



Hamilton Wetlands. Photo by Shira Bezael.

# Ecotone levees and wildlife connectivity: A technical update to the Adaptation Atlas

**SFEI** San Francisco  
Estuary Institute



## PREPARED BY

San Francisco Estuary Institute

## FUNDED BY

San Francisco Bay Regional Water Quality Control Board

## AUTHORS

Ellen Plane (Ecotone Levees)

Kelly Iknayan (Wildlife Connectivity)

## WITH SUPPORT FROM

Katie McKnight

April Robinson

Scott Dusterhoff

Jeremy Lowe

Letitia Grenier

# ACKNOWLEDGMENTS

The San Francisco Bay Regional Water Quality Control Board provided the majority of funding for this project and report.

This project benefited from a close synergy with Bay Area Clean Water Agencies (BACWA) Nature-Based Solutions for Nutrient Reduction project. We would like to thank BACWA, and in particular the members of the Contract Management Group, for their support and guidance in the ecotone levee mapping process.

We are grateful for the technical guidance, engagement, and enthusiasm contributed by our Wildlife Connectivity Advisory Committee: Julian Wood (Point Blue), Jules Evens (Avocet Research Associates), Cory Overton (U.S. Geological Survey), Jen McBroom (San Francisco Estuary Invasive Spartina Project), Joy Albertson (U.S. Fish and Wildlife Service), Howard Shellhammer (San Jose State University), Laureen Thompson (U.S. Fish and Wildlife Service), Mark Statham (UC Davis), Cody Aylward (UC Davis), Katie Smith (WRA, Inc).

Thank you to Donna Ball (SFEI) and Christina Toms (SF Bay Regional Water Quality Control Board) for reviewing the spatial datasets which served as the foundation for the wildlife connectivity analysis. Thanks also to Sam Safran (SFEI) and Clarissa Pickett (SFEI CivicSpark Research Fellow) for their helpful contributions.

Julie Beagle is the visionary behind this report, which would not have been possible without her leadership.

## SUGGESTED CITATION

SFEI. 2021. *Ecotone Levees and Wildlife Connectivity: A Technical Update to the Adaptation Atlas*. Publication #1037, San Francisco Estuary Institute, Richmond, CA.

*Version 1.0 (August 2021)*

## IMAGE PERMISSION

Permissions rights for images used in this publication have been specifically acquired for one-time use in this publication only. Further use or reproduction is prohibited without express written permission from the responsible source institution. For permissions and reproductions inquiries, please contact the responsible source institution directly.

# CONTENTS

<b>Key Takeaways</b>	<b>4</b>
ECOTONE LEVEES	4
WILDLIFE CONNECTIVITY	4
<b>Introduction</b>	<b>6</b>
<b>Ecotone Levees</b>	<b>8</b>
BACKGROUND	8
APPROACH	10
RESULTS SUMMARY	10
<b>Landscape Connectivity for Endangered Wildlife</b>	<b>16</b>
BACKGROUND	16
APPROACH	20
RESULTS	22
<b>Next Steps</b>	<b>34</b>
<b>Appendix A: Ecotone Levee Analysis</b>	<b>35</b>
METHODS	35
RESULTS	38
<b>Appendix B: Wildlife Connectivity Analysis</b>	<b>56</b>
METHODS	56
<b>References</b>	<b>61</b>

# Key Takeaways

The San Francisco Bay Shoreline Adaptation Atlas (SFEI and SPUR, 2019) identified science-based shoreline planning units and mapped suitable sites for nature-based shoreline adaptation measures. This report updates the Adaptation Atlas suitability mapping for ecotone levees and introduces a new habitat connectivity analysis focused on assessing the value of marsh habitat patches for two focal wildlife species. These new analyses address key next steps identified in the Adaptation Atlas by investigating issues related to infrastructure, water quality, wildlife habitat, and endangered species. The ecotone levee and wildlife connectivity analyses presented in this report can be used by Bay restoration and adaptation practitioners to identify possible projects and assess their potential ecological value.

## ECOTONE LEVEES

---

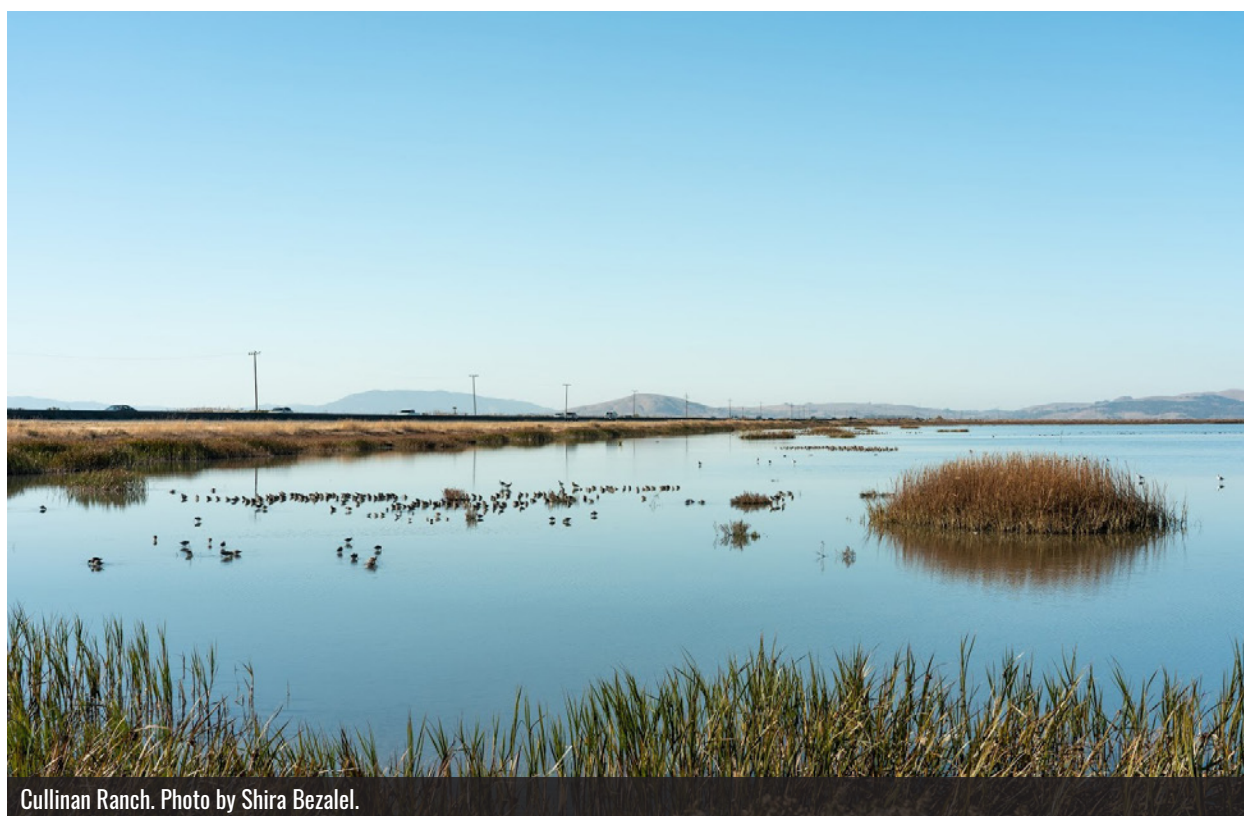
- Ecotone levees, an innovative nature-based adaptation measure mapped in the Adaptation Atlas, are shallow slopes that connect flood risk management levees to tidal marsh. They can provide transition zone habitat, which is important for high-water refuge and habitat connectivity, and attenuate waves to reduce levee erosion. For this report, we updated the first-pass ecotone levee suitability analysis conducted for the Adaptation Atlas to include more opportunities (particularly near wastewater treatment plants), while also adding refinements to the analysis (including updating the mapping of developed areas and conducting a more thorough review of opportunities).
- In total, 23 miles of shoreline were added as ecotone levee opportunities. The OLU with the greatest increases in opportunities were Santa Clara Valley, Walnut, Novato, and Napa-Sonoma.
- In addition, we mapped opportunities for horizontal levees, which are ecotone levees that incorporate subsurface seepage of treated wastewater to remove nutrients and create a fresh-to-brackish habitat gradient. Most OLUs have at least 0.5 miles of shoreline near wastewater treatment facilities potentially suitable for horizontal levees. Santa Clara Valley, Walnut, and Alameda OLUs have the most opportunities for horizontal levees.

## WILDLIFE CONNECTIVITY

---

- To help guide future restoration, this report analyzes habitat connectivity in the San Francisco baylands for two endemic, endangered tidal marsh species: Ridgway's rail (RIRA) and salt marsh harvest mouse (SMHM). A large amount of habitat restoration has occurred in the baylands since the 1980s, and a great deal more is planned and in progress. This work has been critical for bolstering connectivity. The protection and recovery of these species requires a holistic approach that goes beyond enhancing landscape connectivity alone. Supporting viable populations will require maintaining and increasing the amount of suitable habitat, enhancing local-scale connections where isolated populations exist, and improving the quality of existing habitat. Here we identify and prioritize locations where additional restoration opportunities beyond what is already planned would further enhance connectivity for these species. This analysis will be particularly relevant for comparing the benefits and evaluating the tradeoffs of restoring different habitat patches within subregions of the Bay.

- Compared to the 1800s, landscape connectivity for SMHM has decreased the most in the South Bay, particularly along the southeast shoreline. Ongoing restoration has improved connectivity in the region, and additional restoration opportunities have the potential to restore a greater degree of landscape connectivity, particularly in areas that help link adjacent large habitats. There is fairly high landscape connectivity for SMHM in San Pablo and Suisun historically and today; however, key sites that help shorten distances between habitat patches can further enhance connectivity.
- Landscape connectivity for RIRA was high in the North and South Bay historically and is still fairly high today. Some of the most valuable future restoration sites for RIRA are those that: (1) are intermediate distances between large blocks of remnant habitat that are separated by long distances, such as patches along central East Bay, (2) areas that create larger blocks of consolidated habitat, such as those occurring on the southeast shore of South Bay, and (3) areas that provide both connectivity enhancement and marsh migration space in San Pablo Bay.
- High-value restoration sites that would improve connectivity for both RIRA and SMHM:
  - In the South Bay, sites that help connect existing habitat and the large ongoing restoration projects are the most important, particularly near Oro Loma, Eden Landing, and Coyote Hills; fringing marsh along the foreshore and channels of the South Bay Salt Ponds; and Ravenswood Pond SF2.
  - For the North Bay, sites along the inland edges of marshes in these areas not only promote connectivity but will also connect to future marsh migration space, particularly areas along the northern edge of the Napa ponds; and near Petaluma Marsh, American Canyon, and Cullinan Ranch.



# Introduction

The San Francisco Bay Shoreline Adaptation Atlas (SFEI and SPUR, 2019) identified science-based shoreline planning units and mapped suitable sites for nature-based sea-level rise (SLR) adaptation measures. The planning units, called Operational Landscape Units (OLUs), are a practical way to manage the physical and jurisdictional complexity of the Bay shoreline. The Adaptation Atlas divides the Bay shoreline into 30 OLU—connected geographic areas that share common physical characteristics and would benefit from being managed holistically. OLU cross traditional jurisdictional boundaries of cities and counties but adhere to the boundaries of natural processes like tides, waves, and sediment movement. Taken as a whole, OLU include areas potentially vulnerable to future SLR where science-based shoreline adaptation strategies that are appropriate for the particular geographic setting can be developed.

For each OLU, the Adaptation Atlas mapped opportunities for nature-based shoreline adaptation, focusing primarily on the physical suitability of the shoreline for various types of nature-based measures, rather than the potential benefits and ecosystem services they might provide. The Adaptation Atlas identified a number of next steps for future research to improve the suitability mapping of nature-based measures, including:

- investigate SLR planning issues related to infrastructure (including landfills, contaminated sites, and wastewater treatment plants)
- assess potential impacts (positive or negative) of nature-based measures on water quality
- explore effects of nature-based adaptation strategies on habitat for endangered wildlife

In this technical update to the Adaptation Atlas, we focus on these next steps by identifying additional opportunities for natural and nature-based flood infrastructure to return benefits by protecting infrastructure, treating wastewater, and supporting endangered wildlife.

*Infrastructure protection & wastewater treatment* — This analysis updates the ecotone levee suitability analysis from the Adaptation Atlas. These low-slope levees are a nature-based adaptation approach that helps protect essential infrastructure with co-benefits of improved water quality and wildlife habitat. The refined analysis detailed here provides a more thorough assessment of the suitability of the shoreline for ecotone levees (shallow slopes connecting a flood risk management levee to tidal marsh) and horizontal levees (ecotone levees incorporating a subsurface wastewater seepage slope) than was conducted for the initial Adaptation Atlas. The new version both expands the range of opportunities identified (by updating the areas delineated as “development” and “marsh”) and refines the analysis (through more comprehensive review of opportunities).

*Wildlife habitat* — Next, this update investigates the importance of nature-based adaptation for wildlife habitat connectivity. This analysis assesses the relative importance of tidal marsh, diked marsh and transition zone habitat patches for two focal species: the federally endangered Ridgway’s rail (RIRA) and salt marsh harvest mouse (SMHM). This section focuses on assessing opportunities for improving wildlife connectivity, based on existing habitat patches, planned restorations, and potential future nature-based adaptation measures (additional restored marshes, transition zone, and ecotone levees).

Together, these analyses augment the Adaptation Atlas by identifying additional potential benefits of nature based measures, focusing in particular on infrastructure, water quality, and wildlife habitat. Future phases of work on the Adaptation Atlas may add additional co-benefits and develop methods that can compare projects across multiple co-benefits.

## MULTI-BENEFIT ADAPTATION

The Adaptation Atlas focused on flood risk management, but nature-based measures along the shore also provides other benefits. These other benefits, like carbon sequestration, wildlife habitat, water quality improvement, and recreation (Figure 1), may be equally important for guiding priority actions. This appendix focuses on two such benefits: (1) wildlife connectivity from tidal marsh restoration, migration space protection, and ecotone levees; and (2) water quality benefits from horizontal levees.

While various multi-benefit measures were highlighted in the Adaptation Atlas, the choice of policy, nature-based, and engineered measures was based on their ability to help alleviate coastal flooding, especially flooding driven by SLR. The maps provided in the Adaptation Atlas are explicitly for the purpose of SLR planning, and the factors that drove the suitability mapping are based on SLR criteria. For instance, the extent of mapped marsh migration space is based on projected extents of SLR flooding, as are the boundaries of the OLU's themselves. Heights and widths of proposed ecotone levees were based on projected water levels with 6.9 ft of SLR (the projection with a 1-in-200 chance of occurring under the high emission scenario by 2100; CA OPC, 2018).

In the Adaptation Atlas, the same level of quantitative analysis was not applied to determine the suitability of mapped opportunities for achieving other goals (including ecological benefits like habitat connectivity). Nature-based shoreline projects can achieve multiple goals, so there is a need to better understand and quantify these benefits under one framework.

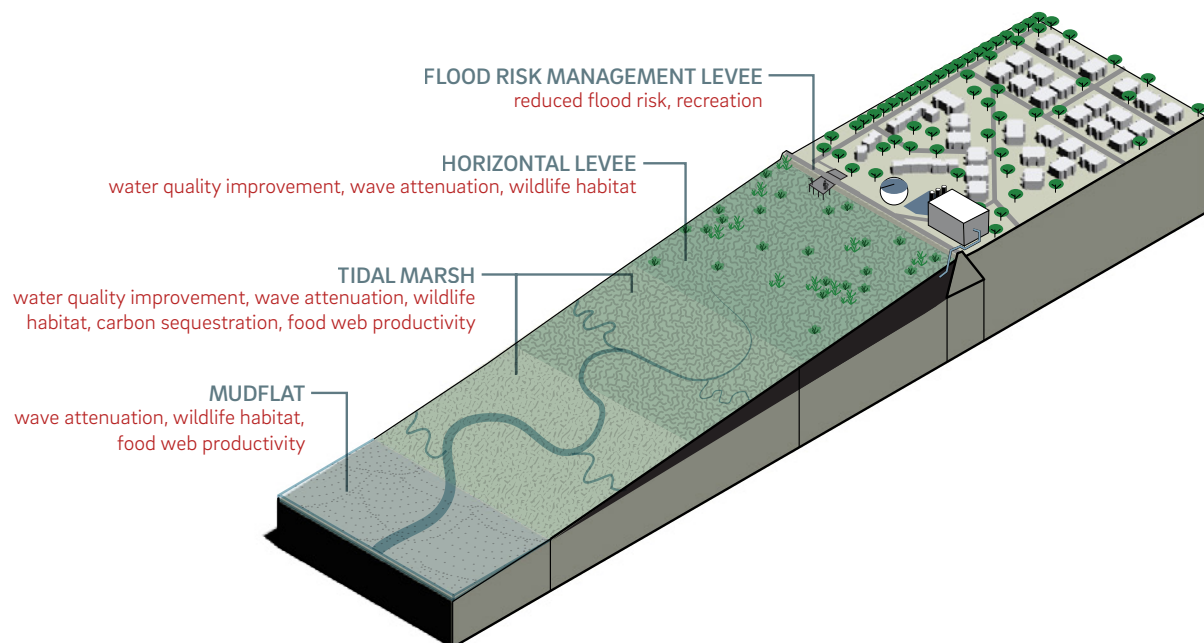


Figure 1. Nature-based adaptation measures provide multiple benefits beyond flood protection, including the services highlighted in red in the figure. The drawing shows a hybrid set of adaptation measures, including both nature-based measures and an engineered levee. The ecotone slope shown here is a “horizontal levee” because it incorporates subsurface discharge from a wastewater treatment plant.

# Ecotone Levees

## BACKGROUND

Ecotone levees are gentle slopes bayward of flood risk management levees and landward of a tidal marsh. They connect the levee to the marsh surface and can provide high quality transition zone habitat when vegetated with appropriate native plants. Ecotone levees provide multiple benefits, including high tide refuge, nesting, and foraging habitat for wildlife, space for marshes to migrate as sea level rises, and wave damping that reduces erosion and required height for flood risk management levees. They are suitable as a SLR adaptation technique where urban development requiring flood protection is adjacent to tidal marsh habitat. Ecotone levees may be incorporated into flood-risk management projects for neighborhoods, commercial, or industrial developments. They may also help protect transportation corridors and bayfront landfills from erosion and flooding.



Ecotone Levee at the Sears Point Restoration Project. Photo courtesy of Julian Meisler, Sonoma Land Trust.

In 2015, the levee at the Sears Point restoration site was breached to restore nearly 1,000 acres of subsided diked agricultural land to tidal habitat along Highway 37 in southern Sonoma County. As part of this Sonoma Land Trust/Ducks Unlimited project, a 2.5-mile long setback levee was constructed to protect the SMART railroad. An ecotone slope was constructed on the bayward side of the levee to create transition zone habitat adjacent to the restored marsh. The slope of the ecotone levee varies from 10:1 to 20:1. This ecotone levee provides flood protection as well as high tide refuge for marsh species. Material was borrowed from the six miles of channels dug within the tidal restoration area to construct the levee. The project also included the construction of intertidal mounds to attenuate wind waves and act as catalysts for the colonization of marsh plants in the subsided site.

When located near wastewater treatment facilities, ecotone levees present special opportunities for multi-benefit SLR adaptation and nutrient load reduction projects, as they may include seepage slopes to polish treated wastewater effluent and recreate a fresh-to-brackish marsh habitat gradient that historically existed in many more places in the Bay. This type of ecotone levee is known as a “horizontal levee.” In this update, a particular emphasis was placed on identifying opportunities for horizontal levees. This analysis was conducted in conjunction with a parallel effort for the Bay Area Clean Water Agencies (BACWA). The BACWA effort is a regional evaluation of the potential to use nature-based measures for nutrient reduction and fulfills a requirement under the San Francisco Bay Regional Water Quality Control Board’s 2019 nutrient watershed permit.

The Oro Loma Horizontal Levee Project has successfully demonstrated the potential value of horizontal levees for improving the quality of treated wastewater discharged to the Bay. With subsurface flow, the pilot project’s seepage slope is effective at removing nutrients and some contaminants of concern from treated effluent. Experiments at Oro Loma have shown high removal efficiencies for nitrate (>97% removed), phosphate (>83% removed), trace organic contaminants (>97% removed), and pathogens like F+ coliphage (up to 99% removed) (Cecchetti et al., 2020).



Experimental horizontal levee project at the Oro Loma Sanitary District (image courtesy of Google Earth).

## APPROACH

---

In this analysis, an updated method was developed to expand and refine the range of opportunity sites for ecotone levees originally identified in the Adaptation Atlas. Areas mapped as suitable for ecotone levees were identified by selecting places where development is adjacent to tidal marsh (today or in the future). The “developed areas” layer and the “marsh” layer used as inputs to the analysis were expanded from the 2019 Adaptation Atlas. The development layer was updated with the most recent available National Land Cover Database from 2016 and development types not accounted for previously (e.g. wastewater infrastructure) were added. The marsh layer was expanded to include existing marsh as well as areas of potential future marsh, including undeveloped areas that are at marsh elevation today, low-elevation areas where restoration is planned, and undeveloped inland areas at marsh migration space elevations. An extensive review process was undertaken to identify missed opportunities not captured in the Adaptation Atlas and remove opportunities now recognized as infeasible. See Appendix A for a complete description of the updated method.

Though the results of this analysis represent a more comprehensive set of opportunities than the original Adaptation Atlas version, not every possible local opportunity can be identified through regional-scale analyses, and some opportunities identified may not be feasible due to constraints not accounted for in the method.

## RESULTS SUMMARY

---

### ***Updated ecotone levee opportunities***

A full set of maps showing updated ecotone levee opportunities is provided in Appendix A. The following section provides a summary of results.

In the update, some OLU have more shoreline length identified as ecotone levee opportunity than was identified in Phase I (e.g., Figure 2), while others have reduced opportunities compared to Phase I due to removal of model artifacts in the levee shapes and more careful review of opportunities to eliminate options that are likely not feasible (e.g., Figure 3). In total, 23 miles of shoreline were added as ecotone levee opportunities in the update, and each OLU had an average net gain of about one mile of ecotone levee opportunity. A table summarizing the amount of opportunity added or removed in each OLU is provided in Appendix A.

### ***Focus on horizontal levees***

Incorporating wastewater seepage slopes into ecotone levees is most feasible near a wastewater treatment facility. BACWA representatives indicated that two miles was a reasonable radius around a wastewater treatment facility to consider potential opportunities for nature-based treatment, including seepage slopes. Table 1 shows the length of shoreline identified as suitable for horizontal levee seepage slopes using the two-mile radius, along with the number of wastewater facilities located within each OLU and the approximate volume of effluent associated with those facilities. These results are also represented in the map in Figure 4. However, it is important to note that many of the identified opportunities may not be feasible due to factors not included in this analysis, including the engineering constraints associated with piping wastewater to seepage slope locations.

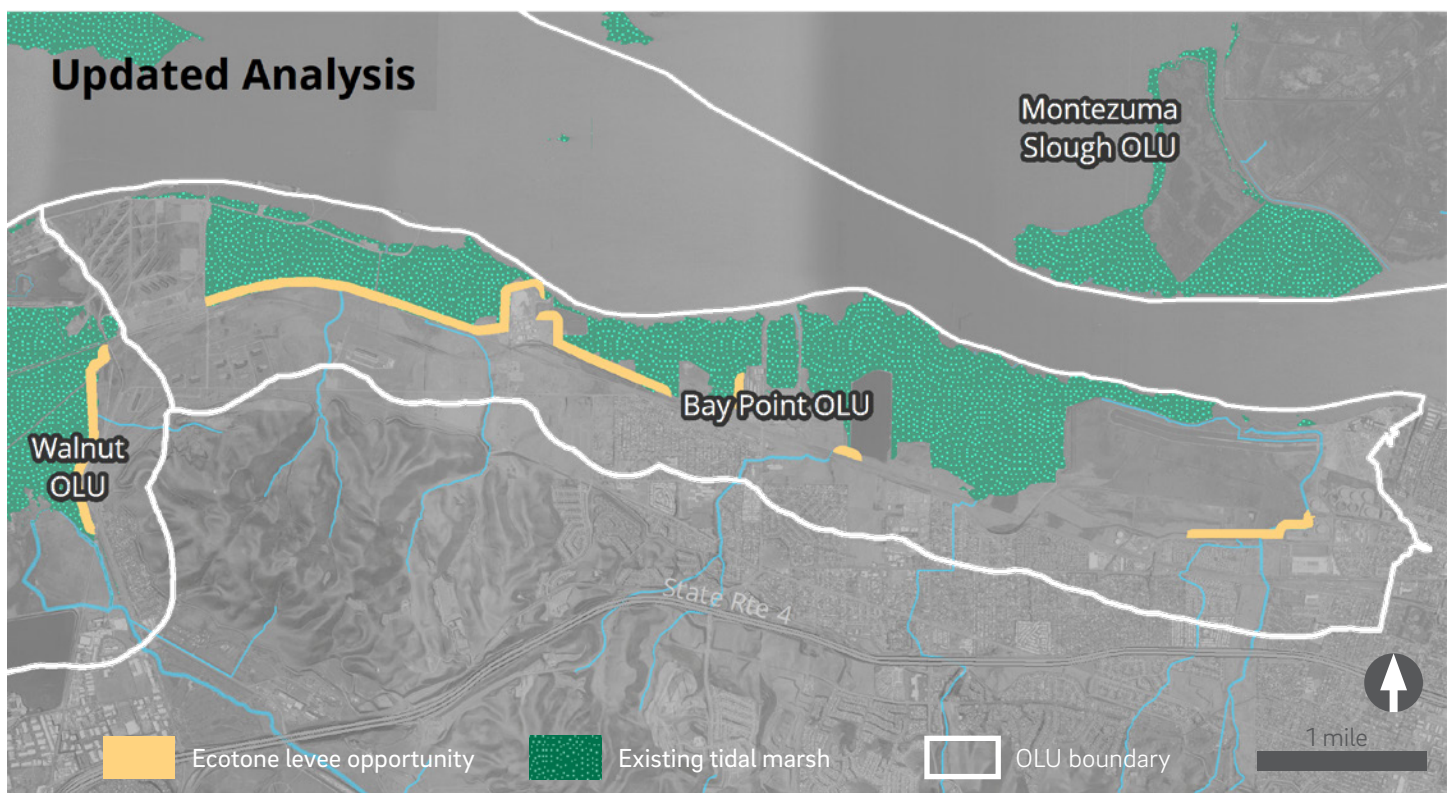
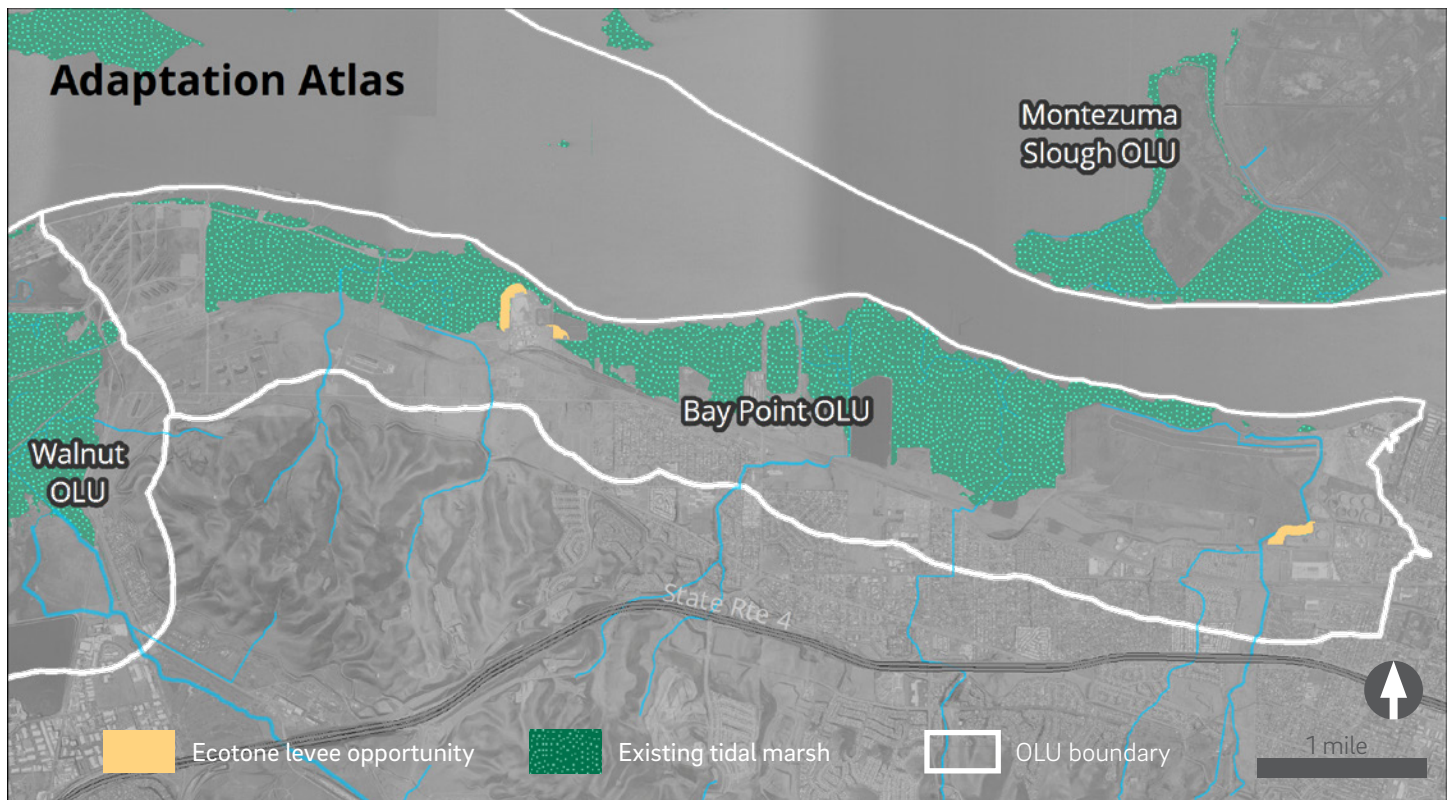


Figure 2. In the Bay Point OLU, 3.8 more miles of shoreline were identified as ecotone levee opportunity with the updated analysis relative to the Adaptation Atlas analysis, due to the expansion of the development overlay (in this case, the addition of rail lines and Superfund sites as development types).

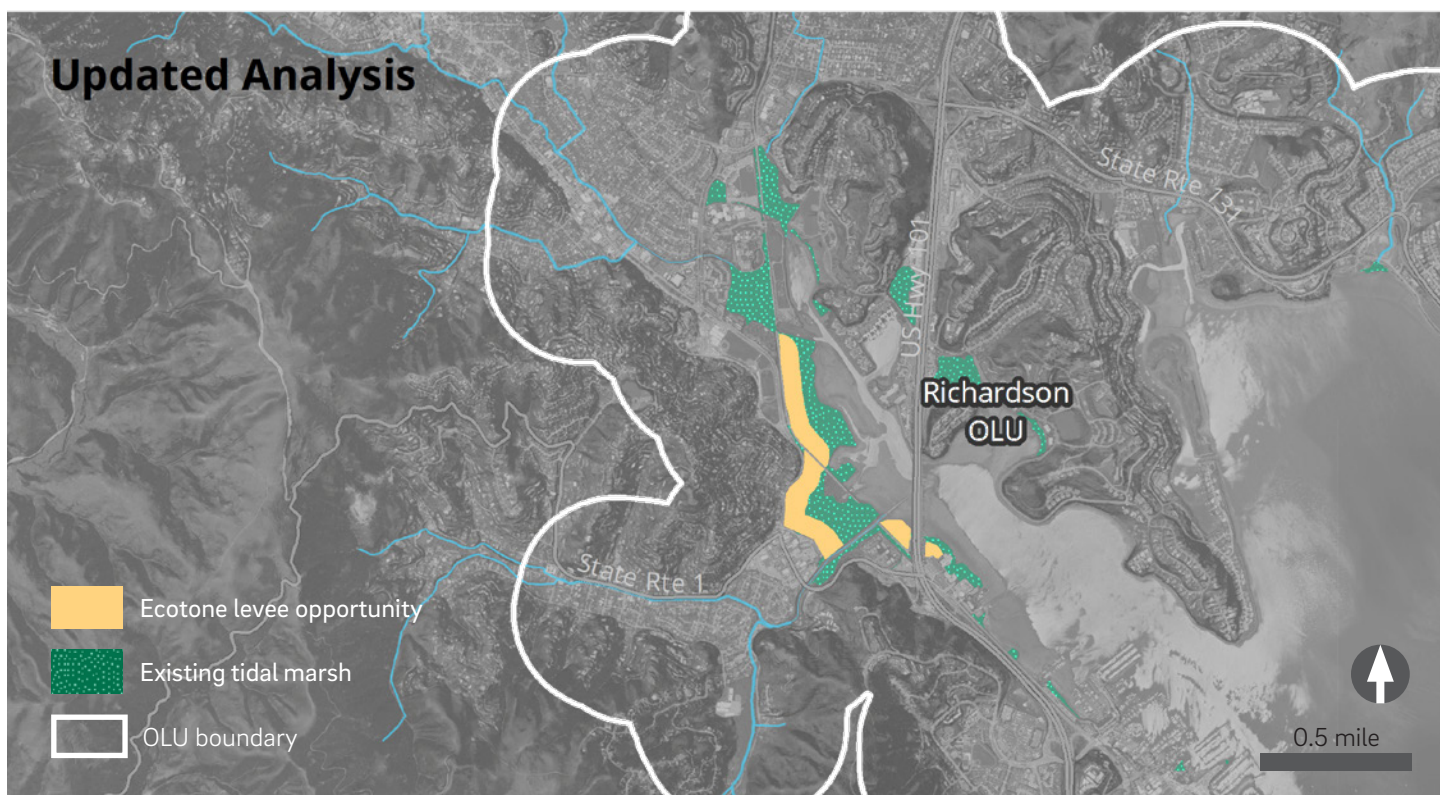
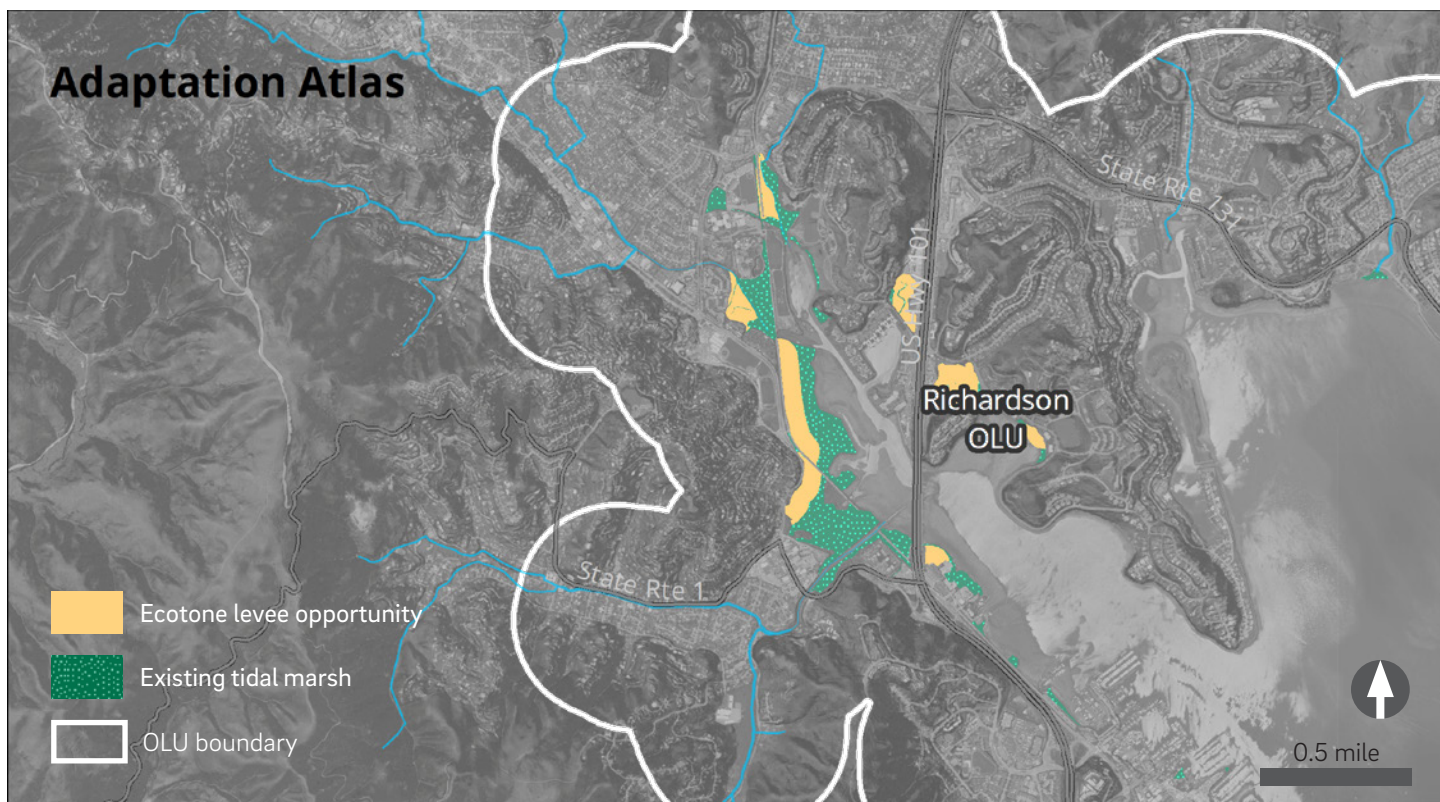


Figure 3. In the Richardson OLU, 1.5 miles less shoreline was identified as ecotone levee opportunity with the updated analysis relative to the Adaptation Atlas analysis due to removal of model artifacts in the levee shapes and more extensive review of opportunities to eliminate options that are likely not feasible.

Table 1. Number of wastewater plants and miles of horizontal levee opportunity near wastewater plants in each OLU. As a coarse estimate, one mile of horizontal levee can polish approximately 2-3 million gallons per day (mgd) of treated effluent, reducing nutrients and trace organic contaminants discharged to the Bay. This estimate is based on published flow rates for nitrate removal in woodchip bioreactors, a proxy for horizontal levees (Christianson et al., 2012; Ghane et al., 2016).<sup>1</sup>

OLU	Number of wastewater plants*	Approximate dry season discharge of treated effluent (mgd)**	Miles of horizontal levee opportunity***
Richardson	3	3.4	1.2
Corte Madera	1	0.2	3.1
San Rafael	1	6.2	1.9
Gallinas	1	0.2	2.3
Novato	1	1.3	3.1
Petaluma	1	0	3.6
Napa - Sonoma	4	9.8	5.1
Carquinez North	1	1.9	0.9
Suisun Slough	1	11	1.3
Montezuma Slough	-	-	-
Bay Point	-	-	-
Walnut	2	33.2	7.8
Carquinez South	-	-	1.3
Pinole	2	2.8	0.5
Wildcat	1	6.5	5.4
Point Richmond	-	-	-
East Bay Crescent	1	4.8	1.5
San Leandro	2	51.8	-
San Lorenzo	2	21.2	6
Alameda	1	22.8	7.5
Mowry	-	-	-
Santa Clara Valley	1	79.3	12.5
Stevens	2	28.6	3.0
San Francisquito	-	-	4.2
Belmont - Redwood	1	12.3	3.3
San Mateo	1	9.5	0.7
Colma - San Bruno	4	12.8	2.2
Yosemite - Visitacion	-	-	-
Mission - Islais	1	53.6	-
Golden Gate	-	-	-

\*4 treatment plants included in the Nutrient Watershed Permit are not included in the table because they do not fall within an OLU.

\*\*5-year average dry season discharge

\*\*\*Miles of shoreline identified as suitable for ecotone levees according to the methods detailed in Appendix A, limited to only those opportunities within 2 miles of a wastewater treatment plant.

<sup>1</sup> Assuming a 0.5 m thick layer of woodchips along a 10:1 slope of a 3.14 m-high levee, a drainable porosity value of 0.41, and a hydraulic residence time of 24 hours.

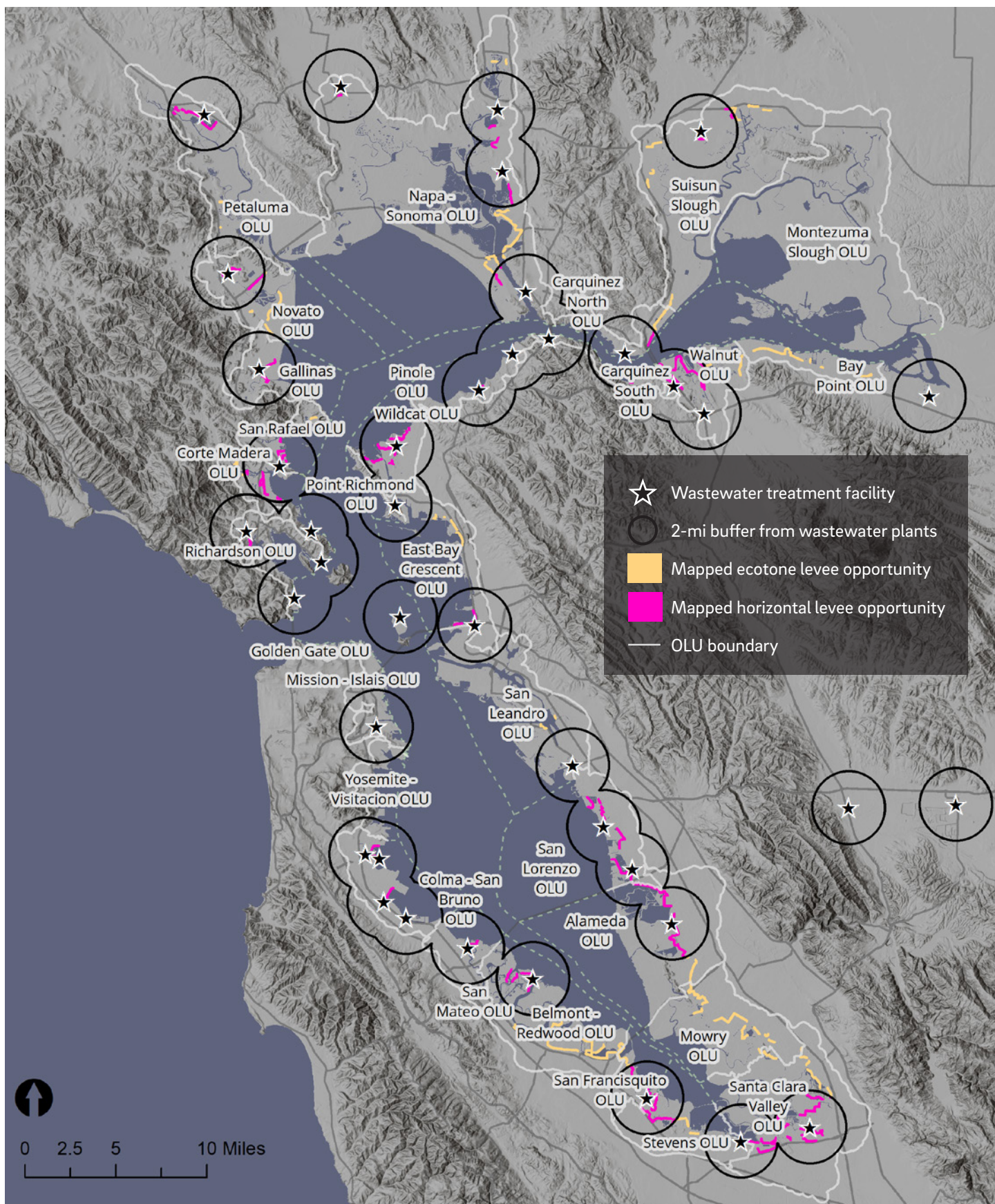


Figure 4. Ecotone levee opportunities identified within two miles of a wastewater plant could potentially be designed as horizontal levees, incorporating subsurface seepage slopes for nutrient reduction and freshwater-to-saltwater habitat gradients. These opportunities are called out in pink as potential horizontal levee locations in the map.

## **NATURE-BASED TREATMENT SOLUTIONS: BAY AREA CLEAN WATER AGENCIES**

The Bay Area Clean Water Agencies (BACWA) are studying the potential to use nature-based treatment measures (as opposed to traditional chemical and mechanical methods) to assimilate nitrogen and reduce nutrient loads in discharged wastewater. These nature based systems can also be designed to help achieve other benefits like providing wildlife habitat and protecting facilities from flooding. The first phase of the Nature Based Solutions project was a regional-scale GIS analysis to identify opportunities and constraints for the implementation of two types of nature-based systems — horizontal levees and open-water treatment wetlands.

The horizontal levee analysis was conducted in tandem with the update to the ecotone levee analysis described in the preceding section. For identified horizontal levee opportunities (ecotone levees within two miles of a wastewater plant), potential nutrient load reductions were calculated using published removal values from existing horizontal levee and woodchip bioreactor treatment systems.

Open water treatment wetland opportunities were identified using SFEI's Green Plan-IT site locator tool to determine site suitability, primarily considering existing physical and land cover conditions (i.e. slope, elevation, habitat, development). Nutrient reduction potential was also calculated for a subset of open water wetland opportunities located near each plant using published nitrogen removal values for existing California open water treatment wetlands.

Results of the desktop analysis indicate that physical opportunities for nature based treatment solutions vary from facility to facility. At some facilities, nature based systems implemented at large opportunity sites close to the facility could reduce over 90% of total inorganic nitrogen and provide co-benefits like wildlife habitat and flood protection, while others have almost no opportunity for nature based systems due to steep slopes, high-intensity development surrounding the site, or other factors.

The next phase of the Nature Based Solutions project will involve site-specific outreach and investigations at facilities with high potential for nature-based nutrient management. A more thorough investigation of opportunities and constraints will be carried out at a site scale for a subset of facilities. In the final phase, planning-level designs will be developed for a few facilities to enable cost estimation, identify regulatory and land-use conflicts, and establish feasibility for agency-led planning. Consideration of which facilities to focus on in the final stages will be based on interest from facility managers, exposure to SLR impacts, level of opportunity identified through the desktop analysis, and potential nutrient reduction capacity.

Nature-based treatment system opportunities will continue to be developed in close coordination with the Adaptation Atlas updates. In particular, considering results from the landscape connectivity analysis (presented in the following section) when designing new horizontal levees can help leverage these levees to improve habitat connectivity in addition to reducing nutrient loads and flood risk.

# Landscape Connectivity for Endangered Wildlife

## BACKGROUND

Landscape connectivity is a critical element of ecological function (Taylor et al., 1993). Landscape connectivity is the extent to which movement of individual organisms is facilitated or hindered by the landscape. A highly-connected landscape is one where an animal can easily disperse between habitat patches, which promotes healthy and persistent populations of wildlife by maintaining gene flow, allowing recolonization of patches after disturbance events, and allowing immigrating individuals to bolster declining populations. Loss of habitat generally drives fragmentation and isolation; habitats that were once more contiguous are broken up into smaller patches that become separated by greater distances. Depending on the pattern of habitat loss, the ability of animals to disperse amongst patches could be greatly impacted.

### RELATING ECOTONE LEVEES TO CONNECTIVITY

Ecotone levees are likely to be constructed to protect developed areas, as preserving natural transition zone habitat is more logical where land adjacent to marshes is undeveloped. Therefore, connectivity from ecotone levees to suitable upland habitat is largely absent. Instead, it is important to consider the lateral habitat connectivity the levees might provide. The Landscape Connectivity analysis described in this section helps identify places where ecotone levees would be most helpful in enhancing habitat connectivity between marsh patches.

Marshes are naturally separated from each other on the landscape where they are constrained by topography. At the northern and southern reaches of the Bay, tectonic faults have caused large flat areas to develop, while along the north to south peninsulas and coastal hills, narrower baylands constrain marshes to smaller patches (SFEI and SPUR, 2019). Marshes in the Bay have become increasingly fragmented with time through habitat loss and degradation (Goals Project, 1999), making present-day marshes more isolated and, presumably, less likely to be reached by dispersing wildlife. Here, we evaluate the landscape connectivity of Bay wetlands for two endangered and endemic species that span the spectrum of dispersal abilities: the salt marsh harvest mouse (*Reithrodontomys raviventris*; SMHM), which is ground-dwelling and has more limited dispersal potential, and the Ridgway's rail (*Rallus obsoletus*; RIRA), which can fly and has the potential to move much longer distances (USFWS, 2013). When we use the term "connectivity" throughout this document, we are referring to the landscape connectivity among bay marshes as measured through the lens of these two species.

Both RIRA and SMHM were listed as endangered by the federal government in 1970 and by the state of California in 1971 (USFWS, 2013). The study, conservation, and the on-going work to recover these species has involved immense amounts of work from federal and state agencies, non-governmental organizations, academic institutions, consulting groups, and individuals (Overton, 2007; Smith et al., 2018; USFWS, 2013). Groups involved in this work include U. S. Fish and Wildlife Service, U. S. Geological Survey, California Department of Fish and Wildlife, California Coastal Conservancy, Invasive Spartina Project, Point Blue Conservation Science, Avocet Research Associates, WRA Inc, UC Davis, and East Bay Regional Park District, among others.

Both species are likely impacted by the loss of connectivity among Bay wetlands. Vast amounts (>75%) of tidal marsh habitat that were present historically were lost through diking and filling (Figures 5 and 6), however, efforts since the 1980s have restored some of this lost habitat throughout the Bay (Goals Project, 2015). A large amount of habitat restoration has occurred since this time and a great deal more is planned and in progress. For RIRA, landscape connectivity is believed to be needed for maintaining both stable population sizes that are resilient to disturbances (Zhang & Gorelick, 2014) and genetic diversity (Wood et al., 2017) across the baylands. The flow of genetic diversity for RIRA appears to already be impaired by loss of connectivity, with present day fragmentation limiting the movement of individuals between the North and South baylands (Wood et al., 2017). There is still much to learn about how loss of connectivity has impacted SMHM (Smith et al., 2018). Populations of SMHM have always been separated by geographic barriers and the genetic division of the two subspecies of SMHM, the northern *R. r. halicoetes* and the southern *R. r. raviventris*, is ancient and predates human modification of the landscape (Statham et al., 2016). However, local-scale connections between populations are certainly important in promoting population persistence within the subspecies. Genetic evidence shows that contemporary connectivity varies by sub-embayment: the Suisun Bay population appears to be functioning as a single well-connected population (Statham & Sacks, 2019), however, the southern subspecies whose range has a higher degree of habitat fragmentation also has the lowest amount of genetic diversity (Statham et al., 2016).

The protection and recovery of these species requires a holistic approach that goes beyond enhancing landscape connectivity alone (USFWS, 2013). Supporting viable populations will require maintaining and increasing the amount of suitable habitat, particularly in large contiguous patches. Enhancing local-scale connections where isolated populations exist will help bolster their resilience, even if these connections do not greatly enhance the connectivity of the landscape as a whole. Additionally, it will be critical to improve the quality of existing habitat, which includes mitigation of the myriad threats to these species, such as non-native predation and chemical contaminants. By focusing this report on landscape connectivity the intent is to complement, rather than supersede, the importance of these other elements for the persistence of these species in the Bay. This analysis will be particularly relevant for comparing the benefits and evaluating the tradeoffs of restoring different habitat patches within subregions of the Bay.



Figure 5. Distribution of historical tidal marshes (circa 1800s).

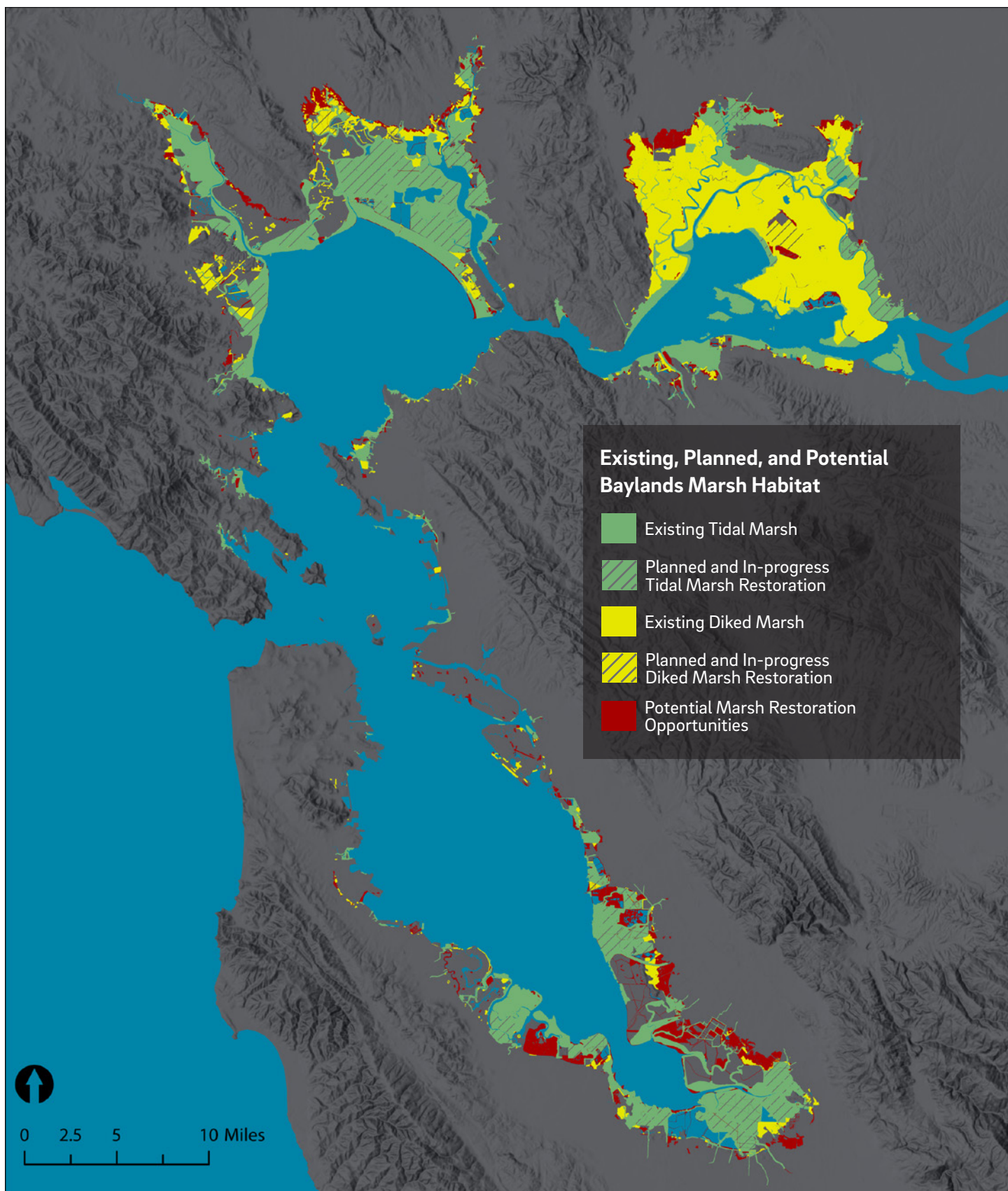


Figure 6. Distribution of existing tidal and diked marshes, planned and in-progress restoration projects, and potential restoration opportunities. Planned and in-progress restoration includes those areas that have been acquired and are slated for marsh restoration and restoration sites that have been breached and are in the process of accreting to intertidal elevations.

## APPROACH

---

Presented here is a bay-wide analysis that integrates spatial patterns of the landscape with the dispersal capabilities and movement behavior of these two species. This approach assesses the “probability of connectivity,” defined as the likelihood that two animals randomly placed on a landscape end up in habitat patches where they can reach each other via dispersal (Saura & Rubio, 2010). This probability of connectivity is used to (1) evaluate how well the entire landscape is connected through estimating the amount of functionally connected habitat (Saura et al., 2011), (2) identify which wetlands are the most important to maintaining connectivity, and (3) which locations should be prioritized for wetland restoration to enhance the connectivity of the existing landscape. Bay wetland connectivity was analyzed for three scenarios:

1. tidal marsh habitat of the historical Bay (circa 1800; Figure 5),
2. the contemporary landscape (Figure 6) with planned and on-going restoration included, which represents our best understanding of current and planned Bay conditions, and
3. the locations of potential restoration opportunity sites beyond what is currently planned (Figure 6).

The connectivity of the historical marsh network of the Bay was analyzed to serve as a baseline to which the contemporary landscape and potential restoration opportunities can be compared. Connectivity measures are dependent on the spatial configuration of all marshes on the landscape; thus restoration planning for connectivity should take into consideration the most complete account of ongoing and planned restoration efforts possible. The contemporary landscape used for comparison included existing marsh habitat, restoration sites that have been breached and are in the process of accreting to intertidal elevations, and areas that have been acquired and are slated for marsh restoration (Figure 6). Additional potential restoration opportunities, which are updated in this amendment to the SF Bay Shoreline Adaptation Atlas (SFEI and SPUR, 2019), encompass potential marsh (undeveloped areas at the appropriate elevation for tidal marsh), marsh migration space (undeveloped areas at the appropriate elevation for tidal marsh in the future as sea level rises), and ecotone levees where future marsh restoration could potentially occur (described in the preceding section) (Figure 6). Subsided areas, which could be restored to marsh elevation via sediment delivery, are not considered in this analysis as potential marsh restoration opportunities.

SMHM appear to have similar survival rates and abundances in both tidal and diked marshes (Smith et al., 2020). In this analysis, habitat patches of both wetland types were included throughout the known range of SMHM (i.e., in all three sub-embayments: San Francisco, San Pablo, and Suisun Bays). Although outside the boundaries of analysis, there are recent records of mice on Lower Sherman Island and with SLR there is anticipated movement of SMHM further east into the Delta (L. Thompson *pers. comm.*). This boundary constraint may downplay the importance of Winter Island and Corteva Wetlands for current or future connections eastward.

For the RIRA analysis, only tidal marshes west of the Carquinez Strait were considered. Although RIRA are known to occur in the tidal marshes of Suisun Bay, these observations are likely capturing itinerant, dispersing individuals rather than an established breeding population (Evens & Collins, 1992; Gill, 1979; Overton, 2007; USFWS, 2013). RIRA are rarely recorded in nontidal or diked habitat (USFWS, 2013).

The connectivity model presented here is a static model of spatial connectivity which characterizes habitat “reachability” given known dispersal distances for a species and biologically reasonable movement pathways. For example, rails were assumed to preferentially move along the shoreline when searching out new habitats. Larger and higher quality patches were also assumed to produce more emigrating individuals,

which was accounted for in our model by more highly weighting these patches' importance to overall connectivity. This approach provides a generalization of connectivity with modest data requirements. For subsequent studies, we can build on this approach by modeling the movement of individual animals, while taking into account population densities and movement probabilities on an annual timestep; this will provide an even more nuanced representation of dispersal across the Baylands.

The results presented here are also dependent on how individual animals move through the landscape. We have made assumptions about the ways dispersing animals of both species are likely to move across the landscape, based on scientific literature and expert opinion. As more information about the movement behavior of these species is gained, either through movement tracking or genetic studies, a clearer understanding of the connectivity of the Bay will continue to develop. The full details of the analysis and data sources are in Appendix B.

### ***Change in Amount of Functionally Connected Habitat***

Due to the greater dispersal ability of rails compared to mice, more of the historical landscape was reachable via dispersal by RIRA than SMHM. Compared to the historical baseline, current conditions reflect a 21% and 55% decline in fully-functionally connected habitat for salt marsh harvest mice and Ridgway's rails, respectively. Two factors caused rails to experience a relatively greater loss in amount of functionally connected habitat than mice: (1) geographic barriers to dispersal consistently constrained SMHM connectivity in both the historical and contemporary landscape, and (2) SMHM have lost relatively less contiguous, suitable habitat, particularly in the North Bay. Though much of the tidal habitat has been converted to diked marsh in North Bay, it has remained largely suitable for SMHM. Implementation of all potential restoration opportunities (areas in addition to the ongoing and currently planned restoration) would greatly improve the amount of functionally connected habitat for both species and would amount to an 18% and 40% improvement from current conditions for SMHM and RIRA, respectively. For SMHM, this improvement would largely result from connecting habitat patches in the South Bay. For RIRA, restoration in the South Bay would also improve connectivity as would improving smaller patches of habitat along the eastern Central Bay which could help enhance movement between the North and South Bay.

However, restoring all potential opportunities is not feasible given practical constraints, such as the monetary costs of land acquisition or restoration. Additionally, restoration of tidal marsh habitat in the Bay can convert other habitat types that are critical to other species, such as the playa habitats for snowy plovers and ponds for waterbirds (Stralberg et al., 2009). Given these constraints, prioritization of restoration opportunities is needed.

### ***Importance of Individual Patches***

To evaluate prioritization, we analyzed the importance of individual patches. Each marsh patch in each of the three scenarios was evaluated for its importance for maintaining connectivity to the rest of the patches in the landscape. To understand the importance of individual patches in contributing to landscape connectivity, we assessed:

1. areas that were historically connected and areas that were historically lacking in connectivity,
2. areas that are restored or planned for restoration that are important for maintaining connectivity, which can help focus where protection of habitat could be most important or could help determine the most beneficial order for restoration projects to occur in, and
3. for new restoration opportunities, areas that should be prioritized in order to improve connectivity were identified.

In some highly connected areas, the loss or addition of an individual patch may not greatly impact the ability to reach other patches in the landscape. In the model results, such patches will be less important to maintaining landscape connectivity. Nevertheless, these patches still provide important habitat and further provide redundant connectivity that will help bolster the resilience of landscape for wildlife movement.

## RESULTS

---

### ***Salt Marsh Harvest Mouse***

#### Historical Connectivity

Large, well-connected habitat patches in North and South Bay characterized the connectivity of the historical landscape (Figure 7). Embedded within these highly-connected areas are a few marshes that provide equivalent connectivity to the other marshes on the landscape, and thus may not be critical to maintaining landscape connectivity, but still serve other functions for wildlife. Further, the importance of Winter Island for maintaining connections eastward towards the Delta may be undervalued given the boundaries of our analysis.

Notably, a lack of connection between North and South Bay is apparent in the historical Bay, with marshes along Central Bay – stretching from Emeryville Crescent to Point Pinole along the eastern shore and Point San Bruno to Point San Quentin on the western shore – only contributing limited amounts to the overall connectivity of the Bay. This area of low connectivity is congruent with where the division between the northern and southern subspecies of SMHM is believed to occur (Smith et al., 2018). Another potential disjunct is apparent between Suisun and San Pablo Bays, where the coastal mountain range reduces connectivity, despite the presence of Southhampton marsh (Benicia State Recreation Area). The recent records of mice in Southhampton (K. Smith *pers. comm.*) indicate that this marsh is reachable by mice, but potentially at low levels of dispersal.

#### Contemporary Connectivity

In the contemporary landscape (Figure 8), highly-connected patches in northern Suisun and San Pablo Bay still characterize the landscape, and the geographic barriers that limited connection between the sub-embayments are still apparent (USFWS, 2013). Genetically, the mice in the northern marshes of Suisun Bay behave as a single population, whereas populations along the Contra Costa shoreline are more distinct (Statham & Sacks, 2019). Our analysis indicates that the marshes from Port Chicago to Mallard Island on the south coastline and Chips Island on the north coast, may be important for bridging these two subregions. Some marshes embedded in larger contiguous patches, such as Joice Island in Suisun Bay, provide equivalent connectivity to other marshes, and thus are shown as less important, however, these marshes promote resiliency through the redundancy of connections.

Habitat in the South Bay has become more fragmented and less connected, particularly along the southeast shore, including Eden Landing. Known SMHM population centers in the South Bay (e.g., Eden Landing and Hayward Marsh) are currently separated from each other beyond the dispersal distance of this species. Large-scale planned restoration – such as the South Bay Salt Pond Restoration Project – could help unite these populations. Nevertheless, large gaps in habitat between the existing and planned restoration, for example, gaps along the Sunnyvale and Mountain View shoreline and between Eden Landing and Dumbarton Point, will continue to limit the functional connectivity of the South Bay.

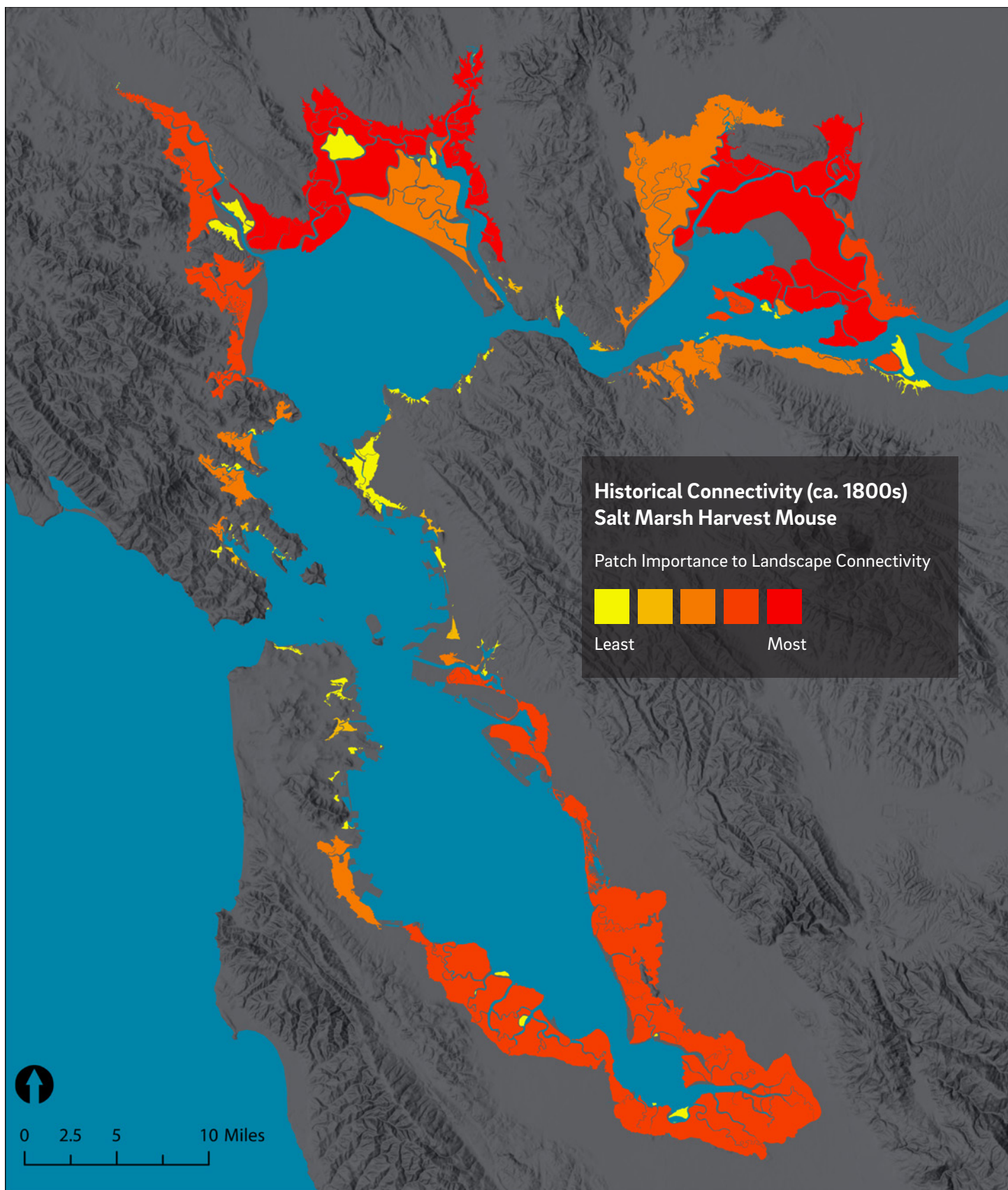


Figure 7: Connectivity of the historical baylands (circa 1800s) for salt marsh harvest mouse.



### Restoration Prioritization

Habitat restoration opportunities beyond what is currently planned occur in each sub-embayment and could help further enhance connectivity for SMHM (Figure 9). Habitat connections that help locally link adjacent large habitats are some of the most important for this species. Though connectivity is already high in northern Suisun and San Pablo Bays, remaining restoration opportunities along the inland edges of these bays, where future marsh migration space is also located, are high priority for promoting connectivity in these regions. Connectivity would be greatly enhanced if linkages could be established between the large, on-going restoration projects in South Bay. Restoring marshes in the Central Bay will do little to support connectivity across the whole Bay for this species. However, where local relict, isolated populations exist, linking adjacent marshes (such as connecting San Pablo and Wildcat Marshes along the Richmond shoreline) will be critical for the resilience of these populations, regardless of impact on overall landscape connectivity (M. Statham and K. Smith *pers. comm.*). Further, many potential restoration opportunities in this area, and elsewhere, are below the spatial threshold of our analysis ( $<0.5$  ha), but could provide valuable local connections.

Providing space for SMHM to migrate inland with marshes as sea level rises is important, regardless of whether it enhances overall landscape connectivity. Notably, flat, undeveloped areas like Potrero Hill and Denverton Slough in Suisun Bay, will be critical for the resilience of this species as sea levels rise. With SLR, new connections between Suisun Bay and the Delta may be formed, linking Denverton and Nurse Slough across the Jepson Prairie, a scenario not well captured by our analysis.

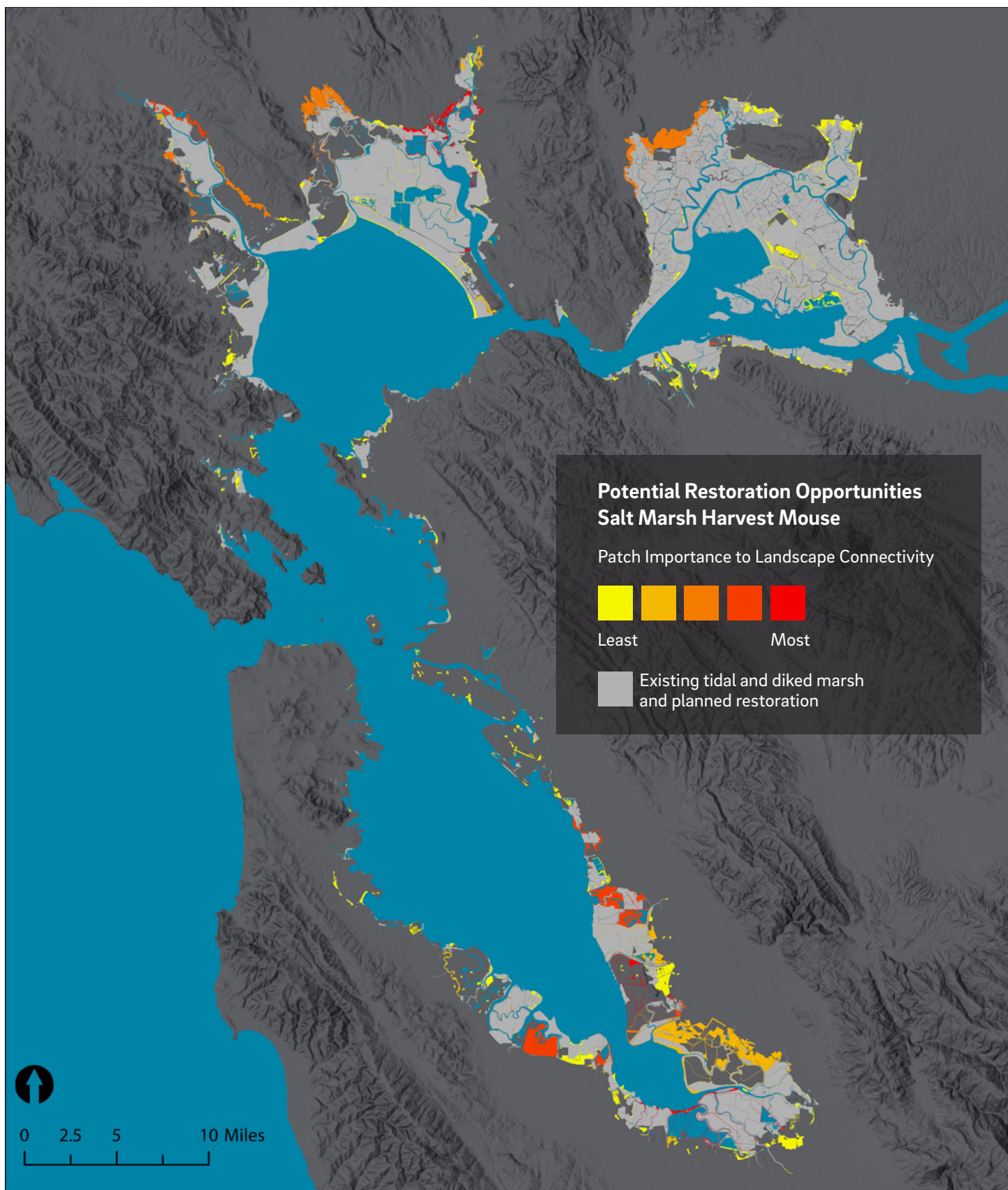


Figure 9. Priority ranked restoration opportunities for salt marsh harvest mouse for enhancement of landscape connectivity. The areas included in this analysis are those not yet slated for tidal or diked marsh restoration: potential marsh, marsh migration space, and ecotone levees.

## **Ridgway's Rail**

### **Historical Connectivity**

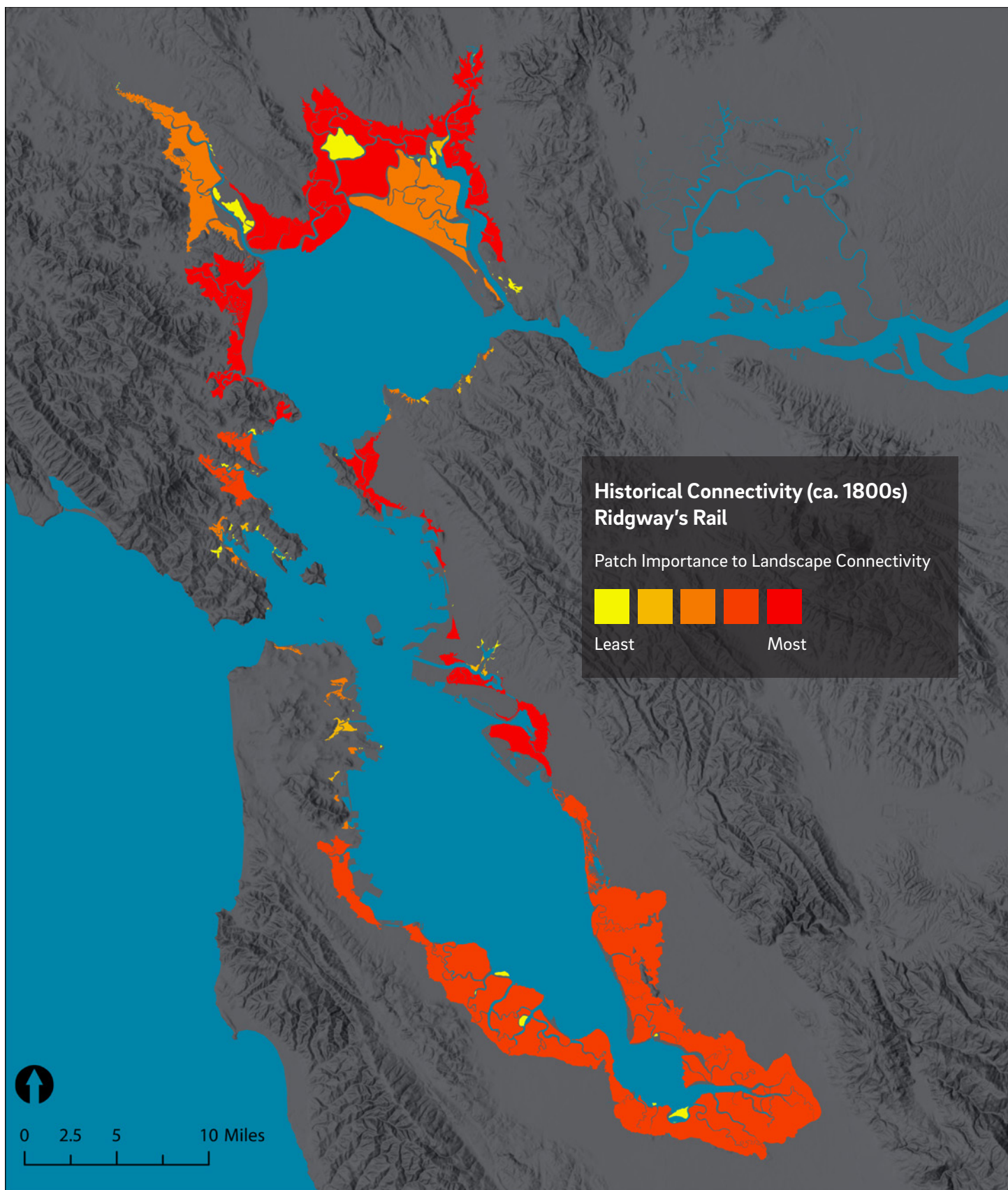
The historical landscape was generally well-connected for RIRA (Figure 10). Most patches had similar levels of importance to overall Bay connectivity, with only small, scattered marshes contributing less. Notably, the patches along the East Bay (stretching from San Leandro Bay to Point Richmond) that were historically areas of low connectivity for SMHM were potentially important for connecting the North and South Bay for RIRA.

### **Contemporary Connectivity**

Though marsh habitat along the eastern shore of the Central Bay has been greatly reduced in the contemporary landscape, the remaining patches still appear to serve as connections for RIRA between North and South Bay and should be protected as such (Figure 11). Connectivity has declined the most along the western shore of the Central Bay, from Foster City to Richardson Bay — an area that had only moderate connectivity historically and which has limited potential for additional habitat restoration, given its high degree of urbanization.

### **Restoration Prioritization**

Prioritized restoration sites for RIRA are those that (1) are intermediate distances between large blocks of remnant habitat that are separated by long distances, (2) create larger blocks of consolidated habitat, such as those occurring on the southeast shore of South Bay, or (3) provide both connectivity enhancement and marsh migration space in San Pablo Bay (Figure 12). A number of important stepping-stone sites are located along the eastern shore of the Central Bay, from San Leandro to Berkeley. A decline in genetic connectivity in the present-day RIRA population has been attributed to a loss of patches in this region (Wood et al., 2017). However, the ability of rails to fly substantial distances — up to 100 km — may favor the restoration of larger, consolidated patches over these smaller habitats (C. Overton *pers. comm.*). Notably, one of the only high-priority stepping-stone sites outside of Central Bay is at the Canalways in San Rafael, which helps link the marshes along the Marin peninsula up to San Pablo Bay. Large blocks of potential habitat in the South Bay, such as at Eden Landing and near Coyote Hills, along with smaller habitat patches along the foreshore of the salt ponds, would potentially help unite this sub-embayment for rails.



**Figure 10: Connectivity of the historical baylands (circa 1800s) for Ridgway's Rail.**

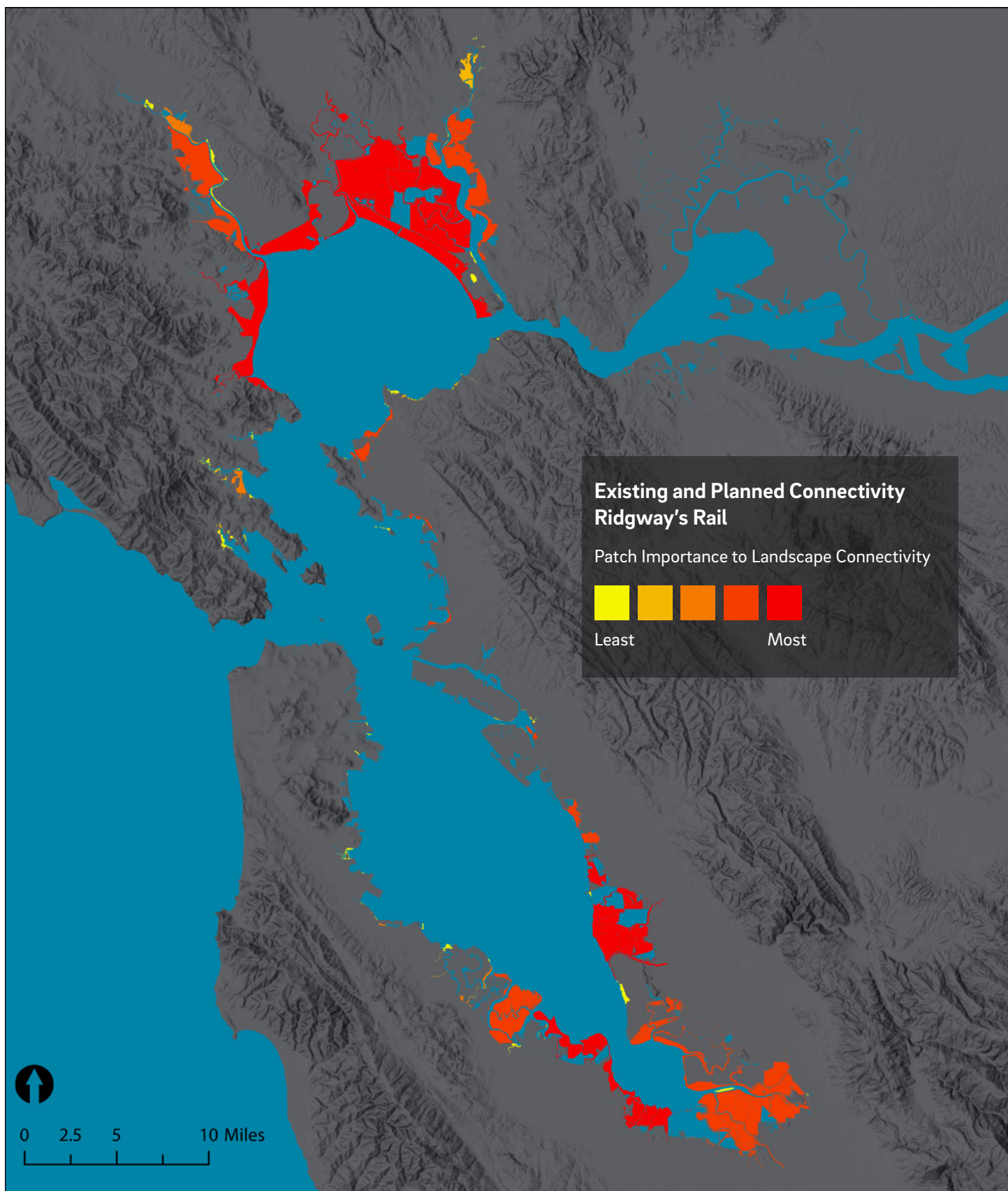


Figure 11. Connectivity of the contemporary baylands for Ridgway's rails. Habitat patches include existing tidal and diked marshes and planned and in-progress restoration projects.

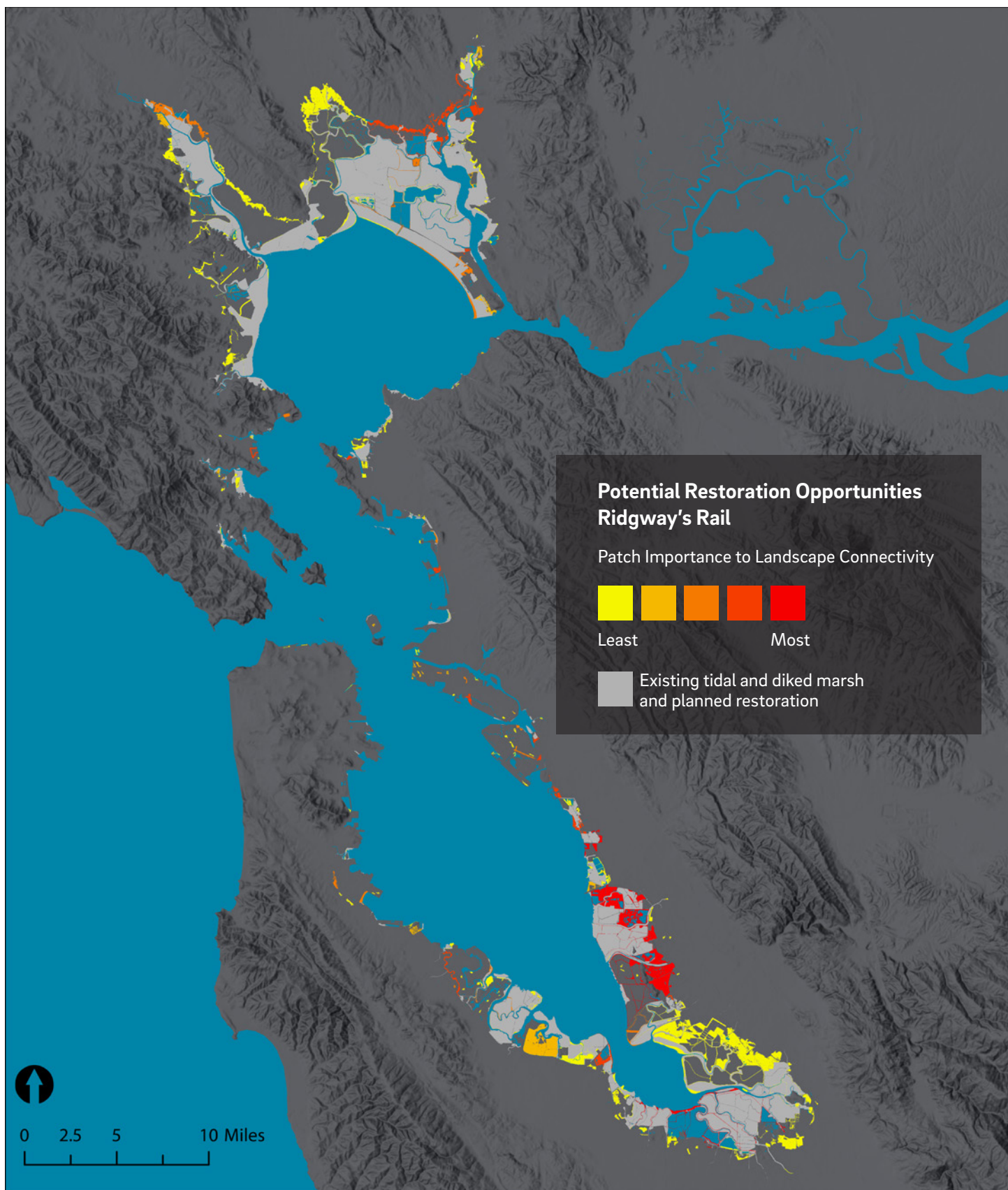
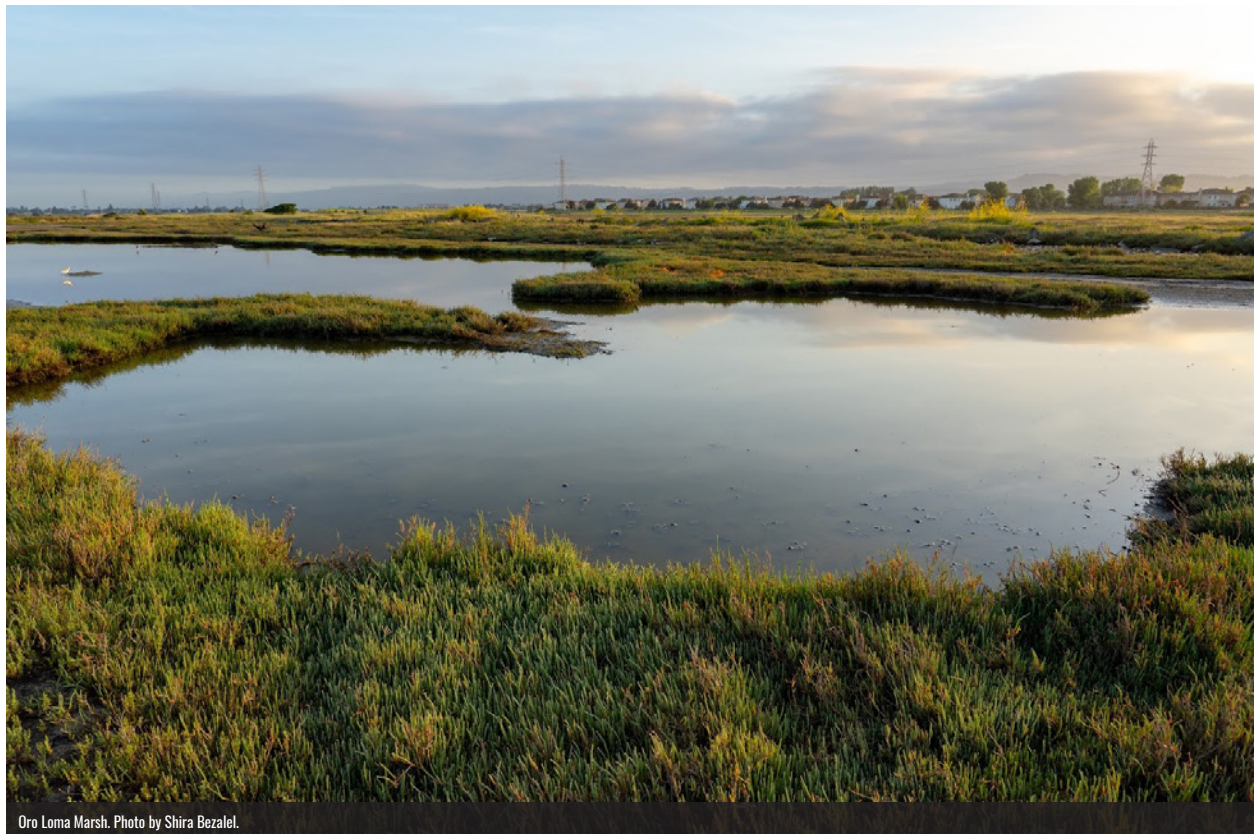


Figure 12. Priority ranked restoration opportunities for Ridgway's Rails for enhancement of landscape connectivity. Considered areas are identified opportunities not currently slated for tidal or diked marsh restoration: potential marsh, marsh migration space, and ecotone levees.

### ***Overlap in Restoration Prioritization***

Combining species-specific restoration prioritizations into a single map highlights where restoration will have important areas of alignment (Figure 13). To look for alignment, we selected the top twenty most impactful patches for each species. This assessment is intended to complement the findings for the individual species discussed above. Connecting nearby patches can have greater benefits for SMHM than for RIRA, which are more able to cross gaps. Many of the best opportunities to improve connectivity for RIRA are in the South Bay and along the Central Bay, while significant opportunities to improve connectivity for SMHM occur in both the South and North Bay. Even with dramatically different dispersal abilities, there are connections that are important for both species. These connections include areas near Oro Loma, Eden Landing, and Coyote Hills; fringing marsh along the foreshore and channels of the South Bay Salt Ponds; Ravenswood Pond SF2; along the northern edge of the Napa ponds; and near Petaluma Marsh, American Canyon and Cullinan Ranch.



Oro Loma Marsh. Photo by Shira Bezael.

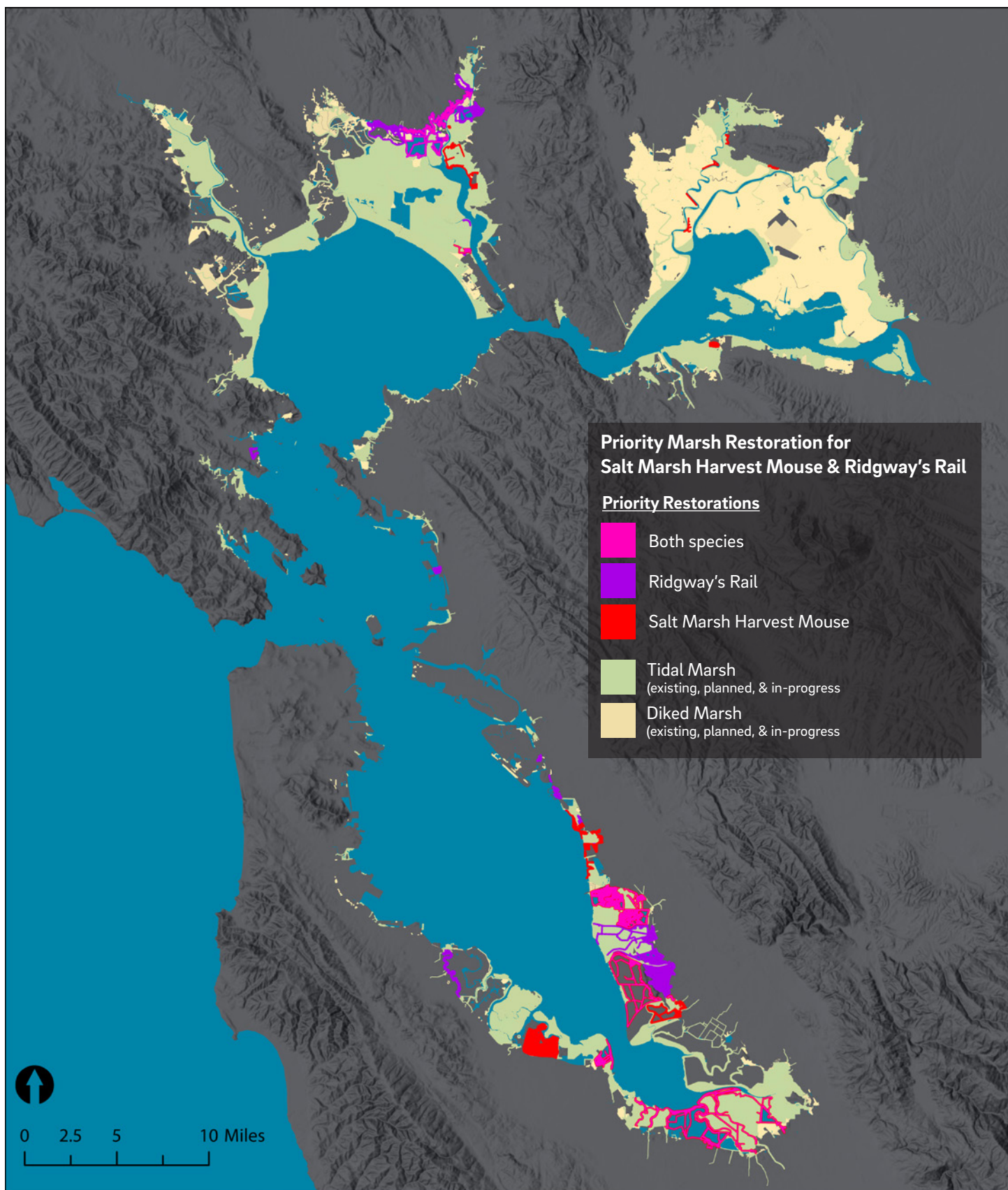


Figure 13. Overlap of the top 20 priority ranked restoration opportunities for Ridgway's rails and salt marsh harvest mouse for enhancement of landscape connectivity. Considered areas are those not yet currently slated for tidal or diked marsh restoration, which includes potential marsh, marsh migration space, and ecotone levees.

### ***Realities of Establishing On-the-Ground Connectivity***

The results here can be used to identify where critical connections should exist and where to prioritize restoration of these connections. However, decisions regarding restoration of potential marshes in particular locations will need to consider the best available science on habitat suitability for each species and should be done in consultation with regional wildlife experts. Managing for landscape connectivity is only one element of managing for wildlife persistence, which should balance several factors to promote population size and persistence, e.g., increasing habitat extent, enhancing local small-scale connections, mitigating other stressors, and improving habitat quality. We chose to incorporate relatively simple measures of suitability in this analysis: marsh type (i.e., tidal or diked), patch size thresholds, amount of core-to-edge habitat, salinity gradients, and presence of high-tide refugia. We chose these measures to provide not only for a straightforward and transparent analysis but also to be agnostic to the conditions at a site that would be responsive to restoration efforts. This allows the analysis to identify marshes that are needed to maintain connectivity, regardless of current condition. Habitat requirements and threat mitigation needs for both species are much more nuanced; for example, marsh channelization is an important habitat suitability factor for RIRA (Liu et al., 2012). Further, managing for these species is more complicated than only creating suitable habitat. Threats beyond habitat loss and degradation must be controlled and mitigated to the greatest extent possible. Both of these species are likely threatened by native and non-native predators and contaminants, such as methylmercury, and will ultimately be threatened by SLR induced by climate change (USFWS, 2013).

A shortcoming of this analysis is that the quality of habitat along potential paths between marshes was not evaluated, which could be of particular relevance to the ground-dwelling SMHM. However, SMHM can swim short distances and intervening habitat quality may not be the only factor in short-distance dispersal (USFWS, 2013). Thus, additional attention should be paid to the quality of connections and the intervening matrix between existing and newly restored patches. Connecting habitat will need to be as broad as possible and be appropriately vegetated. Narrow marshes may not be able to serve as functional corridors because they lack appropriate habitat complexity and escape cover. Research suggests that narrow marshes – those less than 50 meters or 55 yards wide, also known as strip marshes – may be of limited value for SMHM movement, and marshes < 25 meters wide may provide no value (USFWS, 2013).

## Next Steps

Continuing work on the Adaptation Atlas will focus on integration of strategies to achieve multiple benefits at the OLU scale. The Adaptation Atlas and the ecotone levee portion of this technical update focused on mapping suitability for various adaptation measures. These individual measures can be combined and phased to create place-based adaptation strategies. In the next phase of work, the team's focus will shift to developing timelines, triggers, and thresholds for adaptation measures that allow for adaptive decision making as environmental conditions change over time. This effort, which will focus on a few example OLUs, is already funded by the San Francisco Bay Regional Water Quality Control Board and will be completed within the next year.

Following that effort, a subsequent phase of work on the Adaptation Atlas will focus on connectivity between the Bay and its watersheds. This watershed phase will integrate results from the Adaptation Atlas, this technical update, and other relevant studies, e.g. *Sediment for Survival: A Strategy for the Resilience of Bay Wetlands* (Dusterhoff et al., 2021) to suggest strategies that can enhance resilience of ecosystems and urban environments from the uplands to the Bay. These planned updates to the Adaptation Atlas will continue to broaden and deepen the framework, providing a scientific basis for the development of holistic strategies that can enhance the resilience of the estuary to environmental change.

# Appendix A: Ecotone Levee Analysis

## METHODS

---

The same basic method used to identify ecotone levees in the original Adaptation Atlas was used for this enhanced analysis, but with updated and expanded input layers and more extensive manual review and editing.

Areas identified as potentially suitable for horizontal levees were places where development is adjacent to tidal marsh (today or in the future). The original method relied on the 2011 National Landcover Database to identify developed areas. For this analysis, more areas were included to improve resolution and smooth edges in the raster-based NLCD. Included in the “developed areas” layer for the updated analysis:

- National Land Cover Database 2016: low, medium, and high-intensity development (NLCD, 2016)
- Wastewater facility footprints (facilities included in regional nutrient permit)
- Bayfront landfills: approximate polygons based on elevation, NLCD, and historical baylands, then cross-referenced using information provided by the SF Bay Regional Water Quality Control Board (RB2)<sup>1</sup>
- Roads: 50m line buffer of interstate, state, and US highways (US Census, 2019)
- Railroads: 20m line buffer (California Department of Transportation, 2020)
- Electric substations: Added any bayfront substation parcels not covered by NLCD (California Energy Commission, 2020)
- Superfund sites: National Priority List for Region 9

The original method relied on areas at the proper elevation for tidal marsh ( $z^*$ ) to identify marsh areas. Included in the expanded “marsh” layer for the updated analysis are areas both above and below current tidal marsh elevation that may become marsh in the future:

- Areas at the suitable elevation for tidal marsh today (see  $z^*$  description, Appendix 5 of the Adaptation Atlas p. 239) (SFEI and SPUR 2019)
- Undeveloped areas at the suitable elevation for marsh migration with SLR (see methods in Appendix 5 (p. 242) of the Adaptation Atlas).<sup>2</sup>
- Planned tidal marsh restoration, based on mapping completed for the 2015 Goals Project and updated for the SF Bay Shoreline Adaptation Atlas per interviews with several key landowners and

---

1 The bayfront landfill layer was created by selecting high-elevation (>4m) areas within the footprint of historical baylands (marsh, mudflat, other aquatic features) that are currently undeveloped (National Land Cover Database). The resulting polygons were manually reviewed and compared to aerial imagery; non-landfill features such as levees and marinas were removed. The remaining polygons were cross-referenced with a list and map of bayfront landfills provided by RB2. Some missing polygons were added at this stage (these were mostly landfills that have been redeveloped). Polygons that were not represented on the RB2 list and map were removed. DOD/federal landfills are not included in this layer.

2 Identified ecotone levee opportunities at the inland edge of marsh migration space would be constructed in the future. As sea levels rise and the marsh migrates inland, ecotone levees will need to be constructed at higher elevations to provide the same transition zone and flood protection benefits.

stakeholders (same layer used in the wildlife connectivity analysis and described above).

A GIS layer delineating existing bayland habitats (BAARI, 2017) was used to clip the development layer and create a cleaner shoreline.

Next, opportunity sites were identified by buffering developed areas by the necessary ecotone levee width (wide enough to support a levee with a 1:30 slope, assuming a crest height equal to the height of the 100-year storm surge plus 2.1 m of SLR). Necessary ecotone levee widths were calculated on an OLU-by-OLU basis (Table A1). Buffered ecotone levee footprints (split at regular intervals of approximately 100 m) were selected if they mostly (>85%) overlapped existing marsh or potential future marsh and migration space (see “marsh” layers included above).

From this selection, we performed an extensive manual removal and addition process. The following procedures were used to modify the model output:

- Ecotone levees that had minimal connection to a marsh or potential future marsh were removed.
- Ecotone levees that did not front buildings and infrastructure (e.g. fronting a salt pond berm) were removed.
- Ecotone levees fronting road/rail with undeveloped area landward of the transportation corridor were removed, as other adaptation strategies (such as raising the road) could be more ecologically beneficial in these areas.
- Ecotone levees crossing creek/slough channels were removed.
- Ecotone levees conflicting with known restoration and enhancement plans were removed.
- Ecotone levees were added where they are currently planned or under construction.
- Ecotone levees were edited by hand to reduce artifacts of the modeling process (nonstandard shapes, pixelated areas, protrusions), to better align with marsh/development edges based on aerial imagery, and to fill gaps where there was no logical reason for a break in the levee (included if >75% marsh overlap and filled a gap).

The alignment of flood risk management levees in the future may change. In some cases, the modeling resulted in multiple possible ecotone levee alignments. In some places, both alignments are shown. In most cases where there were multiple possible levee alignments, the most inland alignment was selected to allow more room for marsh migration over time — however, in some of these cases, a shorter and more bayward levee alignment may prove most feasible to construct.

Volumes of fill material required for construction were calculated for each levee segment. These volumes were calculated using the widths and crest heights described in Figure A1 and so represent maximum volumes. While the volume estimates vary due to the different required crest heights calculated for the various areas of the Bay, the average is about 240,000 m<sup>3</sup> (320,000 yd<sup>3</sup>) for a mile of ecotone levee. Annotations were added to the geospatial data file for each levee describing whether the levee is planned as part of an existing restoration or flood control project, whether it connects to existing marsh, future marsh (migration space), and/or restoration would be required to reconnect the site to tidal action and make the levee an effective transition zone.

Table A1. Calculating ecotone levee widths for each OLU (from SFEI and SPUR, 2019). Maximum widths of ecotone levees were calculated using the formula above. Ecotone levees may have a steeper slope than 1:30 (as steep as 1:10), and they may be lower than the crest of the levee. The use of a generous 1:30 slope reaching from the crest of the levee to the marsh captures opportunities with marshes wide enough to support the widest levee. Slopes and elevations of individual designs may vary.

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

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

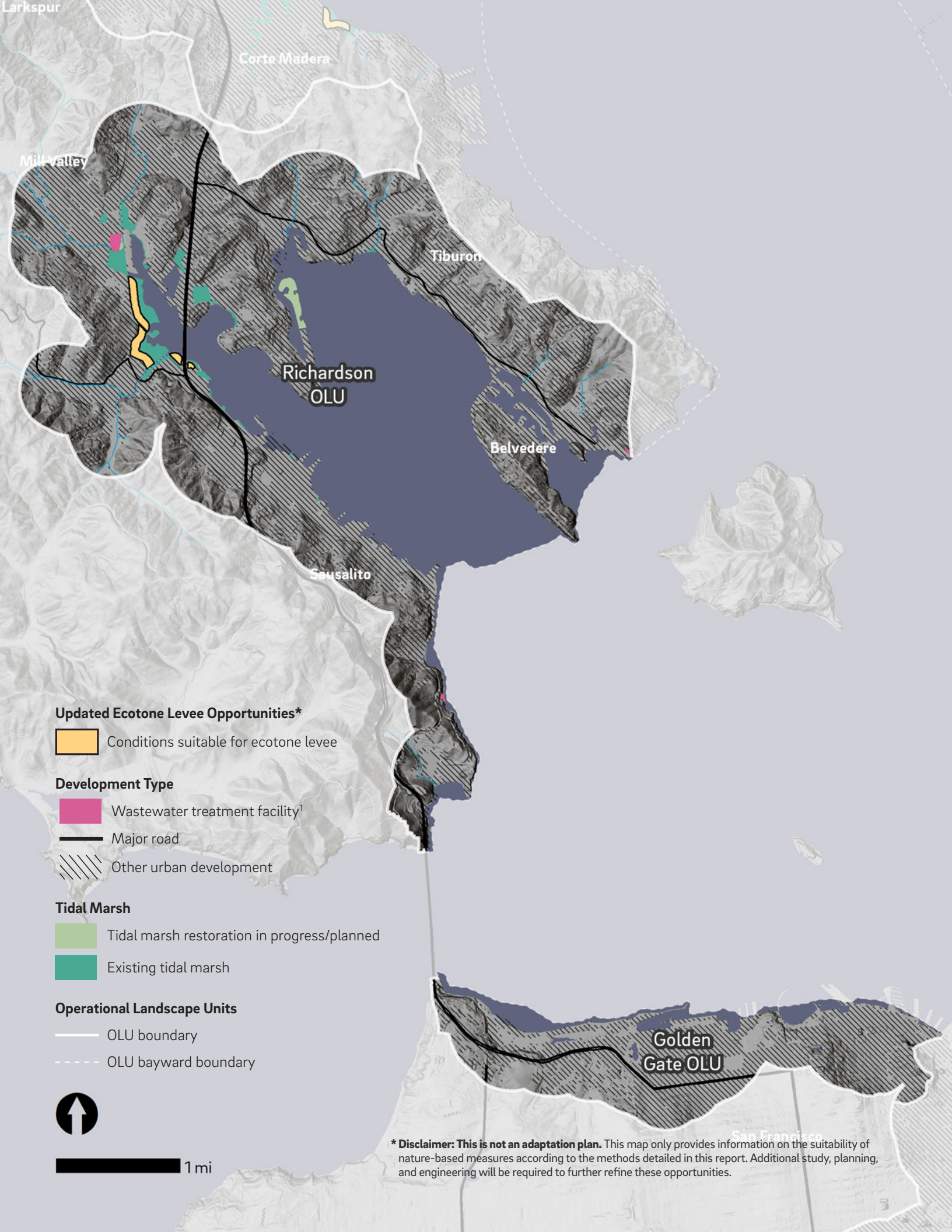
## RESULTS

Table A2 shows the length of shoreline identified as suitable for ecotone levees in this update compared to the Adaptation Atlas. Lengths in Table A2 are approximate. Each levee opportunity segment was associated with the OLU in which the majority of the segment is located.

Table A2. Approximate length of ecotone levee opportunity identified in each OLU in the Adaptation Atlas and the updated analysis.

OLU	Length: Adaptation Atlas (2019) (miles)	Length: Updated Analysis (miles)	Difference (miles)
Richardson	2.7	1.2	-1.5
Corte Madera	1.8	3.7	1.9
San Rafael	1.4	2.4	1.0
Gallinas	1.6	2.3	0.7
Novato	2.1	6.2	4.1
Petaluma	1.2	4.2	3.0
Napa - Sonoma	9.0	13.0	4.0
Carquinez North	1.7	2.9	1.2
Suisun Slough	3.2	6.0	2.7
Montezuma Slough	0.0	0.0	0.0
Bay Point	1.0	4.8	3.8
Walnut	5.1	9.6	4.6
Carquinez South	2.0	1.3	-0.7
Pinole	0.7	0.5	-0.2
Wildcat	4.5	5.4	0.9
Point Richmond	0.0	0.0	0.0
East Bay Crescent	4.2	3.8	-0.4
San Leandro	1.8	0.8	-1.0
San Lorenzo	7.0	6.0	-1.0
Alameda	12.0	9.6	-2.4
Mowry	9.4	8.4	-1.0
Santa Clara Valley	9.6	16.7	7.1
Stevens	2.4	4.6	2.2
San Francisquito	6.5	5.9	-0.6
Belmont - Redwood	17.5	13.8	-3.7
San Mateo	1.1	0.7	-0.4
Colma - San Bruno	2.5	2.2	-0.3
Yosemite - Visitacion	0.2	0.0	-0.2
Mission - Islais	0.1	0.0	-0.1
Golden Gate	0.4	0.0	-0.4

The following maps summarize the results of the ecotone levee analysis update. Each map shows identified ecotone levee opportunities, along with the type of development the levee would protect and the type of marsh it would connect to (existing tidal marsh, tidal marsh restoration planned/in-progress, or potential future marsh). To keep this appendix concise, some maps are consolidated and show two OLUs rather than one.



### Updated Ecotone Levee Opportunities\*



Conditions suitable for ecotone levee



Conditions suitable for ecotone levee  
(alternate alignments shown)

San Anselmo

San Rafael

San  
Rafael  
OLU

Larkspur

Corte  
Madera OLU

### Development Type



Wastewater treatment facility



Bayfront landfill



Major road



Rail line



Other urban development

### Tidal Marsh



Tidal marsh restoration in progress/planned



Existing tidal marsh

### Operational Landscape Units



OLU boundary



OLU bayward boundary



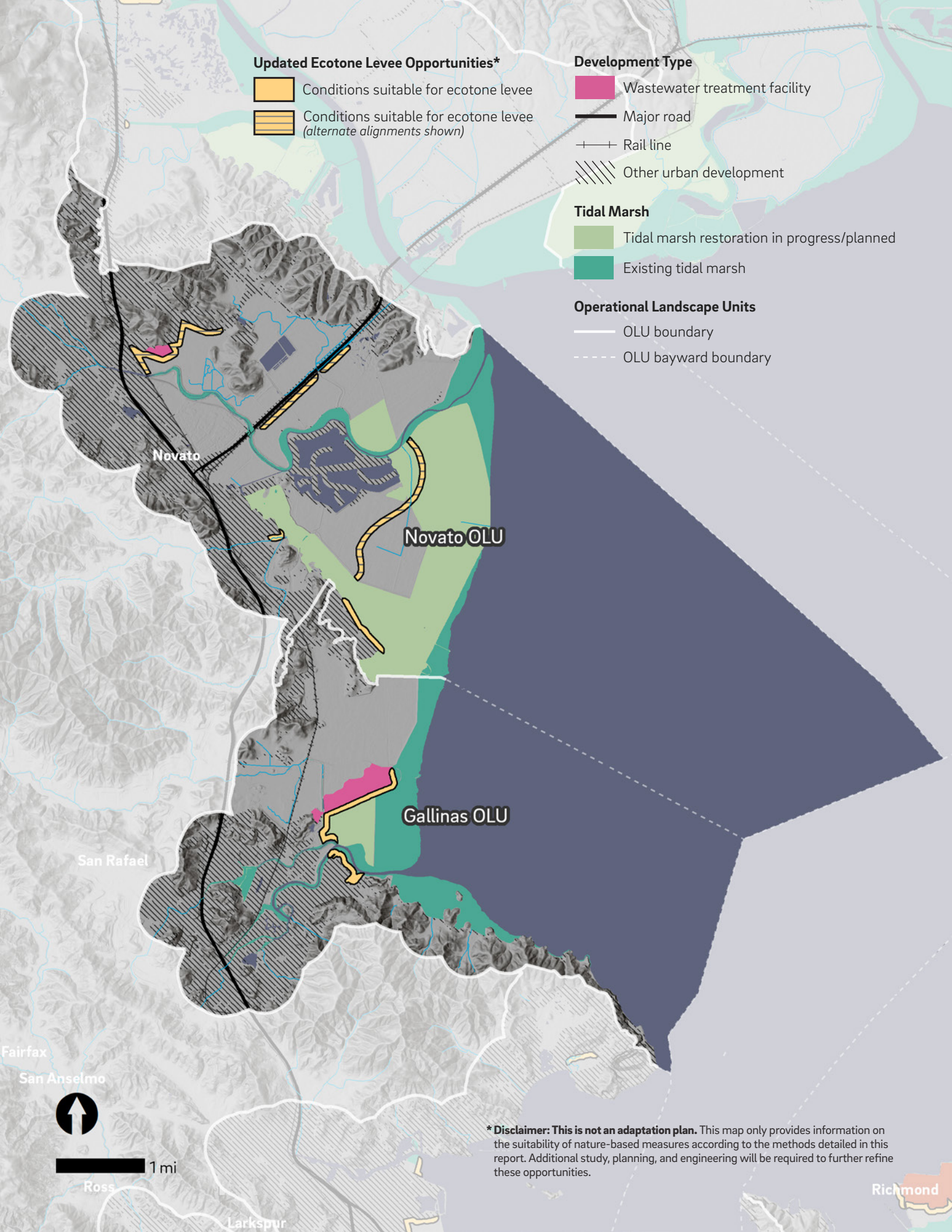
1 mi

**\*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.

Tiburon

Belvedere

Sausalito



**Updated Ecotone Levee Opportunities\***

- Conditions suitable for ecotone levee
- Conditions suitable for ecotone levee (alternate alignments shown)

**Development Type**

- Wastewater treatment facility
- Major road
- Rail line
- Other urban development

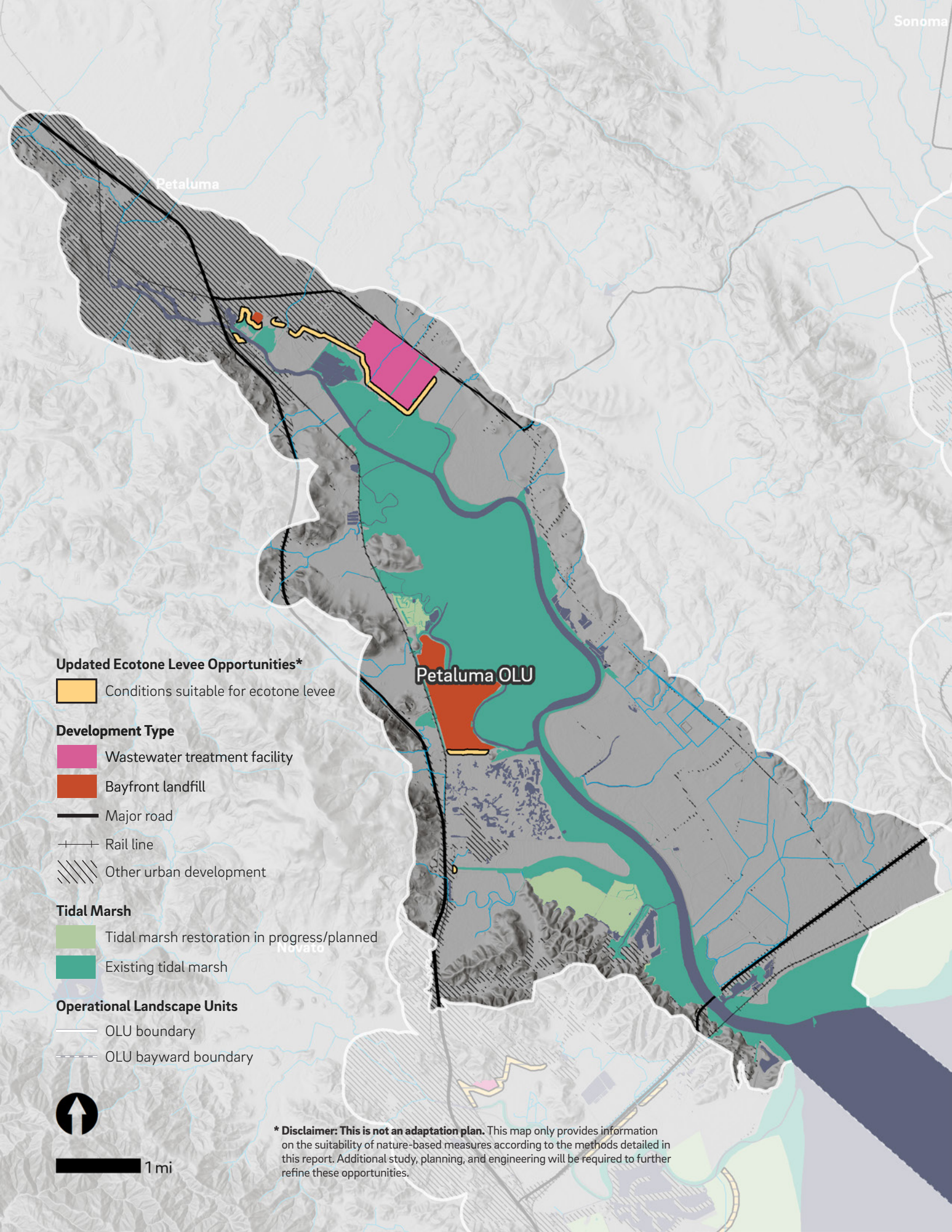
**Tidal Marsh**

- Tidal marsh restoration in progress/planned
- Existing tidal marsh

**Operational Landscape Units**

- OLU boundary
- OLU bayward boundary

**\*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.



### Updated Ecotone Levee Opportunities\*

Conditions suitable for ecotone levee

### Tidal Marsh

Tidal marsh restoration in progress/planned

Existing tidal marsh

### Operational Landscape Units

OLU boundary

OLU bayward boundary

### Development Type

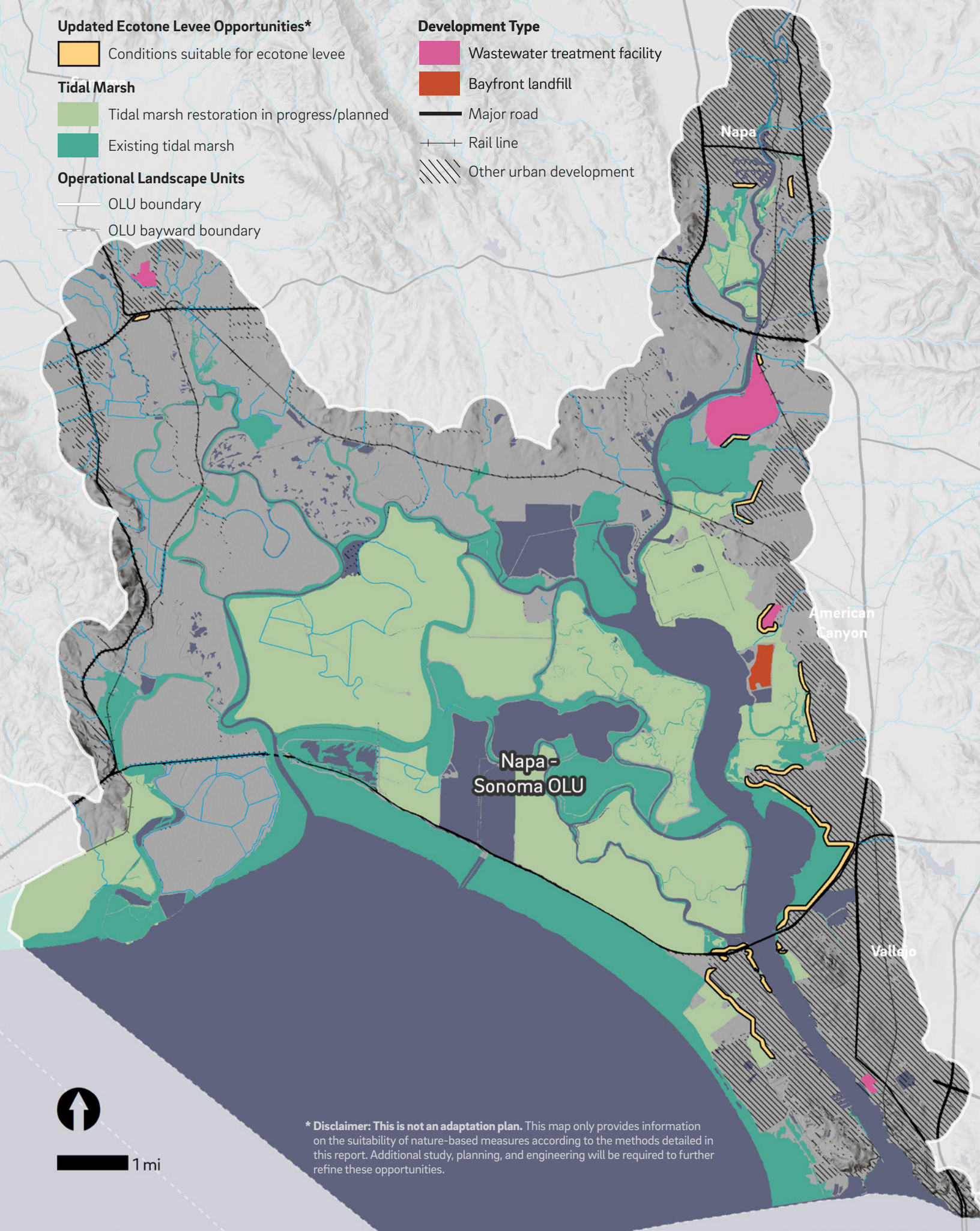
Wastewater treatment facility

Bayfront landfill

Major road

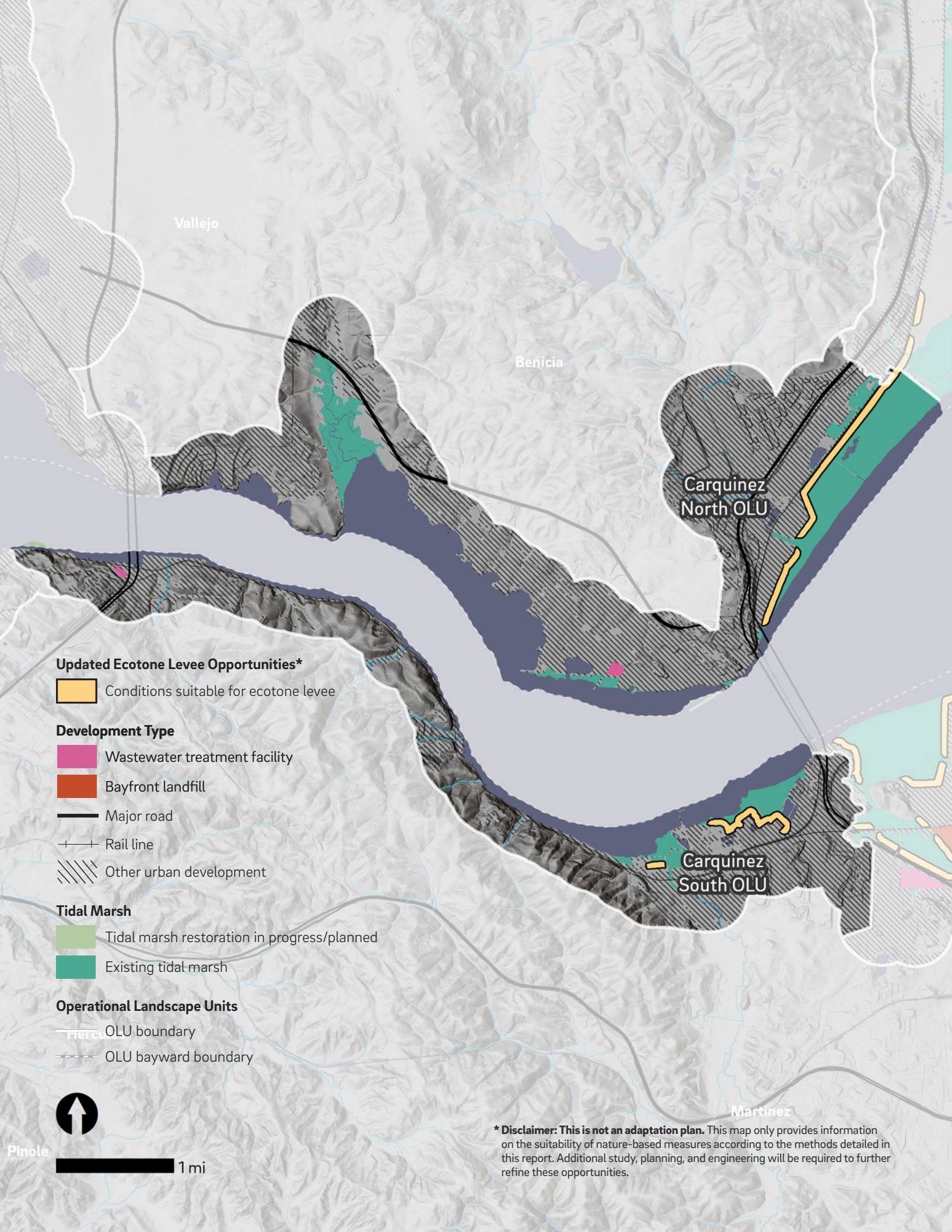
Rail line

Other urban development

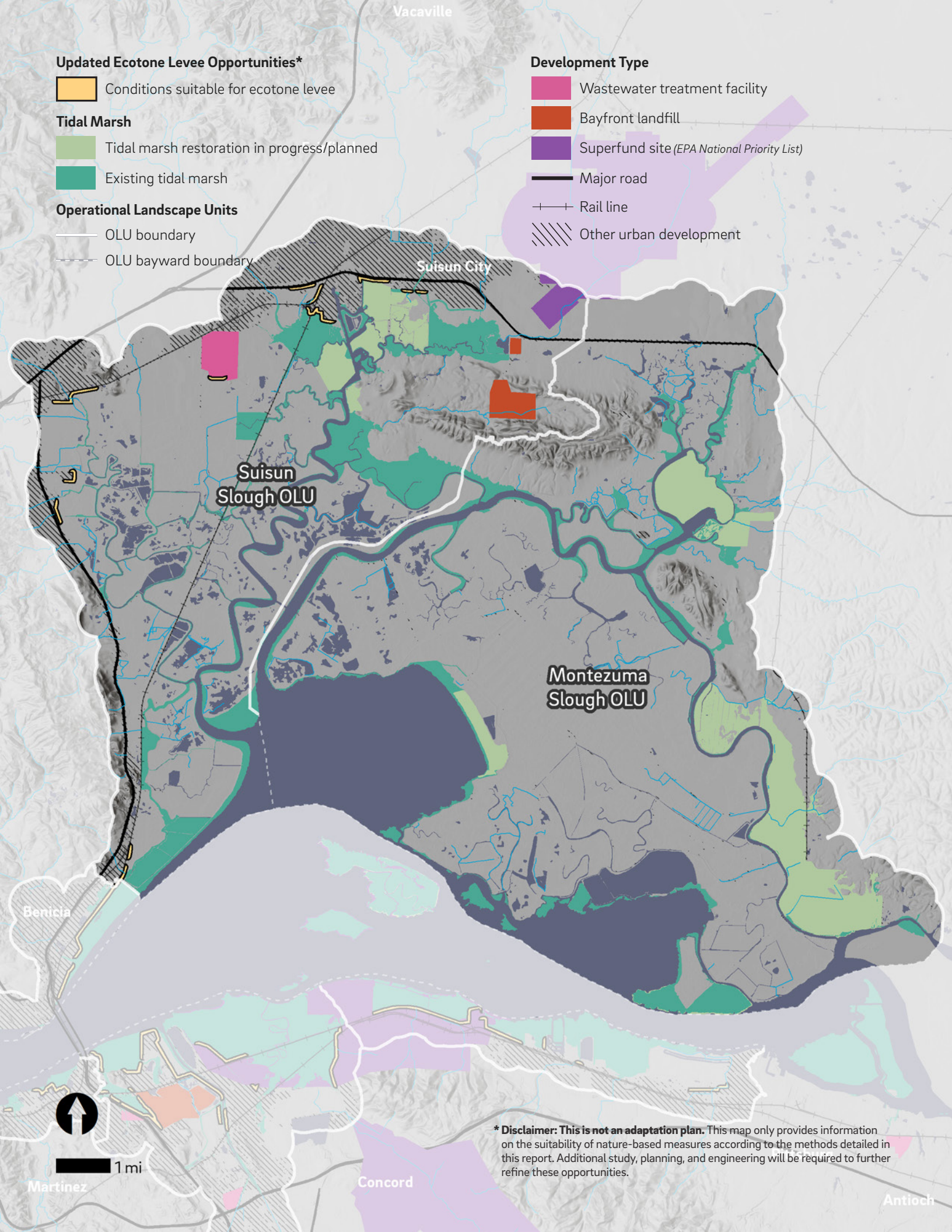


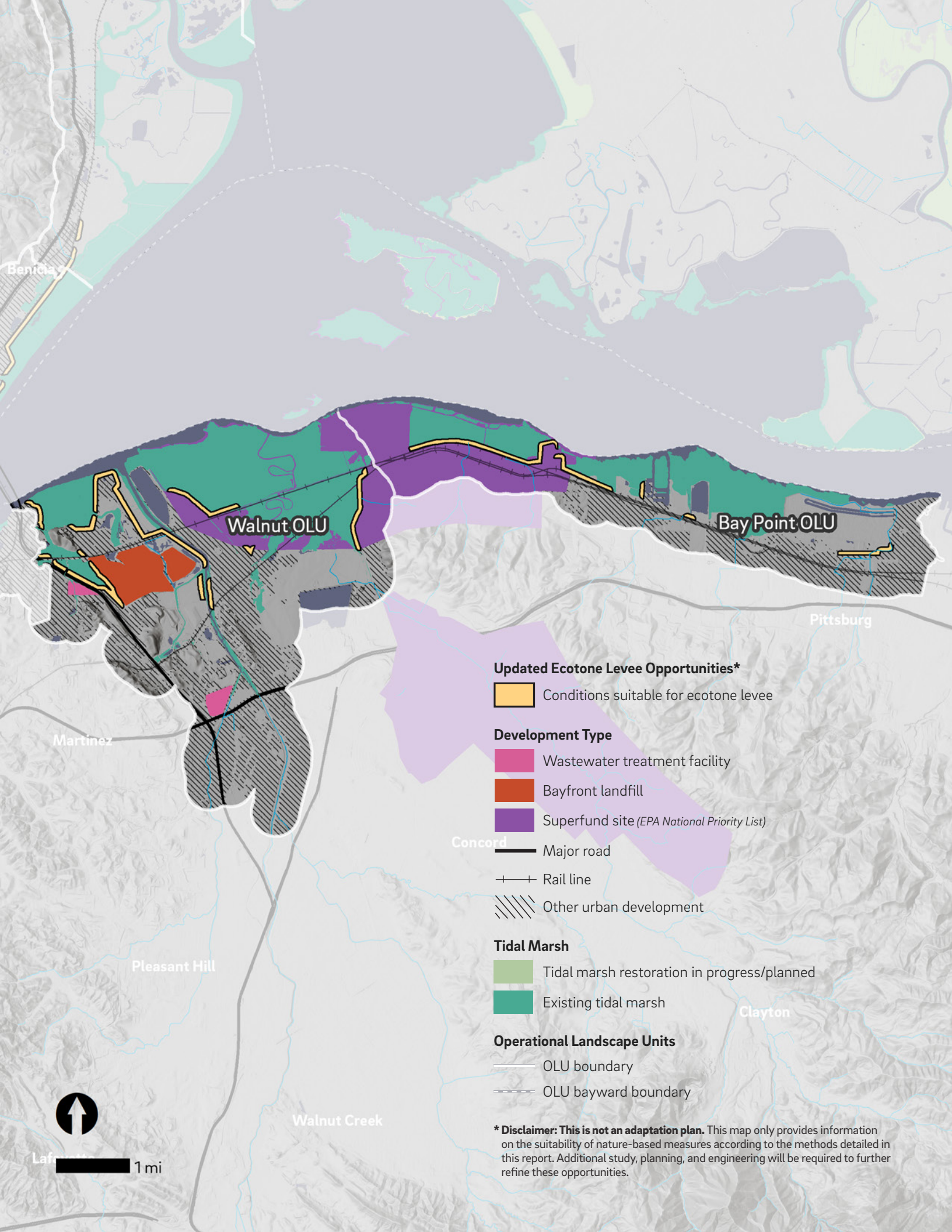
1 mi

**\* 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.




**\* 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.








### Updated Ecotone Levee Opportunities\*


 Conditions suitable for ecotone levee


### Development Type

 Wastewater treatment facility


 Bayfront landfill


 Major road

 Rail line


 Other urban development


### Tidal Marsh

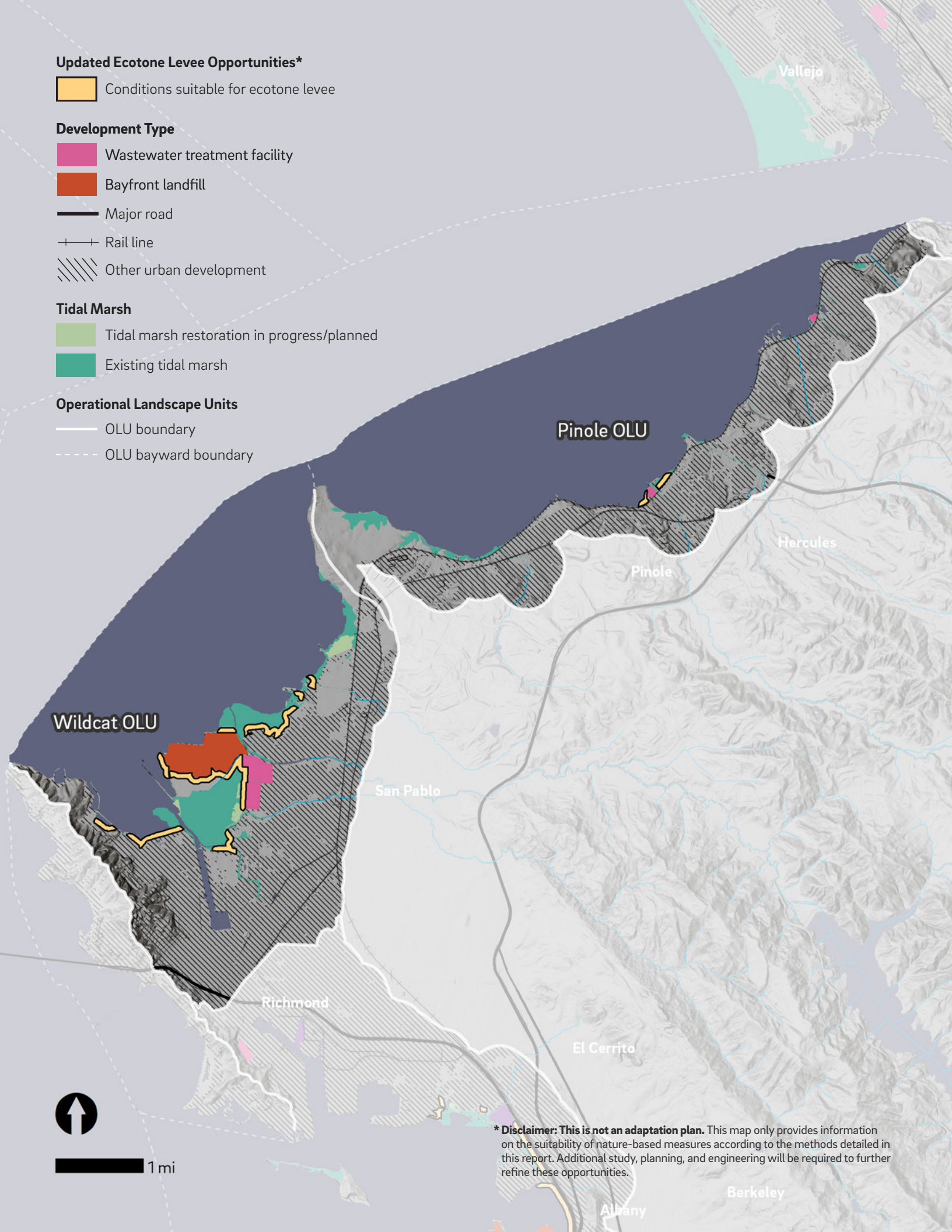
 Tidal marsh restoration in progress/planned

 Existing tidal marsh

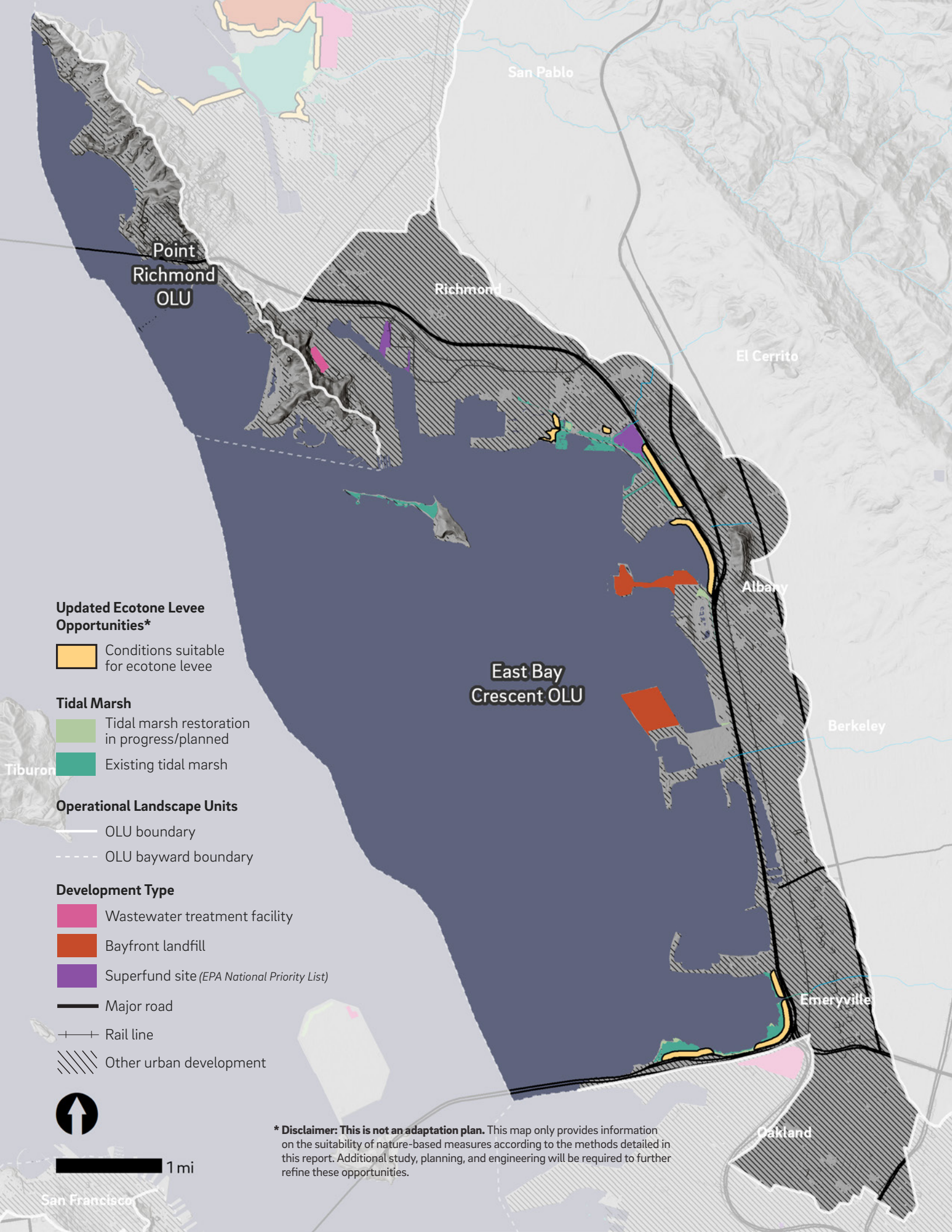
### Operational Landscape Units

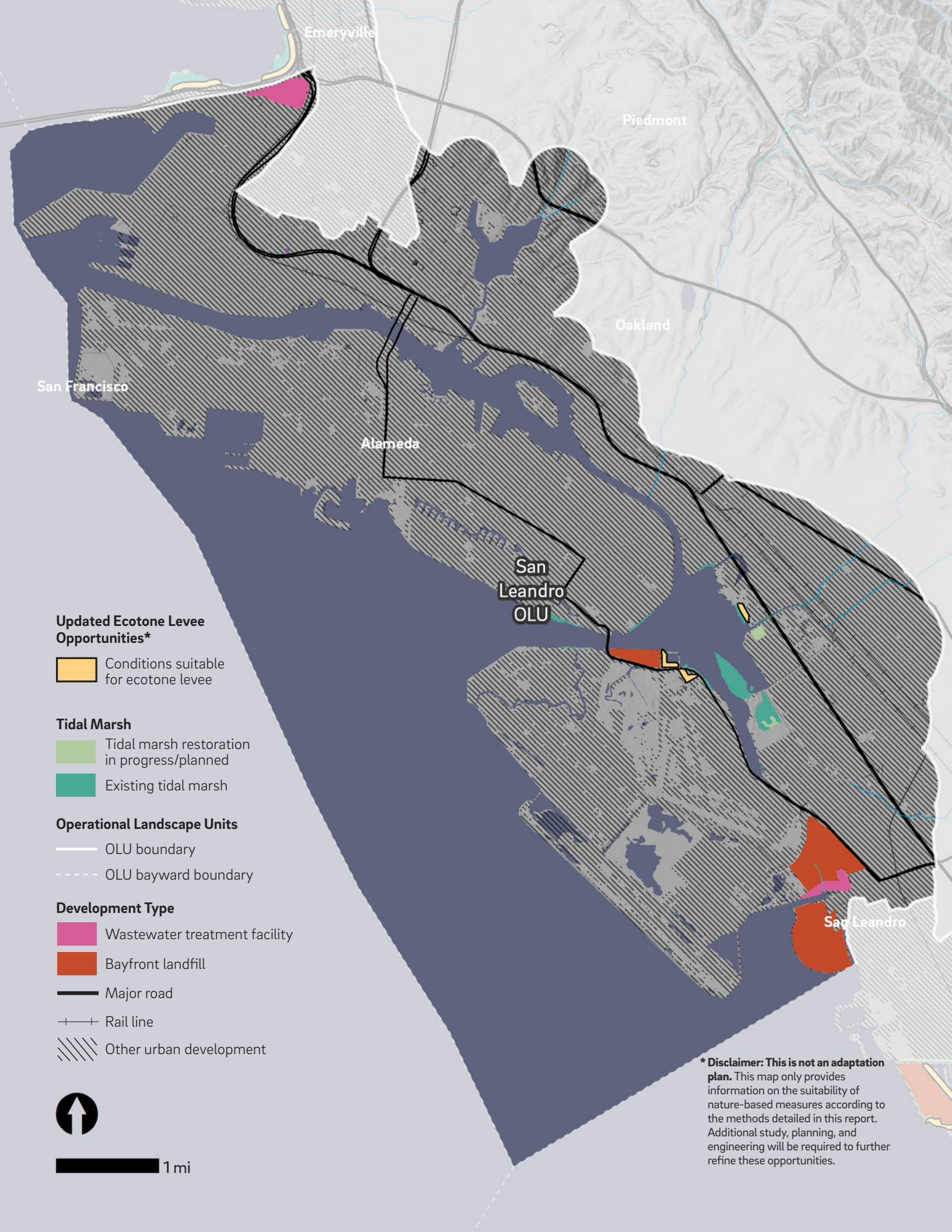
 OLU boundary

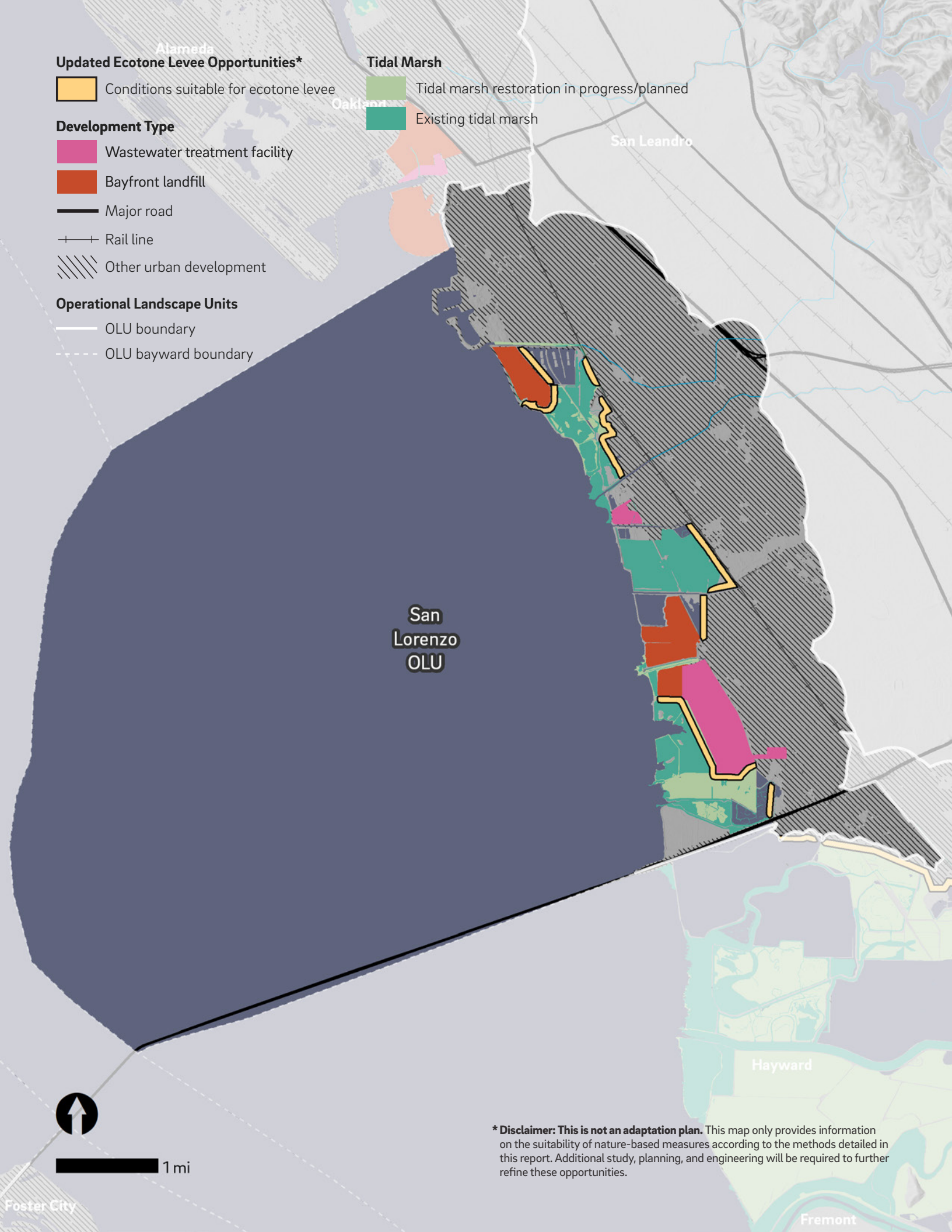
 OLU bayward boundary

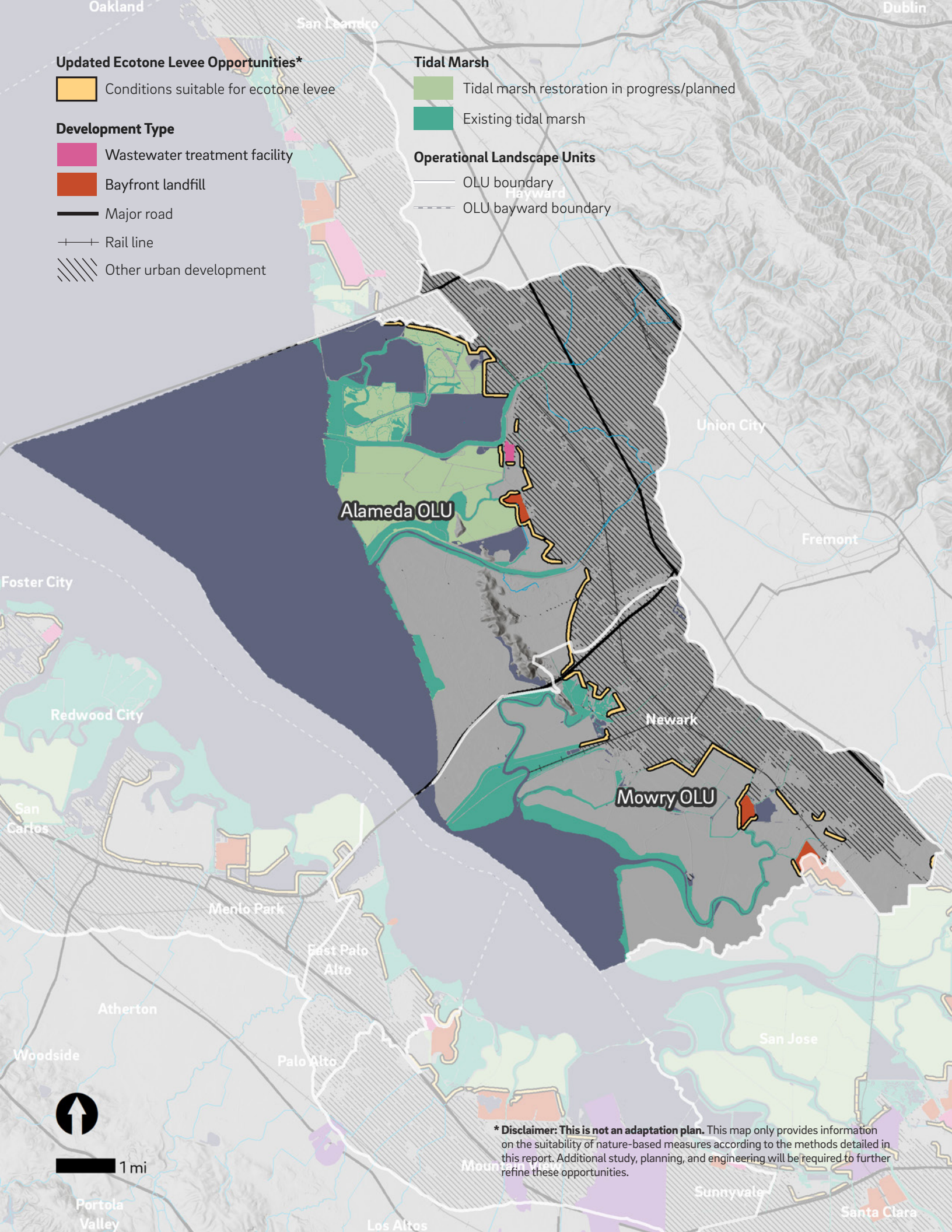


**\* Disclaimer:** This is not an adaptation plan. This map only provides information on the suitability of nature-based measures according to the methods detailed in this report. Additional study, planning, and engineering will be required to further refine these opportunities.

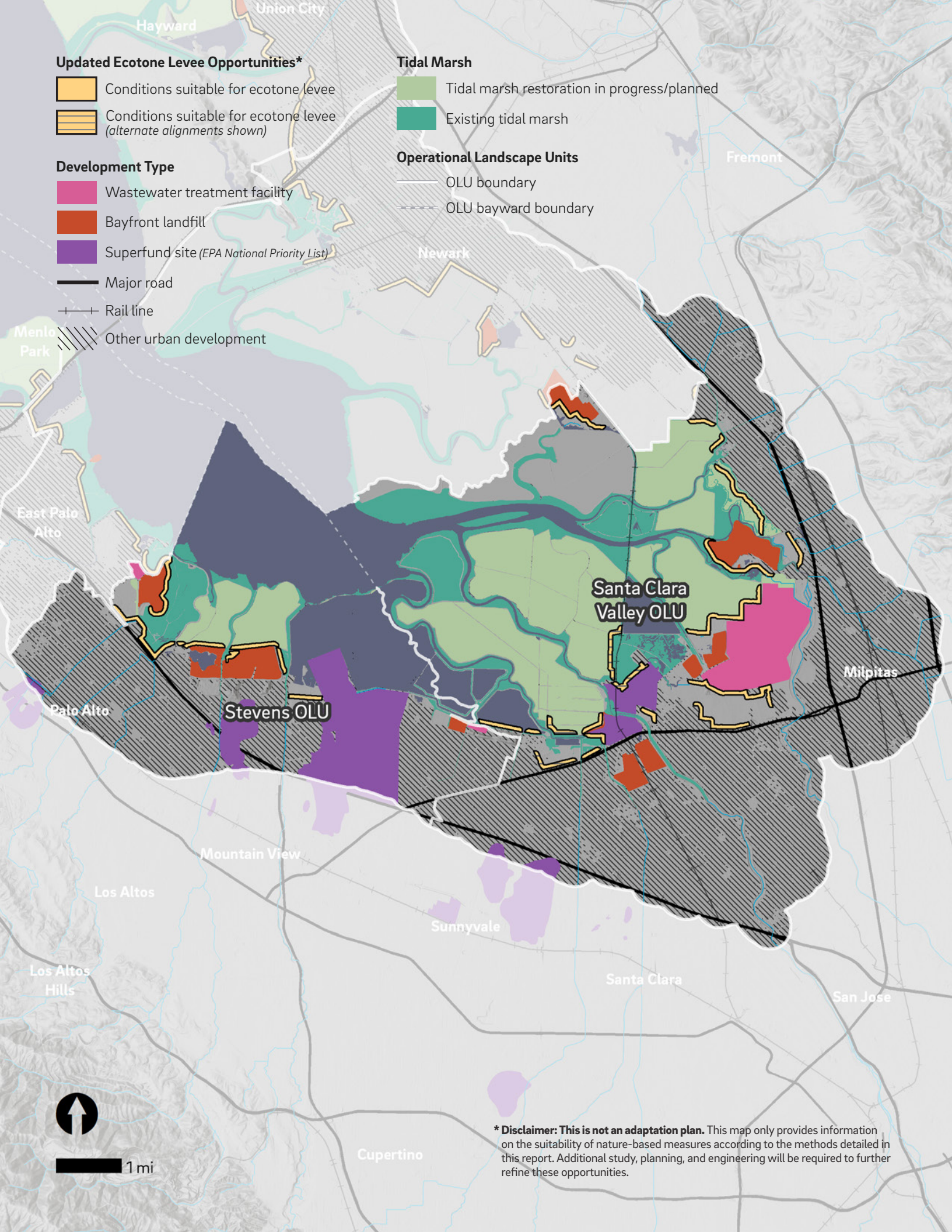


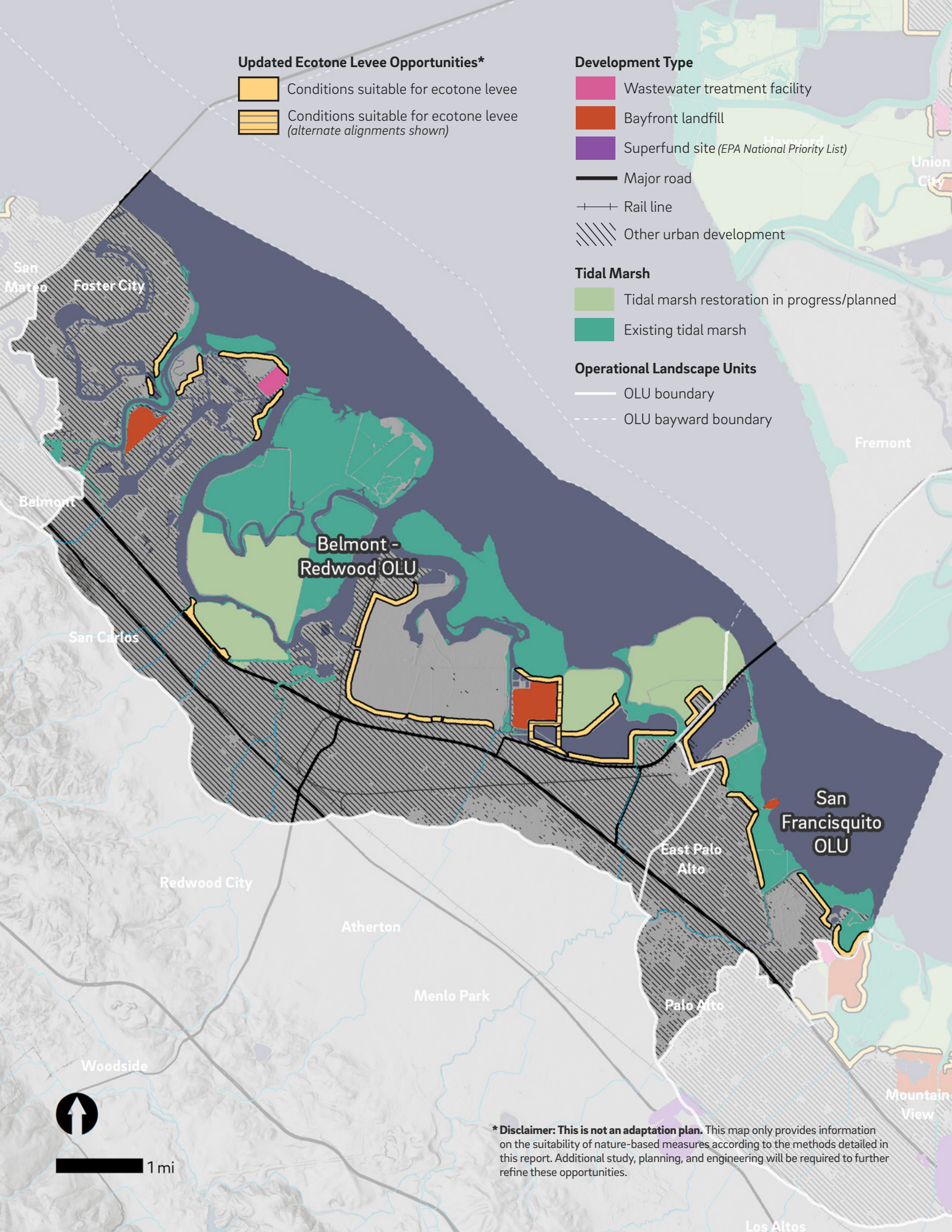


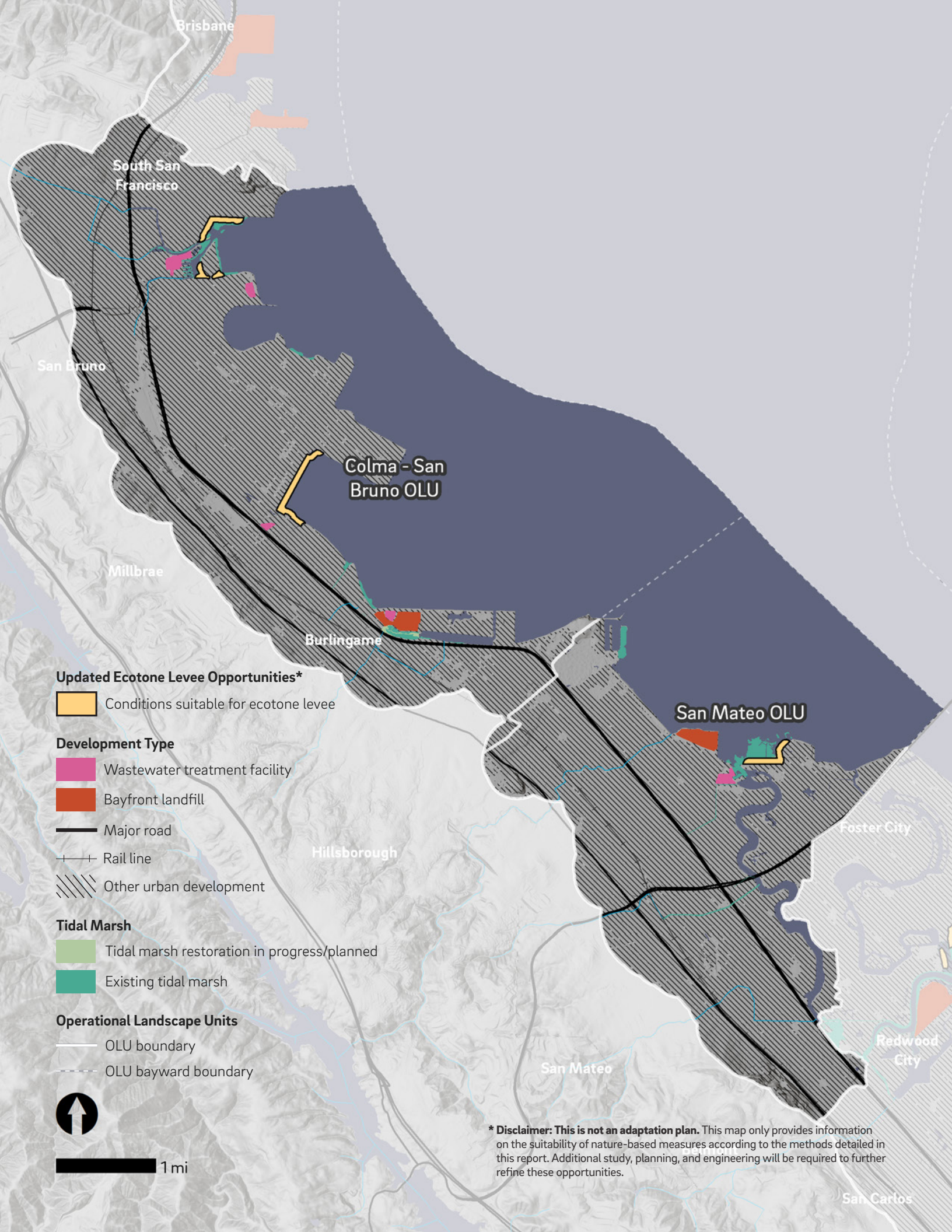




**\* Disclaimer:** This is not an adaptation plan. This map only provides information on the suitability of nature-based measures according to the methods detailed in this report. Additional study, planning, and engineering will be required to further refine these opportunities.







**Updated Ecotone Levee Opportunities\***

Conditions suitable for ecotone levee

**Development Type**

Wastewater treatment facility

Bayfront landfill

Major road

Rail line

Other urban development

**Tidal Marsh**

Tidal marsh restoration in progress/planned

Existing tidal marsh

**Operational Landscape Units**

OLU boundary

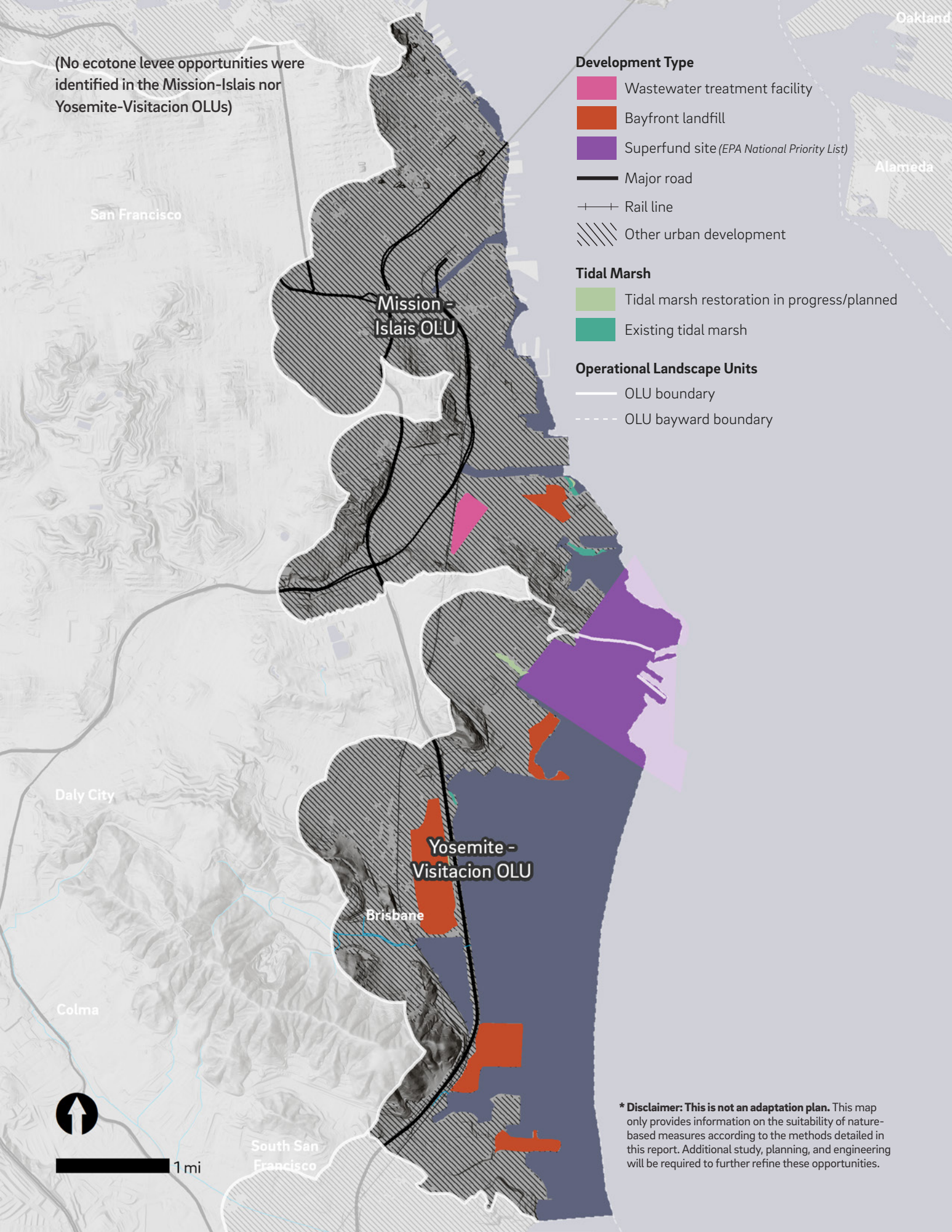
OLU bayward boundary



1 mi

**\* 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.

(No ecotone levee opportunities were identified in the Mission-Islands nor Yosemite-Visitacion OLUs)



**\* 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.

# Appendix B: Wildlife Connectivity Analysis

## METHODS

---

Here, we analyze the connectivity of marsh habitat in San Francisco, San Pablo, and Suisun Bays to evaluate landscape-level connectivity and identify patches of marsh that are the most vital to habitat connectivity. We evaluate both historical and contemporary landscapes (which incorporates the impacts of on-going and planned restoration) and compare this to the capacity of land suitable for restoration to enhance connectivity in the Bay relative to the current conditions. Measures of connectivity are dependent on the species under consideration and their species-specific dispersal abilities. This analysis was done through the lens of two marsh-specialist species: the salt marsh harvest mouse (SMHM; *Reithrodontomys raviventris*) and Ridgway's rail (RIRA; *Rallus obsoletus*). We use these species as a case study here because they represent end-members of the spectrum of wildlife dispersal abilities. SMHM are ground-dwelling and have more limited movement abilities (Bias & Morrison, 1999; Geissel et al., 1988) and RIRA are flighted and capable of long-distance movements of >40 km (Casazza et al., 2008).

We analyze connectivity using the probability of connectivity (PC; Saura & Pascual-Hortal, 2007; Saura & Rubio, 2010). The PC index and its associated indices characterize the functional connectivity of the entire landscape along with which habitat elements are most critical for maintaining connectivity. It considers available habitat, the spatial configuration of that habitat, and the probability that dispersing individuals can move between habitat patches. It should be noted that while this analysis is focused on functional connectivity, it only considers the potential connectivity of the landscape, which is an approximation of how animals may move across the landscape. Documenting actual movements of animals across the landscape requires intensive fieldwork and can be difficult to capture, as dispersal events occur at unpredictable moments, which causes difficulty characterizing connectivity across broad spatial scales. Graph-theoretic approaches, such as the one used here, provide relatively detailed estimates of potential connectivity at large geographic scales, have modest data requirements, and are computationally feasible at scale (Calabrese & Fagan, 2004).

### **Connectivity Model**

PC is a landscape-level connectivity measure and is defined as the probability that two animals randomly placed on a landscape end up in habitat patches that are reachable to each other via dispersal (see Saura & Pascual-Hortal [2007] and Saura & Rubio [2010] for a full description of the calculation of PC and its associated indices). In order to calculate PC, the probability of an individual moving directly from patch *i* to patch *j* without moving through an intermediate patch needs to be characterized for every pair of patches on the landscape. For patches that are very close together, this can be close to 1 and will move towards 0 as patches become more distant and are at the limits of an animal's dispersal abilities. Here, dispersal probabilities between patches were estimated using species-specific dispersal movements from observations reported in the scientific literature (see *Dispersal Probabilities* below) and the length of the most efficient path an animal would take between patches on the landscape (see *Least Cost Paths* below). The "best" path (i.e., the path with the highest probability, also known as the maximum product probability) between patch *i* and *j* is calculated using a shortest path algorithm known as Dijkstra's algorithm. The best path may include moving through other intervening patches if the combination of these movements result in a higher probability than moving directly from patch *i* to *j*.

The importance of individual patches to maintaining connectivity can be derived from PC. An ordered ranking of each patch's contribution to connectivity was calculated using *dPCconnector*. This ranking can be used to identify the most important existing patches for conservation for existing habitat or to identify the locations where newly-restored habitat would be the most impactful. We calculated the degree to which a patch served as an irreplaceable element connecting the rest of the other patches on the landscape, in other words, the extent each patch served as an avenue for dispersal to other patches (i.e., the *dPCconnector* index, a fractional component of PC, see Saura & Rubio [2010: pp 526-7] for details). A patch is considered to have high connectivity if it is: (1) part of the "best" path between other patches and (2) if the patch was lost from the landscape, paths through other patches do not compensate for the theoretical lost connectivity.

While the contribution of each individual patch to the total network connectivity was determined by iteratively removing each patch from the network and quantifying the impact on connectivity, determining areas where new marshes would most improve connectivity used the opposite process – iteratively adding individual hypothetical patches to the network and quantifying how much they increase connectivity. For this analysis, we modified R code for calculation of the PC index and its associated indices from Fletcher and Fortin (2018, Chapter 9).

#### *Marsh Patch Data*

Spatial data of marshes across San Francisco, San Pablo and Suisun Bay during three separate time frames were used in this analysis. For the SMHM connectivity analysis, tidal and diked marshes in all three sub-embayments were included. For RIRA, only tidal marshes in the San Francisco Bay and San Pablo Bay west of the Carquinez Strait were considered based on the recommendation of Cory Overton (pers. comm.). RIRA are known to occur in the marshes of Suisun Bay, however, these observations are likely capturing itinerant, dispersing individuals rather than an established breeding population. RIRA have only been recorded in Suisun in low numbers and are present intermittently across years (Evens & Collins, 1992; Gill, 1979; Overton, 2007; USFWS, 2013). Spatial data were obtained from multiple mapping efforts:

- **Historical (circa 1800) tidal marshes:** Tidal marshes were extracted from the Historical and Modern Baylands dataset available on SFEI's EcoAtlas (SFEI, 1998); Figure 5). Historical distributions of habitat types in the San Francisco Baylands circa the year 1800 were developed from hundreds of independent historical data sources including maps, photographs, and texts.
- **Existing and Planned tidal and diked marshes:** The baylands are constantly evolving, so a map of existing and planned marshes is a moving target. For this effort, we developed a map that represents our best understanding of current and planned conditions (Figure 6); however, it was created specifically for the purposes of this analysis and is not meant to provide a definitive marker of restoration efforts. Existing marshes and planned restoration sites were collated from different mapping efforts and input from restoration practitioners to create an up-to-date representation of existing marsh habitat, and ongoing and planned restoration projects. Ongoing restoration included those sites that have been breached and are in the process of accreting to intertidal elevations. Planned restoration projects included those areas that have been acquired and are slated for marsh restoration. Tidal and diked marshes that existed in the Baylands as of 2009 were mapped by Bay Area Aquatic Resource Inventory (BAARI, 2009). This dataset was iteratively updated to reflect newly restored and planned marshes as part of the Bayland Goals (Goals Project, 2015) and the SF Bay Shoreline Adaptation Atlas (SFEI and SPUR, 2019) projects. The spatial data updated through these

projects was further revised in 2020-2021 through review by regional experts (Donna Ball, Christina Toms, Jeremy Lowe, pers. comm.).

- **Habitat restoration opportunity sites:** Locations that are potentially suitable for future marsh restoration were evaluated using data updated from the SF Bay Shoreline Adaptation Analysis (Figure 6). This included potential marsh (undeveloped areas at the appropriate elevation for tidal marsh), marsh migration space<sup>1</sup> (undeveloped areas at the appropriate elevation for tidal marsh in the future as sea level rises), and ecotone levees (see Appendix A) where future marsh and transition zone restoration could potentially occur. Subsided areas, which could be restored to marsh elevation via sediment delivery, were not considered in this analysis as potential marsh restoration opportunities.

#### *Patch Identification/aggregation*

Here marsh patches were used as the unit of analysis and were defined as a contiguous, suitable habitat for the focal species separated by other habitat types or barriers (Fahrig & Merriam, 1985). In this analysis, marsh habitat was considered as a discrete patch if it was separated by less than 60 meters. The 60-meter patch boundary definition was developed for Bayland marshes by Collins & Grossinger (2004) to reflect habitat and behavioral affinities of marsh specialists, particularly, RIRA and SMHM. This boundary definition was further reviewed for its biological relevance by a regional team of experts (SFEP, 2011, appendix D). Aggregated patches >0.5 hectares were included in the analysis.

#### *Area-weighted Patch Suitability*

Patches were weighted by simple, species-specific suitability measures. While more complex analyses of habitat suitability exist, particularly for RIRA (Liu et al., 2012), we chose these measures to provide not only a straightforward and transparent analysis but also to be agnostic to the conditions at a site that would be responsive to restoration efforts. This allows the analysis to identify marshes that are needed to maintain connectivity, regardless of current condition, that should be considered as high-value targets for habitat conservation and restoration. This analysis, thus, should be paired with current distributions and known habitat requirements of species to fully assess needed restoration of current habitats.

For SMHM, marsh patches >60 ha were ranked higher than smaller marsh patches as this is the minimum acreage thought to sustain a healthy mouse population (USFWS, 2013). Saline marshes were ranked lower than brackish, using salinity gradients identified by (2012) as increasing levels of salinity can reduce vegetation height and structure (Woo & Takekawa, 2012), which is important for high-tide refugia. For the analysis of future restoration opportunities, presence of high-tide refugia in the form of horizontal levees and marsh migration space was ranked higher than marshes lacking refugia. See Table B1 for ranking weights.

For RIRA, marshes >100 ha were the highest ranked, followed by marshes 4.7 ha to 100 ha. Blocks of habitat >100 ha in area have been found to support the highest density of RIRA (Evens & Collins, 1992) and the average home range of RIRA was found to be 4.7 ha in a radiotelemetry study in South SF Bay (Albertson, 1995). Marshes that contained a majority of core habitat relative to edge habitat were also ranked higher than majority-edge-habitat marshes. For the analysis of future restoration opportunities, presence of high-tide refugia was also more highly ranked than it was for the SMHM analysis. See Table B2 for ranking weights.

---

<sup>1</sup> Layer updated from Adaptation Atlas using updated land cover data from the 2016 National Land Cover Database

Table B1. Weights used for area-weighted patch suitability for salt marsh harvest mice.

<b>Salt Marsh Harvest Mouse</b>	<b>Class</b>	<b>Score</b>
Patch size	0.5 to 60 ha	1
	>60 ha	2
Vegetation type (saline gradient)	Brackish	2
	Salt	1
Refugia patch-edge area ratio (for habitat restoration opportunities only)	< 10%	0
	>10%	1

Table B2. Weights used for area-weighted patch suitability for Ridgway's rails.

<b>Ridgway's Rail</b>	<b>Class</b>	<b>Score</b>
Patch size	>100 ha	3
	4.7 ha - 100 ha	2
	0.5 to 4.7 ha	1
Core to edge ratio	>=50%	2
	< 50 %	1
Refugia patch-edge area ratio (for habitat restoration opportunities only)	< 10%	0
	>10%	1

## Dispersal Probabilities

Species-specific dispersal probabilities were derived from records of long-distance dispersal (LDD) events in the scientific literature. For RIRA, observations from radiotelemetry and individually-identifiable marked birds. LDD observations of RIRA (Albertson, 1995; Casazza et al., 2008) and closely related species and subspecies (*R. o. levipes* [Zemba et al., 1985, 1989], *R. crepitans saturatus* [Roth et al., 1972]) were included in the dispersal probability estimation. For SMHM, LDD observations of a closely-related species, *Reithrodontomys megalotis* (Clark et al., 1988), were used as LDD movement data has yet to be recorded for SMHM (Smith et al., 2018). LDD observations were converted into dispersal probability as a function of distance using a negative exponential function (Fletcher & Fortin, 2018).

## Dispersal Path: Least Cost Path Analysis

Instead of straight-line distance between marsh patches, a least-cost path (LCP) analysis was used to calculate the single best ("least-cost") path from each pair of patches. An LCP considers characteristics of the landscape to develop more biologically and behaviorally accurate estimates of potential movement paths across the landscape. Dispersal paths of RIRA were generated to generally follow the shoreline (Figure B1). Based on expert opinion, these paths were generated by considering movement across open water and higher elevations to be higher cost movements. Paths deviate from the shoreline when crossing open water or hills, for example, results in a lower-cost path.

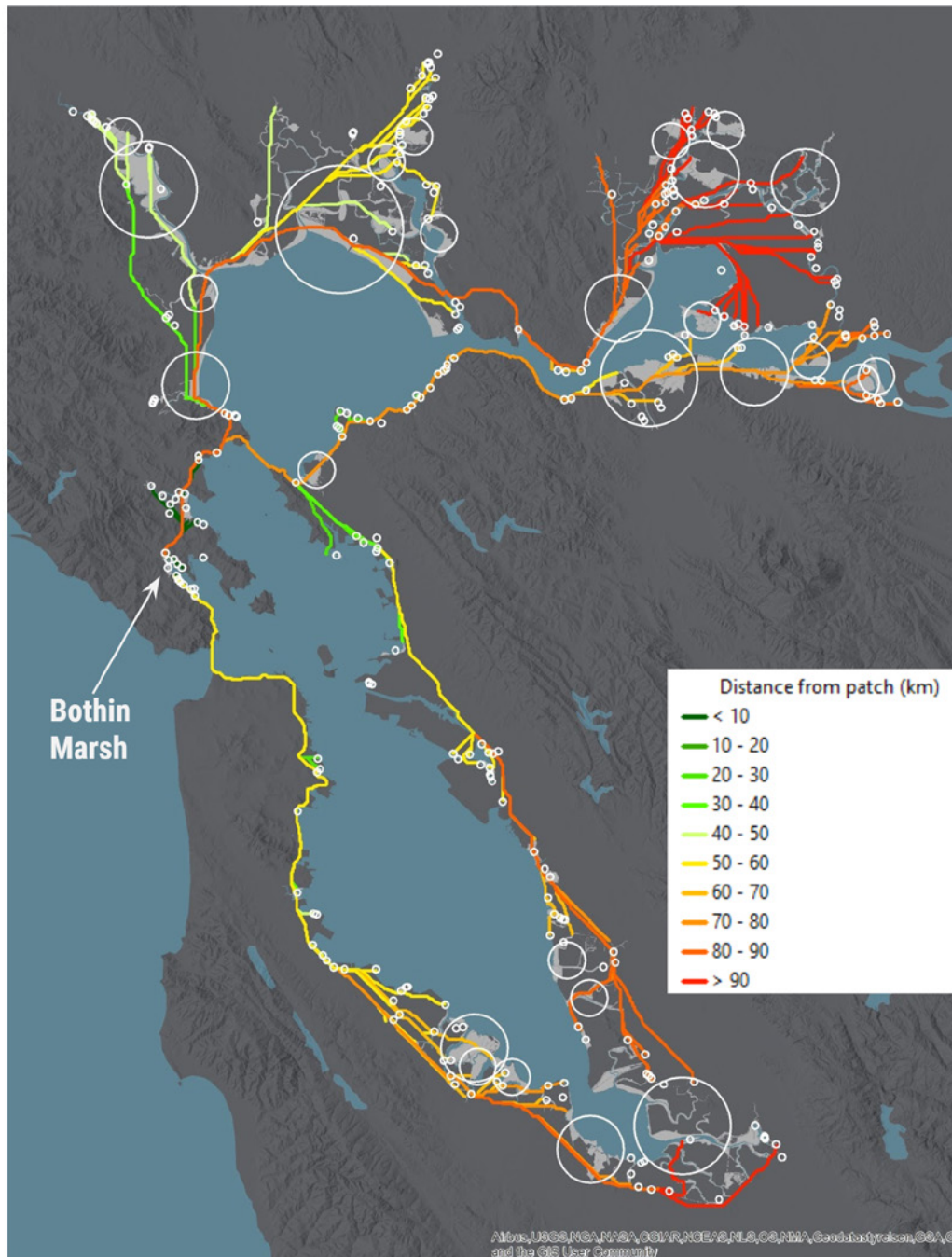


Figure B1. Example of least-cost paths calculated for Ridgway's Rails from Bothin Marsh to all other marshes. Paths were calculated for all marsh pairs.

LCPs for SMHM were also generated by considering open water and higher elevations to be higher resistance. Resistance values for SMHM were used from an existing analysis of connectivity based on the population genetics in Suisun Bay (Mark J. Statham & Sacks, 2019).

LCPs between all pairs of patches were calculated using ArcPy scripting in ArcGIS. Resistance surfaces were generated from open water (BAARI, 2017) and elevation data layers (USGS 2018). LCPs were calculated using the Cost Distance and Cost Path as Polyline tools. Paths were calculated to the boundary of a patch, which is considered more relevant to connectivity than calculating paths to the patch centroid (Saura & Rubio, 2010).

# References

- Albertson, J. D. (1995). Ecology of the California clapper rail in the south San Francisco Bay [PhD Thesis]. San Francisco State University.
- BAARI. (2017). Bay Area Aquatic Resource Inventory (BAARI) Version 2.1 GIS Data. SFEI. <http://www.sfei.org/data/baari-version-21-gis-data>
- Bias, M. A., & Morrison, M. L. (1999). Movements and home range of salt marsh harvest mice. *The Southwestern Naturalist*, 348–353.
- CA OPC. (2018). State of California Sea-Level Rise Guidance: 2018 Update (p. 84). California Ocean Protection Council, California Natural Resources Agency. [https://opc.ca.gov/webmaster/ftp/pdf/agenda\\_items/20180314/Item3\\_Exhibit-A\\_OPC\\_SLR\\_Guidance-rd3.pdf](https://opc.ca.gov/webmaster/ftp/pdf/agenda_items/20180314/Item3_Exhibit-A_OPC_SLR_Guidance-rd3.pdf)
- Calabrese, J. M., & Fagan, W. F. (2004). A comparison-shopper's guide to connectivity metrics. *Frontiers in Ecology and the Environment*, 2(10), 529–536. [https://doi.org/10.1890/1540-9295\(2004\)002\[0529:ACGTCM\]2.0.CO;2](https://doi.org/10.1890/1540-9295(2004)002[0529:ACGTCM]2.0.CO;2)
- California Department of Transportation. (2020). California Rail Network. [https://gis.data.ca.gov/datasets/5386fb3a64c340fca591267f77afa1a0\\_0?geometry=-161.070%2C31.113%2C-77.442%2C43.313](https://gis.data.ca.gov/datasets/5386fb3a64c340fca591267f77afa1a0_0?geometry=-161.070%2C31.113%2C-77.442%2C43.313).
- California Energy Commission. (2020). California Electric Substation. [https://cecgis-caenergy.opendata.arcgis.com/datasets/7f37f2535d3144e898a53b9385737ee0\\_0](https://cecgis-caenergy.opendata.arcgis.com/datasets/7f37f2535d3144e898a53b9385737ee0_0)
- Casazza, M. L., Overton, C. T., Takekawa, J. Y., Rohmer, T. M., & Navarre, K. (2008). Breeding behavior and dispersal of radio-marked California clapper rails. *Western Birds*, 39, 101–106.
- Cecchetti, A. R., Stiegler, A. N., Graham, K. E., & Sedlak, D. L. (2020). The horizontal levee: A multi-benefit nature-based treatment system that improves water quality and protects coastal levees from the effects of sea level rise. *Water Research X*, 7, 100052. <https://doi.org/10.1016/j.wroa.2020.100052>
- Christianson, L. E., Bhandari, A., & Helmers, M. J. (2012). A Practice-oriented Review of Woodchip Bioreactors for Subsurface Agricultural Drainage. *Applied Engineering in Agriculture*, 28(6), 861–874. <https://doi.org/10.13031/2013.42479>
- Clark, B. K., Kaufman, D. W., Kaufman, G. A., Finck, E. J., & Hand, S. S. (1988). Long-distance movements by *Reithrodontomys megalotis* in tallgrass prairie. *American Midland Naturalist*, 120(2), 276. <https://doi.org/10.2307/2425999>
- Collins, J., & Grossinger, R. (2004). Synthesis of scientific knowledge concerning estuarine landscapes and related habitats of the South Bay Ecosystem. Technical report of the South Bay Salt Pond Restoration Project. (No. 308). San Francisco Estuary Institute. <https://www.sfei.org/documents/synthesis-scientific-knowledge-maintaining-and-improving-functioning-south-bay-ecosystem>
- Dusterhoff, S., McKnight, K., Grenier, L., & Kauffman, N. (2021). Sediment for Survival: A Strategy for the Resilience of Bay Wetlands in the Lower San Francisco Estuary (SFEI Contribution No. 1015). San Francisco Estuary Institute.

- Evens, J., & Collins, J. N. (1992). Distribution, abundance, and habitat affinities of the California clapper rail (*Rallus longirostris obsoletus*) in the northern reaches of the San Francisco Estuary during the 1992 breeding season. Final report to California Department of Fish and Game, Yountville, CA. (p. 26). Avocet Research Associates.
- Fahrig, L., & Merriam, G. (1985). Habitat Patch Connectivity and Population Survival. *Ecology*, 66(6), 1762–1768. <https://doi.org/10.2307/2937372>
- Fletcher, R., & Fortin, M.-J. (2018). Spatial ecology and conservation modeling: Applications with R. Springer.
- Geissel, W., Shellhammer, H., & Harvey, H. T. (1988). The ecology of the salt-marsh harvest mouse (*Reithrodontomys raviventris*) in a diked salt marsh. *Journal of Mammalogy*, 69(4), 696–703. <https://doi.org/10.2307/1381624>
- Ghane, E., Feyereisen, G. W., & Rosen, C. J. (2016). Non-linear hydraulic properties of woodchips necessary to design denitrification beds. *Journal of Hydrology*, 542, 463–473. <https://doi.org/10.1016/j.jhydrol.2016.09.021>
- Gill, R., Jr. (1979). Status and distribution of the California clapper rail (*Rallus longirostris obsoletus*). *California Fish and Game*, 65(1), 36–49.
- Goals Project. (1999). Baylands Ecosystem Habitat Goals. A report of habitat recommendations prepared by the San Francisco Bay Area Wetlands Ecosystem Goals Project. U.S. Environmental Protection Agency, San Francisco, Calif./S.F. Bay Regional Water Quality Control Board, Oakland, Calif.
- Goals Project. (2015). The Baylands and Climate Change: What We Can Do. Baylands Ecosystem Habitat Goals Science Update 2015, prepared by the San Francisco Bay Area Wetlands Ecosystem Goals Project. California State Coastal Conservancy.
- Liu, L., Wood, J., Nur, N., Salas, L., & Jongsomjit, D. (2012). California clapper rail (*Rallus longirostris obsoletus*) population monitoring: 2005–2011. PRBO technical report to the California Department of Fish and Game. PRBO Conservation Science. [http://www.prbo.org/refs/files/12220\\_LeonardLiu2012.pdf](http://www.prbo.org/refs/files/12220_LeonardLiu2012.pdf)
- NLCD. (2016). NLCD 2016 Land Cover (CONUS). Multi-Resolution Land Characteristics Consortium. <https://www.mrlc.gov/data?f%5B0%5D=year%3A2016>
- Overton, C. T. (2007). A review of literature regarding California clapper rail (*Rallus longirostris obsoletus*) demographics, habitat use, home range, movements, and effects of disturbance. Prepared for State Coastal Conservancy San Francisco Estuary Invasive Spartina Project. 12.
- Roth, R. R., Newsom, J. D., Joanen, T., & McNease, L. L. (1972). The daily and seasonal behavior patterns of the clapper rail (*Rallus longirostris*) in the Louisiana coastal marshes. *Proceedings of the Annual Conference of the Southeastern Association of Game and Fish Commissioners*, 26, 136–159.
- Saura, S., Estreguil, C., Mouton, C., & Rodríguez-Freire, M. (2011). Network analysis to assess landscape connectivity trends: Application to European forests (1990–2000). *Ecological Indicators*, 11(2), 407–416. <https://doi.org/10.1016/j.ecolind.2010.06.011>

- Saura, S., & Pascual-Hortal, L. (2007). A new habitat availability index to integrate connectivity in landscape conservation planning: Comparison with existing indices and application to a case study. *Landscape and Urban Planning*, 83(2), 91–103. <https://doi.org/10.1016/j.landurbplan.2007.03.005>
- Saura, S., & Rubio, L. (2010). A common currency for the different ways in which patches and links can contribute to habitat availability and connectivity in the landscape. *Ecography*. <https://doi.org/10.1111/j.1600-0587.2009.05760.x>
- SFEI. (1998). Bay Area EcoAtlas V1.50b4 1998: Geographic Information System of wetland habitats past and present (V1.50b4) [Computer software]. San Francisco Estuary Institute. <http://www.sfei.org/content/ecoatlas-version-150b4-1998>
- SFEI and SPUR. (2019). San Francisco Bay Shoreline Adaptation Atlas: Working with Nature to Plan for Sea Level Rise Using Operational Landscape Units (Publication #915). San Francisco Estuary Institute.
- SFEP. (2011). The State of San Francisco Bay 2011. San Francisco Estuary Partnership. <https://www.sfestuary.org/our-estuary/about-the-estuary/sotb/>
- Smith, K. R., Barthman-Thompson, L. M., Estrella, S. K., Riley, M. K., Trombley, S. N., Rose, C. A., & Kelt, D. A. (2020). Demography of the salt marsh harvest mouse (*Reithrodontomys raviventris halicoetes*) and associated rodents in tidal and managed wetlands. *Journal of Mammalogy*, 101(1), 129–142. <https://doi.org/10.1093/jmammal/gyz183>
- Smith, K. R., Riley, M. K., Barthman–Thompson, L., Woo, I., Statham, M. J., Estrella, S., & Kelt, D. A. (2018). Toward salt marsh harvest mouse recovery: A review. *San Francisco Estuary and Watershed Science*, 16(2). <https://doi.org/10.15447/sfews.2018v16iss2art2>
- Statham, M. J., Aamoth, S., Barthman-Thompson, L., Estrella, S., Fresquez, S., Hernandez, L. D., Tertes, R., & Sacks, B. N. (2016). Conservation genetics of the endangered San Francisco Bay endemic salt marsh harvest mouse (*Reithrodontomys raviventris*). *Conservation Genetics*, 17(5), 1055–1066. <https://doi.org/10.1007/s10592-016-0843-4>
- Statham, Mark J., & Sacks, B. N. (2019). Salt marsh harvest mouse landscape genetics and connectivity within the Suisun Bay Area Recovery Unit. Report to the California Dept. Of Water Resources. (p. 39). [https://markstathamdotcom.files.wordpress.com/2019/12/final\\_report\\_suisun\\_smhm\\_landscape\\_genetic\\_study.pdf](https://markstathamdotcom.files.wordpress.com/2019/12/final_report_suisun_smhm_landscape_genetic_study.pdf)
- Stralberg, D., Applegate, D. L., Phillips, S. J., Herzog, M. P., Nur, N., & Warnock, N. (2009). Optimizing wetland restoration and management for avian communities using a mixed integer programming approach. *Biological Conservation*, 142(1), 94–109. <https://doi.org/10.1016/j.biocon.2008.10.013>
- Taylor, P. D., Fahrig, L., Henein, K., & Merriam, G. (1993). Connectivity is a vital element of landscape structure. *Oikos*, 571–573.
- US Census. (2019). TIGER/Line Shapefile, State, California, Primary and Secondary Roads State-Based Shapefile. <https://catalog.data.gov/dataset/tiger-line-shapefile-2019-state-california-primary-and-secondary-roads-state-based-shapefile#sec-dates>
- USFWS. (2013). Recovery plan for tidal marsh ecosystems of northern and central California (p. 434). U.S. Fish & Wildlife Service. [https://www.fws.gov/sfbaydelta/documents/tidal\\_marsh\\_recovery\\_plan\\_v1.pdf](https://www.fws.gov/sfbaydelta/documents/tidal_marsh_recovery_plan_v1.pdf)

- Vasey, M., Parker, V. T., Callaway, J., Herbert, E. R., & Schile, L. M. (2012). Tidal Wetland Vegetation in the San Francisco Bay-Delta Estuary. *San Francisco Estuary and Watershed Science*, 10(2). <https://doi.org/10.15447/sfews.2012v10iss2art2>
- Woo, I., & Takekawa, J. Y. (2012). Will inundation and salinity levels associated with projected sea level rise reduce the survival, growth, and reproductive capacity of *Sarcocornia pacifica* (pickleweed)? *Aquatic Botany*, 102, 8–14. <https://doi.org/10.1016/j.aquabot.2012.03.014>
- Wood, D. A., Bui, T.-V. D., Overton, C. T., Vandergast, A. G., Casazza, M. L., Hull, J. M., & Takekawa, J. Y. (2017). A century of landscape disturbance and urbanization of the San Francisco Bay region affects the present-day genetic diversity of the California Ridgway's rail (*Rallus obsoletus obsoletus*). *Conservation Genetics*, 18(1), 131–146. <https://doi.org/10.1007/s10592-016-0888-4>
- Zemba, R., Fancher, J. M., Nordby, C. S., & Bransfield, R. J. (1985). Intermarsh movements by light-footed clapper rails indicated in part through regular censusing. *California Fish and Game*, 71(3), 164–171.
- Zemba, R., Massey, B. W., & Fancher, J. M. (1989). Movements and activity patterns of the light-footed clapper rail. *The Journal of Wildlife Management*, 53(1), 39. <https://doi.org/10.2307/3801302>
- Zhang, H., & Gorelick, S. M. (2014). Coupled impacts of sea-level rise and tidal marsh restoration on endangered California clapper rail. *Biological Conservation*, 172, 89–100. <https://doi.org/10.1016/j.biocon.2014.02.016>