoreline as mapped by SFEI 2015, capturing shoreline features such as engineered levees, berms, embankments, transportation structures, wetlands, natural shoreline, channel openings, and water control structures. Features are attributed every 100 m with elevation, FEMA accreditation, how a structure was armored, whether a structure was fronted by a wetland or beach, ownership, and the entity responsible for maintenance, if known. For this analysis, features were classified into natural (i.e., wetlands, natural shoreline, channel opening) or built (i.e., engineered levees, berms, embankments, transportation structures, water control structures) to distinguish between protected and unprotected shoreline reaches. A subset of the shoreline infrastructure data set was used to reflect the “first line of defense” and natural frontages.	San Francisco Bay Shore Inventory (SFEI 2016)

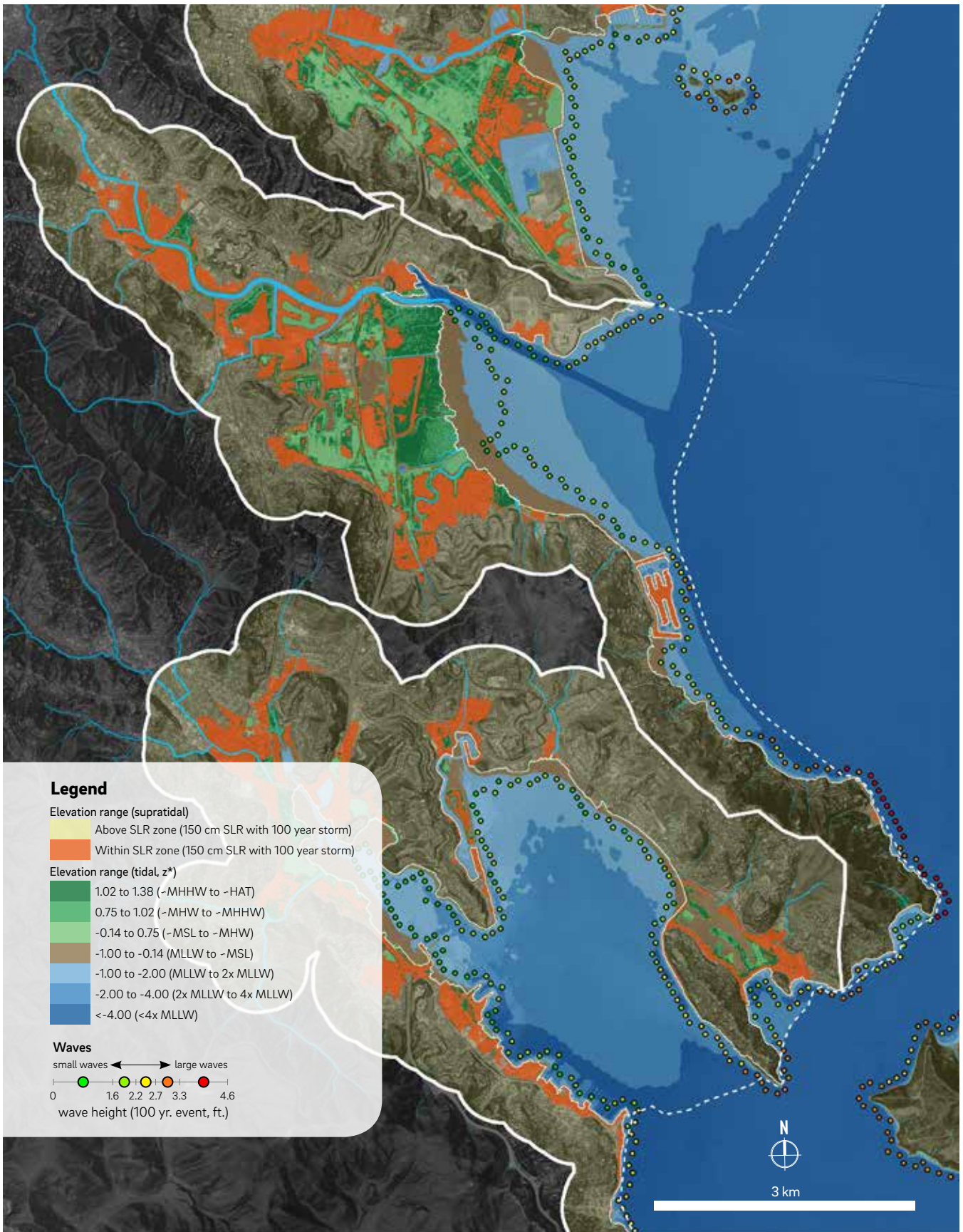
PHYSICAL PROCESSES & DRIVERS MAP
Richardson OLU



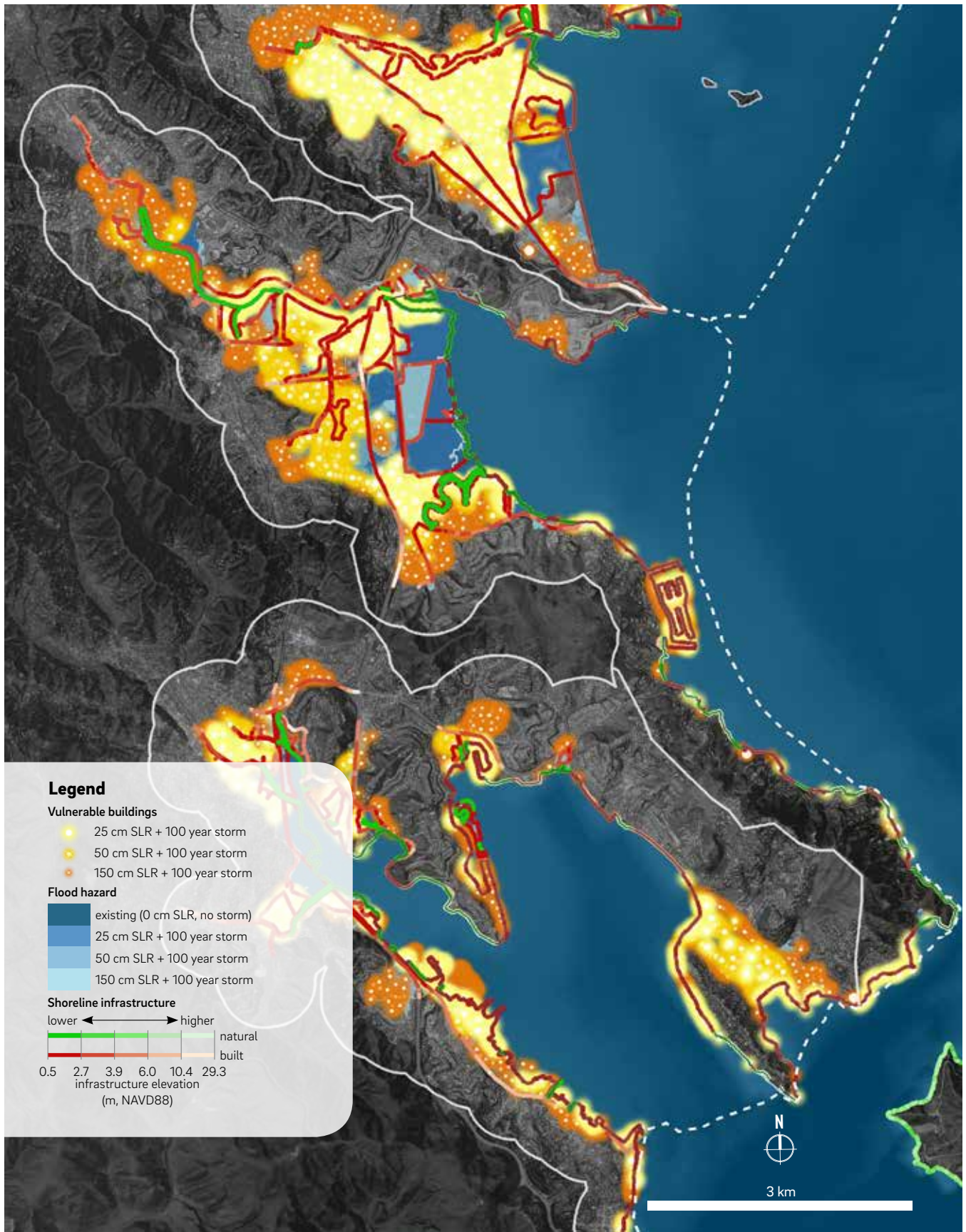
VULNERABILITY MAP
Richardson OLU



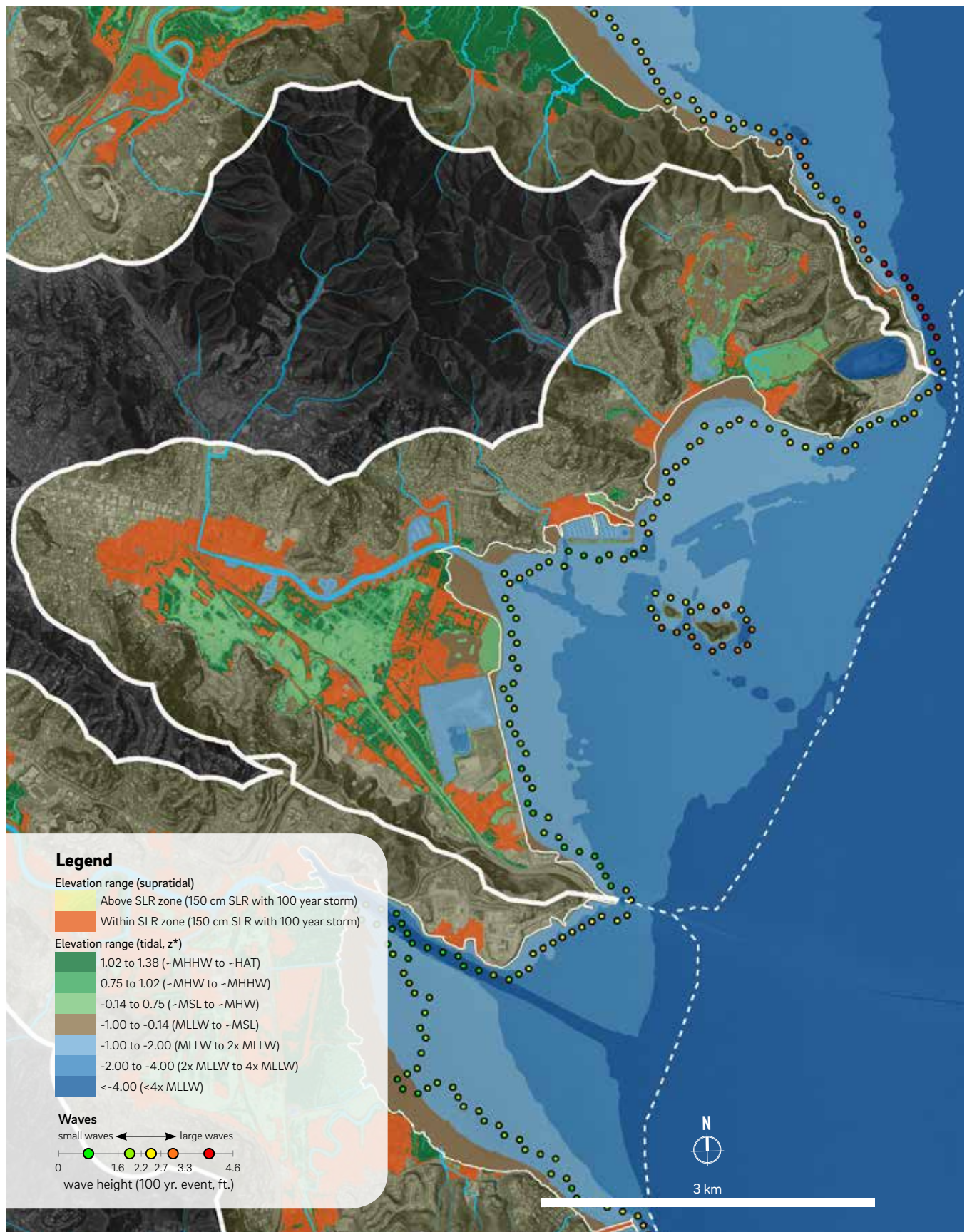
PHYSICAL PROCESSES & DRIVERS MAP
Corte Madera OLU



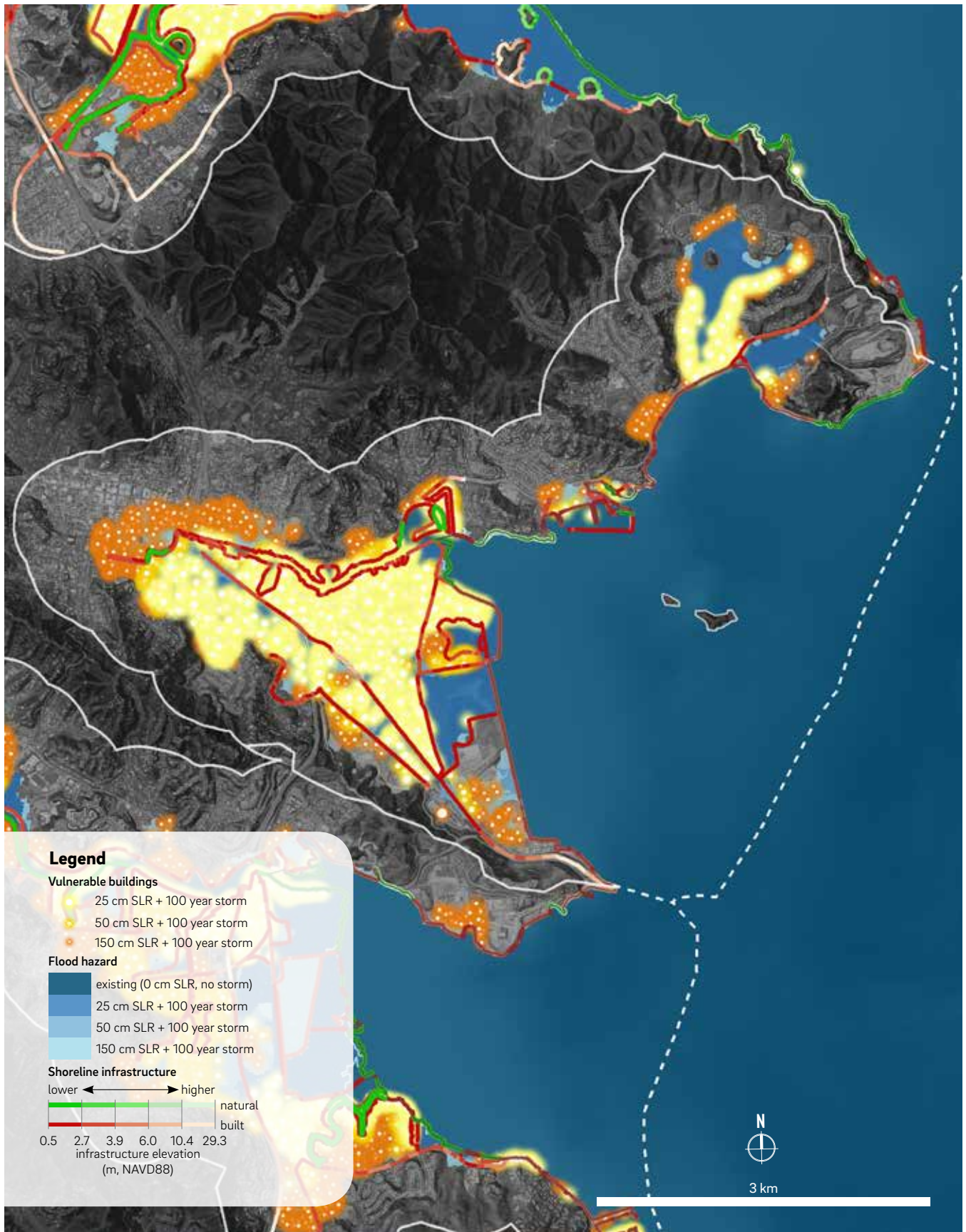
VULNERABILITY MAP
Corte Madera OLU



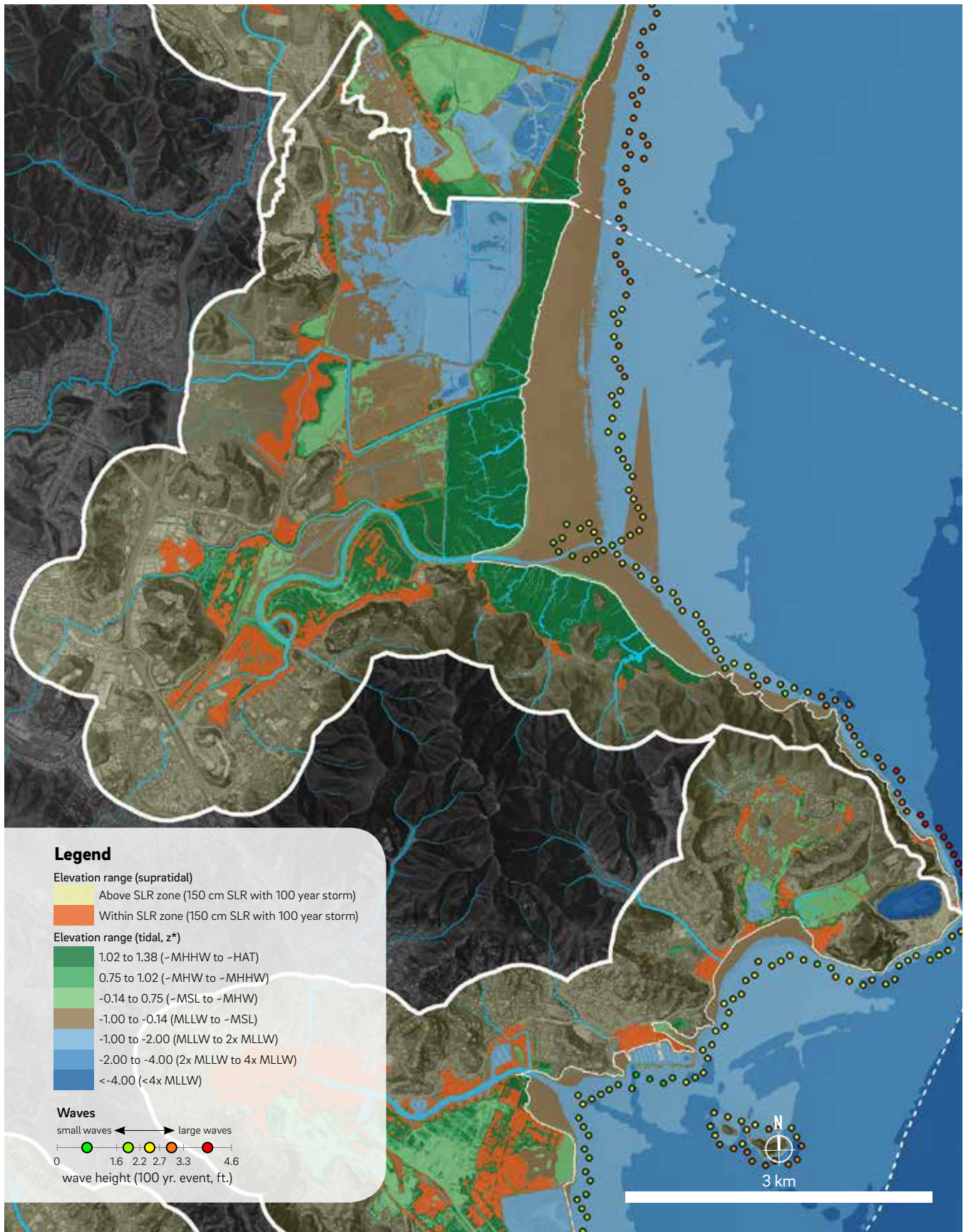
PHYSICAL PROCESSES & DRIVERS MAP
 San Rafael OLU



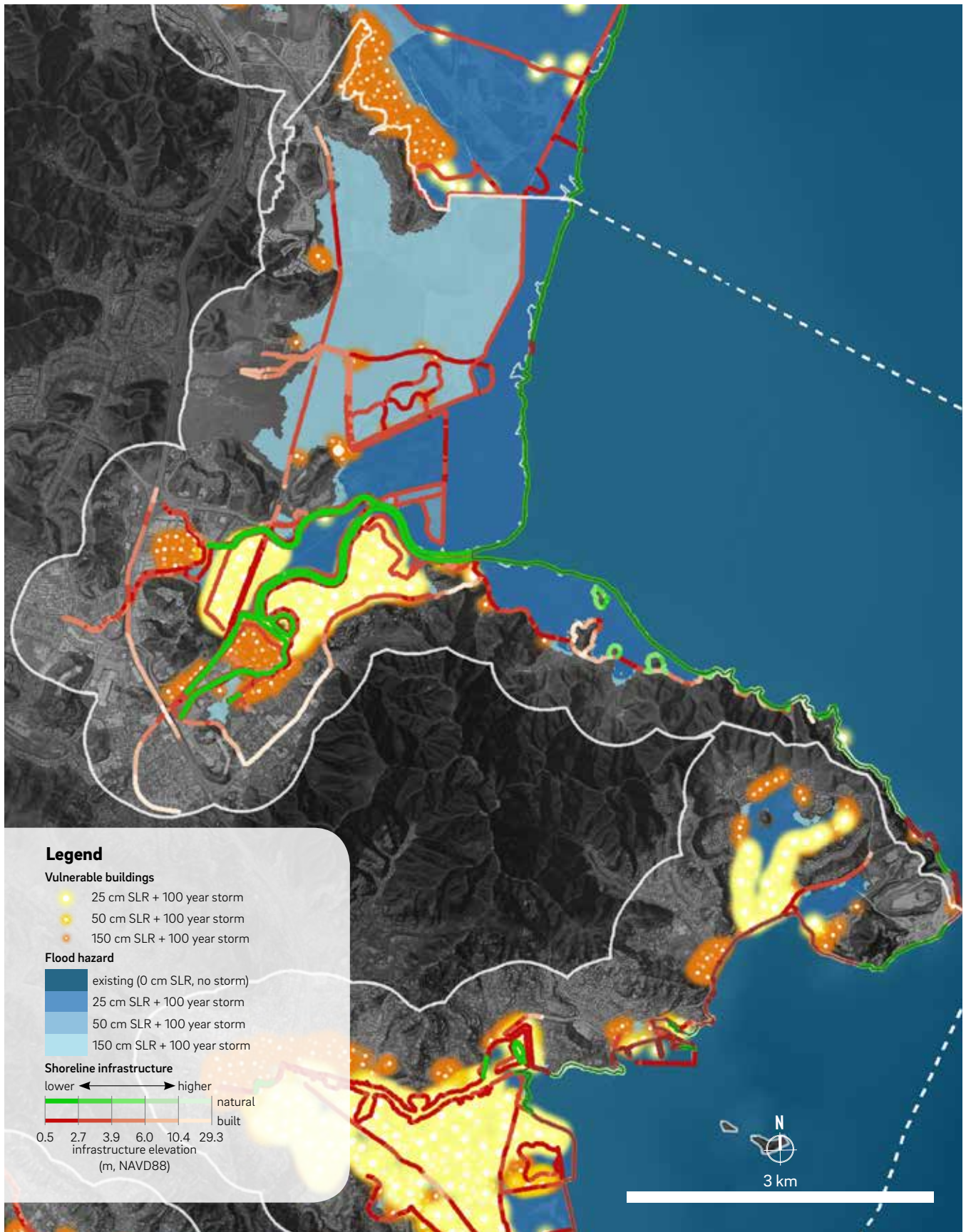
VULNERABILITY MAP
San Rafael OLU



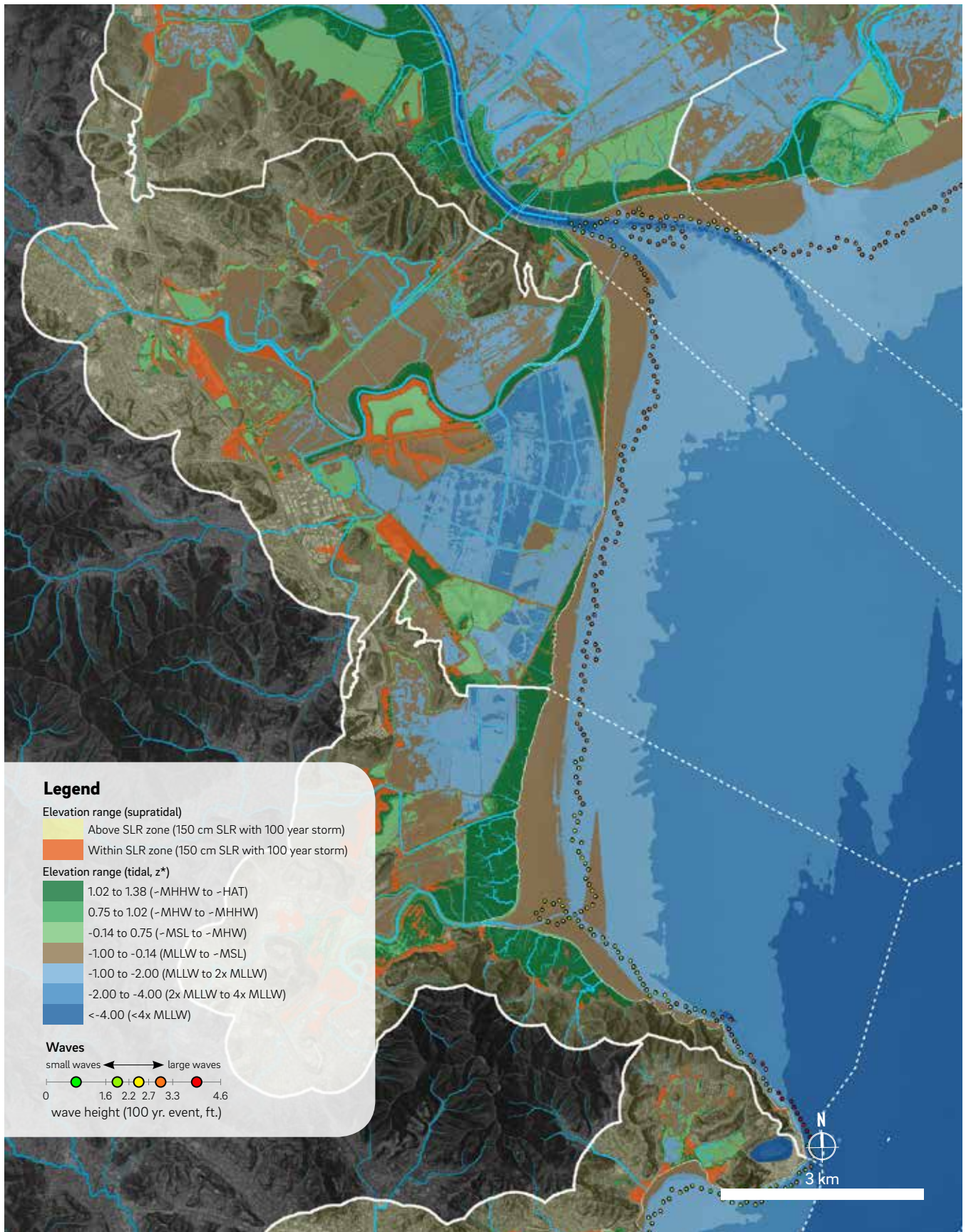
PHYSICAL PROCESSES & DRIVERS MAP
 Gallinas OLU



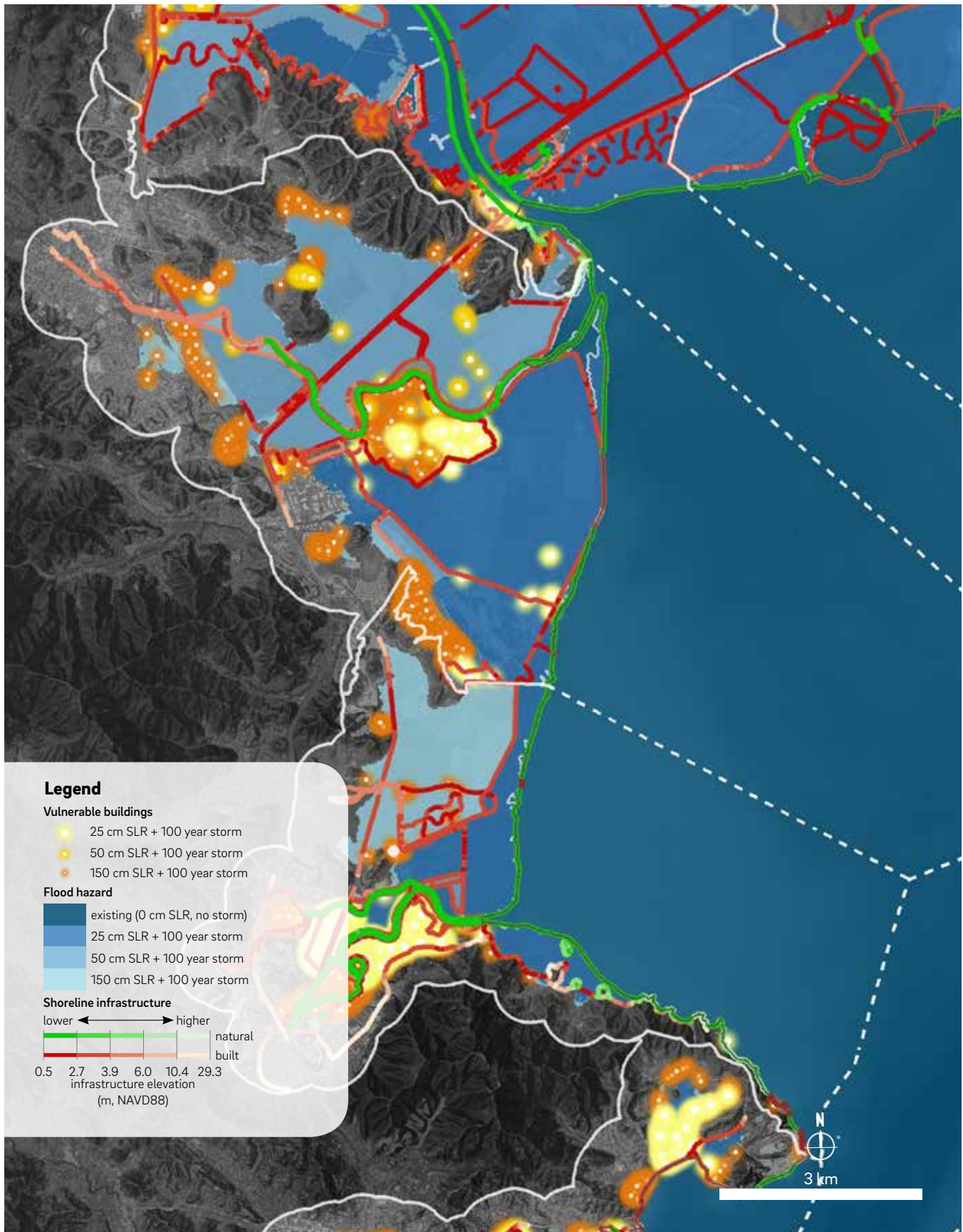
VULNERABILITY MAP
Gallinas OLU



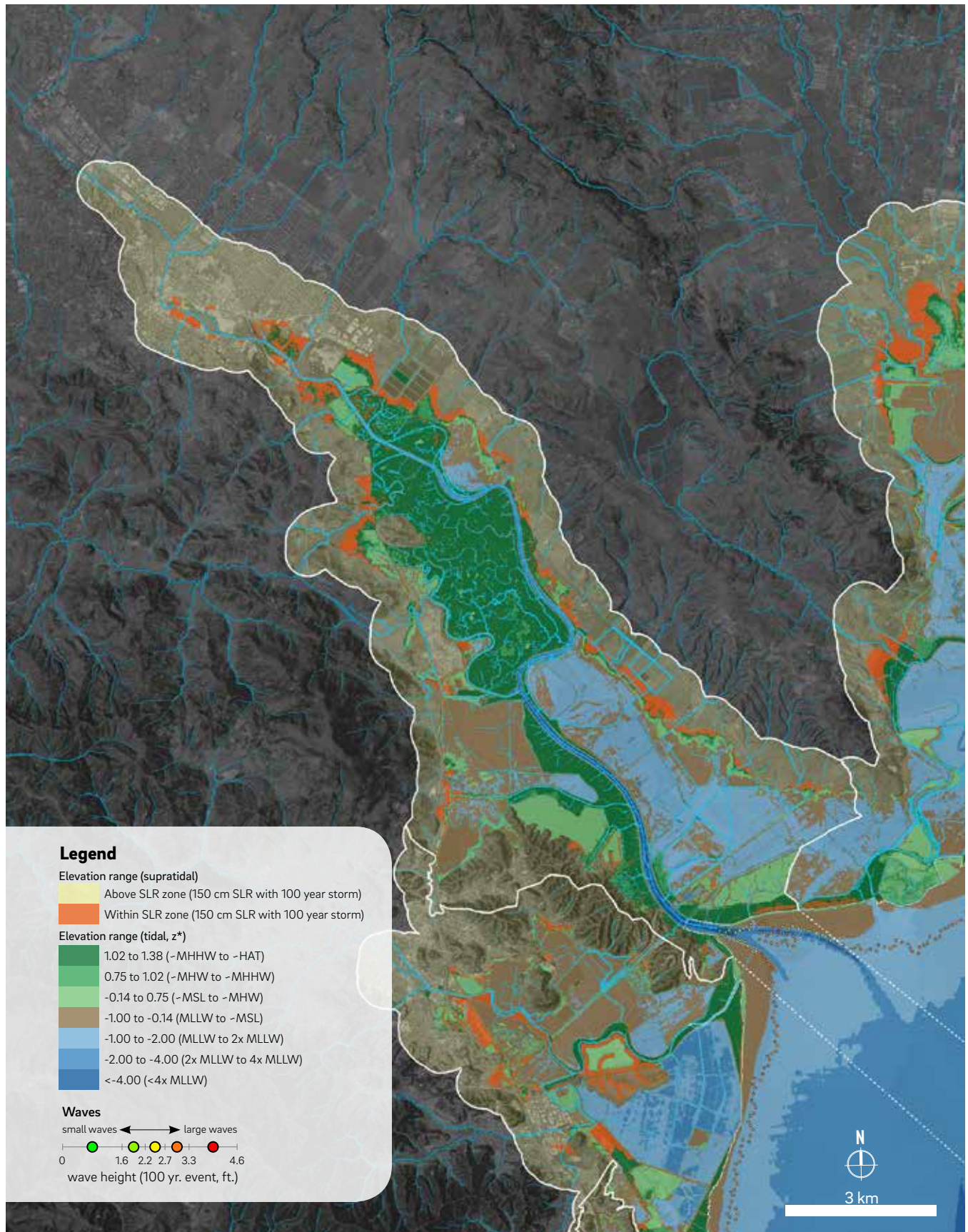
PHYSICAL PROCESSES & DRIVERS MAP
 Novato OLU



VULNERABILITY MAP
Novato OLU

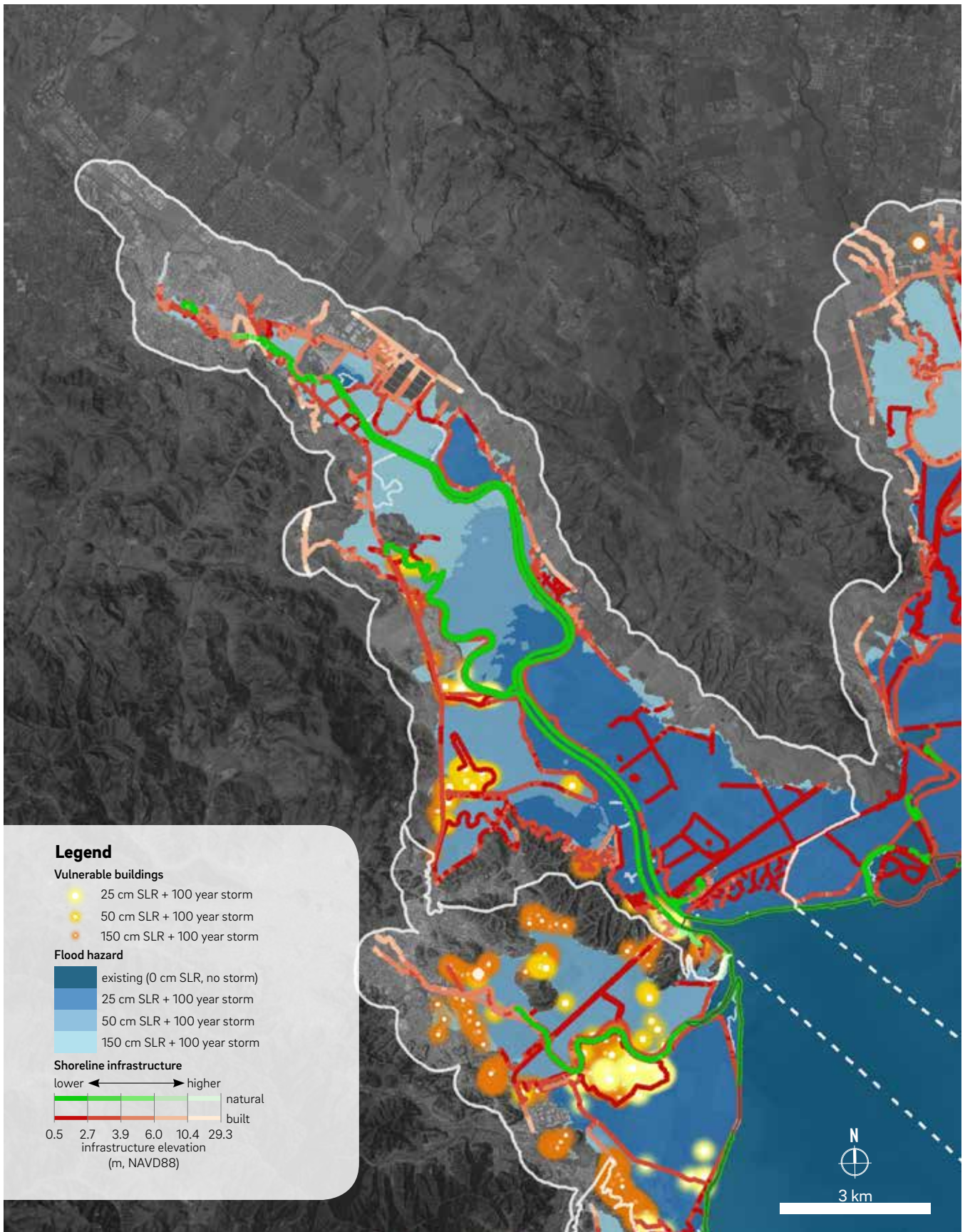


PHYSICAL PROCESSES & DRIVERS MAP
 Petaluma OLU

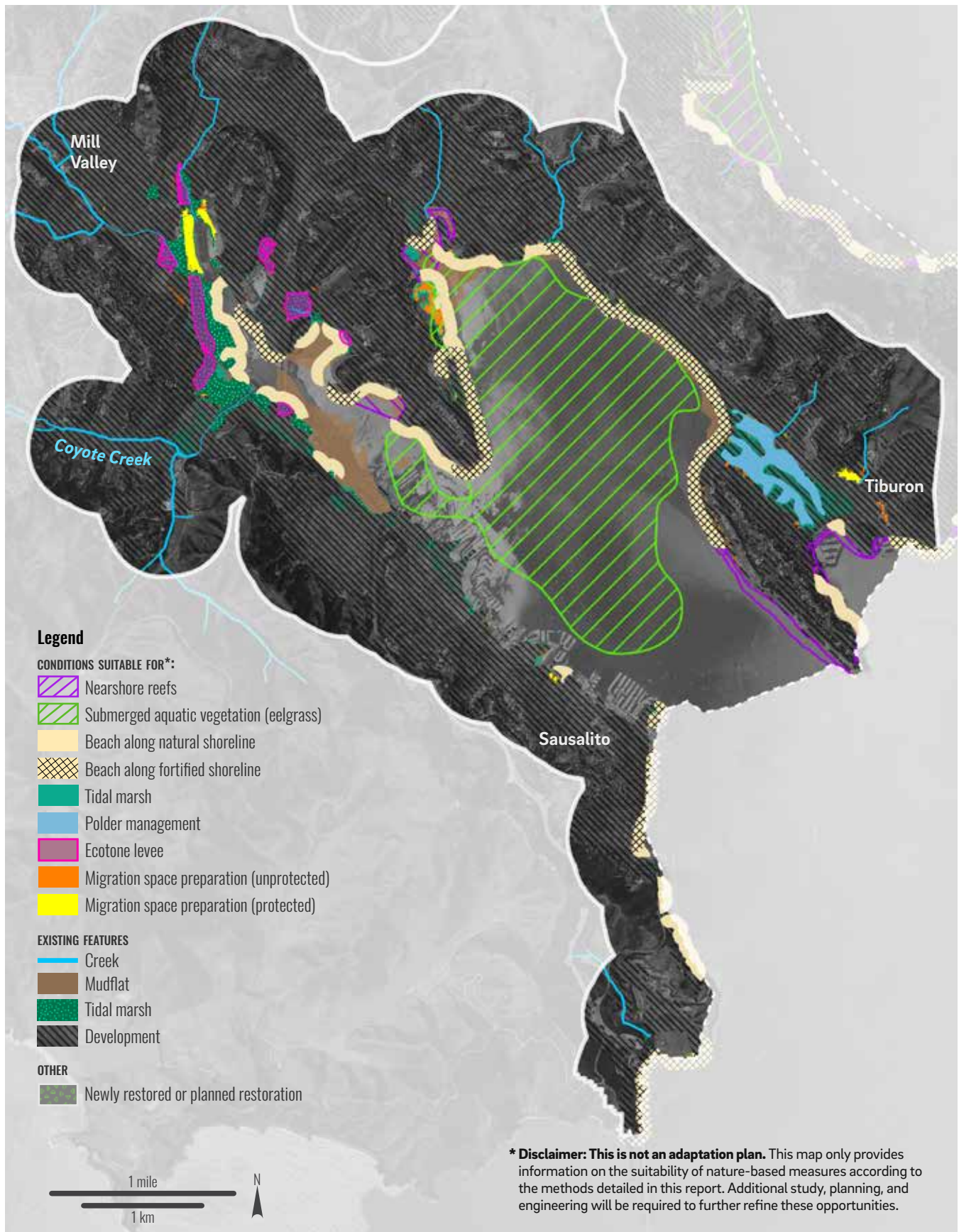


VULNERABILITY MAP

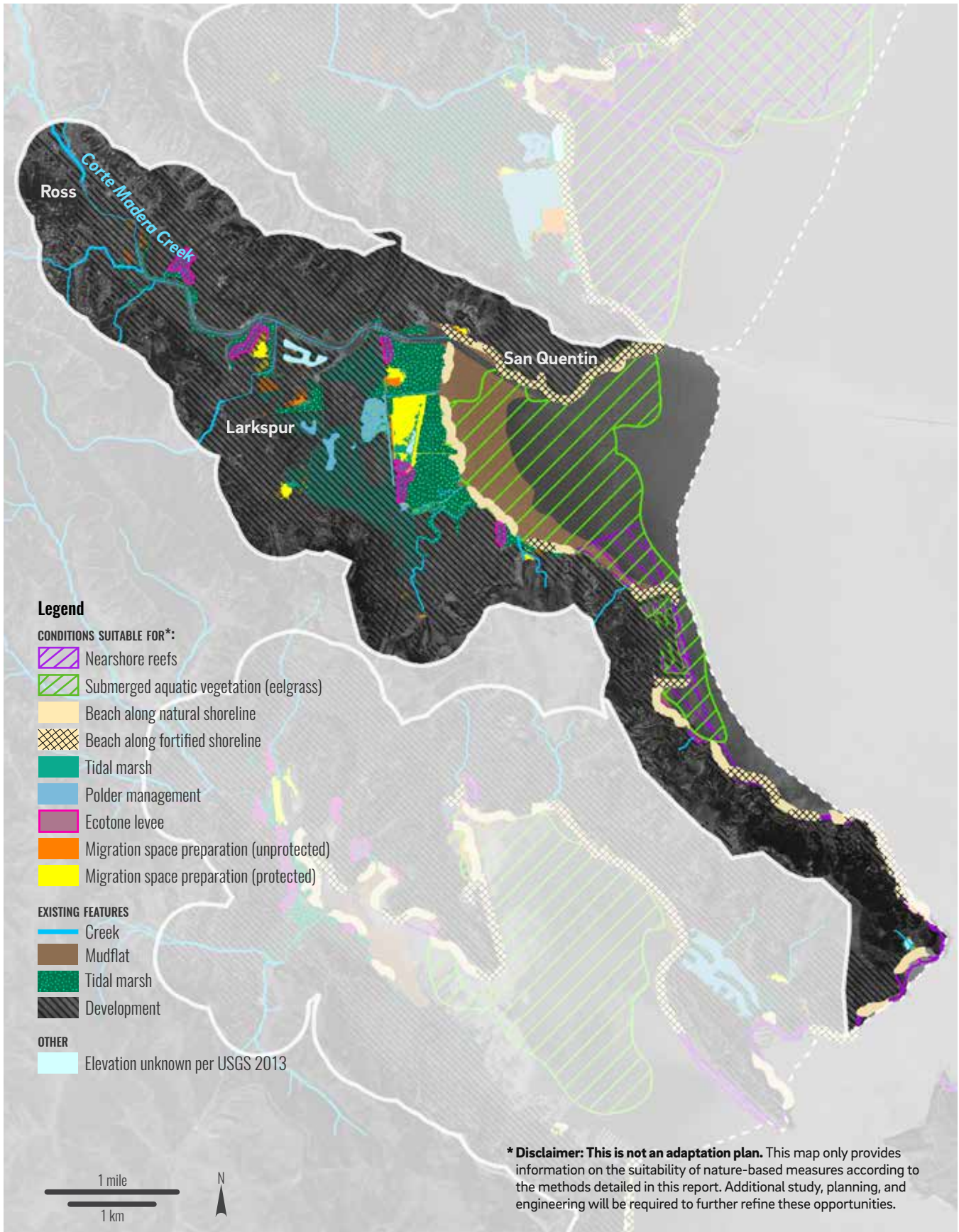
Petaluma OLU



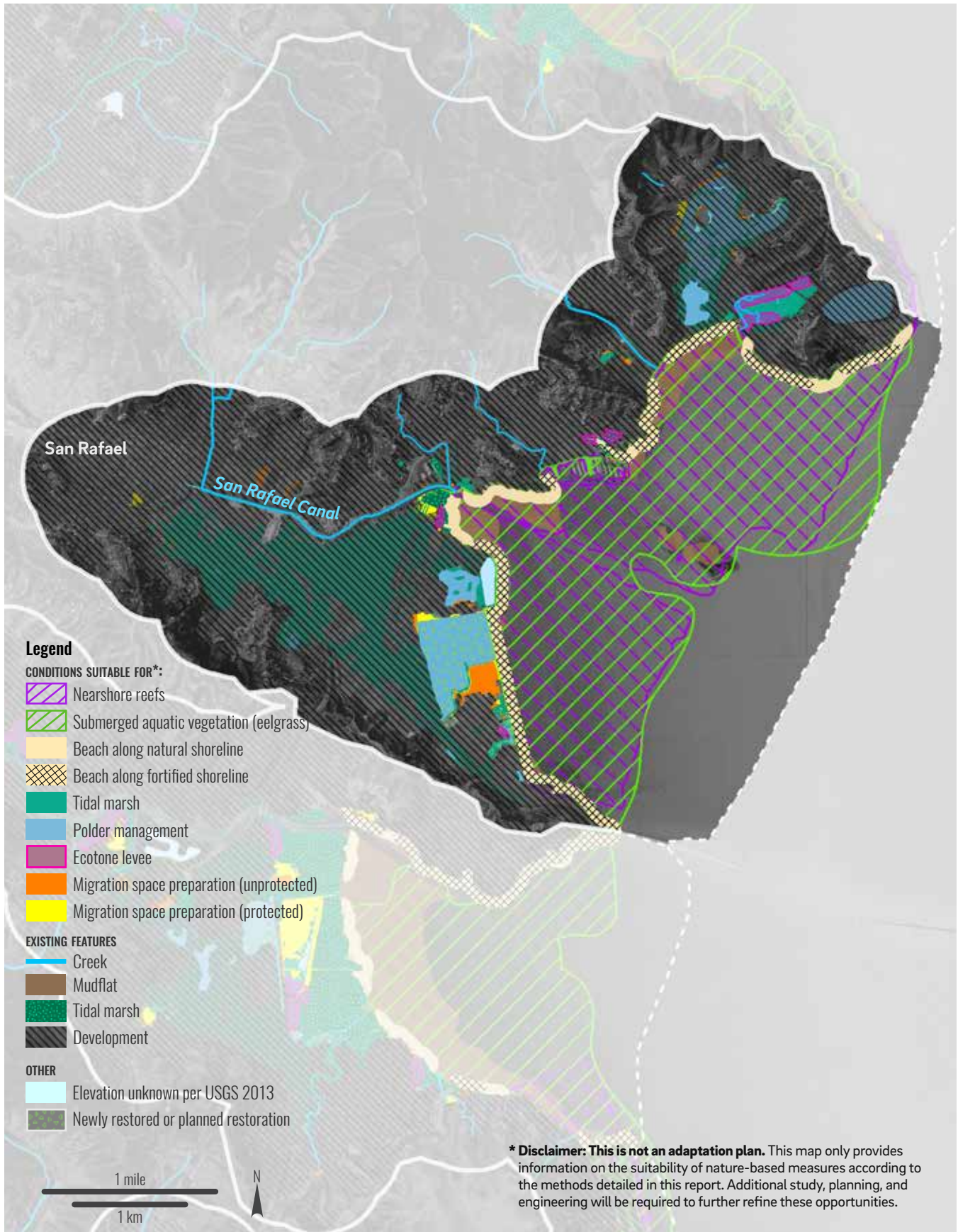
Appendix 2: NATURE-BASED ADAPTATION OPPORTUNITIES MAP Richardson OLU



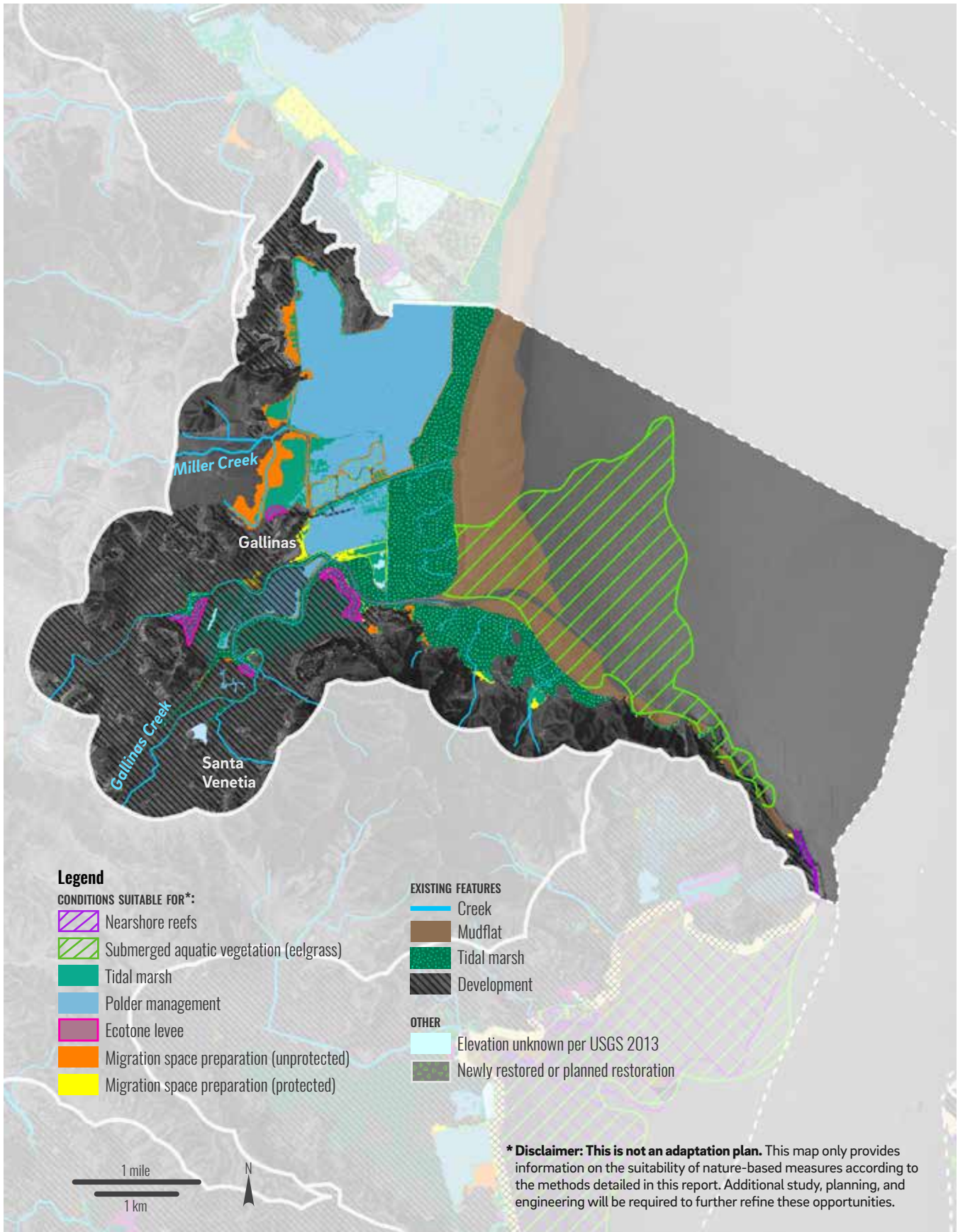
NATURE-BASED ADAPTATION OPPORTUNITIES MAP
Corte Madera OLU



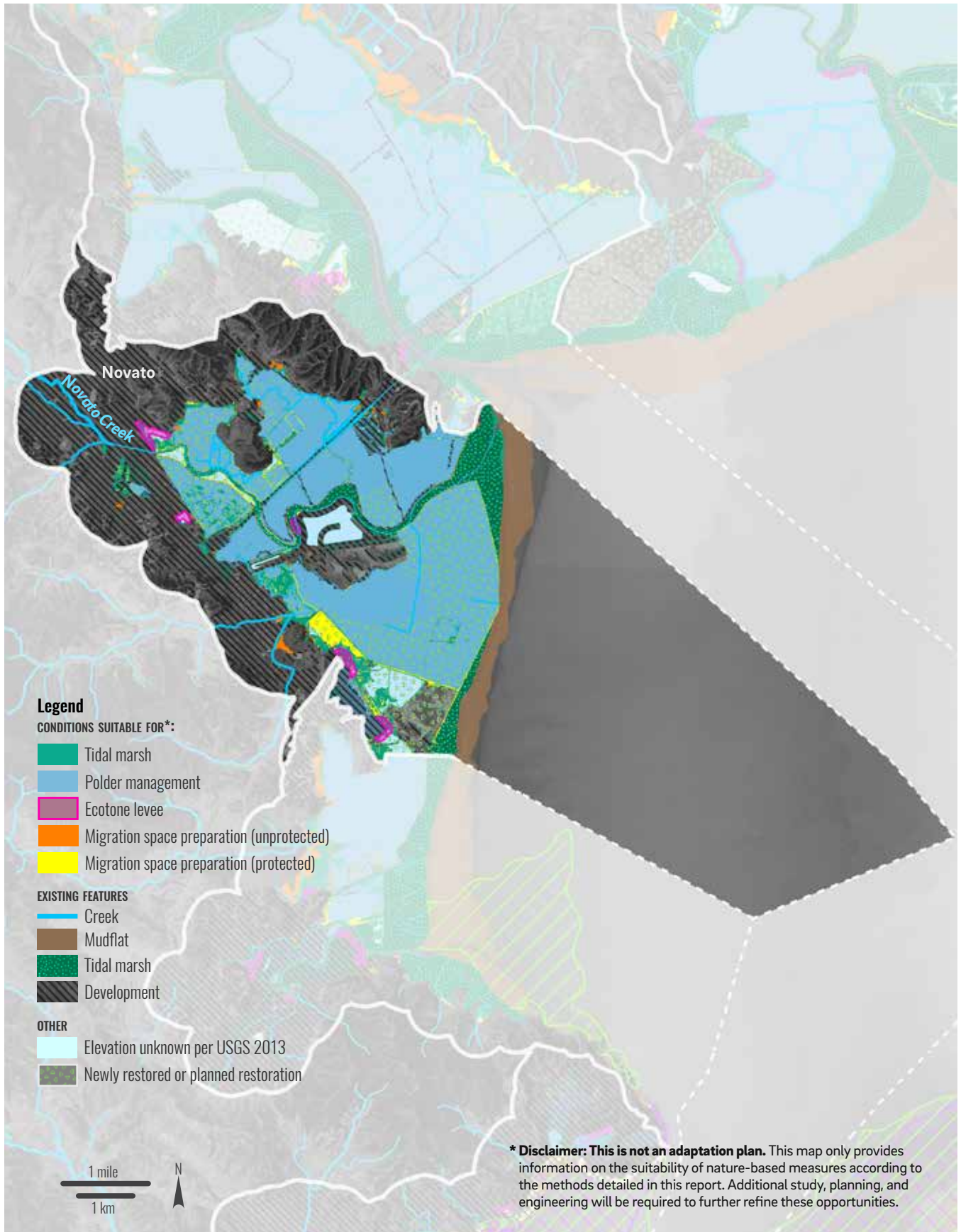
NATURE-BASED ADAPTATION OPPORTUNITIES MAP
 San Rafael OLU



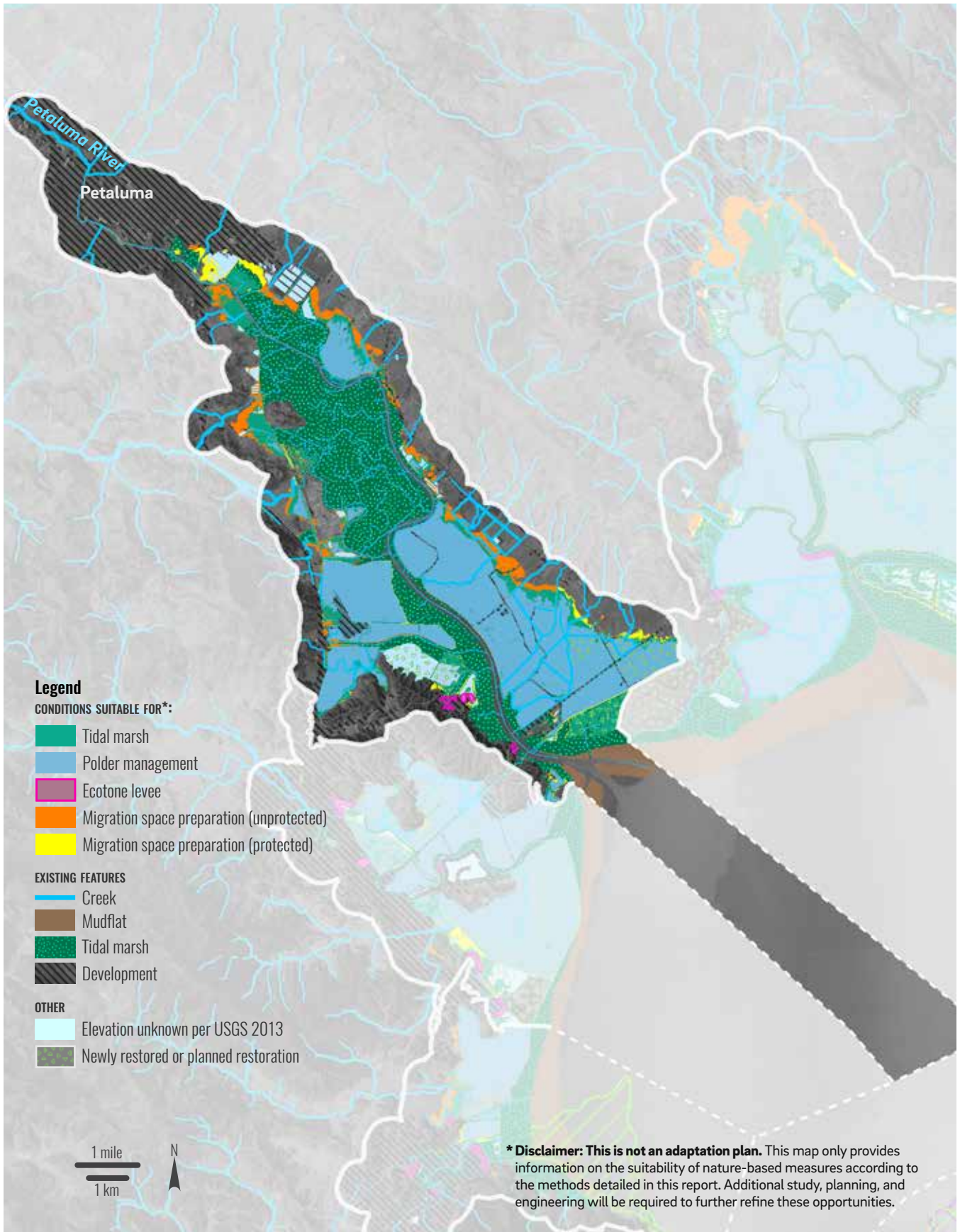
NATURE-BASED ADAPTATION OPPORTUNITIES MAP
 Gallinas OLU



NATURE-BASED ADAPTATION OPPORTUNITIES MAP
 Novato OLU

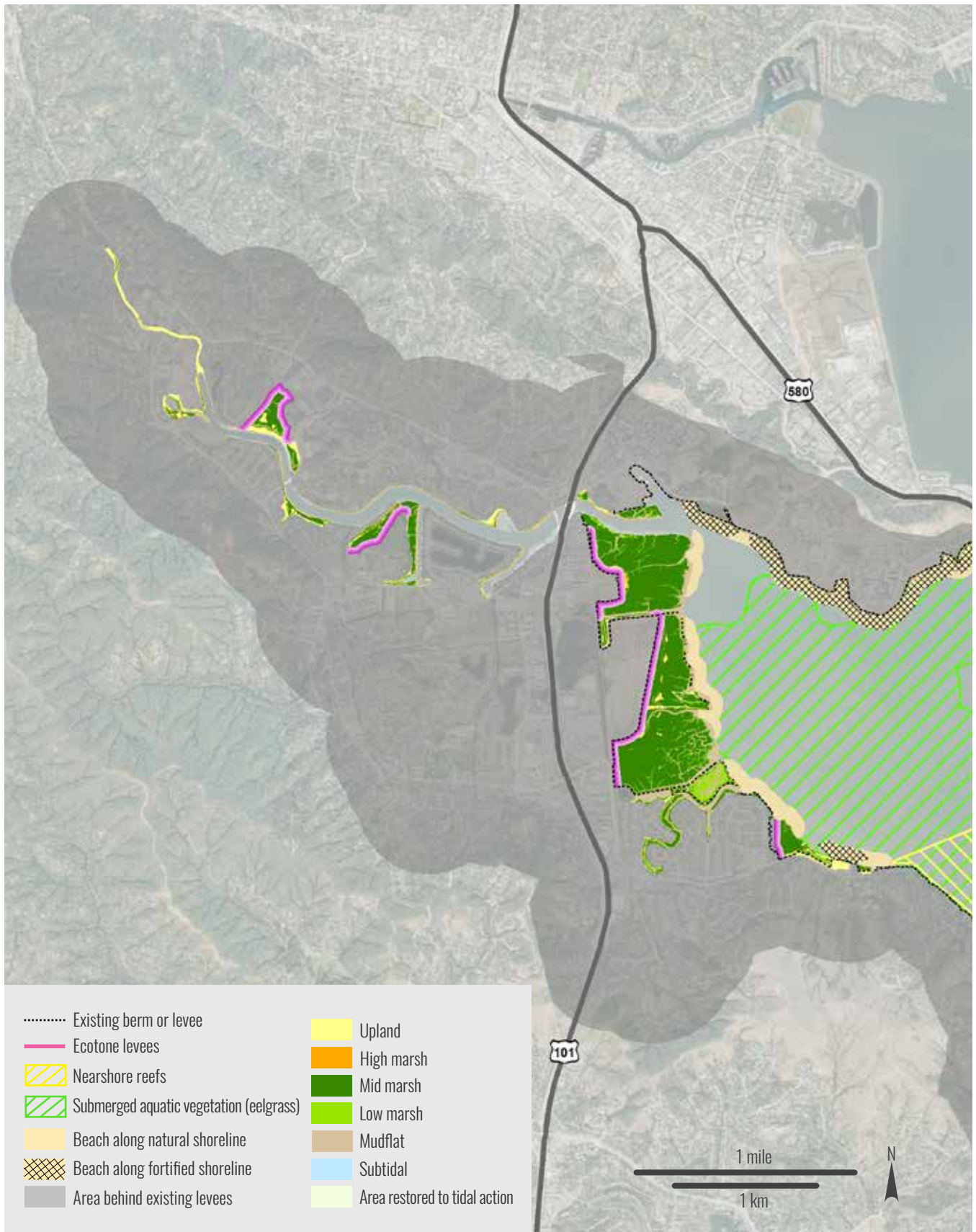


NATURE-BASED ADAPTATION OPPORTUNITIES MAP
 Petaluma OLU



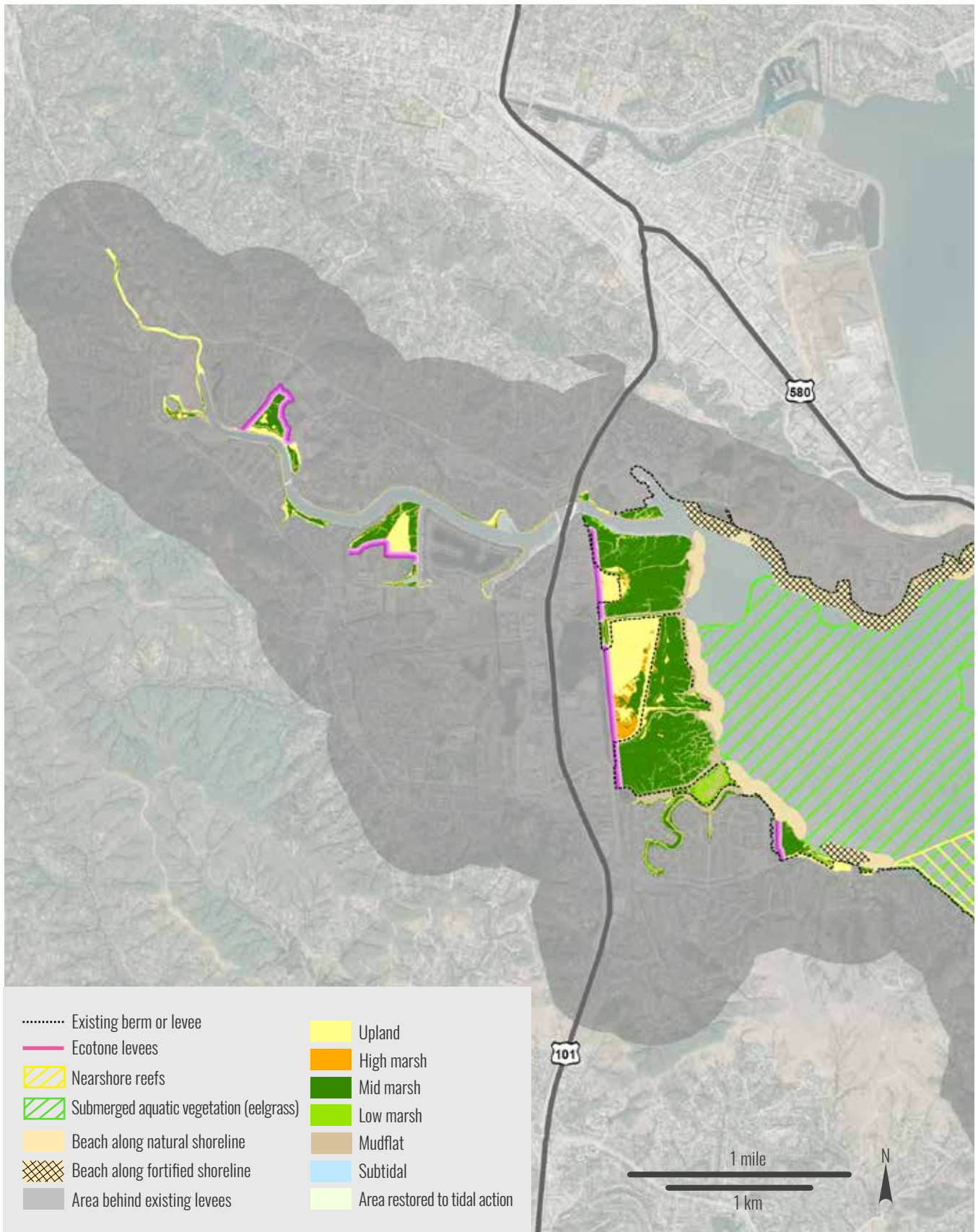
Appendix 3: STRATEGY MAPS

Corte Madera OLU: Hold the line

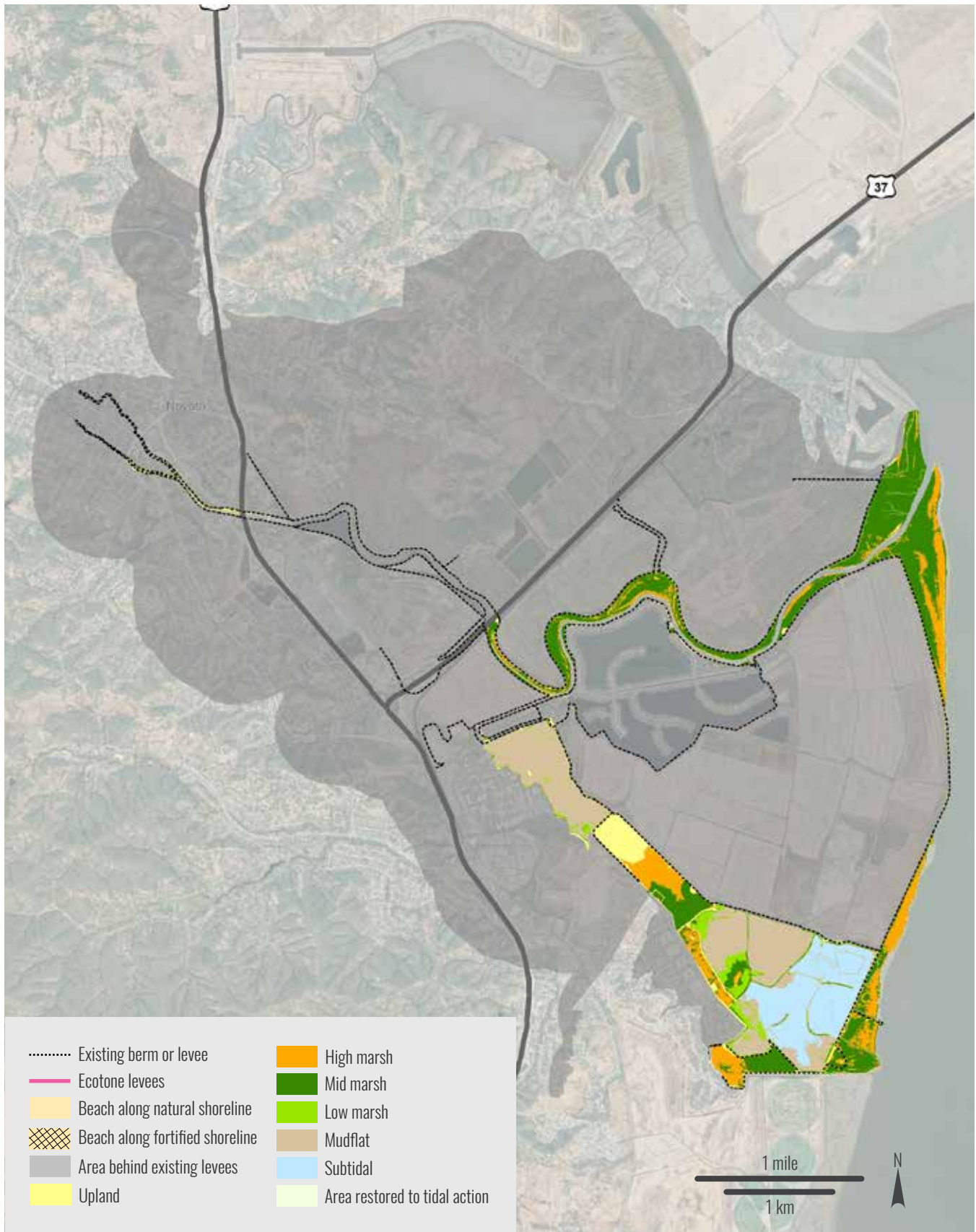


STRATEGY MAPS

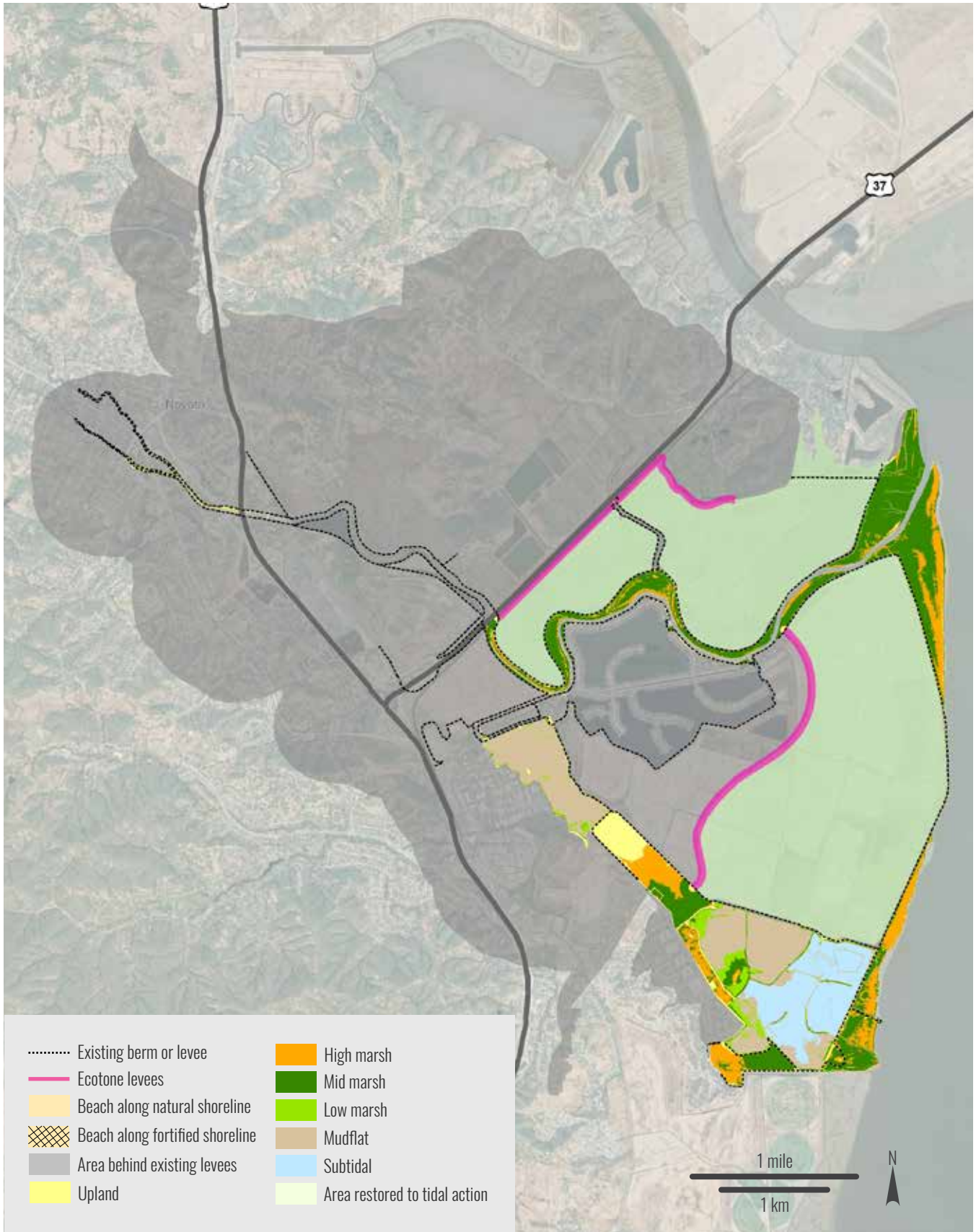
Corte Madera OLU: Buffer with public open space



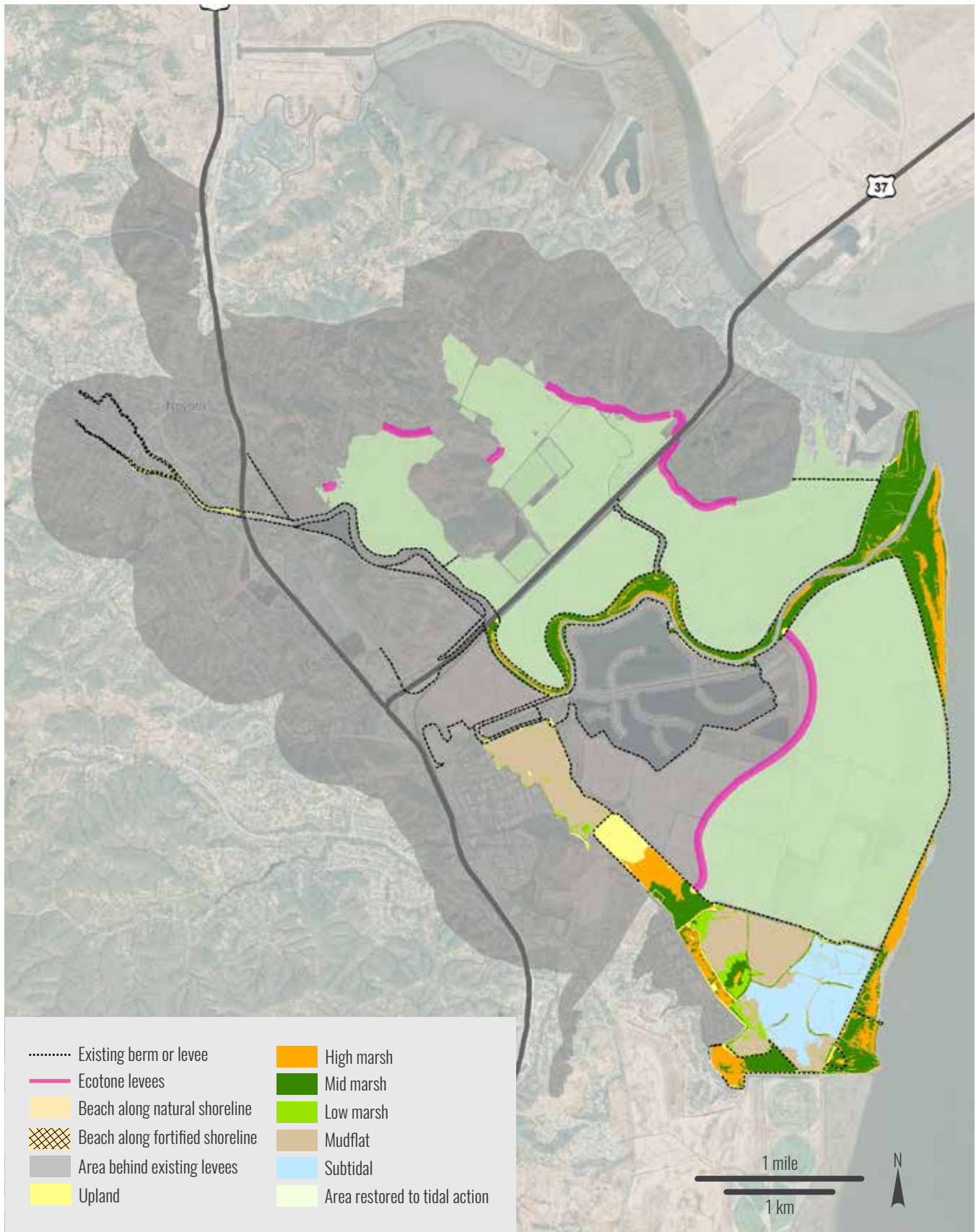
Novato OLU: Hold the line



Novato OLU: Buffer with public open space



Novato OLU: Maximize habitat/minimize risk





Appendix 4: UNDERSTANDING HOW SEA LEVEL RISE MAY AFFECT ADAPTATION MEASURES AND OBJECTIVES OVER TIME

We modeled how tidally-influenced elevations may change through time with rising seas for all case study strategies to understand how implementation timing of nature-based measures affects long-term habitat outcomes, and to ask the questions: How long do adaptation measures last? How do you compare among strategies if your goal is to use nature-based measures to achieve multiple benefits? How might adaptation objectives or outcomes change with sea level rise?

Leveraging recent modeling work led by Point Blue Conservation Science (Hayden et al. 2019), we modified the existing topography in our two case study OLUs (Novato and Corte Madera) to include proposed ecotone levees and areas that would be restored to tidal action for each of the case study adaptation strategies (see case studies Step 4). We then applied a spatially-explicit model of vertical accretion for tidally influenced elevations, whose rate depends on water depth (affected by sea level rise), availability of suspended sediment, and rate of organic accumulation (Orr et al. 2003, Stralberg et al. 2011). Because the Novato OLU case study strategies included opening large areas of currently diked baylands to tidal action, we also looked at the effect that timing of opening these areas would have on the trajectory of habitat change through time (e.g., what happens if areas are restored to tidal action in 2030 vs. waiting until 2050).

Our goal was to illustrate a few examples of how this type of quantitative modeling could be used to inform development of adaptation strategies. We thus applied only a single sea level rise curve, a single uniform assumption of sediment availability, coarse placement and basic designs for ecotone levees. Additional sea level rise/sediment scenarios and more site-specific design standards can certainly be accommodated in future work.

Model Inputs for Case Studies

Key inputs to the refined accretion model included (1) an initial elevation surface relative to the MHHW tidal datum that was modified to include proposed ecotone levees, (2) suspended sediment concentration, (3) organic accumulation rate, (4) projected sea level rise, and (5) timing of opening new areas to tidal action (for Novato OLU only).

Initial elevation surface and design assumptions for ecotone levees

Vertical accretion rates based on a mass-balance approach depend on the depth of the water column, requiring data on the elevation of a given wetland surface relative to the tidal frame (Orr et al. 2003). We previously compiled a 2-m resolution Digital Elevation Model (DEM) of current marsh areas from shallow subtidal elevations to upland transition zones, which may become marshes in the future (Hayden et al. 2019, Stralberg et al. 2011). The DEM was based on the most recent (2010) multi-sourced Light Detection and Ranging (LiDAR) remote sensing data and multi-beam bathymetry data available for the region (Foxgrover and Barnard, 2012). Elevations were then converted to a local mean-higher-high water (MHHW) tidal datum using methods described in Stralberg et al. (2011).

We then modified this initial elevation surface for each case study strategy to include proposed ecotone levees. We digitized levee crest lines and developed simple designs to size the levees and evolve the DEM. We designed the levee crest such that it would overtop at approximately 50cm of sea level rise, which would occur by 2050 based on the sea level rise curve we applied (see section titled “Projected sea level rise” below). The crest elevation included the current Total Water Level (tides + surge + waves) plus an additional 50cm of sea level rise relative to today’s mean higher high water (MHHW). The bayward facing side of the levee would then gradually slope down at a 1:30 slope with the toe elevation at MHHW (mid-marsh elevation). In the Novato OLU, where ecotone levees were added to subsided areas, we placed an additional 80m wide fronting marsh at the toe of the bayward levee slope, which was calculated as the width of marsh necessary to reduce incoming wave height by 30cm (1 ft). In the Corte Madera OLU, the ecotone levees would grade into the existing marsh elevations; thus there was no need for an additional marsh buffer. The landward side of the levee was designed to a more traditional 1:3 slope to minimize the overall footprint and graded in to any existing higher elevation topography.

Suspended sediment concentration

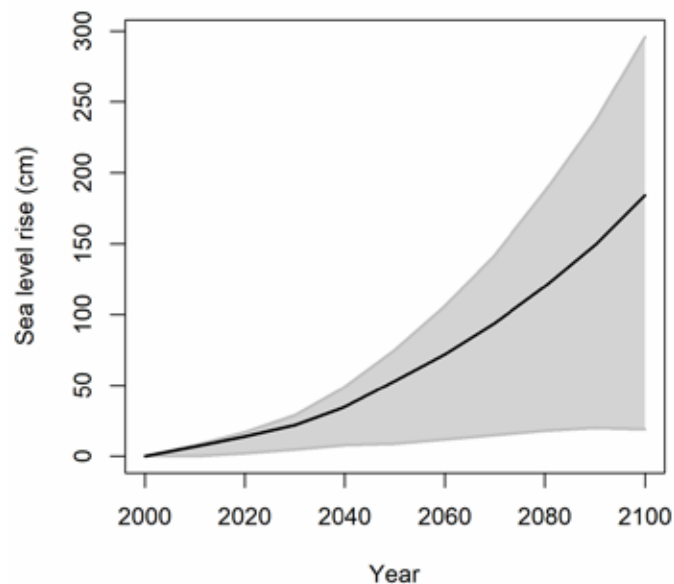
Accretion rates also depend on the available sediment suspended in the water column. For the purposes of our case studies, we applied a single, spatially-uniform, mid-range suspended sediment concentration (SSC) of 200 mg/L based on data compiled by Stralberg et al. (2011) for San Francisco Bay. Additional suspended sediment concentrations could be used in the future to better bracket the range of potential future sediment availability, and concentrations could also differ spatially to better represent spatial variability across the landscape.

Organic accumulation rate

Organic matter accumulation also affects the rate of vertical accretion (mm/yr), and data across the Bay Area ranged from 1-3 mm/yr (Stralberg et al. 2011). The model is largely insensitive to these small organic matter accumulation rates (Stralberg et al. 2011), so for the purposes of our case studies we applied a “high” value of 3 mm/yr to be present uniformly across the study area.

Projected sea level rise

We used the updated State of California Sea Level Rise Guidance (OPC 2018), and selected a “medium-high risk aversion” sea level rise scenario. Specifically, we used the high emissions (Representative Concentration Pathway 8.5) 99th percentile curve that reaches 50cm of sea level rise by 2050.



The rate of sea level rise used as an input for our marsh accretion modeling (black line) was based on the high emissions (RCP 8.5) 99th percentile curve that reaches 50cm by 2050, which was the overtopping threshold of our ecotone levees. The grey band represents the 1 to 99.9 percentile range of the high emissions (RCP 8.5) scenario. Data source: OPC 2018.

Vertical accretion and habitat change

We ran the accretion model from a year 2010 baseline (initial elevation surface modified with ecotone levees) to year 2100. The model adds the corresponding depth-dependent mineral sediment accumulation plus organic accumulation at yearly time steps, producing a new elevation surface relative to the projected MHHW level at yearly timesteps. We then output DEM raster surfaces for each decade, though we only display results for 2030, 2050, 2070, and 2100 in the following maps. Based on relative elevation within the tidal frame, we classified output elevations following Stralberg et al. 2011 (Table 1) for mapping habitat change.

Timing of opening areas to tidal action

The Novato OLU case study strategies included opening large areas of currently diked, subsided baylands (polders) to tidal action. In order to understand the effect that timing of opening these areas would have on the trajectory of habitat change through time, we modeled different restoration timing scenarios for the “Buffer with Public Open Space” and “Maximize Habitat” strategies. For each strategy, we modeled restoring the areas by 2020, 2030, 2040, 2050, and 2060. The earlier that the area is restored to tidal action, the longer it will have to build elevation while the rate of sea level rise remains relatively low. After about 2050, the rate of sea level rise is projected to increase significantly, and polder areas may not be able to build elevation fast enough to achieve certain desired future habitat (e.g., vegetated marsh). We presented an example in the “Timing Matters” box on page 32. The bar chart figure on page 75 shows that significant low marsh habitat can be achieved by 2100 for both strategies, if tidal action is restored by 2030. If restoration occurs by 2050 or beyond, the polder areas are projected to build only to mudflat elevation. Vegetated marshes and mudflats both provide a host of important ecological functions and services, but the benefits are different. Thus, the timing of restoring large polder areas to tidal action will influence the long-term outcomes of an adaptation strategy. It is important that the trajectory of change with rising seas be factored in to development of strategies and desired future outcomes.

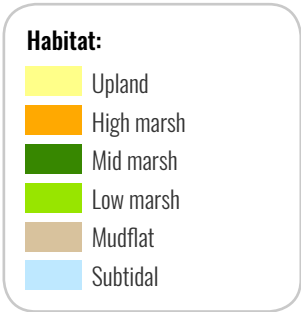
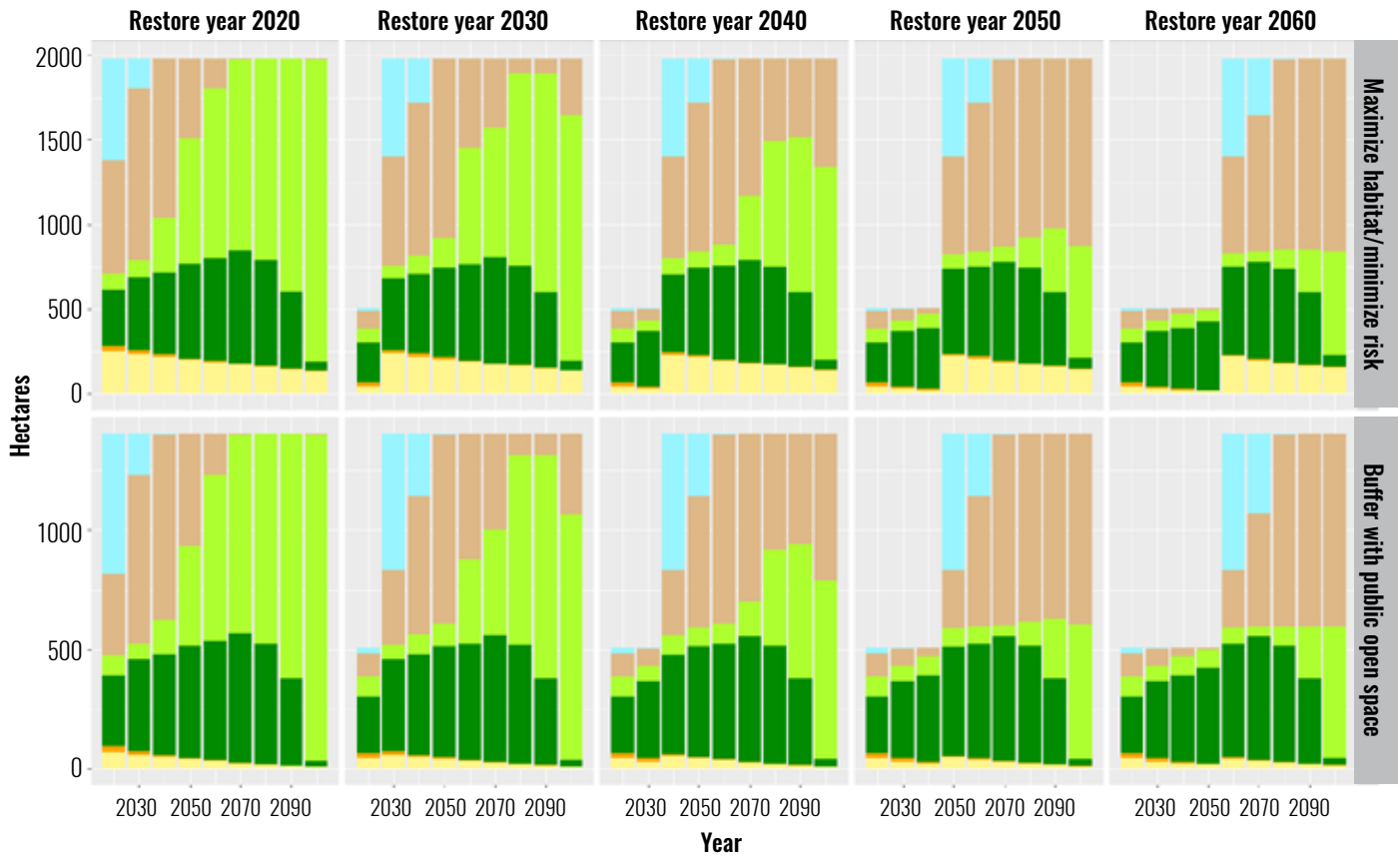
For the Corte Madera OLU “Buffer with public open space” strategy, we used a single timing assumption for areas currently protected by levees because most of these areas are already at high relative elevations now (i.e., upland), so the timing of restoration is less critical to achieving marsh habitat in the future. Thus, we assumed they would be exposed to tidal action by 2030.

Table 1. Habitat classes based on elevation relative to mean higher high water (rMHHW), following Stralberg et al. (2011).

Habitat type	Elevation range (rMHHW)
Upland	>0.3m
High marsh	0.2 to 0.3m
Mid marsh	-0.2 to 0.1m
Low marsh	-0.5 to -0.3m
Mudflat	-1.8 to -0.6m
Subtidal	<-1.8m

MARSH ACCRETION MODELING TIME SERIES MAPS

Novato OLU: Effect of timing of opening areas to tidal action

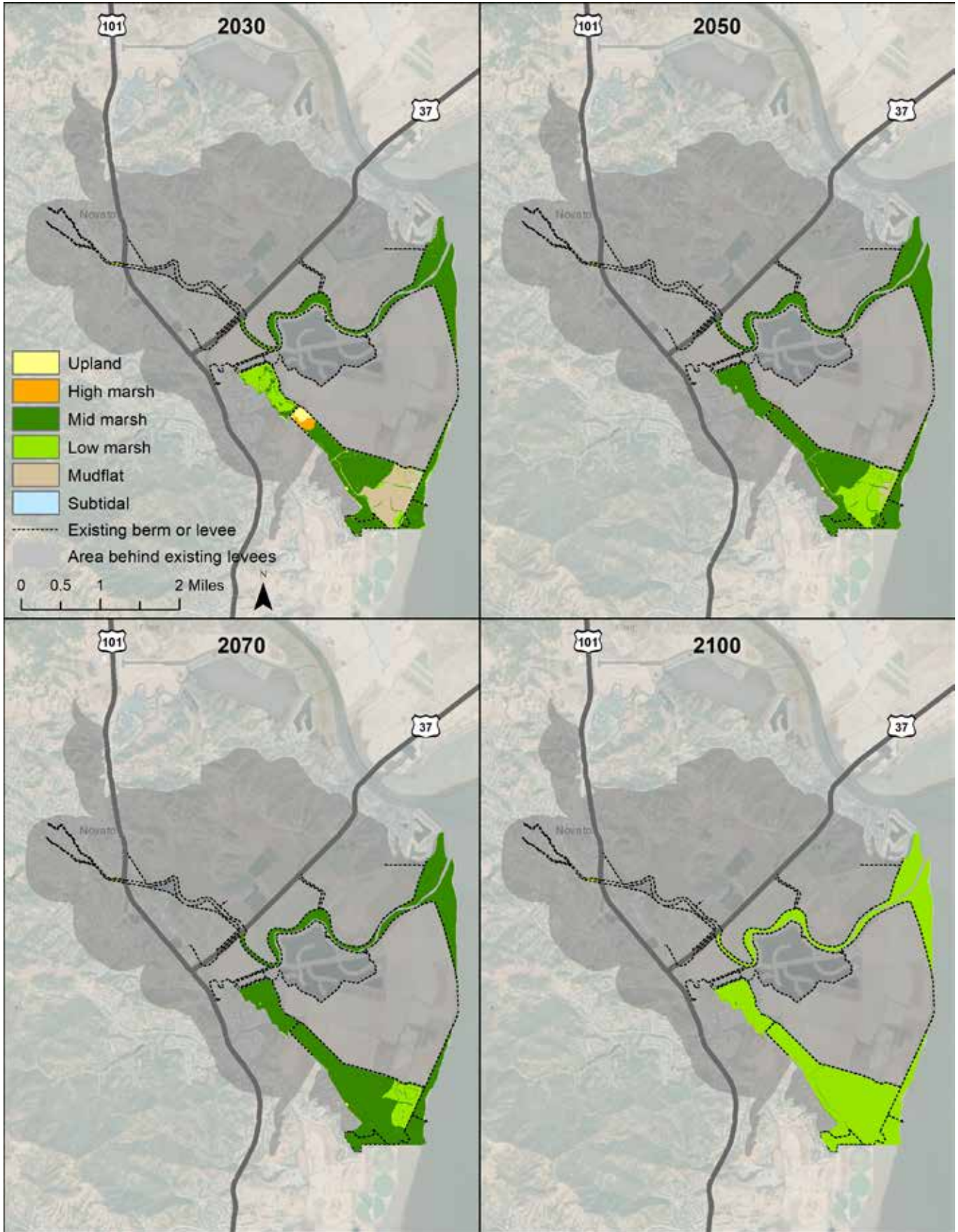


The Novato OLU case study strategies for “Buffer with public open space” and “Maximize Habitat/Minimize Risk” included opening large areas of currently diked, subsided baylands (polders) to tidal action. In order to understand the effect that timing of opening these areas would have on the trajectory of habitat change through time, we modeled restoring these areas by 2020, 2030, 2040, 2050, and 2060. Each panel above summarizes total area of each habitat type projected from the accretion model at decadal outputs from 2020 through 2100, for each restoration timing scenario. Significant low marsh habitat can be achieved by 2100 for both strategies, if tidal action is restored by 2030. If restoration occurs by 2050 or beyond, the restored polder areas are projected to build only to mudflat elevation.

Maps on the following pages show projected evolution of tidal wetland habitats with sea level rise by 2030, 2050, 2070, and 2100 for each of the Case Study strategies (3 strategies for the Novato OLU, and 2 strategies for the Corte Madera OLU). Model input assumptions are discussed in detail in the previous text, and are based on 200mg/L of suspended sediment, 3mm/yr of organic matter accumulation, and a high emissions sea level rise scenario (RCP 8.5, 99th percentile) from the updated State of California Sea Level Rise Guidance (OPC 2018). For “Buffer with public open space” and “Maximize Habitat/Minimize Risk” scenarios, outputs shown assume tidal action is restored to previously diked/protected areas in 2030.

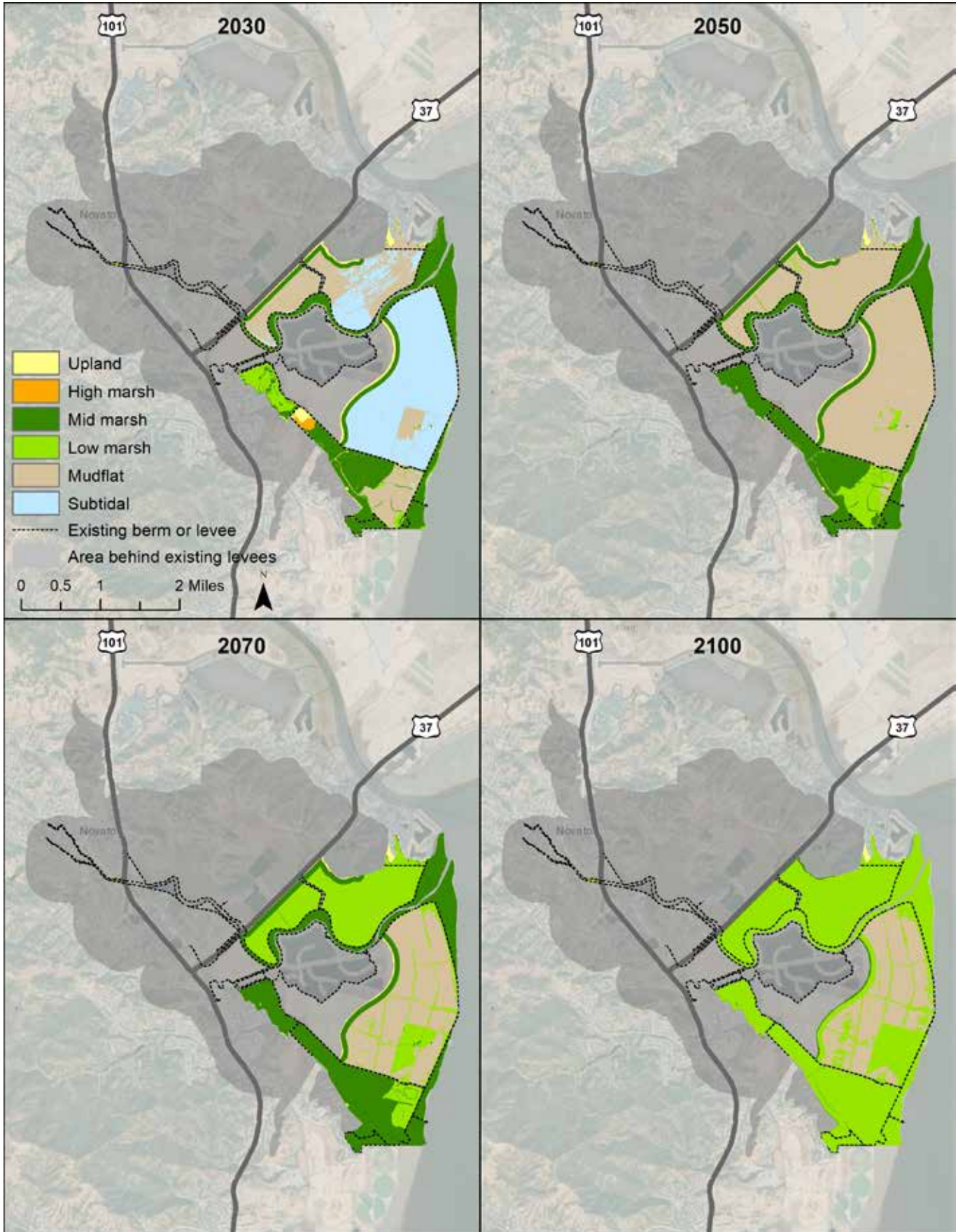
MARSH ACCRETION MODELING TIME SERIES MAPS

Novato OLU: Hold the line



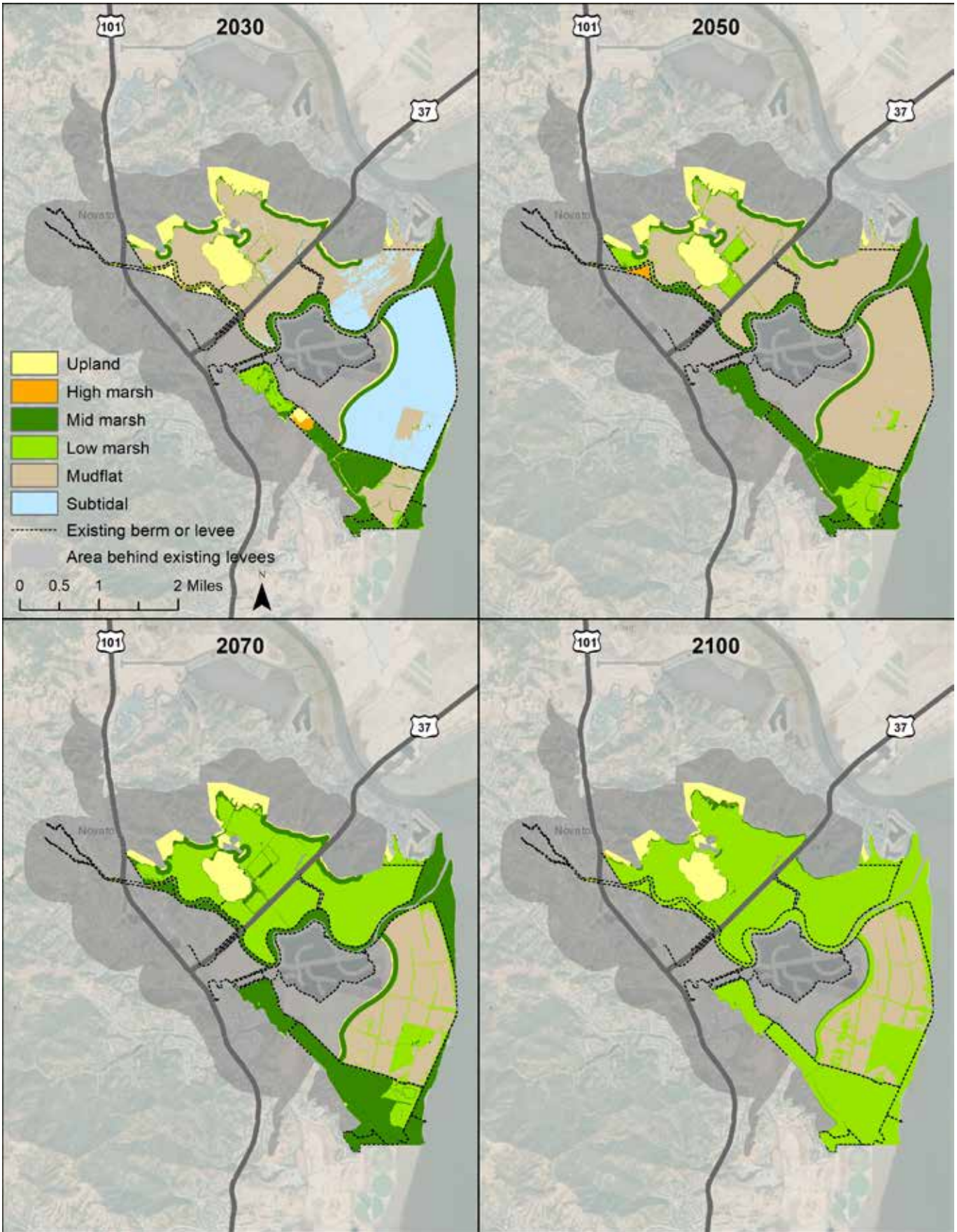
MARSH ACCRETION MODELING TIME SERIES MAPS

Novato OLU: Buffer with public open space



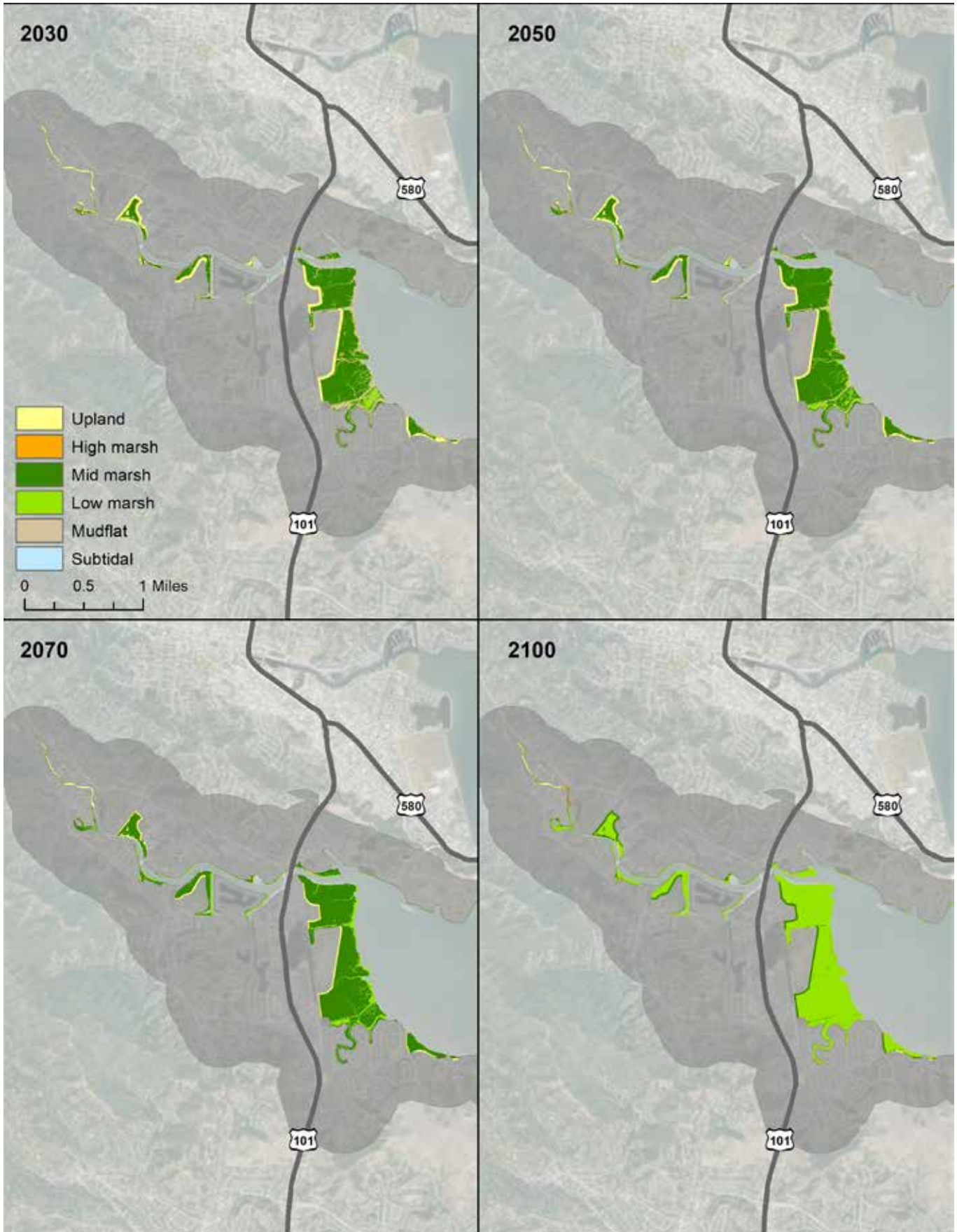
MARSH ACCRETION MODELING TIME SERIES MAPS

Novato OLU: Maximize habitat/minimize risk



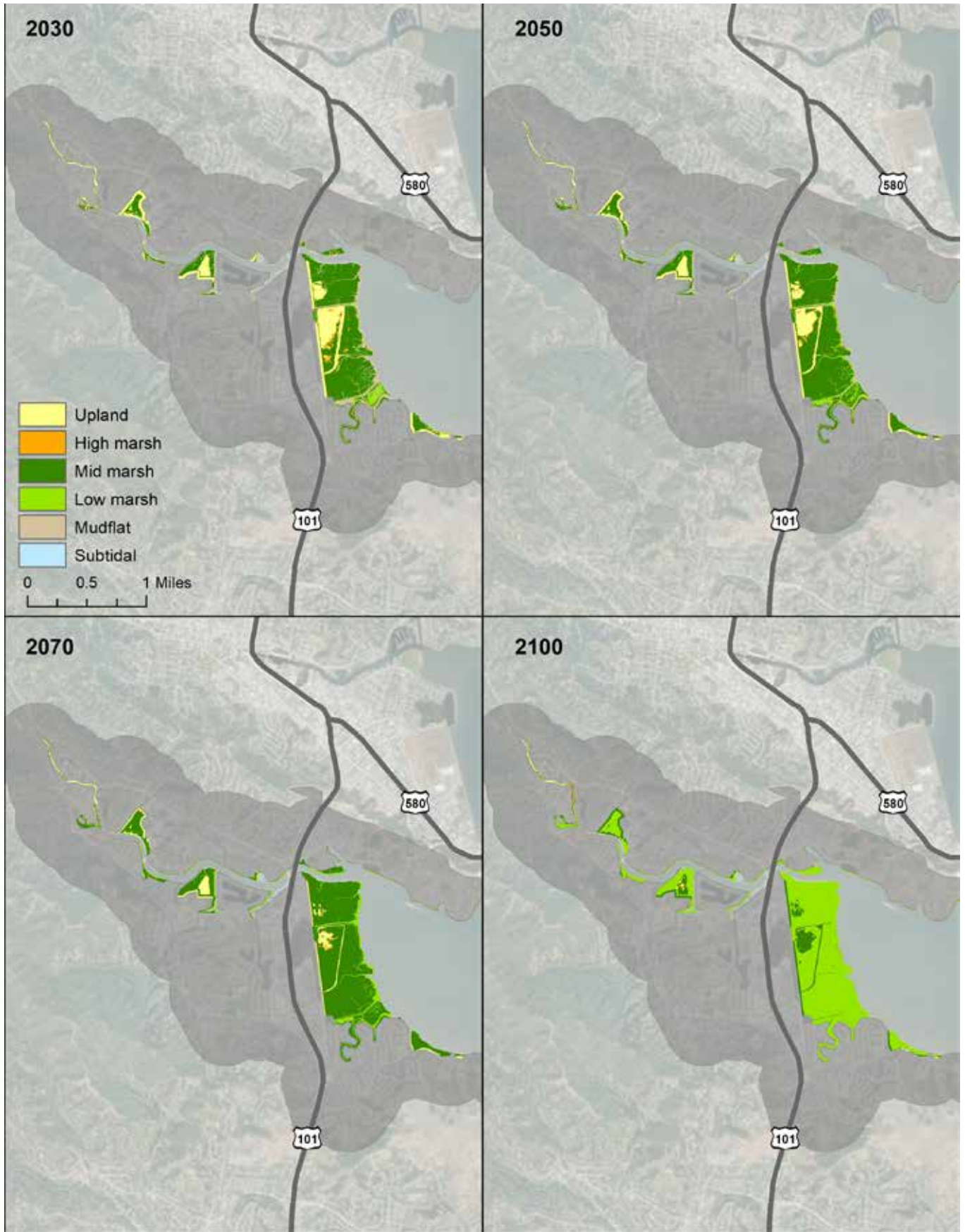
MARSH ACCRETION MODELING TIME SERIES MAPS

Corte Madera OLU: Hold the line



MARSH ACCRETION MODELING TIME SERIES MAPS

Corte Madera OLU: Buffer with public open space





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