REGIONAL ANALYSIS OF

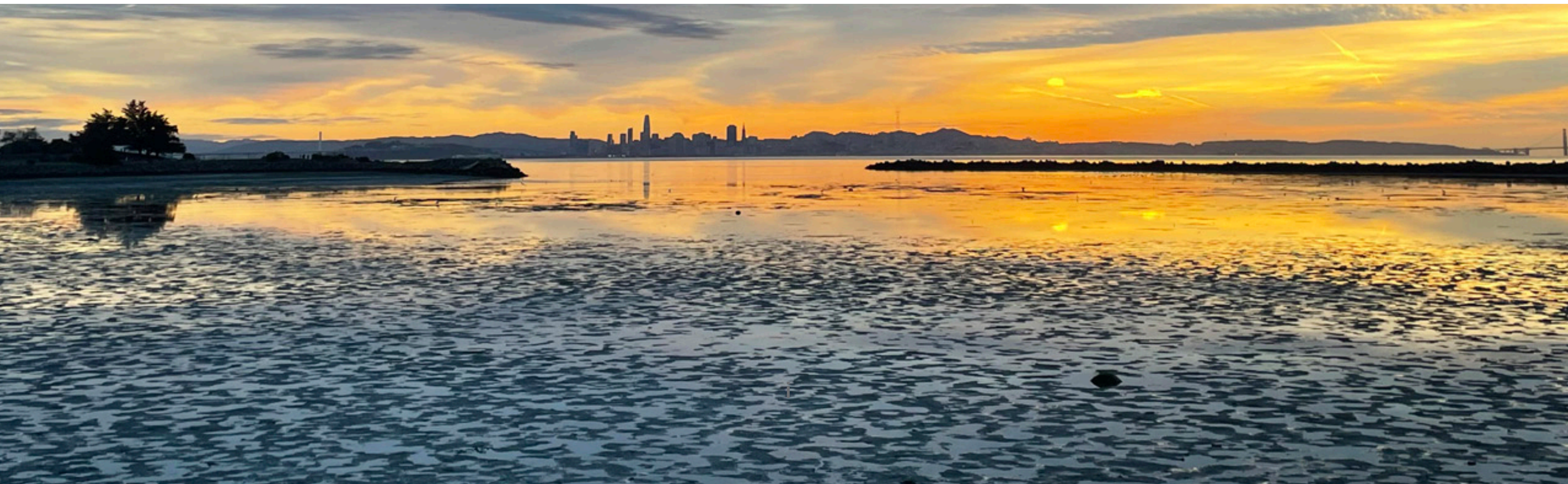
Potential Beneficial Use Locations

SAN FRANCISCO BAY

Conducted for the
San Francisco Bay Regional
Dredged Material Management Plan

SFEI San Francisco Estuary Institute

BAYLANDS
RESILIENCE
FRAMEWORK



Regional Analysis of Potential Beneficial Use Locations

Conducted for the San Francisco Bay Regional Dredged Material Management Plan

A PRODUCT OF THE

BAYLANDS
RESILIENCE
FRAMEWORK

Prepared by

Ellen Plane
Alex Braud
Jeremy Lowe
Kelly Iknayan
Melissa Foley

Funded by

United States Army Corps of Engineers

SFEI San Francisco Estuary Institute

APRIL 2024

SAN FRANCISCO ESTUARY INSTITUTE PUBLICATION #1178

ACKNOWLEDGMENTS

Thank you to the USACE staff who guided the development of the resilience metrics, especially Julie Beagle, Arye Janoff, Justin Yee, and Jade Ishii from the San Francisco District as well as David Smith from the Engineering and Research Development Center (ERDC). We are also grateful to the members of the Wetlands Regional Monitoring Program Technical Advisory Committee (WRMP TAC) who provided valuable feedback on the wildlife support metrics and contributed to the development of the Baylands Resilience Framework for Wildlife Support that underlies this work. Members of the Regional Dredged Material Management Plan Interagency Working Group (RDMMP IWG) also contributed useful guidance on the creation of the resilience metrics, as well as the Gaps Analysis process that led to its development. Finally, we would like to acknowledge the support of Google and the San Francisco Bay Regional Water Quality Control Board; funding from those entities supported other efforts of the Baylands Resilience Framework that are foundational to the resilience metrics presented here.

We also appreciate the contributions of numerous current and former SFEI staff to the development of this report and the associated metrics, especially Gwen Miller, Kat Palermo, Scott Dusterhoff, Donna Ball, Caitlin Crain, Katie McKnight, Letitia Grenier, Ruth Askevold, Denise Walker, and April Robinson.

SUGGESTED CITATION

San Francisco Estuary Institute. 2024. Regional Analysis of Potential Beneficial Use Locations. Conducted for the San Francisco Bay Regional Dredged Material Management Plan. Prepared by the San Francisco Estuary Institute for the US Army Corps of Engineers, San Francisco District. SFEI Report #1178. San Francisco Estuary Institute, Richmond, CA.

Version 1.0 (April 2024)

REPORT AVAILABILITY

Report is available at sfei.org

COVER AND FRONT MATTER CREDITS

Photo by Ellen Plane

IMAGE PERMISSION

CONTENTS

INTRODUCTION

Numerous planning efforts in the San Francisco Bay Area (Bay Area) aim to increase the resilience of the baylands and shoreline to rising sea levels. Due to the region's commitment to protecting and restoring bayland habitats, "nature-based solutions" such as wetlands and beaches are often promoted as the preferred way to enhance resilience. However, the resilience of the baylands has not been clearly defined. The San Francisco Estuary Institute (SFEI) and partners are engaged in a long-term effort to define and quantify baylands resilience for San Francisco Bay (Bay) through the Baylands Resilience Framework. In developing this framework, we ask: How can baylands resilience be measured? How can it be increased?

By defining elements of resilience for a range of shoreline ecosystem services and then mapping metrics associated with those elements, we can begin to understand the relative resilience of shoreline ecosystems around the region. This understanding can help inform (1) identification of appropriate adaptation strategies to improve resilience, and (2) tracking of changes in resilience over time in response to adaptation actions. The present study, conducted in partnership with the US Army Corps of Engineers San Francisco District (USACE), maps metrics associated with two ecosystem services—wildlife support and flood attenuation—and the feasibility of beneficially using sediment.

THE BAYLANDS RESILIENCE FRAMEWORK

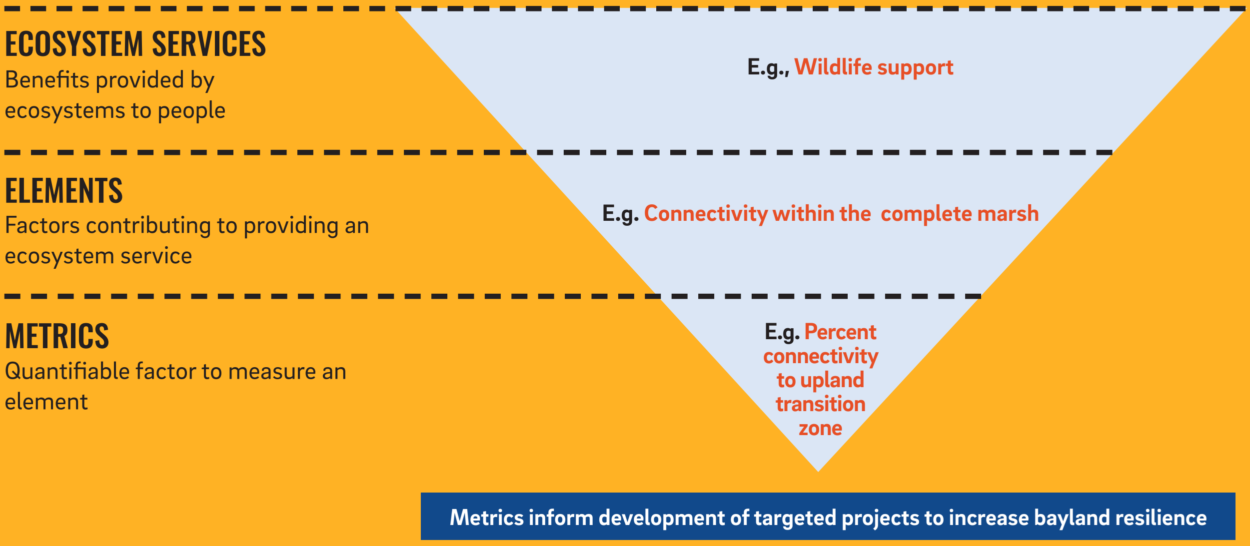
SFEI helps planners, regulatory agencies, community-based organizations, and other stakeholders make informed decisions about where and how to implement nature-based solutions for sea-level rise adaptation. The Adaptation Atlas identified places suitable for various types of nature-based solutions, including tidal marshes, mudflats, eelgrass, beaches, and oyster reefs. The *Baylands Resilience Framework* goes beyond opportunity mapping, creating tangible tools to inform the development of targeted projects in a data-driven process. These resilience metrics provide a starting point for site design and planning and the regional context needed for comparison when making strategic decisions on prioritization.

To tackle the question of what constitutes bayland resilience, an organizing principle is needed to divide the relevant concepts into understandable categories. The Baylands Resilience Framework is organized around the concept of "ecosystem services": the benefits provided by ecosystems to people. When baylands planners and managers talk about resilience, they are often interested in ensuring the persistence of the ecosystem services that a well-functioning shoreline can provide: services like flood attenuation, carbon sequestration, water quality improvement, wildlife support, and recreation. The goal of the Baylands Resilience Framework is to define and measure the factors that contribute to the resilience of bayland ecosystem services to climate change.

We are approaching work on the Baylands Resilience Framework in three stages, starting with broad concepts and honing into specific quantitative measurements (Figure 1). For each ecosystem service (Figure 2), we create a list of elements (Figure 3): the ways that marshes provide the service. Next, we develop metrics to describe each of those elements (Figure 4).

BAYLANDS RESILIENCE FRAMEWORK

Purpose: to measure the resilience of baylands ecosystem services to sea-level rise and other flooding



ECOSYSTEM SERVICES
Benefits provided by ecosystems to people

E.g., Wildlife support

ELEMENTS
Factors contributing to providing an ecosystem service

E.g. Connectivity within the complete marsh

METRICS
Quantifiable factor to measure an element

E.g. Percent connectivity to upland transition zone

Metrics inform development of targeted projects to increase bayland resilience

Figure 1. The Baylands Resilience Framework breaks down the process of understanding resilience into three stages, starting with broad ecosystem services and honing down to specific, quantifiable metrics.

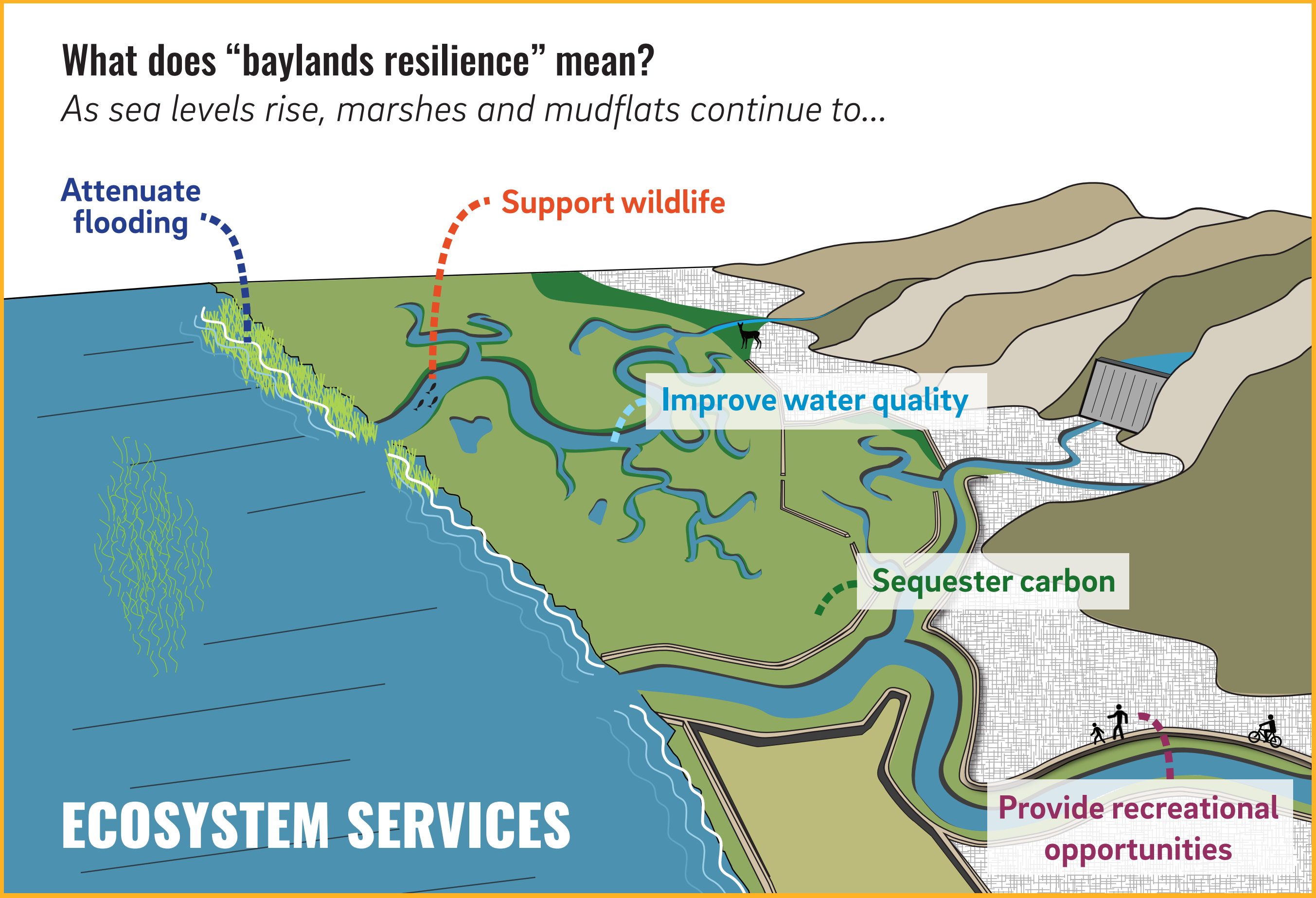


Figure 2. The Baylands Resilience Framework uses the concept of “ecosystem services” as an organizing principle.

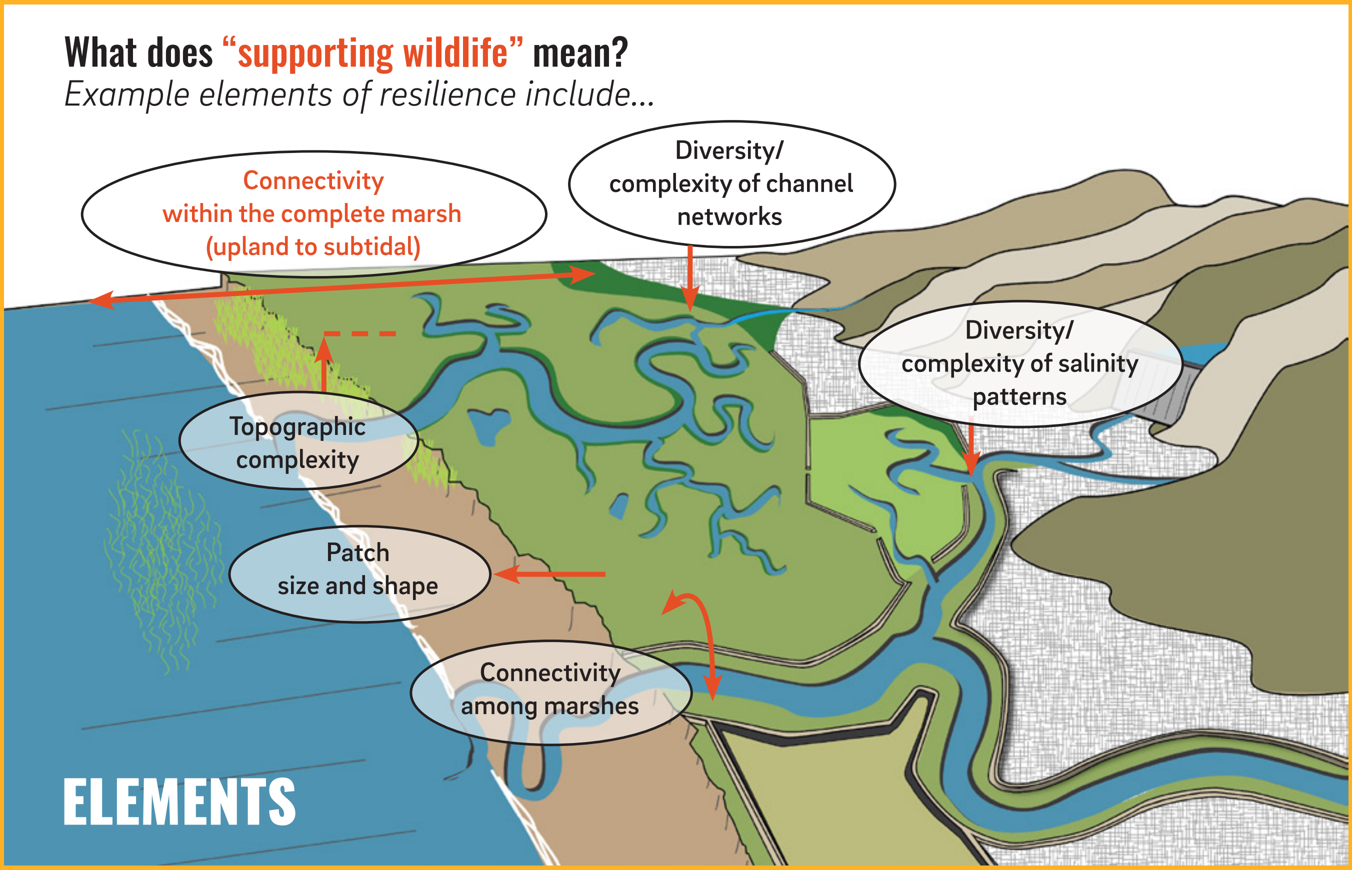


Figure 3. Each ecosystem service can be broken down into constituent elements of resilience.

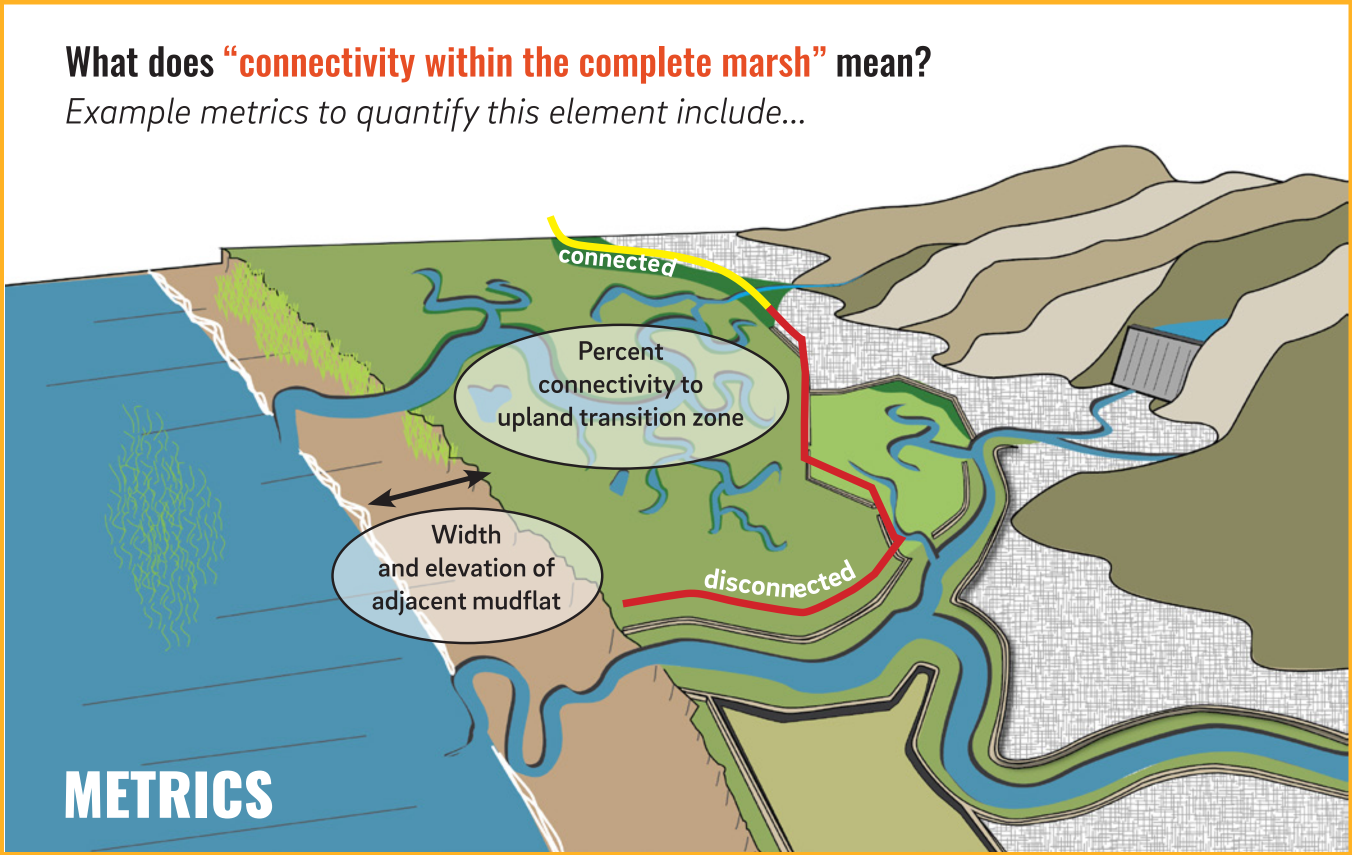


Figure 4. Each element can be described by a set of quantifiable metrics.

The first ecosystem service we tackled was wildlife support. The Baylands Resilience Framework for Wildlife Support, developed by SFEI and funded by Google, defines the essential elements of tidal marshes for supporting wildlife, such as connectivity between marshes and the complexity of channel networks. Next, we defined elements of resilience for flood attenuation, such as attenuation of waves, storm surges, and combined flooding. These elements are described in the Baylands Resilience Framework for Flood Attenuation (final draft in progress). Once the elements of resilience are defined, they can be broken out into quantifiable metrics. In this report, we describe the metrics we have mapped for wildlife support and flood attenuation. Outside of the ecosystem service framework, we also explore additional placement feasibility metrics relevant for sediment placement.

The metrics mapped for this study describe the elements of resilience associated with wildlife support (section A), flood attenuation (section B), and the feasibility of sediment placement (section C). The metrics studied here were chosen to inform decision-making about the beneficial use of sediment, including dredged material from San Francisco Bay's navigational channels as well as from upland and other sources. Beneficial use of dredged material is important because it provides sediment to create and sustain marshes and mudflats over time as sea levels rise. These metrics are the first tranche to be mapped; future efforts will map additional metrics associated with wildlife support and flood attenuation, and create new frameworks and metrics for additional ecosystem services like carbon sequestration and water quality improvement.

The USACE San Francisco Bay Regional Dredged Material Management Plan (RDMMP) will identify a long-term plan for managing dredged material from the 11 federally authorized channels in San Francisco Bay. The objectives of the RDMMP planning process are to:

> Ensure San Francisco Bay's federally dredged navigation channels have placement site capacity over 20 years, to identify the array of dredged material placement alternative plans, and to determine the federal standard base plan for USACE maintenance dredging projects (USACE San Francisco District 2023).

The metrics produced for this report support the development of the RDMMP by providing quantitative data that allows comparison of tradeoffs and benefits between potential dredged material placement sites, for both existing marshes and future marshes in the diked baylands. At present, the metrics can help provide quantitative justification for federal cost-share and help prioritize sites for future beneficial use pilot projects. This is part of USACE's intent to increase the beneficial use of dredged materials significantly in the near future, given the critical connection to shoreline resilience, biodiversity and wildlife support, and flood attenuation. In the future, the metrics can be re-analyzed to track how beneficial use projects have changed shoreline resilience for wildlife support and flood attenuation. In many cases, assessing combinations of metrics may be most useful to inform decision-making. For instance, marshes that are low in elevation, drowning due to sea-level rise, and lacking sediment supply from adjacent wide and high mudflats may be particularly well-suited for sediment placement.

Though the metrics described in this report were developed specifically to support the development of the RDMMP, they can be used to support beneficial use projects for dredged material from non-federal channels and to support restoration and adaptation projects more broadly. For example, the development of the Baylands Resilience Framework for Wildlife Support (SFEI 2023a), a key precursor to this document, and wildlife support metrics were informed by the Technical Advisory Committee of the Wetlands Regional Monitoring Program (WRMP). Many of the metrics developed for the RDMMP will be used and improved by the WRMP as part of the larger regional monitoring and adaptive management analysis.

The desktop analyses conducted in this study are not meant to serve as a definitive or final evaluation of bayland health or resilience. The WRMP is developing a thorough monitoring plan that will create a framework for monitoring to better understand the health, function, and persistence of established and restoring tidal wetlands in the San Francisco Estuary.

Despite data gaps and data quality limitations, this early analysis is an important first step to take given the urgency of implementing restoration projects and the challenge of limited resources. The metrics can be used to compare relative resilience across restoration sites, even if they do not perfectly capture real-world conditions, and help managers weigh the benefits of restoring certain sites before others. We hope the metrics will be used in their current form to inform today's decision-making. They will continue to be improved and refined over time as new data sets become available and our understanding of bayland processes evolves.

DOCUMENT STRUCTURE

The resilience metrics mapped for this study are organized according to ecosystem services. Each metric maps an element of resilience described in one of the ecosystem service framework documents. For each metric, we briefly describe the following:

(1) the relevance of the metric to baylands resilience;

(2) the application of the metric to decision-making for bayland restoration, especially beneficial use;

(3) an example of the metric as applied to a San Francisco Bay marsh or diked bayland location; and

(4) the method used to map the metric, as well as ideas for future improvement.

To link to a **web map of all the metrics for the whole Bay**, please visit:

- www.sfei.org/projects/regional-analysis-beneficial-use-locations

For more information on the relevance of each metric to baylands resilience, please refer to:

- Baylands Resilience Framework for San Francisco Bay: Wildlife Support
- Baylands Resilience Framework for San Francisco Bay: Flood Attenuation (in progress)

For more information on the method used to map each metric, please refer to:

- Appendix A: Expanded Methods

ANALYSIS UNITS

The metrics developed for this study are reported at the scale of analysis units, which include both marsh units and diked bayland units. The analysis units are based on data from the **Baylands Habitat Map 2020** (included as a foundational layer in the web map).

> **Marsh units** include tidal marsh, muted marsh, intertidal channels, and marsh ponds and pannes. In some cases, recently restored areas that have yet to accrete to marsh elevation were also added despite classification as tidal flat or shallow subtidal. Marsh units enclose one or more tidal watersheds. They are bounded by non-vegetated open water features (e.g., subtidal channels, tidal flat), upland features (including levees and transition zone), and creeks that are connected to fluvial watersheds. We used perennial creeks mapped in the National Hydrography Dataset extending from the estuarine-terrestrial transition zone (the inland boundary of the Operational Landscape Unit or OLU boundary (SFEI and SPUR 2019) to the Bay edge.
>
> **Diked bayland units** are areas that historically had full tidal connection to the Bay but today are cut off from full tidal action by dikes, levees, etc. This includes areas within the historical baylands boundary that are below extreme astronomical tides (approximately 2-year flood return), areas disconnected from the tides, and undeveloped areas. For the purposes of this study, we consider these diked baylands to be areas that could be restored to tidal action in the future, whether intentionally or unintentionally. The diked baylands layer includes salt ponds (active and former), diked agricultural baylands, and diked seasonal wetlands, including duck clubs.

Ownership and current management regime are not considered in this study, and the metrics are not meant to constitute a management plan. For example, named marshes that are managed as part of the same unit may be categorized as multiple units in this analysis.

To create a manageable set of analysis units, we removed small units less than 10,000 square meters (2.5 ac) and removed strips narrower than 10 meters. In addition, we split units using an adapted version of the SFEI Shoreline Inventory (SFEI 2016) to separate marshes divided by human-engineered features like berms and levees, including remnant levees.

Most metrics are analyzed for both marshes and diked baylands. Some are only applicable to one type of unit. For clarity, we use “analysis units” when describing the full set of units (including both marshes and diked baylands), and “marsh units” or “diked bayland units” when describing the sets separately.

We report most of the metric results as “quantiles” or rank order values relative to the distribution of values for all the analysis units. The rank order values are divided into groups, so there are the same number of analysis units in each group. The groups allow comparison between analysis units across the region. The threshold values separating each group are rounded for ease of interpretation and do not necessarily have a physical or ecological meaning.

USING THE WEB MAP

A web map displaying the metrics described in the following chapters is linked from: www.sfei.org/projects/regional-analysis-beneficial-use-locations. In addition to the results for each metric (provided at the analysis unit scale), we also include foundational layers used to calculate the metrics. For example, we include elevation relative to the tides (z*, see section A4.1 for more details) as well as estuarine-terrestrial transition zone layers. These layers are the basis for many of the metrics and serve as accompanying information to help understand the results of the various analyses described below.

We suggest opening the web map and reviewing each metric in tandem with the text included in the report. OLU bookmarks are included in the web map to facilitate easy navigation around the region.

Data Quality and Confidence

The metrics produced here were created entirely using desktop analysis using available datasets and have not undergone local ground-truthing. Elevation data in particular introduced uncertainty into the development of the Bayland Habitat Map 2020 and several of our metrics. To create a regional digital elevation model (DEM), we merged LiDAR datasets collected at different times. In some places, the LiDAR data is outdated and natural and anthropogenic changes have modified the terrain since it was collected. In addition, the quality of LiDAR data varies spatially due to factors such as sensor calibration, atmospheric conditions, and vegetation. Variations in data quality across space can result in inconsistencies in resulting metrics.

To address these uncertainties, ground truthing will be a crucial step for future iterations of this work. Detailed on-site measurements and observations can validate and refine remotely sensed data and improve the parameters we used as inputs in developing the metrics. Additionally, ground truthing provides essential context and local knowledge, aiding in the interpretation and validation of the metrics. We anticipate close collaboration with the Wetlands Regional Monitoring Program (WRMP) to bring ground-truthed data into the process and improve the quality of the resilience metrics in the future. The metrics included in this report should be considered a first-pass effort, and future iterations will improve the quality and usability of the results. We will continue to expand and improve the metrics as the Baylands Resilience Framework effort progresses.

A WILDLIFE SUPPORT METRICS

BAYLANDS RESILIENCE FRAMEWORK FOR WILDLIFE SUPPORT

Much of the work on baylands restoration and resilience conducted in San Francisco Bay over the past few decades has focused on improving conditions for habitats and species (Goals Project 1999, 2015, USFWS 2013). A robust body of knowledge exists regarding the elements of San Francisco Bay marsh systems that are needed to sustain the ecosystem service of native wildlife support. By wildlife support, we mean providing habitat and resources for a full suite of baylands-dependent wildlife, including rare and endemic marsh species such as Ridgway's rail (*Rallus obsoletus obsoletus*) and salt marsh harvest mouse (*Reithrodontomys raviventris*); nursery and foraging habitat for estuarine and anadromous fish; overwintering, migratory stopover, and breeding habitat for waterbirds; and primary productivity.

The Baylands Resilience Framework for Wildlife Support synthesizes the elements needed for functional and resilient marshes that support wildlife (SFEI 2023a). The metrics mapped for this analysis follow from the elements identified in the Baylands Resilience Framework (Table A1). Not every element in the Baylands Resilience Framework has an associated mapped metric in this report.

Table A1. Each metric mapped for this analysis contributes to describing one of the elements of the Baylands Resilience Framework for Wildlife Support.

Framework Element	Metric
A1. Connectivity within the complete marsh	A1.1 Transition zone connectivity
	A1.2 Mudflat connectivity
A2. Connectivity among marshes	A2.1 Patch connectivity
A3. Spatial scale	A3.1 Patch size and compactness
A4. Topographic complexity	A4.1 Marsh elevation
	A4.2 Marsh pannes and unvegetated:vegetated ratio
	A4.3 Marsh islands, mounds, and natural levees
A5. Redundancy	A5.1 Redundancy of complete marshes
A6. Diversity/complexity of salinity	A6.1. Tidal connectivity
A7. Time scale	A7.1 Rate of vertical accretion

A1.1

WILDLIFE SUPPORT METRICS

TRANSITION ZONE CONNECTIVITY

SUMMARY OF METRIC

Estuarine-terrestrial transition zones connect marshes to watersheds, provide space for marsh migration with sea-level rise, and provide essential high-water refuge for marsh wildlife (Figure A1.1.1). This study identifies opportunities to preserve existing transition zone connections and create new connections. We use multiple ways of mapping the transition zone, using the best available science to capture a broad suite of transition zone services.

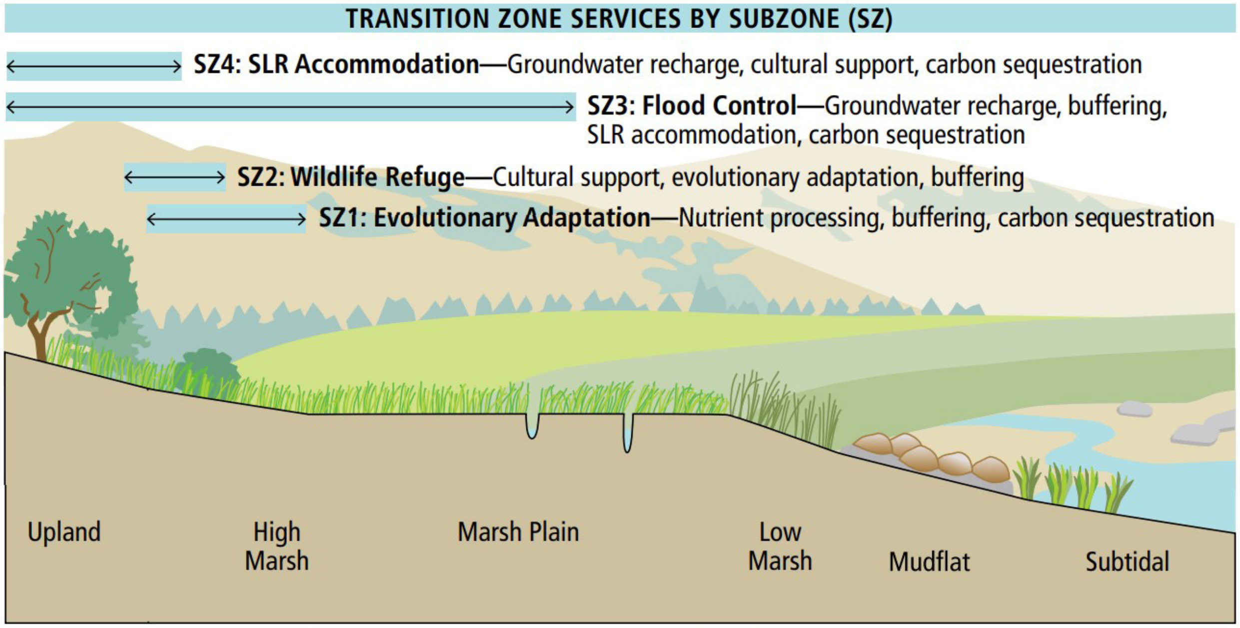


Figure A1.1.1 The Baylands Goals Update identified the ecosystem services provided by different subzones of the transition zone. Figure from Goals Project 2015.

RELEVANCE

Creating “complete marshes” connected from subtidal to uplands is important for improving baylands quality and resilience for wildlife (Goals Project 2015). Complete marshes consisting of subtidal, mudflat, marsh, and transition zone habitat provide a full suite of baylands ecosystem functions and benefits. The estuarine-terrestrial transition zone (hereafter, “transition zone”) provides a range of ecosystem services including flood protection, nutrient processing, and support for diverse native wildlife (Lowe and Bourgeois 2015; Figure A1.1.1). Critical transition zone services in the context of sea-level rise are high water refuge for marsh wildlife and space for natural upland migration of marshes with sea-level rise (“migration space”). Around much of

San Francisco Bay, connections between marshes and transition zones have been interrupted by development. Given the lack of protected, undeveloped transition zones and migration space around most of the Bay, even marginal transition zones (e.g., on levees) can be valuable, unless they increase the threat of predators and invasive species.

APPLICATION

The maps developed for this project can help identify (1) existing marshes with good transition zone connectivity that should be preserved; (2) existing marshes with barriers to transition zone connectivity that could be removed; and (3) diked baylands where complete marshes could be restored through restoration (including sediment placement) projects. Note that this analysis includes all undeveloped transition zones (no buildings/impervious surfaces) but does not specify whether the transition zone is protected by conservation easements or public ownership. Preventing further development in transition zones that could be connected to future marshes is a key step to improving marsh resilience. Some analysis of the "protected" status of marsh migration space is available in the Adaptation Atlas (pages 88 and 242 in SFEI and SPUR 2019); however, further investigation at any particular site of interest is warranted to ensure accuracy.

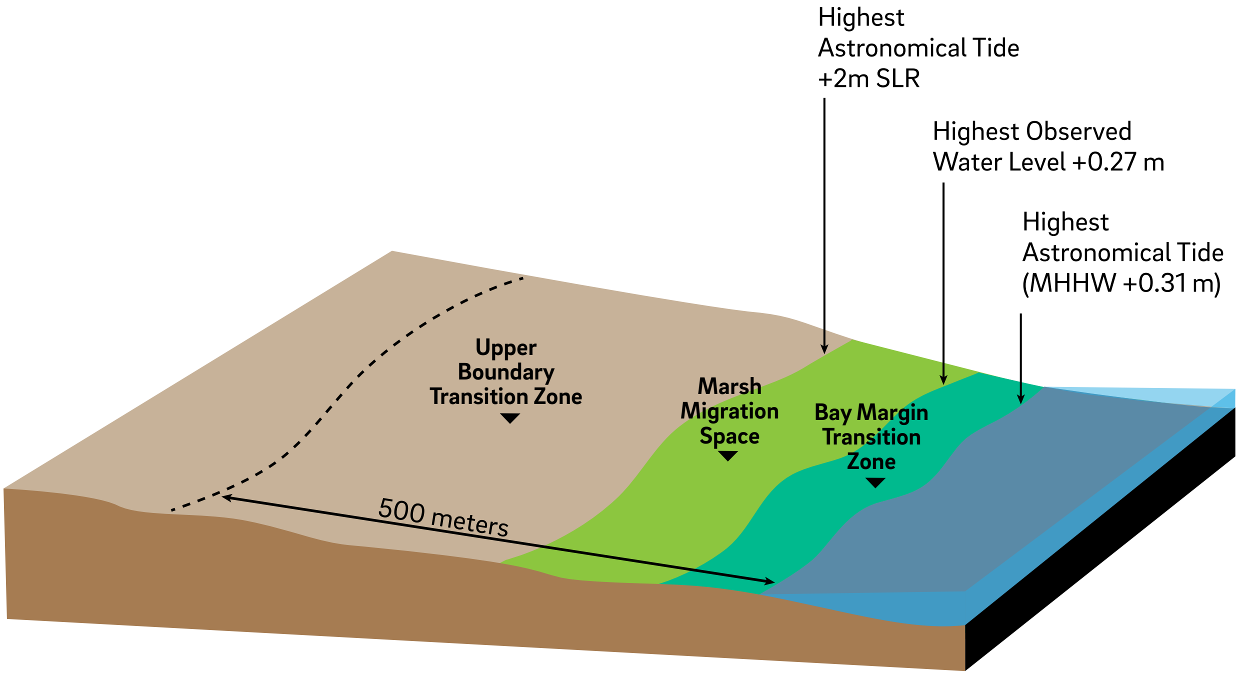
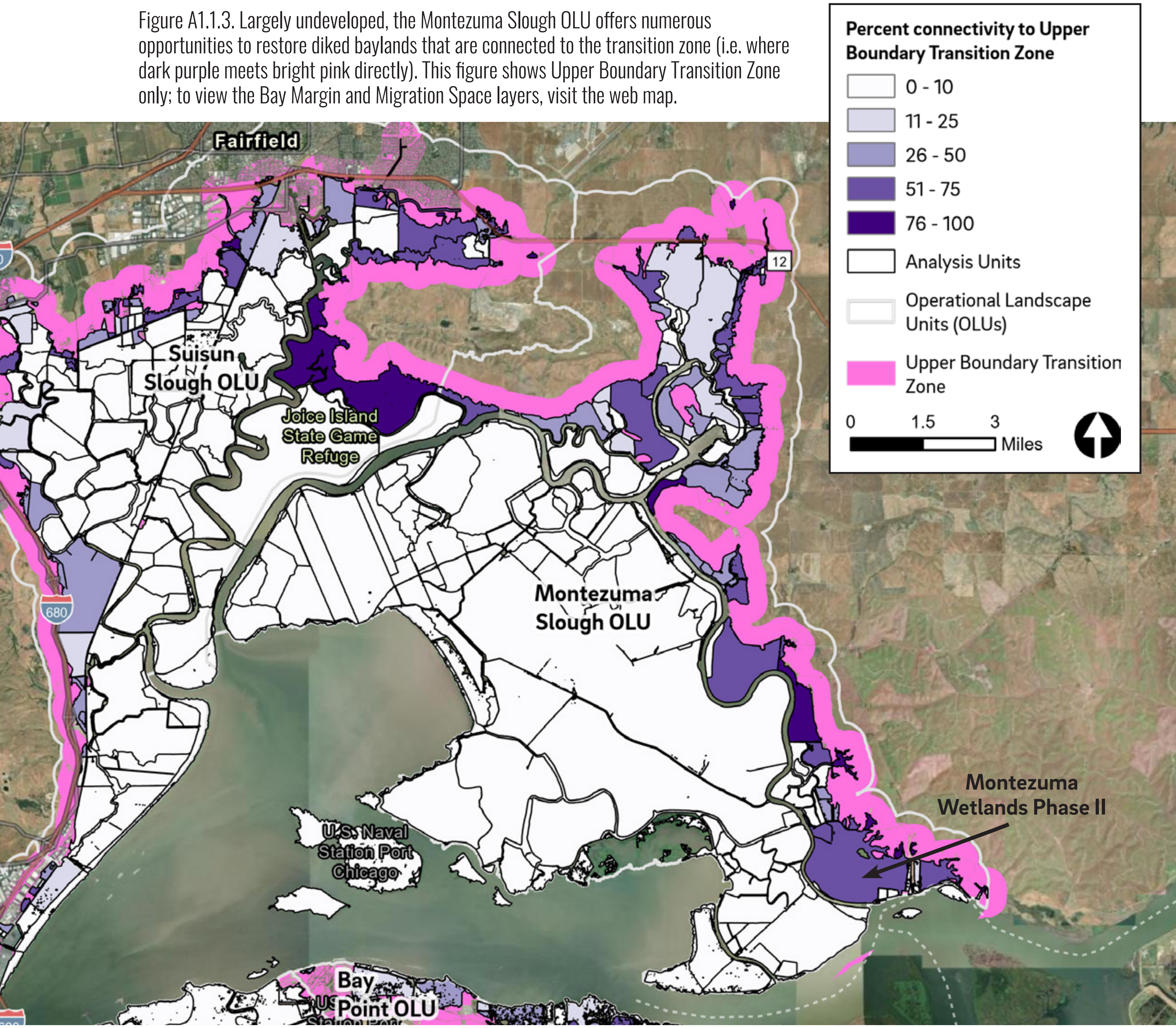


Figure A1.1.2 Three methods for delineating transition zones were used in this analysis: the Marsh Migration Space method used in the Adaptation Atlas (SFEI and SPUR 2019), as well as the Bay Margin and Upper Boundary Transition Zone definitions used in the Baylands Ecosystem Habitat Goals Update (Robinson et al. 2017a, Fulfrost 2018).

EXAMPLE

The Montezuma Wetlands Phase II restoration site is a good example of a complete marsh restoration project opportunity with future wetland connectivity to protected transition zone habitat. Landward of the diked baylands of the Montezuma OLU is largely undeveloped agricultural land and open space (Figure A1.1.3). The percent connectivity to Upper Boundary Transition Zone metric shows that the diked baylands all along the edge of Suisun Marsh have high connectivity to transition zone. If protected, restorations in this area will have high resilience according to this metric as they can provide high water refuge for wildlife and marsh migration opportunities with sea-level rise.

Figure A1.1.3. Largely undeveloped, the Montezuma Slough OLU offers numerous opportunities to restore diked baylands that are connected to the transition zone (i.e. where dark purple meets bright pink directly). This figure shows Upper Boundary Transition Zone only; to view the Bay Margin and Migration Space layers, visit the web map.



METHOD

To measure percent connectivity between marsh and transition zone, we first needed to identify the transition zone. Multiple approaches have been proposed in this region for defining and mapping transition zone (see Science Foundation Chapter 4 of Goals Project 2015 as well as Robinson et al. 2017, 2018). To capture the range of transition zone types and the services they cover, we used three definitions (Figure A1.1.2):

- The **Bay Margin Transition Zone** is based on elevation relative to the tides and is best for identifying existing transition zone habitat, particularly the areas providing high water refuge for marsh wildlife. We used the layer created by Brian Fulfrost in 2018 for the SF Bay Joint Venture (Fulfrost 2018). This layer is best for capturing narrow transition zone opportunities on levees, which we removed from the other two layers to focus on more substantial migration space and transition zone opportunities.
- **Marsh Migration Space** is based on future flood levels and is best for identifying opportunities for marsh migration with sea-level rise. We created a new layer by adapting the migration space method described in the Adaptation Atlas (SFEI and SPUR 2019).
- The **Upper Boundary Transition Zone** is based on a lateral buffer (Robinson et al. 2017) and is best for identifying areas supporting the broad range of ecosystem processes and services provided by the transition zone that are not necessarily solely dependent upon elevation. These include refuge for marsh wildlife, access for upland wildlife to food and resources from the marsh, gradients in salinity, soil moisture, and temperature, and unique habitats like alkali wetlands and salt ponds (Robinson 2018). We created a new layer using the method described in (Robinson et al. 2017).

The connectivity analysis quantifies the length and percentage of the “back of the marsh” (or back of the diked bayland) that is connected to the transition zone according to each of the three definitions.

Both the Migration Space and Upper Boundary Transition Zone layers rely on high-resolution Coastal Change Analysis Program (C-CAP) data to eliminate impervious areas. In some places, low-density residential areas and other unsuitable locations for marsh migration may be identified as feasible marsh migration or transition zone opportunities. It is important to note that there are transition zone wildlife connectivity “barriers” that vary by species and are not fully captured by this analysis. Unpaved roads (e.g., dirt roads) and other narrow or low-contrast barriers may not be picked up in C-CAP. Hydrologic connections under roads and railroads (e.g., on bridges and causeways) can allow transition zone connectivity but may be marked as barriers in this analysis. Future analyses could pursue a more detailed analysis of connectivity by more accurately describing barriers and incorporating a broader range of land use types as possible migration space or transition zone (e.g., decommissioned parking lots).

A1.2

WILDLIFE SUPPORT METRICS

MUDFLAT CONNECTIVITY

SUMMARY OF METRIC

Wide, high-elevation mudflats are valuable habitat for phytobenthos, invertebrates, fish, and shorebirds. They can also support adjacent marshes by attenuating waves, reducing marsh edge erosion, and supplying sediment to marshes. This metric assesses mudflat width and elevation, which is used to determine the duration of exposure during the tidal cycle

RELEVANCE

Mudflats connect subtidal and marsh habitats, allowing aquatic species to access the marsh at high tide and providing important habitat for fish, waterbirds, and invertebrates. Wide mudflats that are exposed for a longer duration at each tidal cycle (i.e., with elevations at the higher end of the intertidal range) are preferred by shorebirds. These mudflats may also have higher coverage of biofilm on the sediment surface, which can support shorebird foraging (Drouet et al. 2013). Tides and wind waves can resuspend sediment on the mudflat and carry it onto the marsh. Shoreline erosion exports sediment from marshes to the mudflats and to the Bay erodible sediment pool (McKnight et al. 2023); however, sediment eroded from the marsh edge can be remobilized for later deposit on the marsh plain (Ferreira et al. 2023). Mudflats are more likely to maintain their width and elevation if they are connected to local creeks for sediment delivery and are not subject to erosional forces from high wind and wave energy (Jaffe et al. 2007). Wide, high-elevation mudflats can attenuate more wave energy and reduce erosion of the marsh edge by reducing waves at normal stages of the tide before they reach the marsh edge (Lacy and Hoover 2011). Sea-level rise may cause transition of mudflats to shallows, affecting mudflat habitat, wave attenuation, and sediment transport onto marshes.

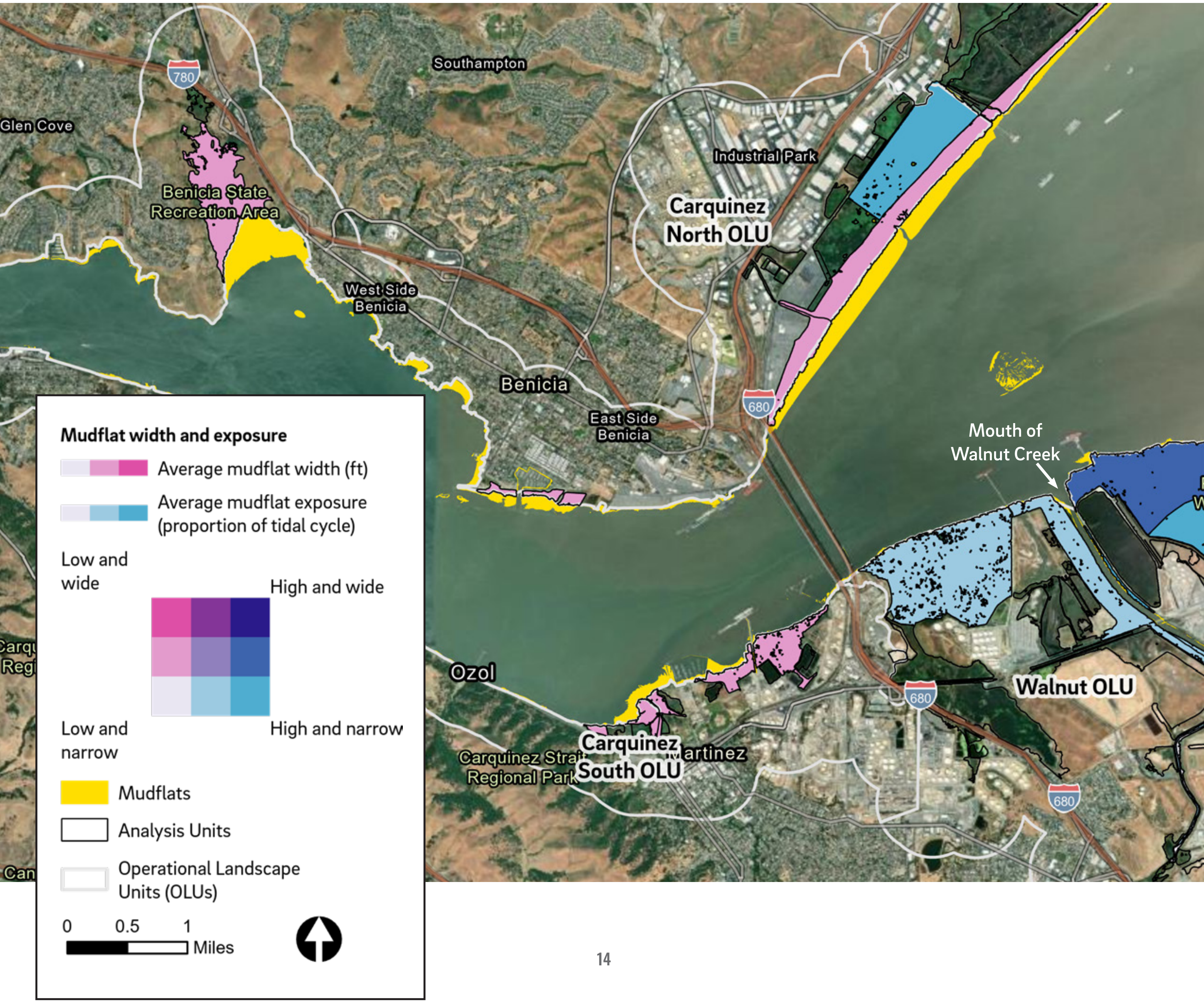
APPLICATION

Understanding the condition of mudflats adjacent to tidal marshes can inform maintenance and enhancement actions. This metric can help identify areas at risk from sea-level rise and areas that have high value for wildlife and may require management actions to maintain. For example, where mudflats are narrow, eroding, or low in elevation due to a lack of sediment supply, sediment placement may help maintain or increase mudflat elevation. Conversely, high elevation, wide mudflats that provide good buffering services for marshes and shorebird foraging have a healthy sediment supply and likely will be self-maintaining in the near-term. Assessing mudflat width in conjunction with other marsh metrics can also inform sediment placement needs and opportunities.

EXAMPLE

Mudflats in the Carquinez North and Carquinez South OLUs are low in elevation and of moderate width, with values in the lower quantile for duration of exposure and the middle quantile for width (Figure A1.2.1). This means that these mudflats may not provide the same benefits for wildlife support as mudflats that are wider and higher in the tidal frame. Mudflats in the Walnut OLU tend to be higher in the tidal frame (longer exposure) but are still relatively narrow compared to other mudflats in the Bay. The narrowness of mudflats in this region are related to the location of the Suisun deep channel, which hugs the southern shore.

Figure A1.2.1. Marsh units of the Carquinez South and Carquinez North OLUs have moderate-width mudflats with shorter durations of exposure, meaning they are submerged for more of the tidal cycle (light pink). In the Walnut OLU, mudflats have longer exposure, meaning they are submerged for less of the tidal cycle. The mudflats to the east of the mouth of Walnut Creek are wider than those to the west



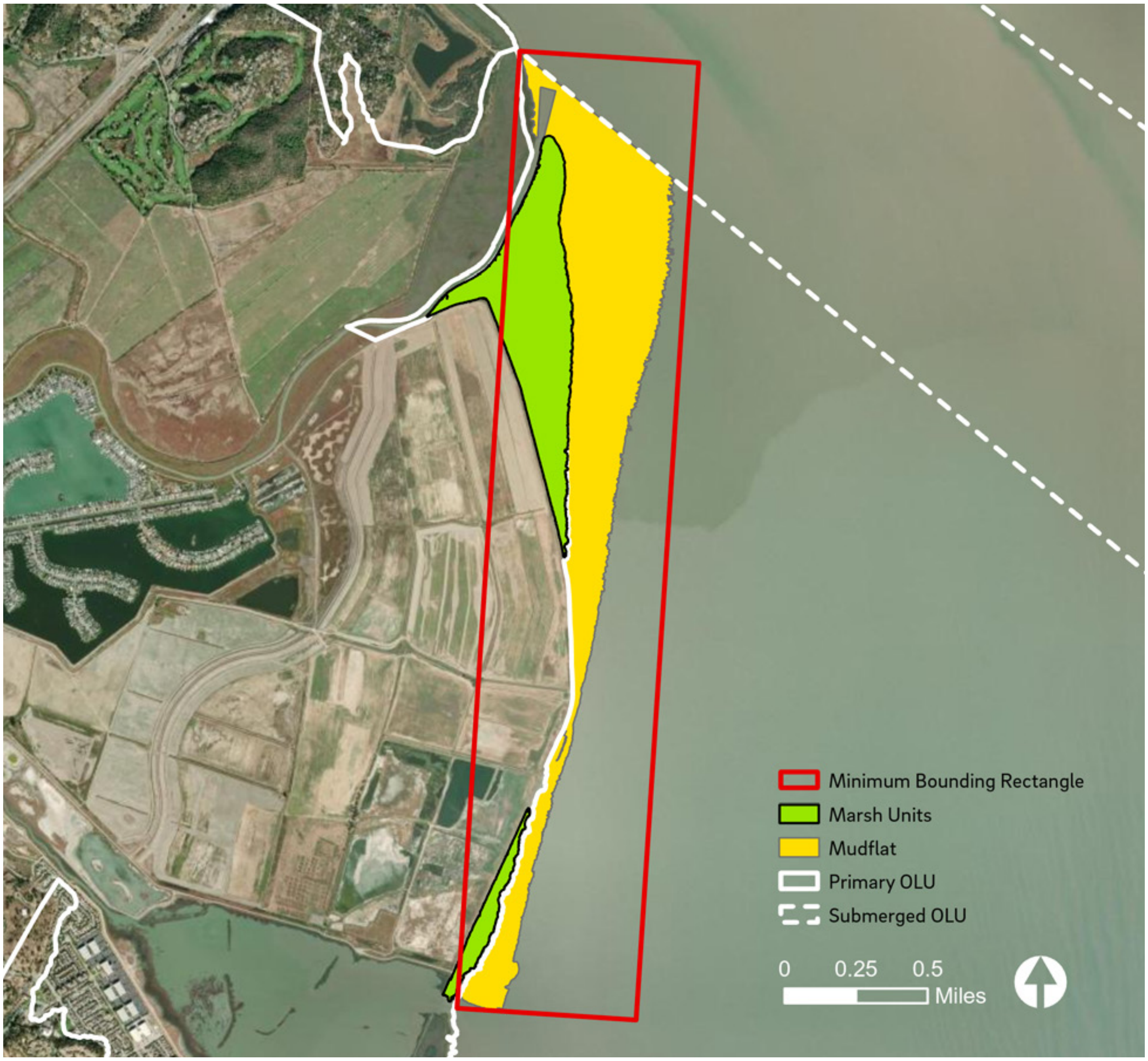


Figure A1.2.2. We used a minimum bounding geometry method to assess mudflat width. We multiplied the percentage of the bounding rectangle filled by the mudflat by the rectangle width to estimate average mudflat width. We then assigned this mudflat width to the adjacent marsh units.

METHOD

We identified mudflats using polygons from the Baylands Habitat Map 2020. We split each mudflat by submerged OLU boundaries, then determined mudflat width using a minimum bounding geometry method (Figure A1.2.2). First, we drew a rectangle around each mudflat polygon. Then, we calculated the percentage area of the mudflat relative to the rectangle and multiplied this percentage by the length of the shorter side of the resulting rectangle to estimate the average width of the mudflat along its length. We assessed mudflat relative elevation (i.e., high or low in the tidal frame) using exposure duration, calculated as the average length of time above the water surface elevation in each tidal cycle using sinusoidal functions evaluating the mixed semi-diurnal tidal regime based upon modeled tidal datum data (BCDC 2016, NOAA 2022) in relation to a digital elevation model (DEM) created for the Baylands Habitat Map (2020)

(Figure A1.2.3). We applied the results to each marsh unit by summarizing the average width and exposure values for all adjacent mudflat polygons to each marsh unit (Figure A1.2.4). The threshold values for this and other metrics are included in Appendix A. Future studies could investigate the connections between shorebird use and mudflat characteristics to gain a better understanding of the features that contribute to high habitat value. Further analysis, extending beyond geometry and elevation, should be conducted to determine sediment transport between marsh and mudflat, including sediment budget and sediment flux, before identifying and implementing any management actions.

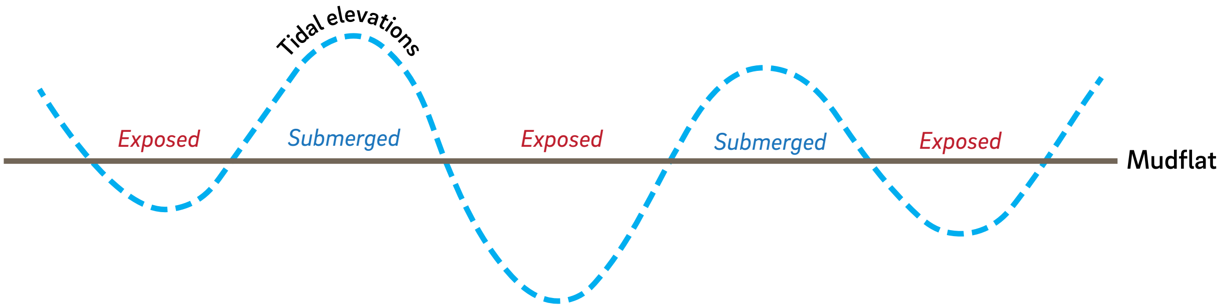


Figure A1.2.3. Average duration of exposure on an average tidal cycle was calculated for each mudflat. Mudflats that are exposed for a longer duration are more likely to support shorebird foraging.

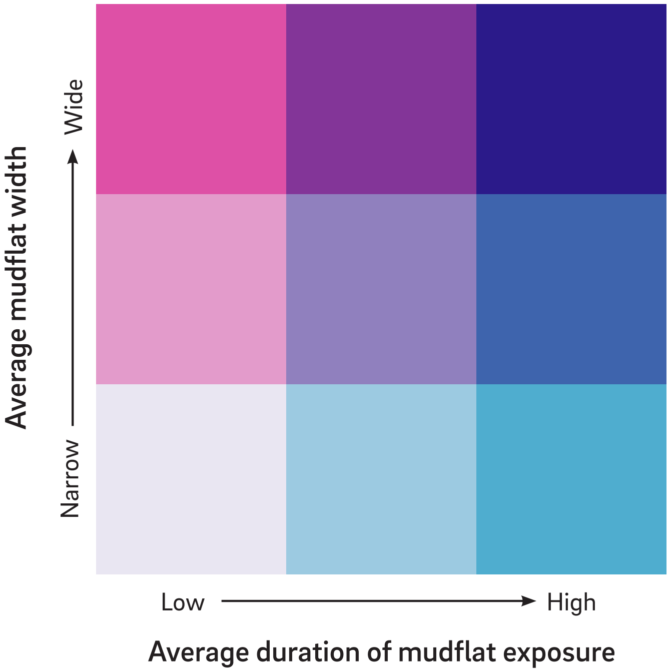


Figure A1.2.4. Marshes were ranked on two axes according to the results mudflat exposure and width analyses. Marshes with wide mudflats that are higher in elevation (higher average duration of exposure) are more resilient for wildlife support.

A2.1

WILDLIFE SUPPORT METRICS

PATCH CONNECTIVITY

SUMMARY OF METRIC

A patch is an area of habitat suitable for a species that is surrounded by boundary or edge habitat. Connectivity among marsh patches is essential for maintaining viable populations of many native wildlife species and is a critical element of ecological function (Taylor et al. 1993). The patch connectivity metric provides insight on how much each marsh and diked bayland (potential future tidal habitats) is contributing or can contribute in the future to maintaining connectivity across the Bay's network of marshes.

RELEVANCE

To support viable wildlife populations, marshes must not only have connectivity across the shoreline (from the uplands to the Bay) but must also be connected to one another along the shoreline. Connectivity between patches promotes genetic diversity, facilitates recolonization following disturbance events, and enables immigrating individuals to bolster declining populations (Forman 1995). Diking of baylands beginning in the mid-1800s has fragmented intertidal habitats into smaller and less connected patches in San Francisco Bay (Goals Project 1999, Collins and Grossinger 2004, USFWS 2013, SFEP 2015).

Two endangered, endemic salt marsh species in the Bay, Ridgway's rail (*Rallus obsoletus obsoletus*), and salt marsh harvest mouse (*Reithrodontomys raviventris*), require different types of connectivity between marshes to maintain population health. Habitat fragmentation limits the movement of Ridgway's rail between the North and South baylands, impairing genetic diversity (Wood et al. 2017). In contrast, the salt marsh harvest mouse population has always been divided into a northern and southern subspecies; however, habitat fragmentation within these subregions may be reducing genetic diversity especially for the southern subspecies (Statham et al. 2016, Statham and Sacks 2019). These species also have unique requirements and abilities (e.g. flight, ability to cross levees or channels) that dictate their movement across the landscape. The connectivity modeling developed for this metric is based on the habitat requirements and movement modalities of each of these two species but it can be used to understand marsh habitat patch connectivity more broadly.

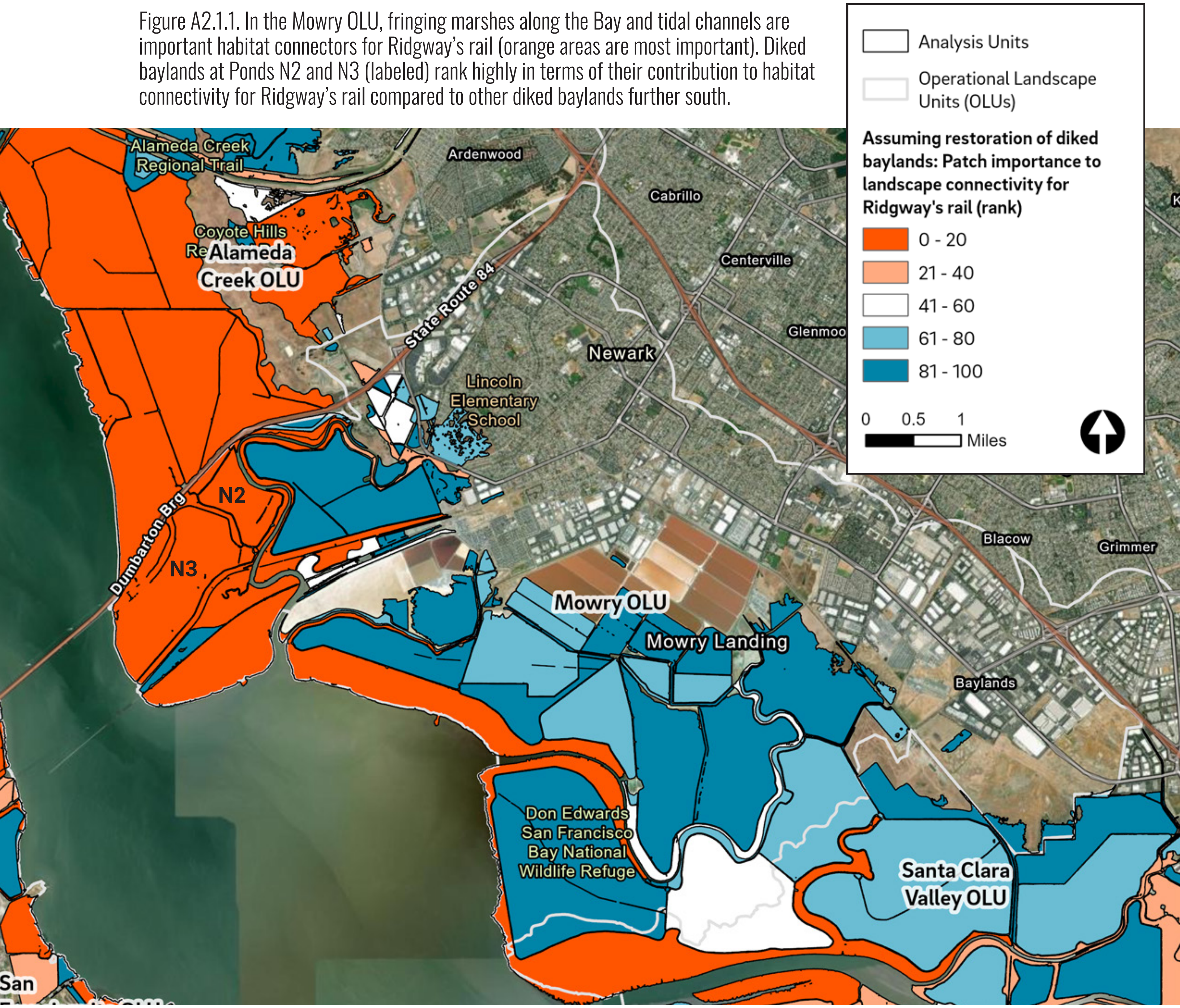
APPLICATION

The landscape connectivity model can be used to identify and prioritize locations where restoration efforts would best support connectivity. By analyzing connectivity between existing marshes and between existing marshes and potential future marshes (diked baylands), it is possible to identify which marshes are essential to maintain given their importance in connecting other marshes, and which diked baylands might provide essential lifts in connectivity by adding stepping stones between existing marshes (Collins and Grossinger 2004). The connectivity model can also be used to evaluate the benefits and tradeoffs of restoring different diked bayland units within the subregions of the Bay.

EXAMPLE

Landscape connectivity modeling demonstrates the importance of maintaining fringing marshes that serve as connectors between larger marsh patches. In the Mowry OLU, fringing marshes on the edge of the Bay and along Mowry Slough are most important to landscape connectivity for Ridgway's rail (Figure A2.1.1). As restoration projects are pursued and management strategies considered, preserving these important habitat-connecting marshes is essential. In addition, diked baylands at Ponds N2 and N3, just south of the Dumbarton Bridge, have higher potential to contribute to habitat connectivity for Ridgway's rail if restored than ponds further south (Figure A2.1.1). However, these ponds currently are under private ownership.

Figure A2.1.1. In the Mowry OLU, fringing marshes along the Bay and tidal channels are important habitat connectors for Ridgway's rail (orange areas are most important). Diked baylands at Ponds N2 and N3 (labeled) rank highly in terms of their contribution to habitat connectivity for Ridgway's rail compared to other diked baylands further south.



METHOD

The connectivity model integrates the landscape's spatial patterns with the dispersal capabilities and movement behavior of Ridgway's rail and salt marsh harvest mouse (Figure A2.1.2). The model assesses the "probability of connectivity" (PC) 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 and Rubio 2010). We specifically evaluated how important each patch is as an irreplaceable element in maintaining connectivity to the other patches in the network of patches, also known as the "stepping stone" component of the probability of connectivity. We analyzed habitat connectivity for two scenarios: existing marshes (which includes managed marshes in diked baylands in the salt marsh harvest mouse analysis) and existing marshes plus all undeveloped diked baylands. For each species, the model's outputs indicate the marshes' relative importance

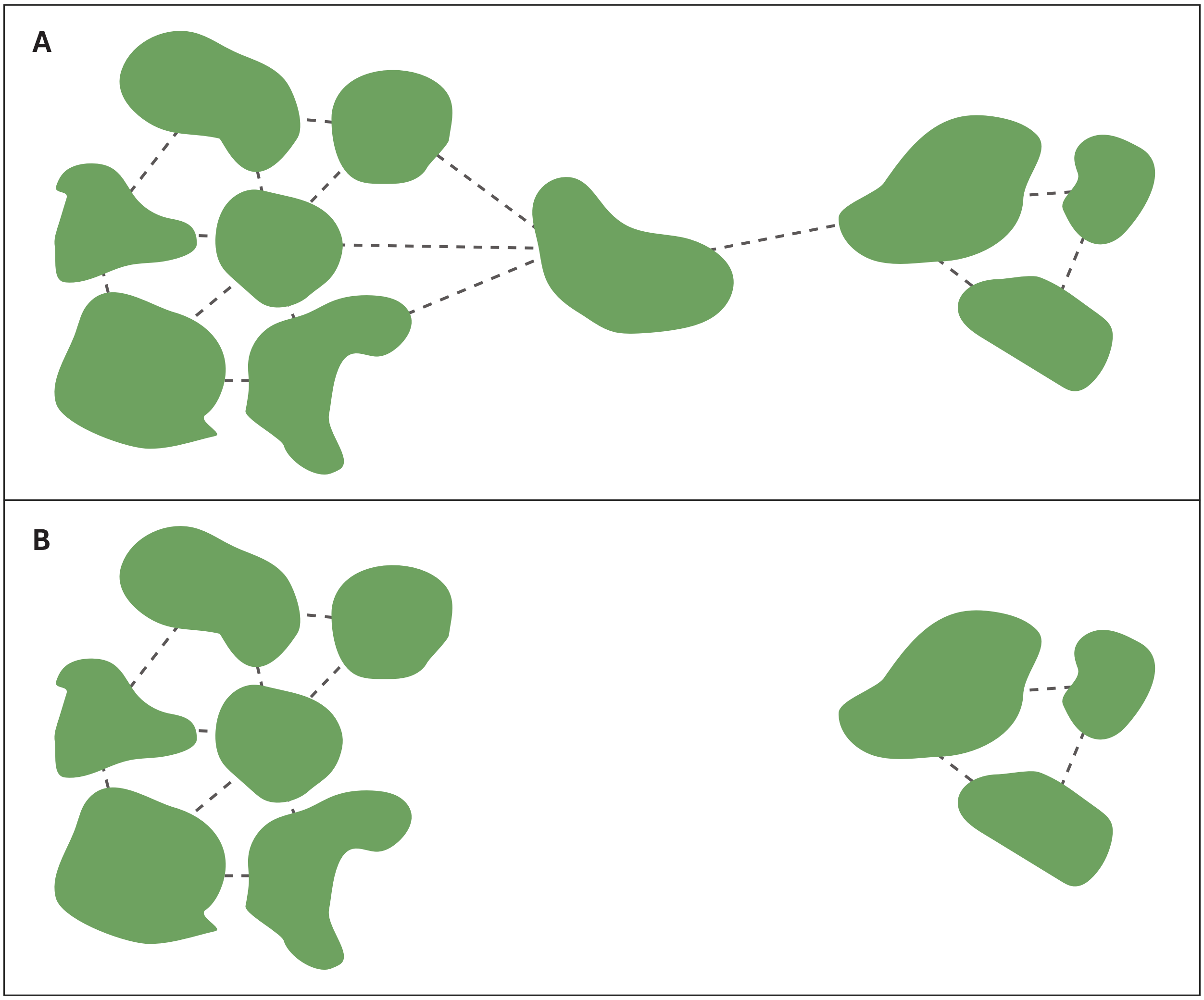


Figure A2.1.2. Probability of Connectivity, a graph network approach, was used to evaluate wildlife connectivity. The most likely path connecting each patch (represented by dashed lines) is determined based on dispersal abilities of species and the least cost movement across the landscape, even if it involves moving through other patches. The importance of each patch to maintaining the connectivity is estimated by hypothetically removing them (e.g., panel B) and evaluating the connectivity impacts on the remaining network. The patch removed in this example will have a high ranked priority as it provides irreplaceable connections across the network. Figure modified from Saura and Pascual-Hortal (2007).

to connectivity today and, in the future, the relative importance of each marsh and diked bayland to connectivity if diked baylands are restored to tidal marsh. This analysis provides an update to a previous connectivity analysis that examined historical, modern, and possible future connectivity conditions conducted for salt marsh harvest mouse and Ridgway's rail for historical, modern, and possible future conditions (Plane and Iknayan 2021).

The connectivity model presented here is a static model of spatial connectivity that characterizes habitat "reachability" given known dispersal distances for a species and biologically reasonable movement pathways. For instance, we assumed that rails would preferentially move along the shoreline when searching for new habitats. Additionally, larger patches were assumed to produce more emigrating individuals, which we accounted for in our model by assigning greater importance to these patches in overall connectivity. This approach offers a generalized view of connectivity with moderate data requirements. Because biological characteristics are built into the model, we ran this analysis on the analysis units, rather than aggregating first into larger habitat patches as we did for the patch size and compactness metric.

In future studies, we can enhance this approach by modeling the movement of individual animals, considering population densities and movement probabilities on an annual basis, leading to a more detailed representation of dispersal across the Baylands. Our assumptions about the ways dispersing animals of both species are likely to move across the landscape are based on scientific literature and expert opinion (see Plane and Iknayan 2021 for more background). As we gather more information about the movement behavior of these species, whether through movement tracking or genetic studies, our understanding of Baylands connectivity will continue to evolve.

A3.1

WILDLIFE SUPPORT METRICS

PATCH SIZE AND COMPACTNESS

SUMMARY OF METRIC

Large and compact patches are essential for maintaining viable populations of tidal marsh species. This analysis helps identify parts of the Bay where large, compact marshes are lacking and where restoration projects may enhance wildlife support by expanding or adding large marsh patches.

RELEVANCE

Size and compactness are important measures of habitat quality. Compactness describes the shape of a habitat patch; more compact shapes, like a circle or square, have less edge and more core habitat than convoluted shapes. Though small and non-compact marshes can provide some benefits particularly in the heavily urbanized Central Bay, including serving as connectivity stepping stones and corridors, they do not provide the habitat benefits of large, compact patches. Large, compact patches contain a range of microhabitats that allow wildlife to find suitable habitat in response to variable environmental conditions, including those from climate change. Larger patches are generally more stable and host a greater diversity of physical features (e.g., channel networks) and wildlife. Large, compact marshes are also less susceptible to edge effects (e.g., invasion, disturbance, pollution) that can negatively impact marsh species. The size of a patch that will support a viable population varies for different species.

APPLICATION

Understanding the distribution of large, compact patches of tidal marsh around the region is important for identifying where additional large patches are needed to support wildlife. Especially in the context of climate change, more large, compact patches are needed to support species (like Ridgway's rail) that tend to thrive only in larger patches. This analysis can help identify where restoration projects (including sediment placement projects) may be prioritized to expand the size of existing marsh patches, to connect existing patches, or create new large, compact patches. This does not imply that non-compact marshes cannot have benefits; for instance, narrow fringing channel marshes can help provide connectivity between larger marsh patches.

EXAMPLE

The Sonoma baylands provide a good example of an area where restoration can increase habitat patch size and compactness. Marshes along Sonoma Creek and the Napa River are aggregated into one large habitat patch, but the fringing marshes along the tidal creeks in this area are very narrow (Figure A3.1.1). Recent restorations along the Napa River have improved patch compactness, but further restorations in the Sonoma Creek watershed can connect between fringing marshes to further increase patch compactness. The restoration strategy identified in the Sonoma Creek Baylands Strategy suggests routing channels through diked baylands so the existing fringing marshes can be preserved as source populations for colonization of newly restored areas (Sonoma Land Trust and partners 2020).

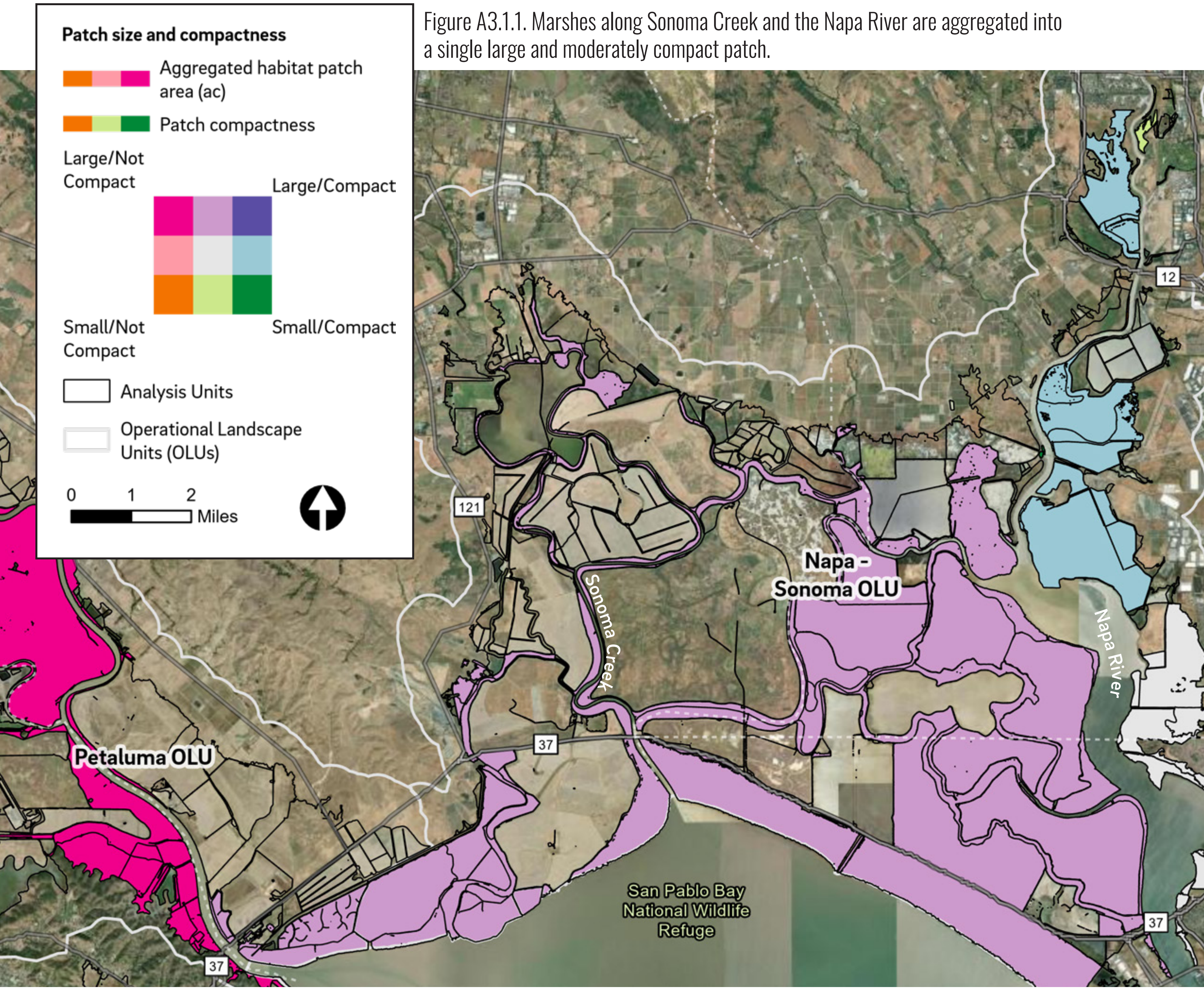


Figure A3.1.1. Marshes along Sonoma Creek and the Napa River are aggregated into a single large and moderately compact patch.

METHOD

We aggregated marsh units within 60 meters of each other into habitat patches—a reasonable threshold for patch connectivity based on the behavioral characteristics of marsh specialist species, e.g. Ridgway's rail and salt marsh harvest mouse (Collins and Grossinger 2004, SFEP 2011, Appendix D). We assessed the area and compactness of these patches and categorized them according to thresholds reported in the literature. A minimum of 150 acres is estimated to be necessary to sustain salt marsh harvest mouse populations, while approximately 1,000 acres is the minimum for sustaining Ridgway's rail populations (USFWS 2013). We used these species-specific thresholds as a proxy for patch size thresholds relevant to tidal marsh species more broadly. Patches were classified as "small" (< 150 ac), "medium " (150-1000 ac), and "large" (> 1000 ac). We also report the area of each individual analysis unit.

We calculated patch compactness using the related circumscribing circle method (Baker and Cai 1992). This index of compactness is not influenced by patch size, unlike other common metrics like core:edge ratio. We drew the minimum bounding circle around each patch and calculated the proportion of the circle covered by the habitat patch (Figure A3.1.2). We then classified marshes along both axes, ranging from "small and not compact" to "large and compact" (Figure A3.1.3).

Figure A3.1.2. The related circumscribing circle method measures the proportion of a bounding circle taken up by a habitat patch. The patch on the left is the most compact, with the highest proportion of patch area (green) relative to the total area of the circle (black). The patch on the right is the least compact, with the lowest proportion of patch area (green) relative to the total area of the circle (black).

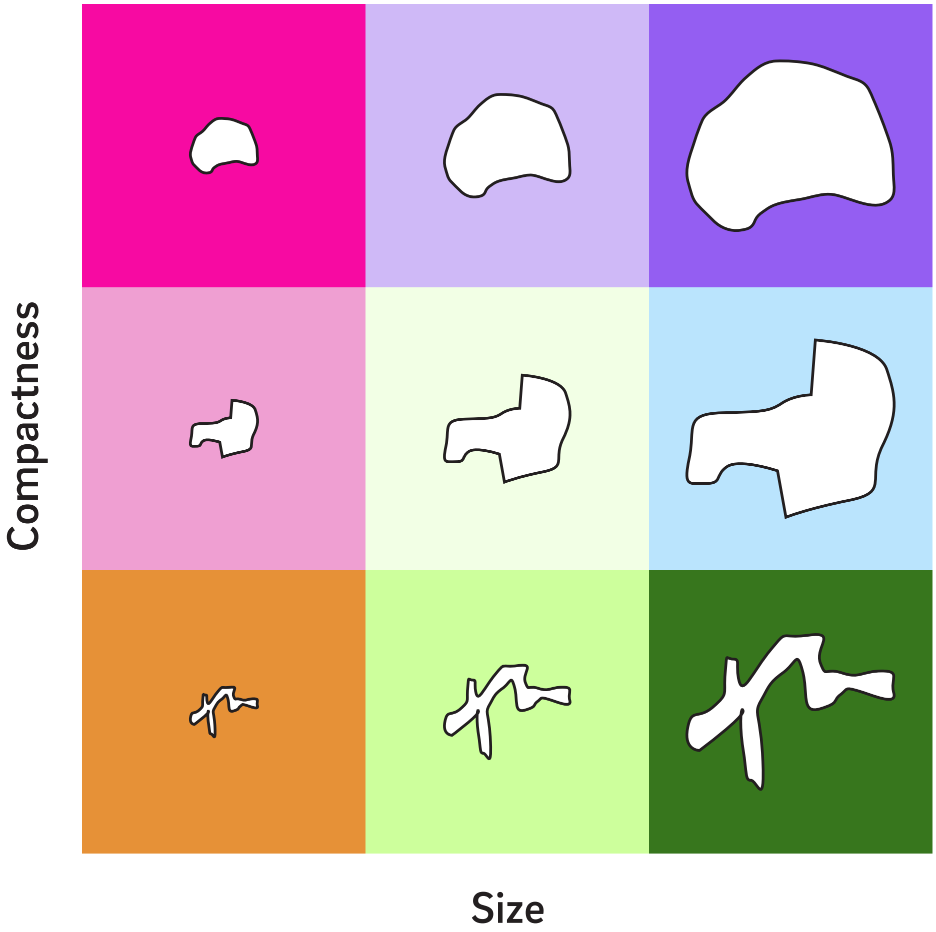


Figure A3.1.3. Large, compact patches (upper right) are valuable for maintaining viable populations of tidal marsh species. Smaller and less compact patches can serve as stepping stones or corridors but do not provide the same overall habitat benefit. The colors in this diagram correspond to the symbology used in the web map.

A4.1

WILDLIFE SUPPORT METRICS

MARSH ELEVATION

SUMMARY OF METRIC

Marshes that have high "elevation capital" (i.e., are located higher in the tidal frame) are more likely to persist with sea-level rise. These metrics allow comparison of ground elevation relative to the tides to assist in targeting where sediment placement projects may have the most benefit.

RELEVANCE

Marsh elevation relative to the tides determines the duration, frequency, and depth of inundation, which, together with salinity, are key drivers of vegetation species and habitat type. The ability of a marsh to maintain its elevation relative to the tides as sea levels rise depends on its initial elevation and its accretion rate. Marshes at relatively high elevations may persist longer than those at lower elevations at the same accretion rate. We use a value called z* to allow comparison of marsh elevations relative to the tides across the Bay (Figures A4.1.1 and A4.1.2). Histograms showing the frequency distribution of z* values in a marsh are a good way to compare and understand the relative differences in elevation between marshes (Figure A4.1.3).

Tracking changes in elevation over space and time can directly measure resilience, however these are "lagging indicators", meaning that they measure what has happened in the past rather than predicting what will happen in the future. Other metrics that describe the shape of the elevation histogram of the marsh can serve as "leading indicators" as they are correlated with elevation change and marsh persistence over time (Raposa et al. 2016, Nowacki and Ganju 2019, Ganju 2019, Wasson et al. 2019). Such metrics include the percentage of a marsh in the lowest third of vegetation distribution, percentage of a marsh below Mean High Water, and the skewness of elevation distributions (Raposa et al. 2016). Here, we explore the latter two metrics.

APPLICATION

Marshes with a high proportion of elevation below Mean High Water and elevations skewed toward the lower end of the vegetation range are less likely to persist into the future (Raposa et al. 2016, Wasson et al. 2019). These two metrics can provide an at-a-glance way to identify marshes low in the tidal frame. Some of these marshes are recent restoration projects that are still accreting to marsh plain elevation, and their elevations are not necessarily an indicator of low resilience. These might be targeted for beneficial use to increase their relative elevation and accelerate the establishment of vegetation. Others are older marshes that are struggling to maintain elevation with natural sediment supply from the watershed or the Bay as sea levels rise; these marshes are ones that might be targeted for strategic actions that can help them maintain their relative elevation. Comparing histograms facilitates direct comparison of elevation distributions between marshes. This allows the identification of marshes within OLUs that are particularly low relative to their neighbors and may require sediment placement to increase their relative elevation and improve resilience to sea-level rise.

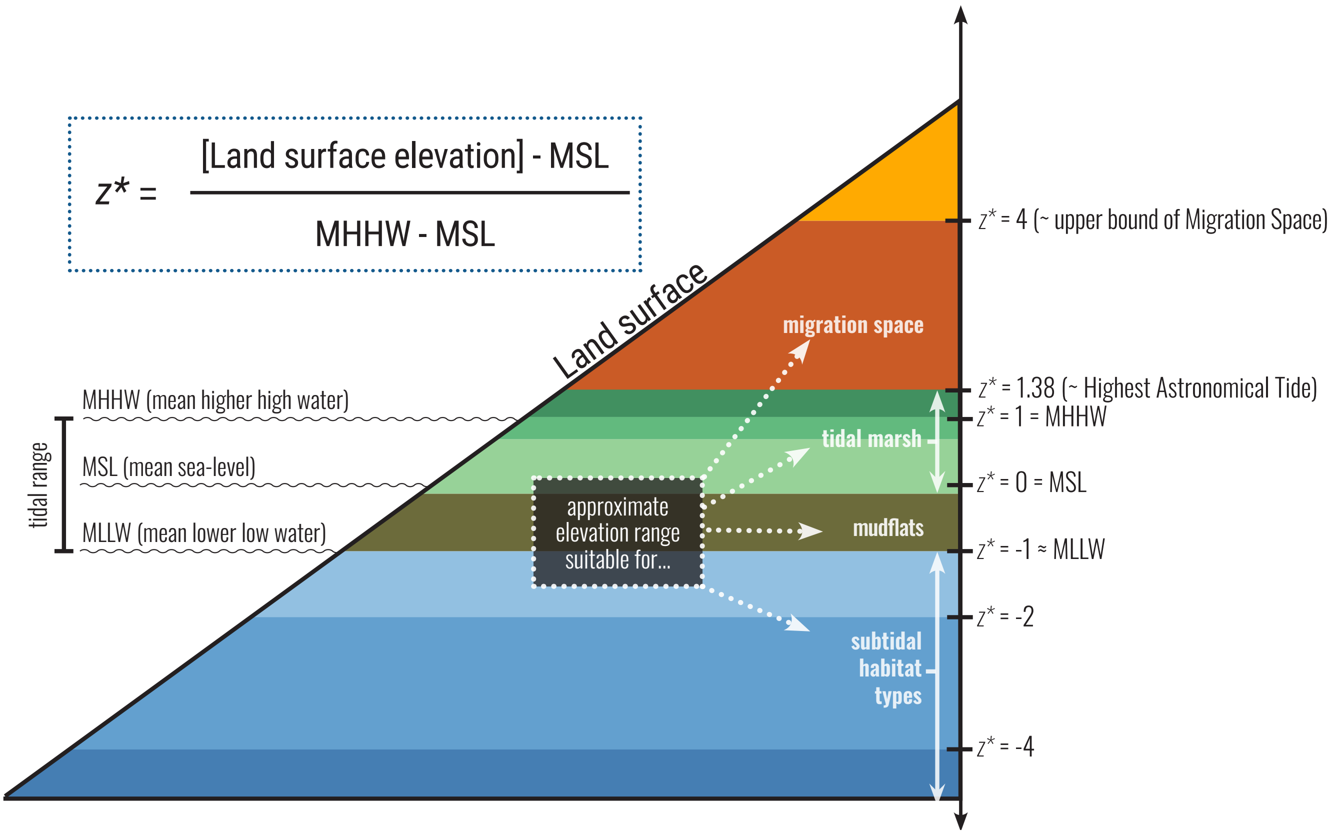


Figure A4.1.1. z* is a dimensionless representation of land surface elevation relative to the tides and is a useful way of comparing relative elevation across marsh units in different parts of the Bay. Figure adapted from the Adaptation Atlas (SFEI and SPUR 2019). Relative elevation ranges for tidal marshes and mudflats from Thorne et al. (2018).

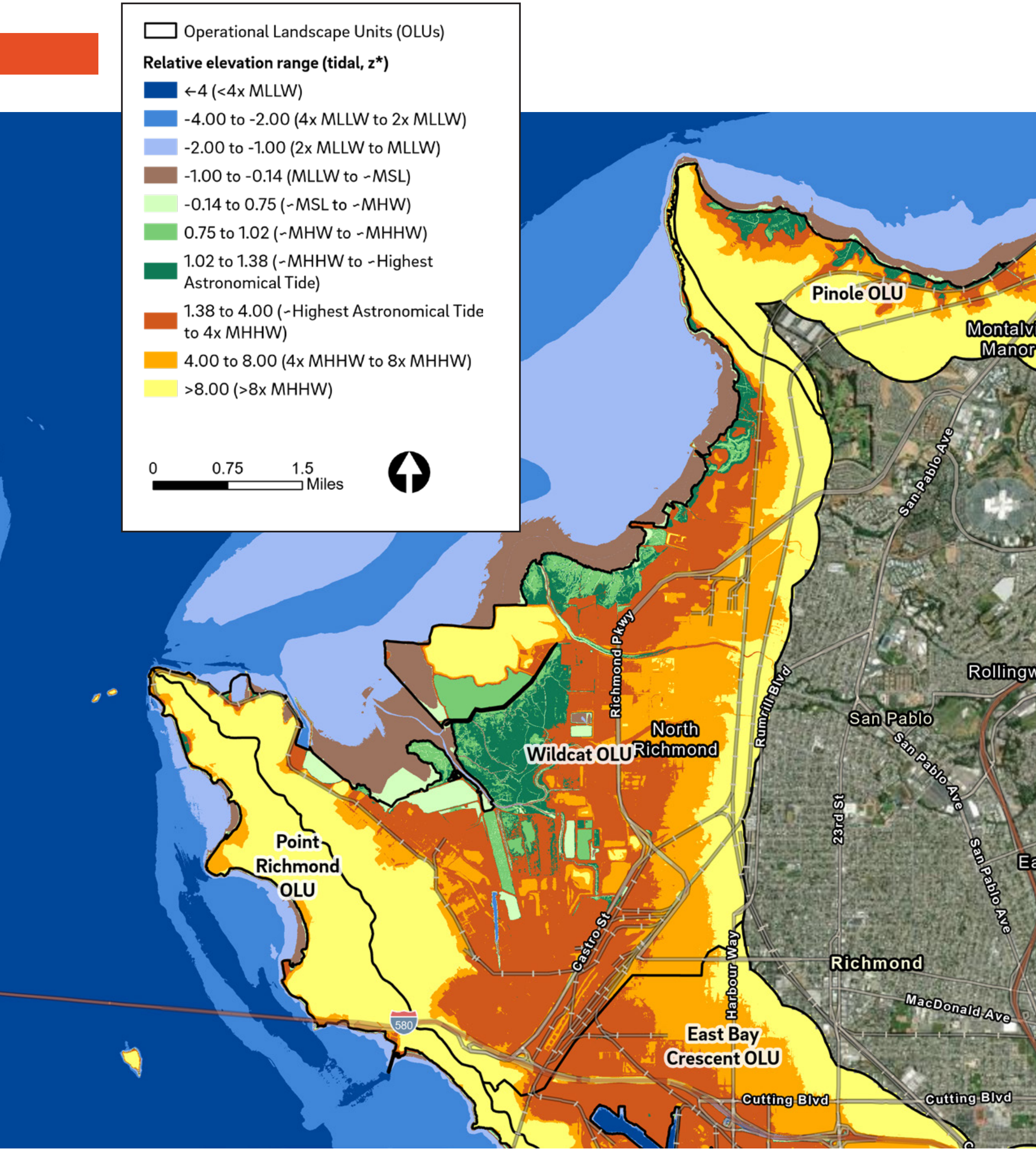
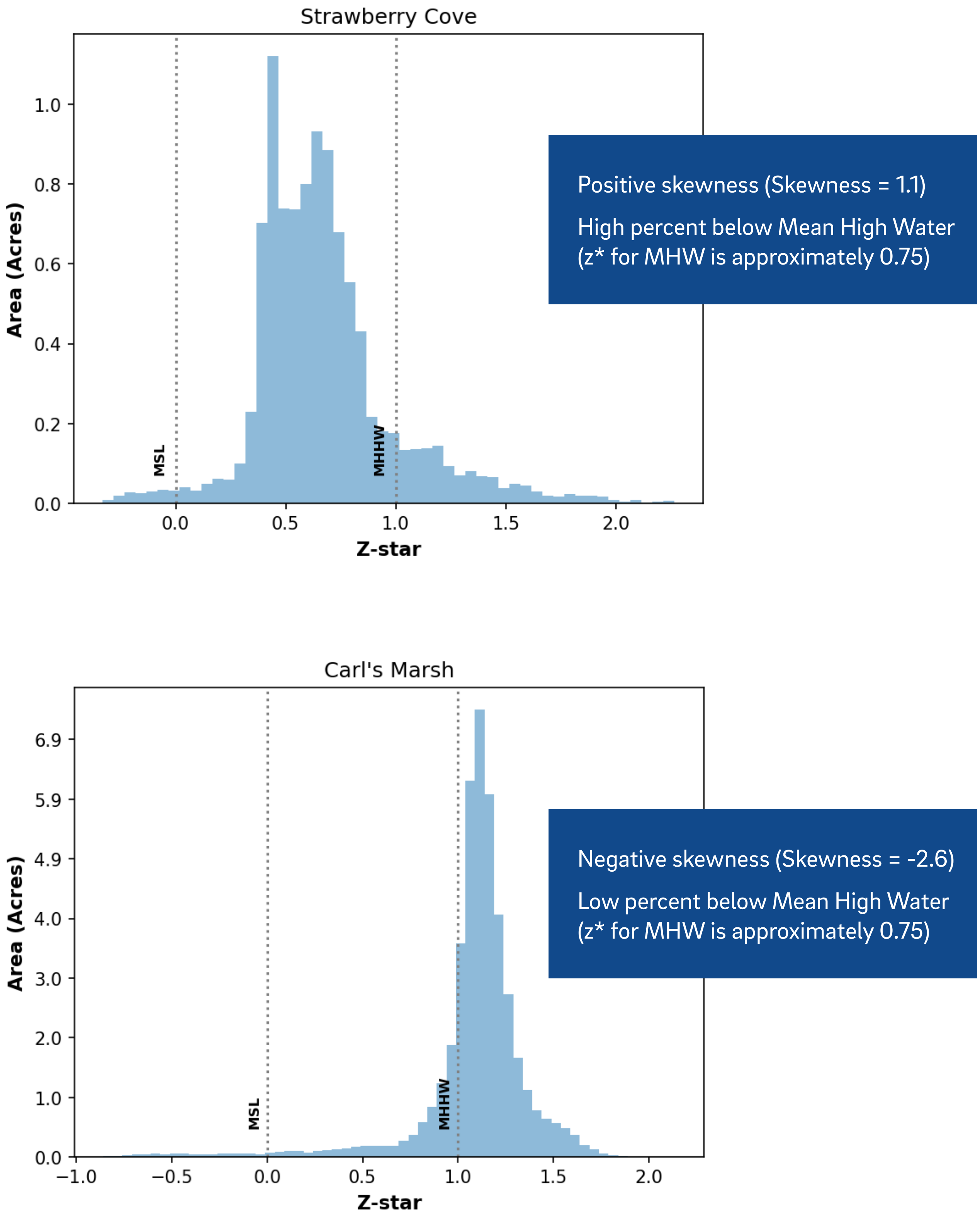


Figure A4.1.2. z* elevations in the Wildcat OLU.



Positive skewness (Skewness = 1.1)

High percent below Mean High Water (z* for MHW is approximately 0.75)

Negative skewness (Skewness = -2.6)

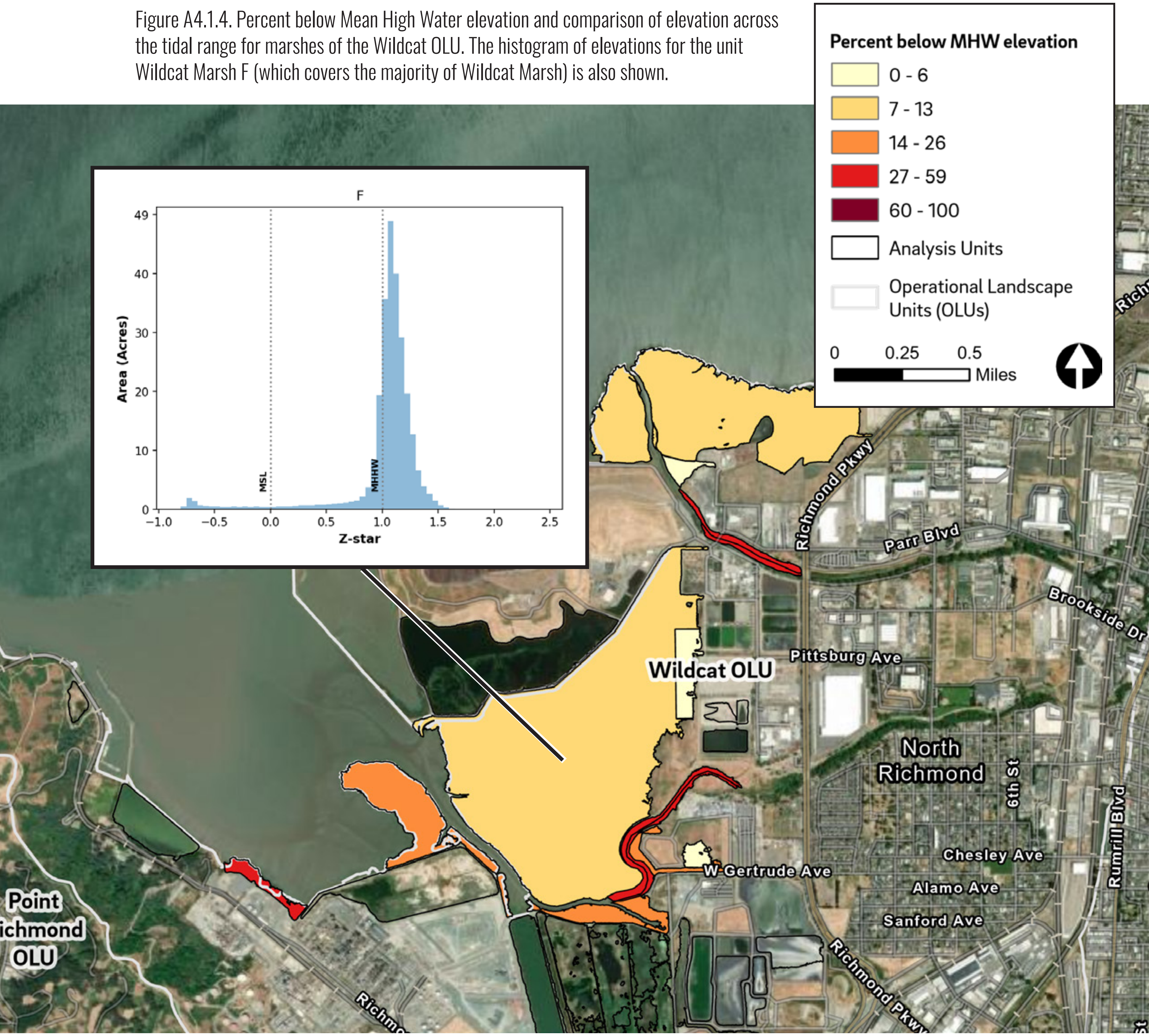
Low percent below Mean High Water (z* for MHW is approximately 0.75)

Figure A4.1.3. We assessed two resilience metrics from the MARS (Marsh Resilience to Sea-Level Rise) indices (Raposa et al. 2016): skewness (asymmetry) of the distribution of marsh elevations and the percentage of marsh below MHW. Negative skewness and a lower percentage below MHW are associated with marsh resilience to sea-level rise. The upper histogram (Strawberry Cove Marsh in the Richardson OLU) scores lower on both metrics than the lower histogram (Carl's Marsh in the Petaluma OLU), indicating that Strawberry Cove Marsh is less resilient to sea-level rise than Carl's Marsh.

EXAMPLE

Wildcat Marsh, in the Wildcat OLU, sits high in the tidal frame and has only 9% of its total area below Mean High Water (MHW) elevation (Figure A4.1.4). In this area, the smaller marshes surrounding Wildcat Marsh are lower in elevation, with higher percentages of area below Mean High Water. These marshes are more in need of sediment placement to maintain elevation capital, as sea levels rise, than the larger Wildcat Marsh.

Figure A4.1.4. Percent below Mean High Water elevation and comparison of elevation across the tidal range for marshes of the Wildcat OLU. The histogram of elevations for the unit Wildcat Marsh F (which covers the majority of Wildcat Marsh) is also shown.



METHOD

We used a digital elevation model compiled for the Baylands Habitat Map 2020 and modeled tidal datum data (BCDC 2016, NOAA 2022) to create a dimensionless layer representing elevation relative to the tides, known as z* (Figures A4.1.3 and A4.1.4). The calculation of z* is performed by dividing a location's absolute elevation relative to mean sea level (MSL) by the difference between the elevation of mean higher high water (MHHW) and MSL. z* equals 0 when the land surface elevation is at MSL, 1 when it is at MHHW, and -1 when it is at approximately mean lower low water (MLLW). Using the z* layer, we derived three hypsometric outputs:

- Histograms showing the frequency distribution of elevation for every analysis unit.
- Percentage of marsh below MHW for each marsh unit.
- Skewness of the frequency distribution of elevation for each analysis unit. Positive skewness values indicate clustering at lower elevations and lower marsh resilience.

The regional elevation data is a mosaic of recent LiDAR surveys (2010-2021) and has limitations. Elevation changes in some recently restored areas may not be reflected. In addition, this elevation dataset does not use a vegetation correction factor to more accurately represent bare earth elevations. The only regional vegetation-corrected DEM for the Bay at present is based on outdated 2010-2011 LiDAR data (Buffington and Thorne 2019). To make well-informed management decisions in the future, it is crucial to have an accurate vegetation-corrected DEM based on more recent LiDAR data. We will re-run these analyses using more recent, comprehensive, LiDAR data when it becomes available in the next few years.

A4.2

WILDLIFE SUPPORT METRICS

MARSH PANNES AND UNVEGETATED:VEGETATED RATIO

SUMMARY OF METRIC

Marsh pannes create habitat complexity within the marsh plain, but if they expand over time, they can be an indicator of marsh degradation. This analysis creates a baseline of panne area for tracking future changes that could trigger adaptive management actions.

RELEVANCE

Marsh pannes are ponds in the marsh plain usually less than a foot deep. They fill with water during very high tides and do not drain at low tide. They can also form due to artificial changes to a marsh and are sometimes an indicator of poor drainage. Evaporation of water in these ponds over time causes hypersaline conditions. Marsh pannes provide habitat for invertebrates, fish, and some rare plants, as well as foraging opportunities for waterbirds (Takekawa et al. 2011, Kellner 2014). Therefore, existence of marsh pannes is generally considered a positive habitat condition and not an indicator of poor resilience. However, expansion of marsh pannes over time can be an indicator of marsh drowning. When pannes cannot accrete sediment faster than the rate of sea-level rise, they grow larger and deeper, eventually creating large enough fetches that waves form and cause erosion of the panne edges (Kearney et al. 1988, Mariotti and Fagherazzi 2013). This can then lead to pannes connecting to the channel network and eventual marsh drowning. Modeling has shown that inorganic sediment is essential for allowing accretion of ponds to prevent the process of marsh drowning via panne expansion (Mariotti 2016).

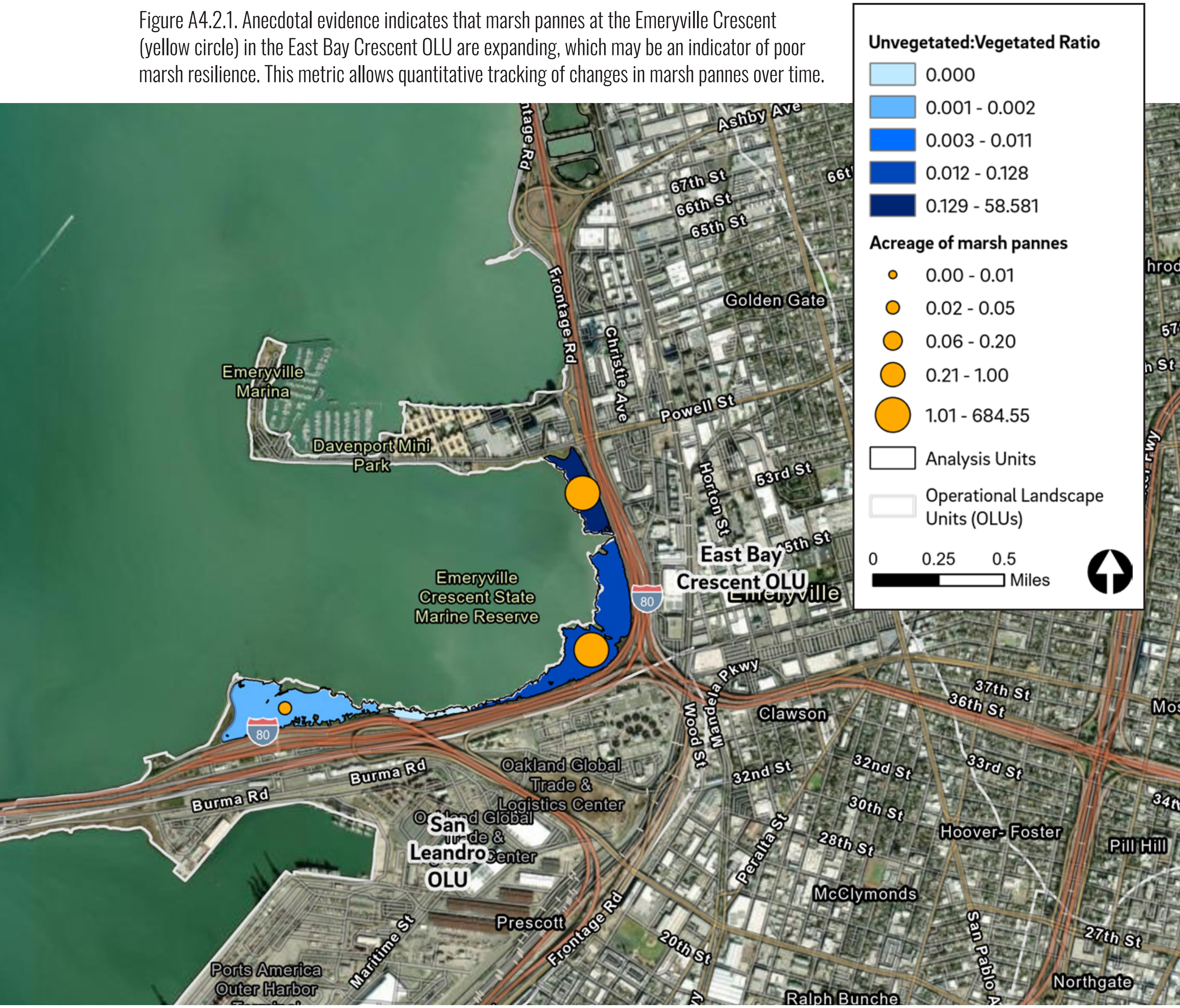
APPLICATION

This analysis sets a baseline for future assessment of change in marsh panne area over time. Future iterations will be published that will allow for comparison to the baseline established here. A static point-in-time assessment of marsh pannes is not necessarily an indicator of resilience; however, an expansion of marsh pannes over time indicates low resilience to sea-level rise. Increased area of open water can allow the development of wind waves and erode marshes from within, creating a positive feedback loop of vegetation loss (Ganju et al. 2017). Therefore, tracking where marsh pannes are expanding may trigger actions to interrupt this feedback loop. Marsh spraying (thin layer sediment placement) could be an appropriate action to take if marsh panne expansion, internal erosion, and drowning are threatening marsh resilience.

EXAMPLE

Marsh pannes and unvegetated:vegetated ratio (UVVR) are important metrics for tracking marsh health over time. Anecdotal observation and aerial imagery indicate that marsh pannes at the Emeryville Crescent Marsh (Figure A4.2.1) have been expanding over time, increasing the UVVR. UVVR will help provide a quantitative way to track changes as future iterations of the Baylands Habitat Map are released. It will help determine the rate of change of pannes and inform interventions (e.g., shallow water placement, marsh spraying, water column seeding) that may reduce panne expansion.

Figure A4.2.1. Anecdotal evidence indicates that marsh pannes at the Emeryville Crescent (yellow circle) in the East Bay Crescent OLU are expanding, which may be an indicator of poor marsh resilience. This metric allows quantitative tracking of changes in marsh pannes over time.



METHOD

Four metrics conducted for this analysis can be used to track change over time in marsh pannes. The first two are the number and total area of marsh pannes in each marsh unit, based on the delineation of marsh pannes as defined for the Baylands Habitat Map 2020 (Figure A4.2.2). The third metric is the ratio of marsh panne area only relative to total marsh unit area. The fourth is the ratio of all unvegetated areas, including intertidal channels as well as marsh pannes, relative to the area of vegetated marsh. This last metric is the unvegetated:vegetated ratio (UVVR), which has been shown to scale with marsh sediment budgets and is considered to be an indicator of marsh health (Ganju et al. 2017).

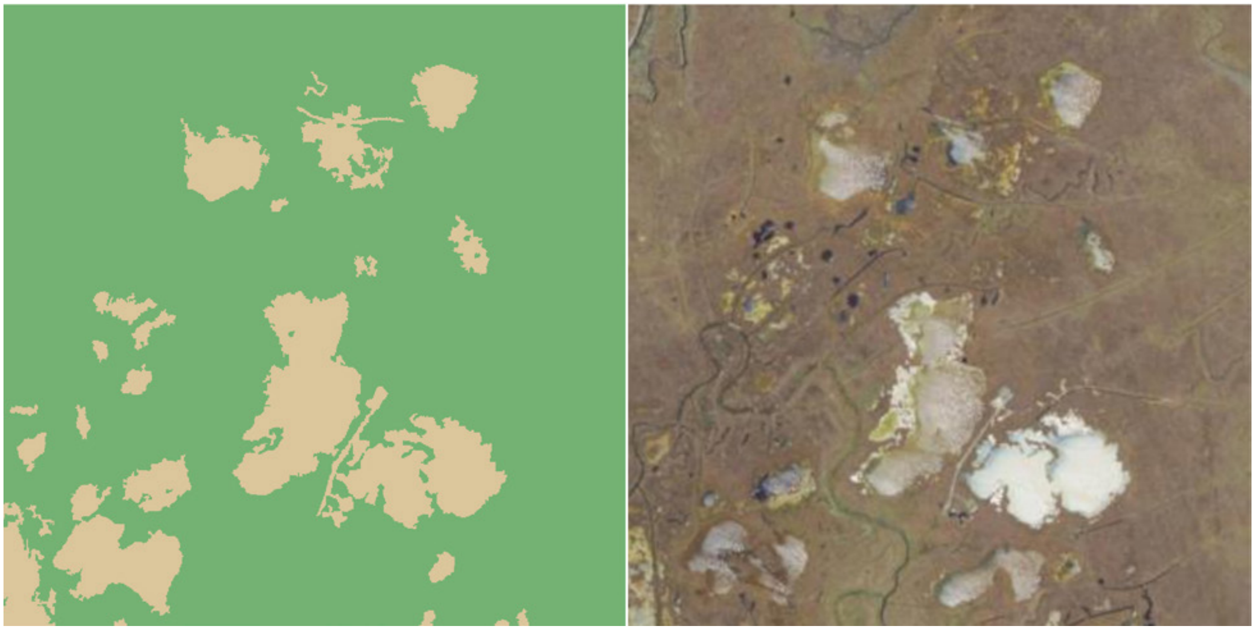


Figure A4.2.2. Marsh pannes within the ancient Petaluma Marsh, as classified in the Baylands Habitat Map (tan color, left) and as seen in NAIP aerial imagery (right).

A4.3

WILDLIFE SUPPORT METRICS

MARSH ISLANDS, MOUNDS, AND NATURAL LEVEES

SUMMARY OF METRIC

Terrestrial wildlife (e.g., salt marsh harvest mouse) use higher ground on marsh mounds and natural levees within the marsh to avoid drowning during high-water events such as storm surges and king tides (Goals Project 2015). This analysis calculates the average distance to high-water refuge within each marsh unit to aid in identifying marshes lacking these important physical features.

RELEVANCE

Higher-elevation areas and taller plants within the marsh are used by terrestrial wildlife, especially birds and small mammals, during high water events (USFWS 2013, Overton and Wood 2015, Smith et al. 2018b). They may also be used as nesting habitat. Higher-elevation areas within the marsh, such as marsh islands or mounds, whether natural or artificial, can provide these essential microhabitats (a small area which differs somehow from the surrounding habitat) for high marsh plants to establish (Figure A4.3.1).

Natural levees are created when tides overtop the channel bank. Coarser sediment deposits adjacent to the channel edges and some finer sediment is carried farther into the marsh (Culberson et al. 2004). Like marsh islands and mounds, natural levees allow high marsh plant species (e.g., gumplant, *Grindelia stricta*) to establish. These plants offer small mammals cover during high tides (Shellhammer and Barthman-Thompson 2015). These high elevation features in the marsh will become even more critical as sea levels rise and the frequency of extreme high water events increases (Overton and Wood 2015, Smith et al. 2018a).

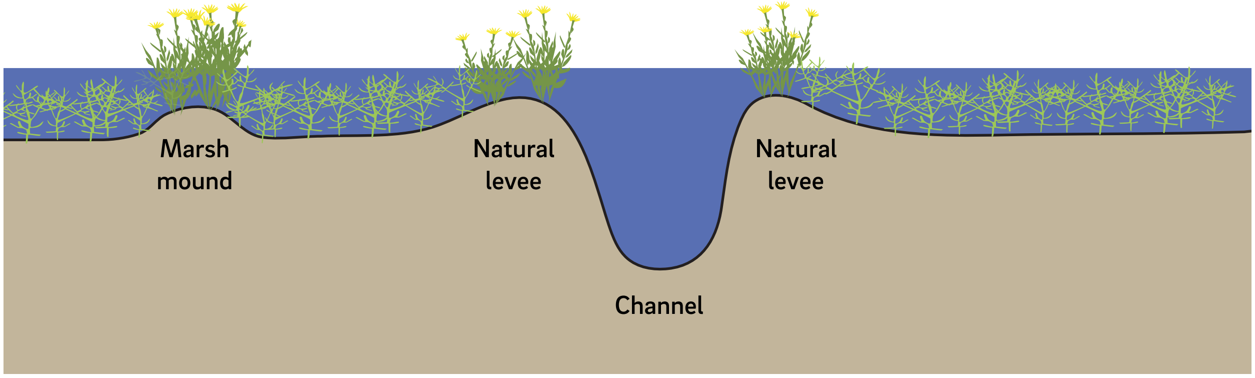


Figure A4.3.1. High-elevation features within the marsh like marsh mounds and natural levees provide essential high water refuge habitat for terrestrial species.

APPLICATION

A lack of marsh mounds, islands, and natural levees indicates a lack of high tide refugia and low resilience for wildlife support, especially for terrestrial wildlife. This analysis highlights marshes where wildlife must travel long distances to reach the nearest high-water refuge. Identifying these marshes can inform related enhancement actions, like placement of marsh mounds. It may also highlight opportunities for new restoration projects, as creating large marshes allows development of complex channel systems with natural levees where gumplant can thrive (Shellhammer and Barthman-Thompson 2015).

A line of marsh gumplant on a natural levee is visible above water during a high tide at Hoffmann Marsh, February 10, 2024. Photo by Ellen Plane, SFEI.

EXAMPLE

The marsh units in the San Leandro OLU demonstrate how this metric can be used to compare the availability of in-marsh high water refuge (Figure A4.3.2). The Martin Luther King Jr. Marsh (MLK Marsh) restoration was designed with topographic complexity to enhance high water refuge opportunities, while Arrowhead Marsh is a low-lying and relatively flat marsh with few in-marsh refuge opportunities. Due to the high population of Ridgway's rail at Arrowhead Marsh and the lack of high water refuge, previous efforts have included placement of artificial floating refuge islands to enhance refuge opportunities (these are no longer present at Arrowhead Marsh and are not included in this analysis). These artificial habitats may provide effective refuge for rail in the context of rising sea levels, at least in the short term (Overton et al. 2015).

Figure A4.3.2. In the San Leandro OLU, in-marsh high tide refuge in Arrowhead Marsh is farther away than in MLK Marsh.

METHOD

The Bay Margin Transition Zone layer (Fulfrost 2018) is based on modeled tidal elevations and identifies areas at transition zone elevation both within and at the back of tidal marshes. This layer is a reasonable proxy for high water refuge within the marsh, including marsh mounds and natural levees. We used a distance accumulation raster approach to assess the accessibility of high-water refuge locations (the Bay Margin Transition Zone layer) to marsh wildlife (Figure A4.3.3). This approach involves calculating the distance from each raster cell to the nearest high-water refuge location and then averaging these distances across the marsh unit. We used open water features (subtidal and tidal flat) and diked baylands as barriers in this analysis.

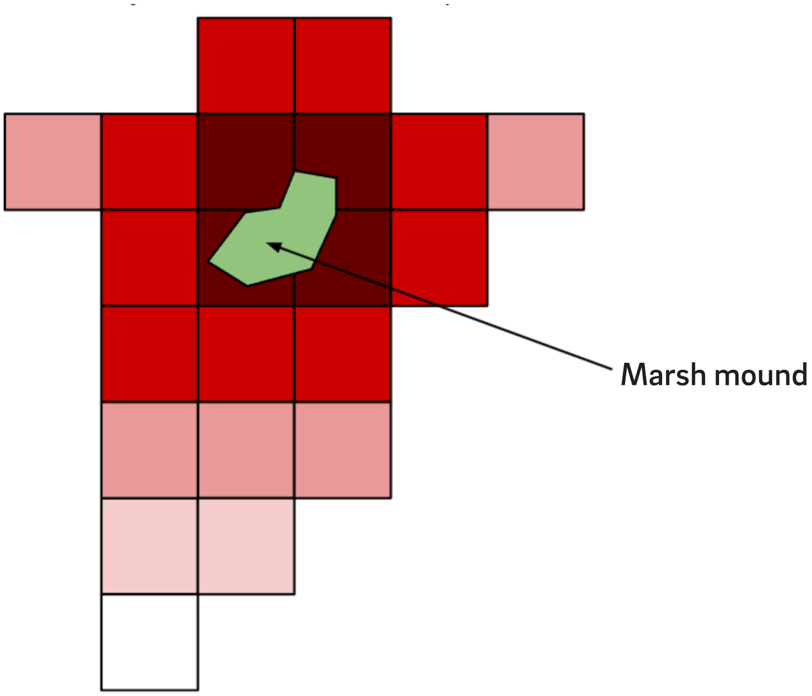


Figure A4.3.3. We used a distance accumulation raster approach to assess availability of high-water refuge features within the marsh. We report the average distance to the nearest high-water refuge feature across all cells in a marsh unit. In this cartoon example, raster cells closest to high-water refuge are shown in dark red and cells farthest from high-water refuge are shown in white.

Note: In comparing results with a high tide refuge study at Faber, Laumeister, and Ravenswood Marshes conducted for the SAFER Bay project (H.T. Harvey & Associates 2023), we found that the results from the localized site survey are not reflected by our metric. A more accurate and updated high water refuge layer is needed to achieve better representation of high water refuge opportunities. Remotely sensed data has limits and marsh mounds and natural levees are not easy to identify at the regional scale using currently available datasets.

A5.1

WILDLIFE SUPPORT METRICS

REDUNDANCY OF COMPLETE MARSHES

SUMMARY OF METRIC

Complete marshes have a continuum of adjacent, connected habitats along a subtidal to upland transect. The redundancy of complete marshes provides a buffer against stressors by ensuring a range of habitat types are available in multiple marshes within a system. This analysis helps identify OLUs and sub-embayments where complete marshes are lacking and where restorations may help to restore them.

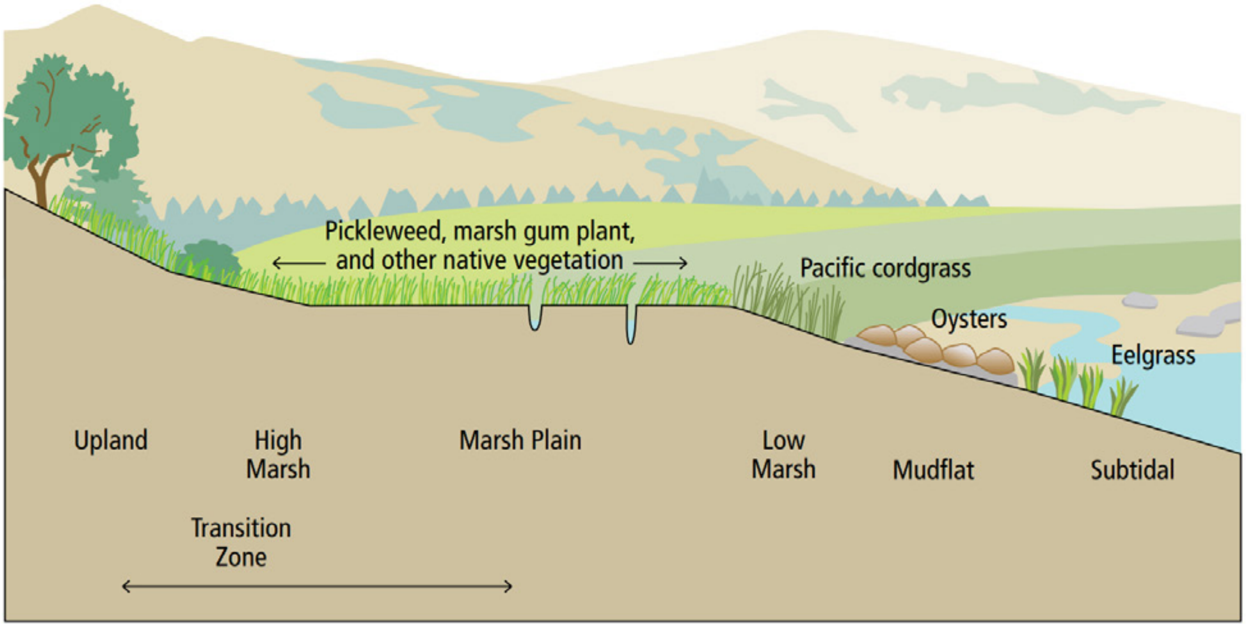


Figure A5.1.1. Diagram of a complete tidal wetland, from the Baylands Goals Update (Goals Project 2015).

RELEVANCE

A “complete marsh” or “complete tidal wetland” includes subtidal, mudflat, tidal marsh, and estuarine-terrestrial transition zone (Goals Project 2015; Figure A5.1.1). The creation of “complete marshes'' is an objective of the Baylands Goals (Goals Project 2015) because solely restoring a tidal marsh without considering its connections to lower elevation mudflats, open water, and higher elevation uplands could lead to a poorly functioning and incomplete ecosystem in terms of providing essential services to people and wildlife. Protection and restoration of complete marshes is especially important in the context of sea-level rise, as robust mudflats and transition zones confer greater resilience to marshes.

Different marshes will face different stressors, so having multiple complete marshes in a given region increases resilience. Redundancy in systems provides backup, so that the loss or impairment of one system (e.g. one complete marsh) will not lead to the loss of an entire species or ecosystem function that relies on complete marsh connectivity (Folke et al. 2009, Ahern 2011, Beller et al. 2015). Redundancy in complete marshes also provides habitat to support distinct or disconnected populations of species which encourages genotypic and phenotypic variability and supports adaptive evolution (Nyström 2006, Beller et al. 2015). This analysis assesses the redundancy of complete marshes at the OLU and sub-embayment scale.

Very few complete marshes exist across the Bay today due to loss of natural baylands and adjacent uplands to agriculture and urban development. This metric will help track changes in complete marsh redundancy over time as restoration efforts proceed.

APPLICATION

The complete marsh redundancy metric builds on the transition zone connectivity analysis and can be used together with the transition zone mapping to identify habitat restoration opportunities. First, the complete marsh redundancy metric can be used to target OLUs and sub-embayments lacking complete marshes. Second, the migration space and transition zone mapping in those OLUs and sub-embayments can be used to identify "complete marsh restoration projects" such as Montezuma wetlands. Diked bayland units with high connectivity scores for transition zone and/or migration space (see section A1.1) are good targets for complete marsh restorations. In most cases, complete marsh restoration efforts will involve working with neighboring landowners to ensure adjacent transition zones remain protected and undeveloped.

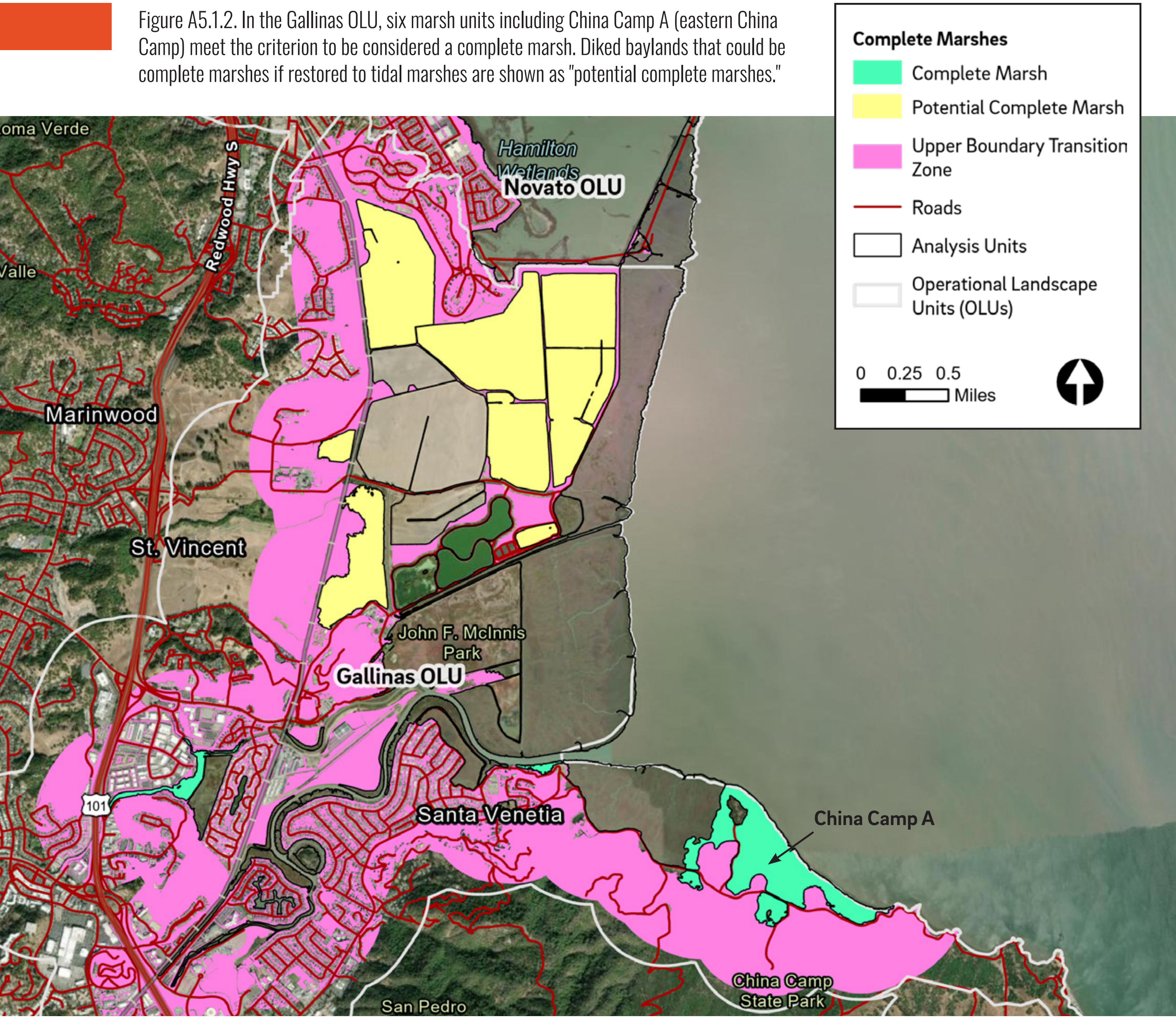
EXAMPLE

The example of the Gallinas OLU highlights how barriers can limit the availability of complete marshes, even in a relatively undeveloped OLU (Figure A5.1.2). The road at the back of the western half of the China Camp marsh inhibits connectivity to migration space and transition zone. Reconnecting marshes across barriers like roads and rail lines is one strategy for improving the availability of complete marshes in the Gallinas OLU and across the North Bay. This may take the form of removing or raising transportation barriers or improving hydrologic connectivity underneath them (e.g., expanding culverts and trestles).

METHOD

All marshes around the Bay have some connectivity with adjacent mudflat and subtidal habitats, though the abundance, width, and quality of the shallow water habitat is variable. Therefore, this complete marsh analysis focuses on connectivity to the upland and the estuarine-terrestrial transition zone. Connectivity is measured by the length of the marshes' upland edge that is adjacent to transition zone. We identified marshes as complete marshes if the percent connectivity to upper boundary transition zone was more than 50%, a threshold determined based on the results for known marshes with connected transition zones (e.g. Rush Ranch, Bahia, eastern China Camp). We then summarized the number of complete marshes in each OLU and each subembayment.

Figure A5.1.2. In the Gallinas OLU, six marsh units including China Camp A (eastern China Camp) meet the criterion to be considered a complete marsh. Diked baylands that could be complete marshes if restored to tidal marshes are shown as "potential complete marshes."



A6.1

WILDLIFE SUPPORT METRICS

TIDAL CONNECTIVITY

SUMMARY OF METRIC

Regular tidal flushing is important for reducing hypersalinity and corresponding stress to wildlife. This metric can be used to identify muted tidal marshes (marshes where infrastructure limits the tidal range, intentionally or unintentionally) that may be less resilient due to increased chances of hypersalinity, longer residence time, reduced sediment inputs, and inhibited migration potential.

RELEVANCE

Hydrologic connectivity describes the ability of water to flow into and out of a marsh (CWMW 2013). Regular tidal flushing reduces hypersalinity and buildup of hydrogen sulfide in salt marshes. Hypersalinity and high concentrations of hydrogen sulfide can negatively impact plant survival and productivity, which can then affect soil stability, organic matter accumulation, and wave dissipation (Koch and Mendelssohn 1989). Hypersalinity also negatively affects wildlife and could prevent the movement of some species across the marsh. In addition to reducing hypersalinity impacts, full tidal connections are also beneficial in allowing full tidal range, maximizing flushing and sediment deposition on marshes, and allowing upland migration. If the highest tides are prevented from entering a marsh, the marsh is not able to adapt and move inland and upland with sea-level rise. In addition, for strategic placement of sediment (water column seeding, shallow water placement), full tidal connectivity is a necessity; therefore, this wildlife support metric doubles as a feasibility metric.

APPLICATION

Understanding which tidal marshes do not have full tidal connectivity aids in the interpretation of other resilience metrics (e.g., elevation and topographic complexity metrics). Muted tidal marshes may score low on multiple resilience metrics, and the actions that should be undertaken to improve their resilience differ from the actions that can be applied at fully tidally connected marshes. For example, strategic placement actions are unlikely to be suitable for muted tidal marshes, but restoring full tidal action or upgrading water control structures prior to placement could increase the effectiveness of those actions.

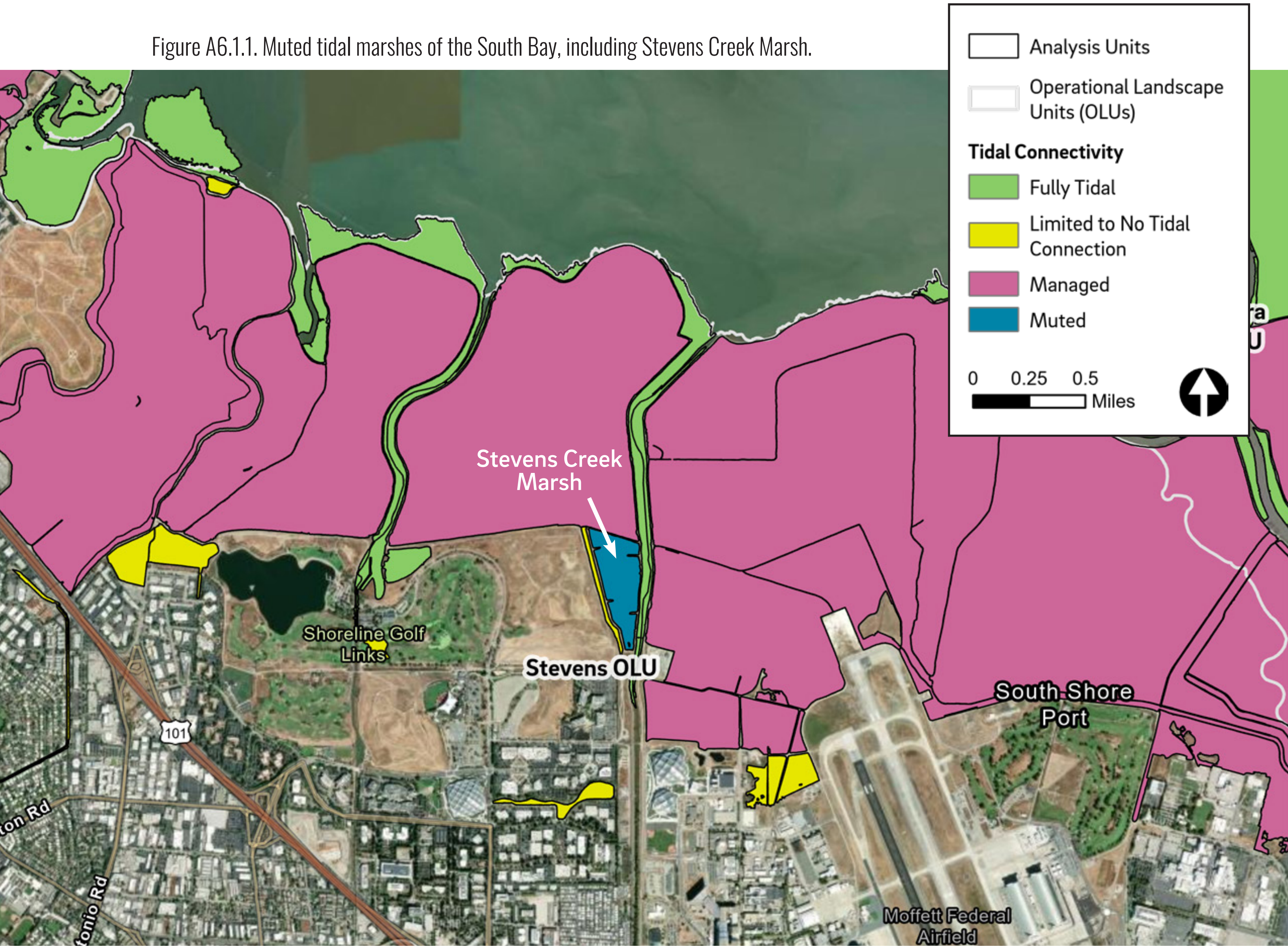
EXAMPLE

Stevens Creek Marsh in the Stevens OLU is an example of a muted tidal marsh. Stevens Creek Marsh is a 30-acre wetland restored in the 1990s by removing soil and restoring tidal action via culverts connected to Stevens Creek. The wetland is currently constrained on all sides by levees with the tidal flow dependent on the culverts. Muted tidal marshes like Stevens Creek Marsh may be particularly vulnerable to sea-level rise as they are subjected to increased durations and depths of inundation but without the benefit of sediment delivery that fully connected tidal marshes receive due to sheet flow over the marsh. Resilience projects at muted tidal marshes like Stevens Creek Marsh might focus on improving tidal flows through culverts or restoring to full tidal action, as sediment delivery via strategic placement is likely to be inhibited by culverts. Often, extreme tides are obstructed from flowing into muted tidal marshes. This can protect them from near term impacts of sea-level rise, but over the long term will inhibit the natural ability of the marsh to adapt vertically (by accreting sediment) and laterally (by migrating inland, if space is available).

METHOD

We leveraged an existing dataset of muted versus fully tidally connected marshes created for EcoAtlas in 1998 and recently modified to reflect restoration projects (SFEI 1998). This dataset was reviewed and improved by regional experts for use in development of the Baylands Habitat Map 2020.

Figure A6.1.1. Muted tidal marshes of the South Bay, including Stevens Creek Marsh.



A7.1

WILDLIFE SUPPORT METRICS

RATE OF VERTICAL ACCRETION

SUMMARY OF METRIC

Understanding projected rates of marsh accretion from natural sources of organic and mineral sediment is important for targeting sediment placement actions to marshes that will be unable to keep pace with sea-level rise without intervention. This first-pass analysis provides a regional view of accretion based on a one-dimensional numerical model (Coastal Wetlands Equilibrium Model; CWEM) (Morris et al. 2002, 2022).

RELEVANCE

The rate of vertical accretion of inorganic and organic sediment in marshes, tidal flats, shallows, and subtidal channels is a key determinant of marsh resilience. During each tidal cycle, suspended sediment is transported into and settles out of the water column onto marshes and mudflats. Marsh plants have both above- and below-ground biomass, contributing organic matter that help marshes accrete. The plants also help trap suspended sediment, further contributing to marsh accretion. Today, tidal wetlands in the Bay are generally accumulating enough sediment to keep pace with sea-level rise (Schile et al. 2014, Thorne et al. 2018, Lacy et al. 2020, Buffington et al. 2021). However, models show that at higher rates of sea-level rise or lower sediment supply, even marshes that are relatively high in the tidal frame will drown, converting to low marsh and mudflat (Parker and Boyer 2019, Buffington et al. 2021). Tracking rates of accretion over time can be a leading indicator of which marshes are and are not keeping pace with sea-level rise, informing adaptive management strategies. For this initial analysis, projecting potential accretion rates over time can help inform sediment placement decision-making processes.

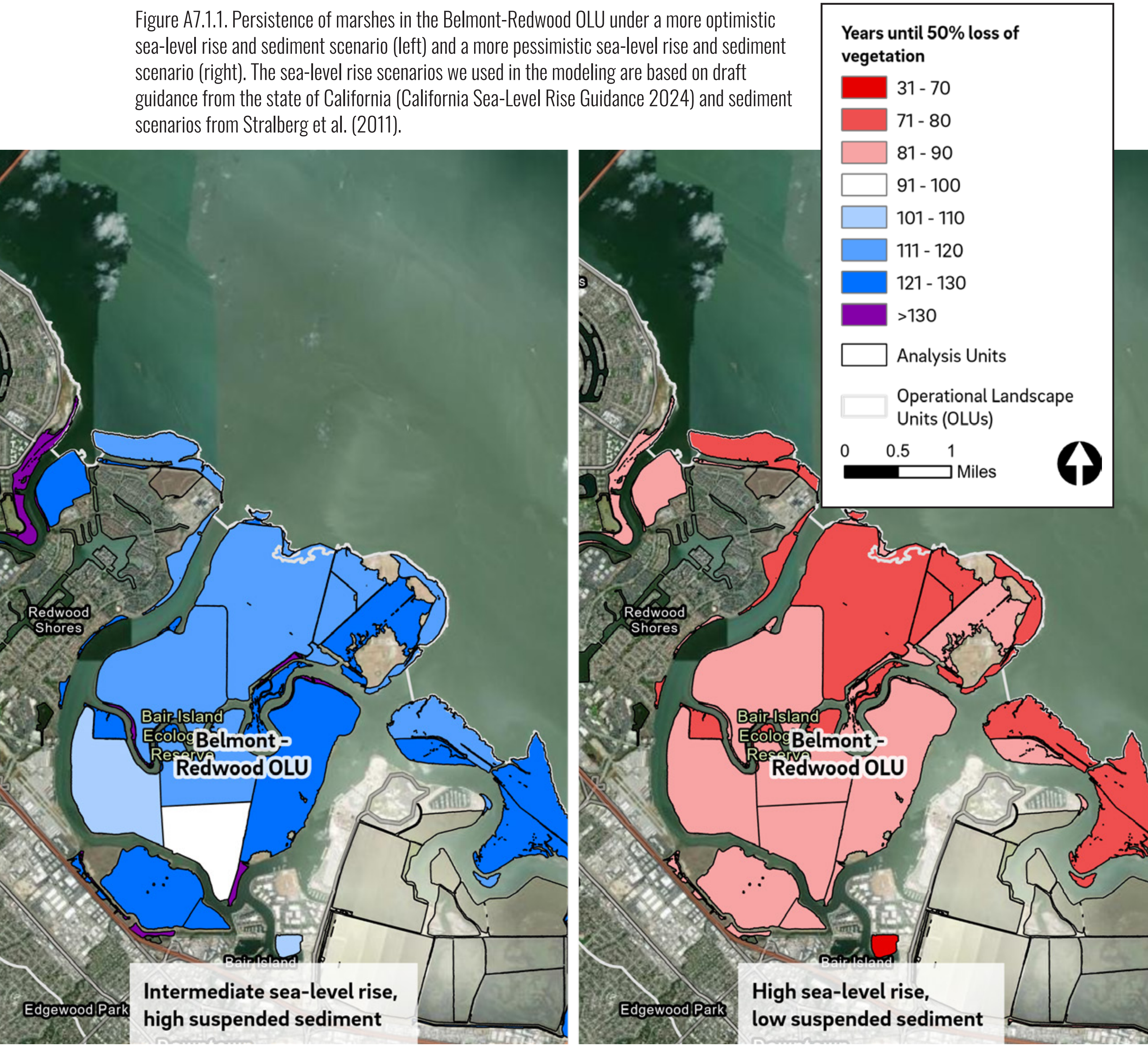
APPLICATION

This is a regional analysis based on available data and generalized parameters and does not capture all the nuances necessary to develop a full picture of accretion rates over time. Important factors affecting local accretion that are not captured here include local fluvial sediment supply, wind-wave exposure, mudflat characteristics, tidal marsh channel network density and complexity, and restrictions to tidal flow (e.g., levees) (McKnight et al. 2023). Additionally, accretion rates vary within and between adjacent marshes, with slightly higher rates of accretion in marshes closer to the Bay and tidal channels (Callaway et al. 2012). Despite lacking a precise estimate of accretion rates at any given marsh, a general picture of relative accretion rates across the region is helpful for understanding where management actions (e.g., sediment placement) may be most needed. Though the parameters used in the model do not capture all the variables associated with accretion, it provides a useful first pass effort that can be used in combination with other metrics (e.g., mudflat width and exposure, tidal connectivity) to develop appropriate sediment placement interventions at marshes vulnerable to drowning.

EXAMPLE

Predicted marsh vulnerability to drowning varies among marshes, as shown at Bair Island in the Belmont-Redwood OLU (Figure A7.1.1). Bair Island's marshes were restored at different times and are at different elevations and stages of evolution, influencing their future persistence as sea levels rise. Due to relatively higher suspended sediment concentrations in the South Bay, persistence of these marshes is predicted to be relatively high compared to the region as a whole.

Figure A7.1.1. Persistence of marshes in the Belmont-Redwood OLU under a more optimistic sea-level rise and sediment scenario (left) and a more pessimistic sea-level rise and sediment scenario (right). The sea-level rise scenarios we used in the modeling are based on draft guidance from the state of California (California Sea-Level Rise Guidance 2024) and sediment scenarios from Stralberg et al. (2011).



METHOD

We used an adapted version of the Coastal Wetlands Equilibrium Model (CWEM) to estimate accretion rates over time (Figure A7.1.2; (Morris et al. 2002, 2022). For marshes, we calculated the projected number of years until 50% vegetation loss and the number of years until 100% vegetation loss, respectively. Key inputs included aboveground biomass values (Woltz et al. 2023), suspended sediment concentration estimates (Veloz et al. 2014), and the LiDAR-derived DEM produced for the Baylands Habitat Map 2020. See Appendix A for a complete list of parameter sources. This model can be improved in the future using better, measured local values for each of the parameters to more closely capture differences in inorganic and organic accretion across the region.

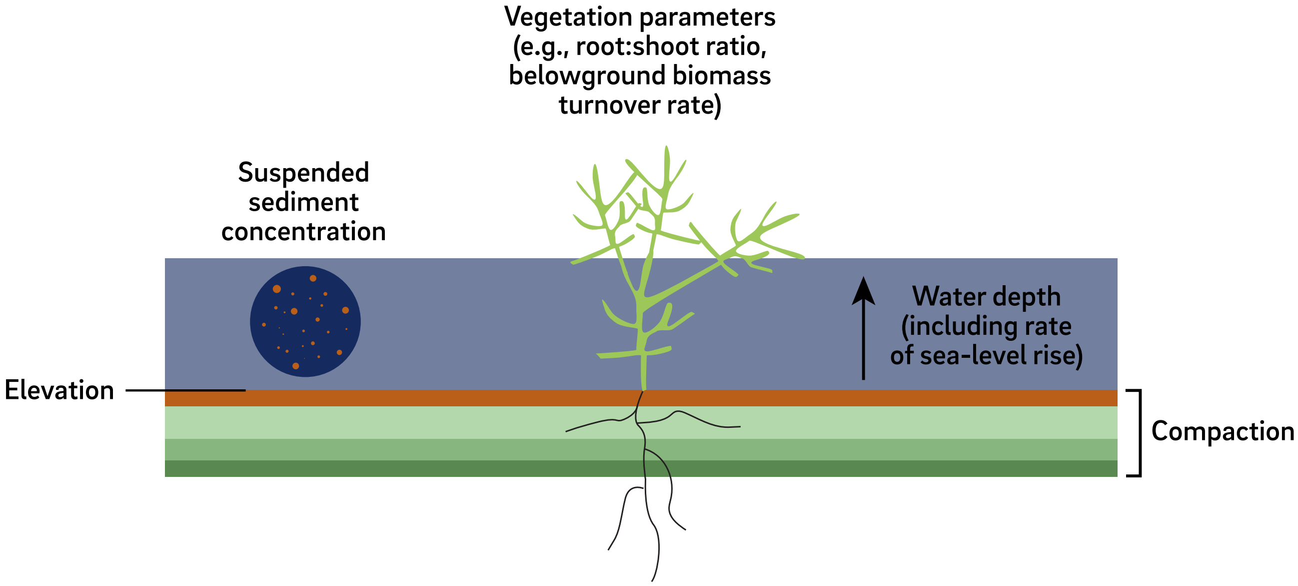


Figure A7.1.2. A visual representation of the input parameters to the coastal wetland equilibrium model.

B FLOOD ATTENUATION METRICS

BAYLANDS RESILIENCE FRAMEWORK FOR FLOOD ATTENUATION

USACE's International Guidelines on Natural and Nature-Based Features for Flood Risk Management ("International Guidelines") describe the value of tidal wetlands and tidal flats in reducing flood and erosion risk for shoreline environments (Bridges et al. 2021, Piercy et al. 2021). Marshes and mudflats in San Francisco Bay can attenuate waves and reduce storm surge by slowing waves that move across them, both through shoaling effects (the water depth becoming shallower) and friction (the water being slowed by resistance from marsh vegetation). The Baylands Resilience Framework for Flood Attenuation (in progress) synthesizes and applies information from the International Guidelines specifically to the San Francisco Bay context. It describes the elements needed for functional and resilient marshes that reduce flood risk to adjacent communities. The metrics mapped for this analysis follow from the modes of flood attenuation identified in the Baylands Resilience Framework (Table B1): flood storage, wave attenuation, and surge attenuation. The wave attenuation metric maps contributions of existing marshes and mudflats, while the flood storage and wave attenuation metrics explore potential future flood attenuation contributions if diked baylands are restored. Not every element in the Baylands Resilience Framework has an associated mapped metric in this report.

Metrics B1 (Compound flooding) and B2 (Storm surge attenuation) are descriptive, high-level metrics meant to help users understand what the potential benefits of restoring diked baylands in different parts of the estuary might be. Metric B3 (Wave attenuation) is a more quantitative analysis based on new modeling for the Bay.

Table B1. Each metric mapped for this analysis contributes to describing one of the elements of the Baylands Resilience Framework for Flood Attenuation.

Framework Element	Metric
B1. Compound flooding	B1.1 Opportunities to restore diked baylands to alleviate compound flooding
B2. Storm surge attenuation	B2.1 Opportunities to restore diked baylands to alleviate storm surge flooding
B3. Wave attenuation	B3.1 Wave attenuation by marshes and mudflats

B1.1

FLOOD ATTENUATION METRICS

OPPORTUNITIES TO RESTORE DIKED BAYLANDS TO ALLEVIATE COMPOUND FLOODING

SUMMARY OF METRIC

Restoring diked baylands, particularly in inner estuaries near the head of tide, can mitigate upstream flooding by creating storage for floodwaters, reducing creek water levels, and lowering upstream water levels (Figure B1.1.1). This metric provides a coarse way to evaluate the potential for baylands restoration to reduce upstream flooding; hydrodynamic modeling can then follow to refine restoration opportunities.

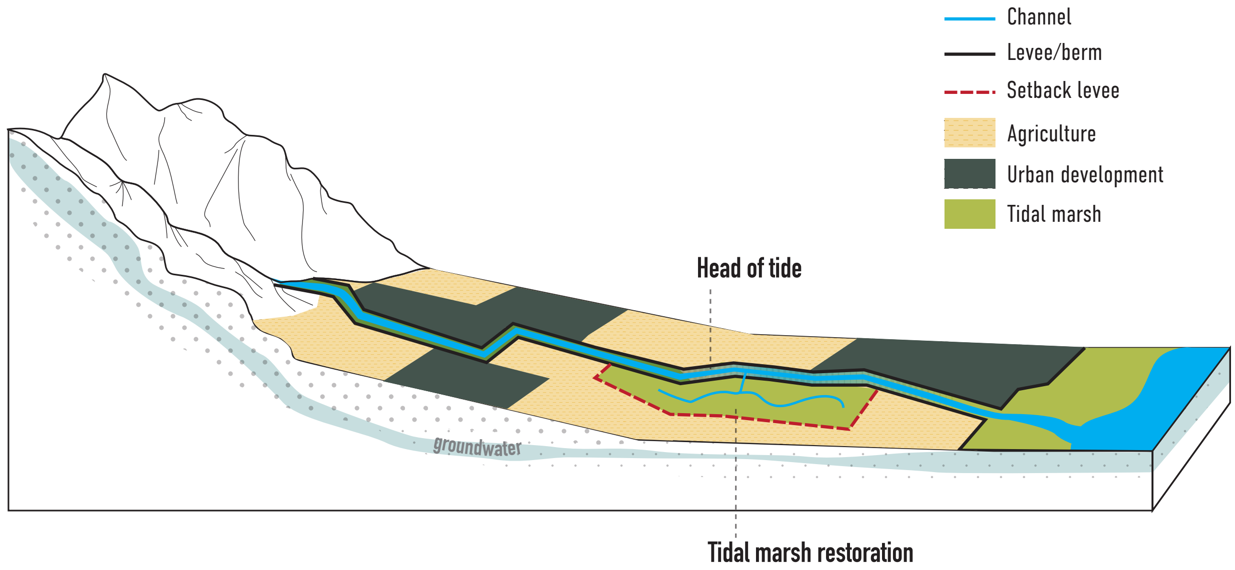


Figure B1.1.1. Restoring baylands near head of tide can reduce upstream water levels by increasing in-channel scour and providing more space for floodwaters to spread out. Figure adapted from Where Creeks Meet Baylands (SFEI 2023b).

RELEVANCE

Many of the baylands fringing San Francisco Bay have been diked, drained, and disconnected from watersheds, confining sediment and floodwaters to leveed, straightened channels. This leads to higher water levels in the channels and causes compound flooding when heavy precipitation events coincide with a high tide in the Bay. Restoring baylands can reduce compound flooding through two mechanisms: (1) increased tidal prism in the lower watershed from opening up formerly diked areas increases in-channel scour and deepens the channel; and (2) restored marshes provide a place for floodwaters to spread out, reducing water levels in channels.

Hydrodynamic modeling conducted for various local projects (e.g., Novato Creek and Sonoma Creek) has demonstrated the potential for downstream tidal restoration projects to reduce upstream flooding (Kamman Hydrology & Engineering, Inc. 2016, ESA 2020). However, if not carefully designed (for example, with appropriate channel capacity), downstream projects may inadvertently increase flooding (Anchor QEA 2021); therefore, hydrodynamic modeling is an essential step for restoration design. A more thorough description and comparison of examples from hydrodynamic modeling results is provided in Where Creeks Meet Baylands (SFEI 2023b).

APPLICATION

This metric can help identify locations where restoration of diked baylands can reduce upstream flooding. Restoration of diked baylands near the head of tide (in inner estuaries as opposed to estuary mouths) may be particularly beneficial in storing water and reducing upstream water levels (Piercy et al. 2021). This metric is not meant to replace watershed-scale hydrodynamic models; rather, when paired with flood maps, it can help identify locations where watershed-scale modeling of restoration alternatives is worth pursuing to determine whether baylands restoration can be part of a larger flood risk management strategy.

EXAMPLE

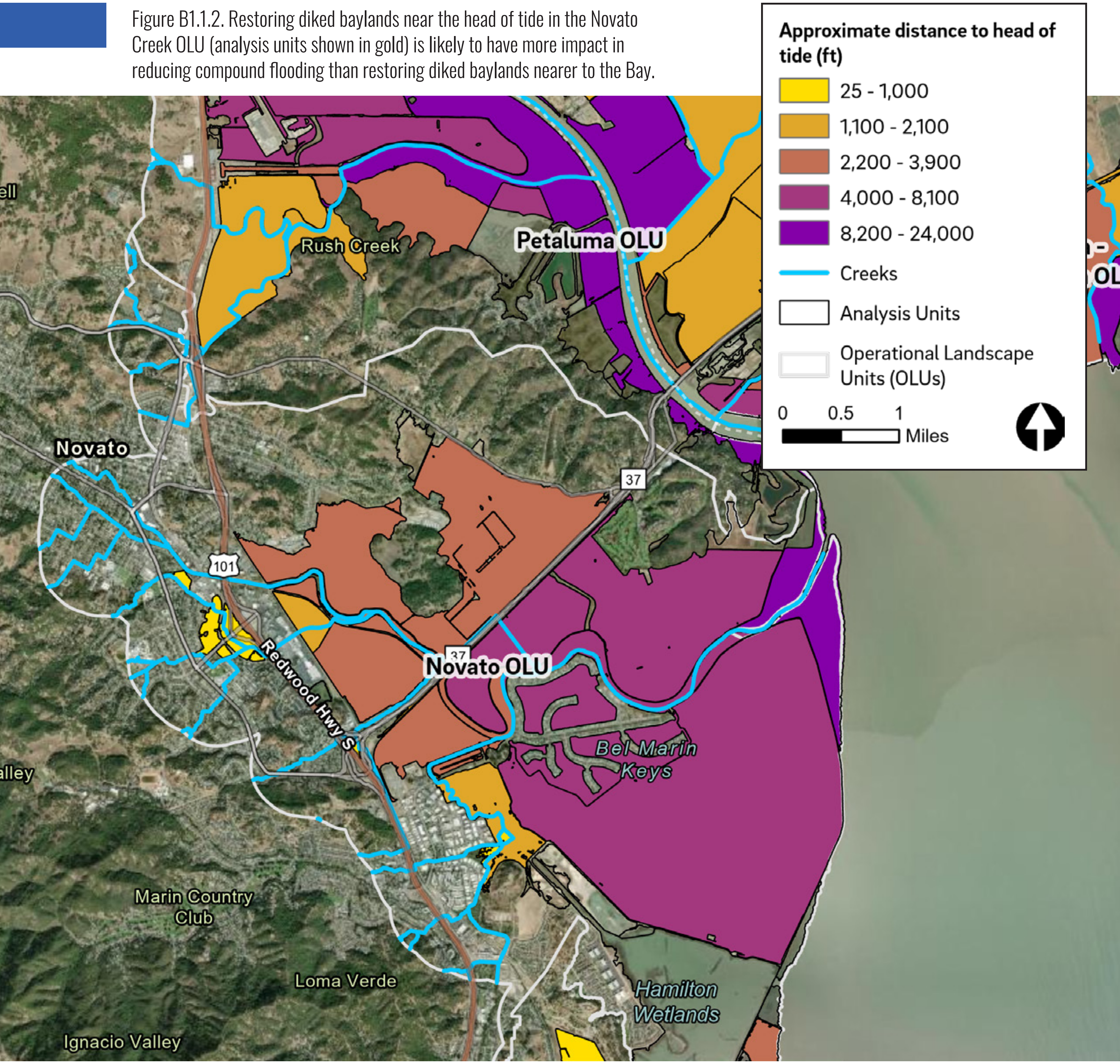
In the Novato OLU, diking and draining of marshes and channelization of Novato Creek has exacerbated impacts of compound flooding upstream in the City of Novato. Restoring diked baylands near head of tide (Figure B1.1.2) could alleviate compound flooding impacts in this watershed by allowing more space for storage of floodwaters.

METHOD

We selected perennial creeks from the National Hydrography Dataset (NHD) that stretch from the upland OLU boundary to the Bay. The creeks are included in the foundational layers section of the web map. Next, we generated points along the creek lines at regular intervals and determined the distance to each point from the line's 'head of tide' location (estimated as 50 meters upstream from MHHW extent). Finally, we summarized the distance to head of tide by averaging the distance values for all points within 100 meters of a diked bayland. This method does not consider elevation and discharge and is purely based on distance to head of tide.

To result in reductions in upstream flooding, a restored area must be close to the head of tide and have storage capacity constituting a significant proportion of the flow volume from the watershed. To illustrate the second of these two parameters, we calculate an additional tidal prism metric to supplement the distance to head of tide metric. The tidal prism metric estimates diked bayland volumes (from MLLW to MHHW) and tidal prism of existing marshes. The tidal prism metric can be used to estimate the additional tidal prism that would be conveyed by the channel after restoration of diked baylands. The tidal prism metric is included with the set of Flood Attenuation metrics as a companion to the "distance to head of tide" metric to aid in identifying restoration opportunities with more significant opportunity for compound flooding reduction.

Figure B1.1.2. Restoring diked baylands near the head of tide in the Novato Creek OLU (analysis units shown in gold) is likely to have more impact in reducing compound flooding than restoring diked baylands nearer to the Bay.



B2.1

FLOOD ATTENUATION METRICS

OPPORTUNITIES TO RESTORE DIKED BAYLANDS TO ALLEVIATE STORM SURGE FLOODING

SUMMARY OF METRIC

Restoring diked baylands at the mouths of creeks may contribute to along-estuary storm surge attenuation effects. This analysis identifies opportunities to pursue marsh restoration projects that would attenuate storm surge from the Bay.

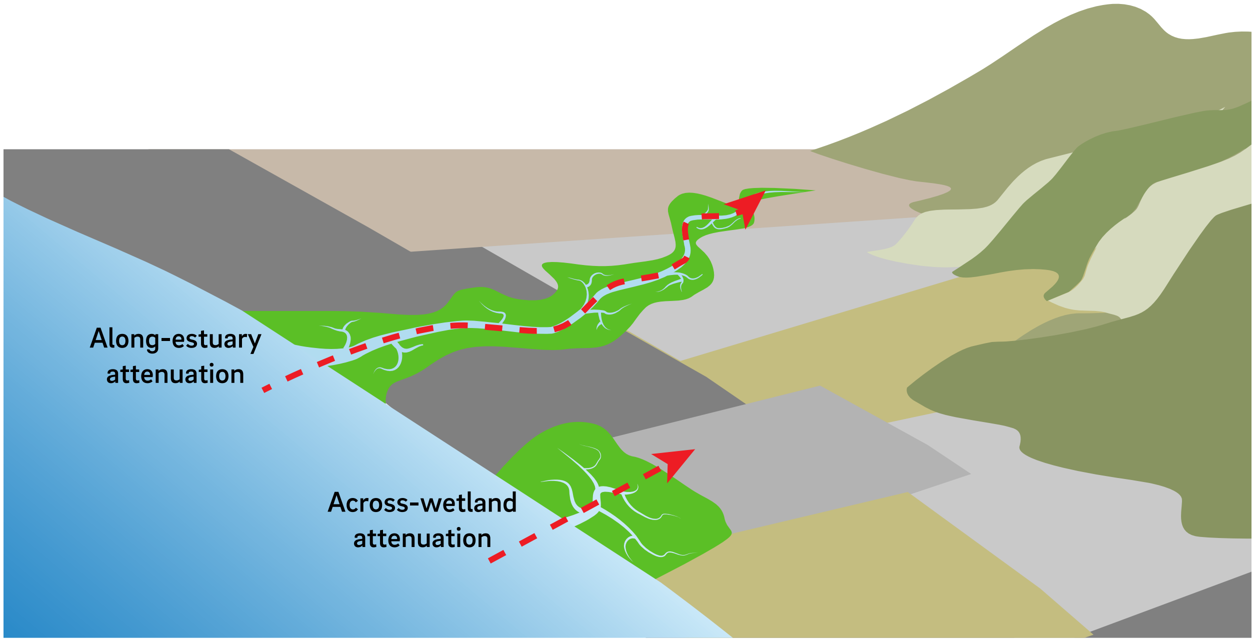


Figure B2.1.1. While there are few marshes wide enough to support across-wetland storm surge attenuation in San Francisco Bay, there are several opportunities to support along-estuary storm surge attenuation. Adapted from Piercy et al. (2021).

RELEVANCE

Most of the tidal marshes ringing the Bay are not wide enough to provide significant reduction of water levels across the marsh during a storm surge. However, tidal wetlands can decrease propagation of surge up an estuary, known as “along-estuary surge attenuation” (Figure B2.1.1). The most pronounced along-estuary storm surge attenuation occurs in funnel-shaped channels (Piercy et al. 2021), indicating that restoration of marshes near the Bay along channels may be a priority if storm surge attenuation benefits are desired. This metric serves as a companion to the compound flooding metric, measuring distance to the Bay rather than distance to head of tide.

APPLICATION

This is largely a qualitative metric. The results of this analysis can be used to identify places where restoration of diked baylands can help attenuate storm surges. In addition to location in the estuary, tidal prism is also a major factor in determining the extent of this effect; we provide tidal prism estimates as a companion metric. Restoration of diked baylands near the mouth of creeks where they discharge to the Bay can increase channel width, decrease water depths, and help create large funnel-shaped floodplains that attenuate storm surges (Piercy et al. 2021). Storm surge attenuation effects diminish when water levels exceed marsh plant heights. Therefore, sediment placement may be important to realizing storm surge attenuation benefits because it can facilitate more rapid colonization of marsh vegetation when subsided diked baylands are restored.

EXAMPLE

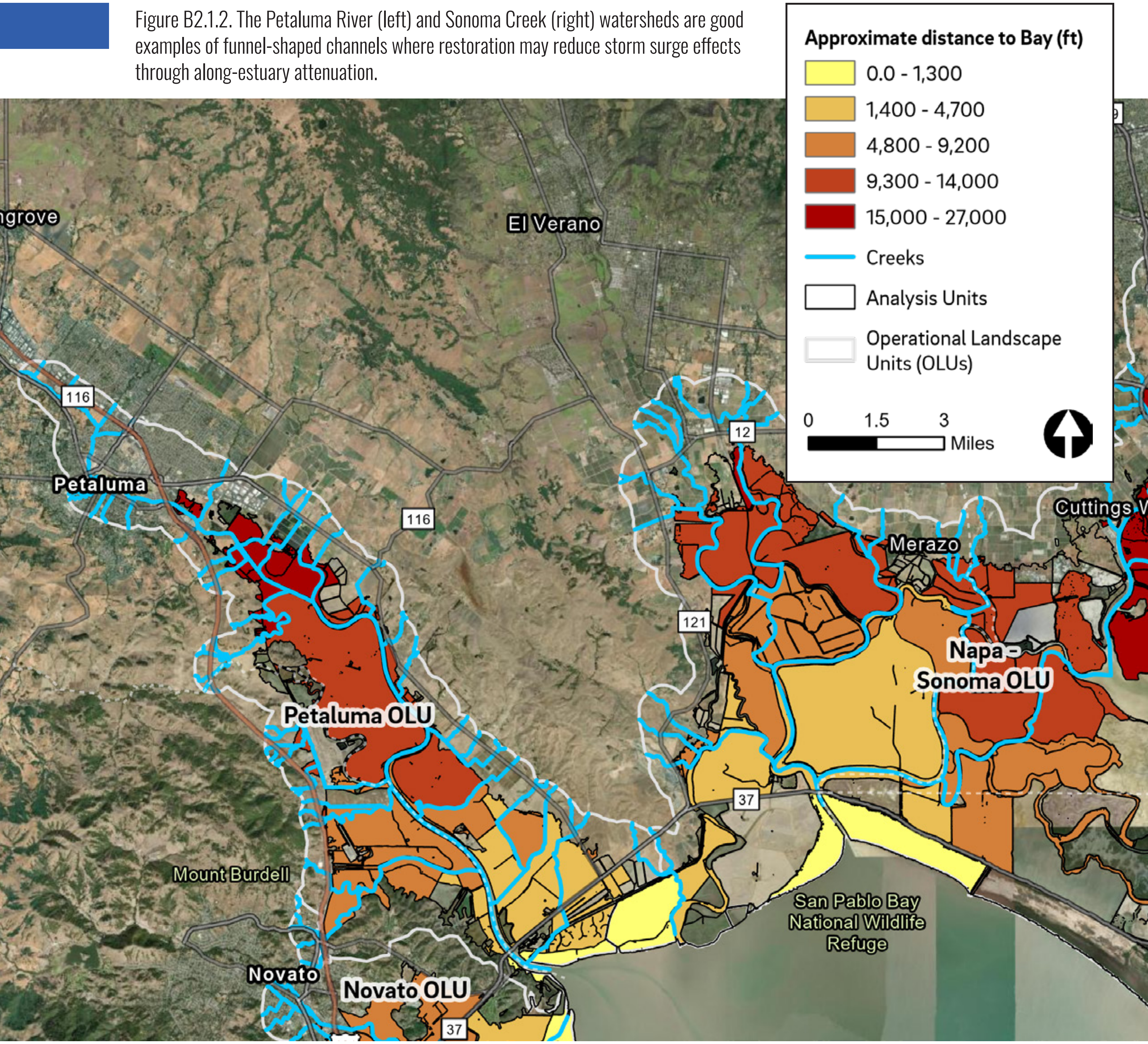
Restoring tidal flow to diked baylands at the mouths of estuaries to create large funnel-shaped floodplains can help attenuate storm surge. Examples of potential funnel-shaped estuaries can be found in San Pablo Bay at the Petaluma River and Sonoma Creek (Figure B2.1.2), and Novato Creek. Strategically restoring diked baylands near the mouths of these rivers (units shown in yellow/gold) may have benefits in attenuating storm surge, with more storm surge benefits from restoring diked baylands with larger tidal prism. Storm surge impacts are fairly evenly distributed across the Bay, though they are responsible for a greater proportion of extreme water levels in the South Bay compared to the North Bay. In the North Bay, discharge from the Delta and local watersheds are also important in driving extreme water levels (Nederhoff et al. 2021).

METHOD

We selected perennial creeks from the NHD that stretch from the upland OLU boundary to the Bay. The creeks are included in the foundational layers section of the web map. Next, we divided these creeks by generating points along the creek line at regular 50 meter intervals. Afterward, we determined the distance from the Bay to each of these points using the NHD “coastline” as the “Bay edge” boundary. We then summarized the distances to the Bay on the generated points within 100 meters to each analysis unit.

Wetlands must occupy a large proportion of total flow area to provide measurable benefit. The mapping of this metric can be used to visually identify large diked baylands that would facilitate creation of funnel shaped estuaries if restored. We also provide diked bayland volumes (from MLLW to MHHW) to estimate the tidal prism that would be added if diked baylands are restored. The tidal prism metric is included with the set of Flood Attenuation metrics as a companion to the “distance to bay” metric to aid in identifying restoration opportunities with more significant opportunity for storm surge reduction.

Figure B2.1.2. The Petaluma River (left) and Sonoma Creek (right) watersheds are good examples of funnel-shaped channels where restoration may reduce storm surge effects through along-estuary attenuation.



B3.1

FLOOD ATTENUATION METRICS

WAVE ATTENUATION BY MARSHES AND MUDFLATS

SUMMARY OF METRIC

Marshes and mudflats attenuate waves, reducing wave runup and overtopping of levees at the back of the marsh. They can also reduce damage to levees and associated maintenance costs. This metric quantifies wave attenuation benefits of existing marshes and mudflats.

RELEVANCE

Tidal marshes, mudflats, eelgrass, and offshore reefs can attenuate waves (Gedan et al. 2011, Shepard et al. 2011, Narayan et al. 2016, Boyer et al. 2017, SFEI and SPUR 2019, Piercy et al. 2021). Here, we have focused on marshes and mudflats, with the wave attenuation benefits of reefs and eelgrass to be studied in a later phase. Through a combination of shoaling, friction, and wave breaking, marshes and mudflats attenuate waves from the Bay (Figure B3.1.1) and help reduce direct wave action, wave run-up, and erosion of levees. This attenuation allows for lower crest heights and reduced maintenance costs of landward seawalls or levees. In San Francisco Bay, wave attenuation is most influenced by the presence of vegetation and the width and elevation of the marsh plain (Taylor-Burns et al. 2023). Greater wetland widths are required to attenuate larger waves, so attenuation of storm waves associated with surges will require larger wetland areas than those required to reduce erosion, which is typically driven by locally generated wind waves and lower water surface elevations. The modeling conducted for this study can illuminate the role mudflats play in protecting marshes from wave erosion and the role marshes play in protecting development and infrastructure behind them.

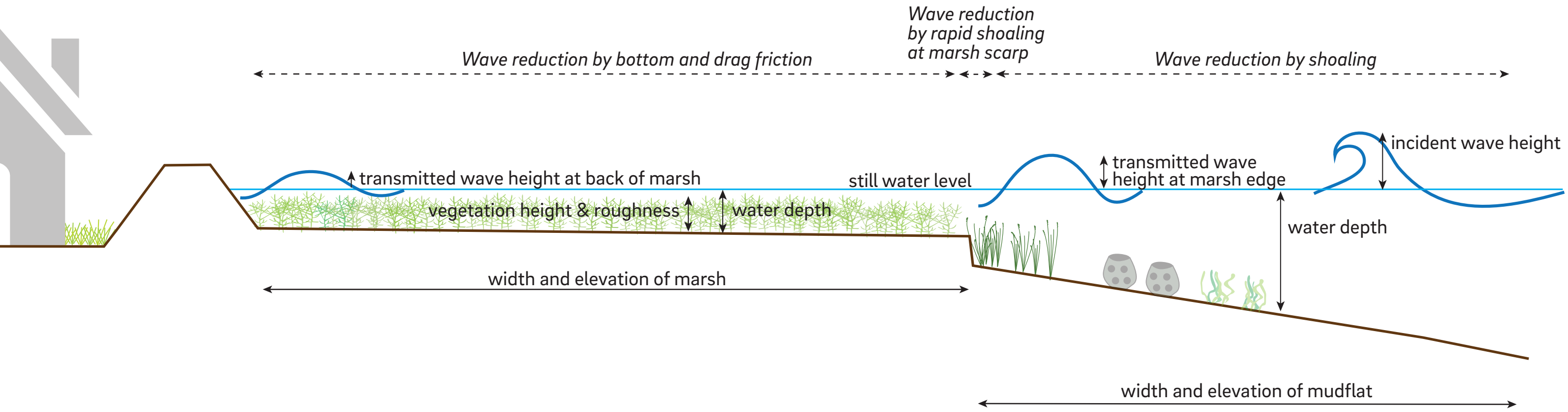


Figure B3.1.1. Depiction of wave height reduction across tidal flat and tidal marsh habitats, accounting for the contribution of changing topography ("shoaling" effects) and the contribution of vegetation ("frictional" effects). Adapted from Narayan et al. (2016).

APPLICATION

Around the Bay, marshes and mudflats reduce wave heights, wave runup, and erosion at the back of the marsh. By understanding where marshes and mudflats are performing this function, we can identify appropriate adaptive management strategies to maintain this function as sea levels rise. For example, where marshes are currently wide enough to provide wave attenuation benefits but are threatened by marsh edge erosion, actions like adding coarse beaches to protect the marsh edge from waves may be warranted. Where marshes are attenuating waves but are threatened by drowning (as revealed by the vertical accretion modeling), strategic placement of sediment (shallow water placement, water column seeding, thin layer placement) may be a suitable adaptation strategy to maintain wave attenuation benefits.

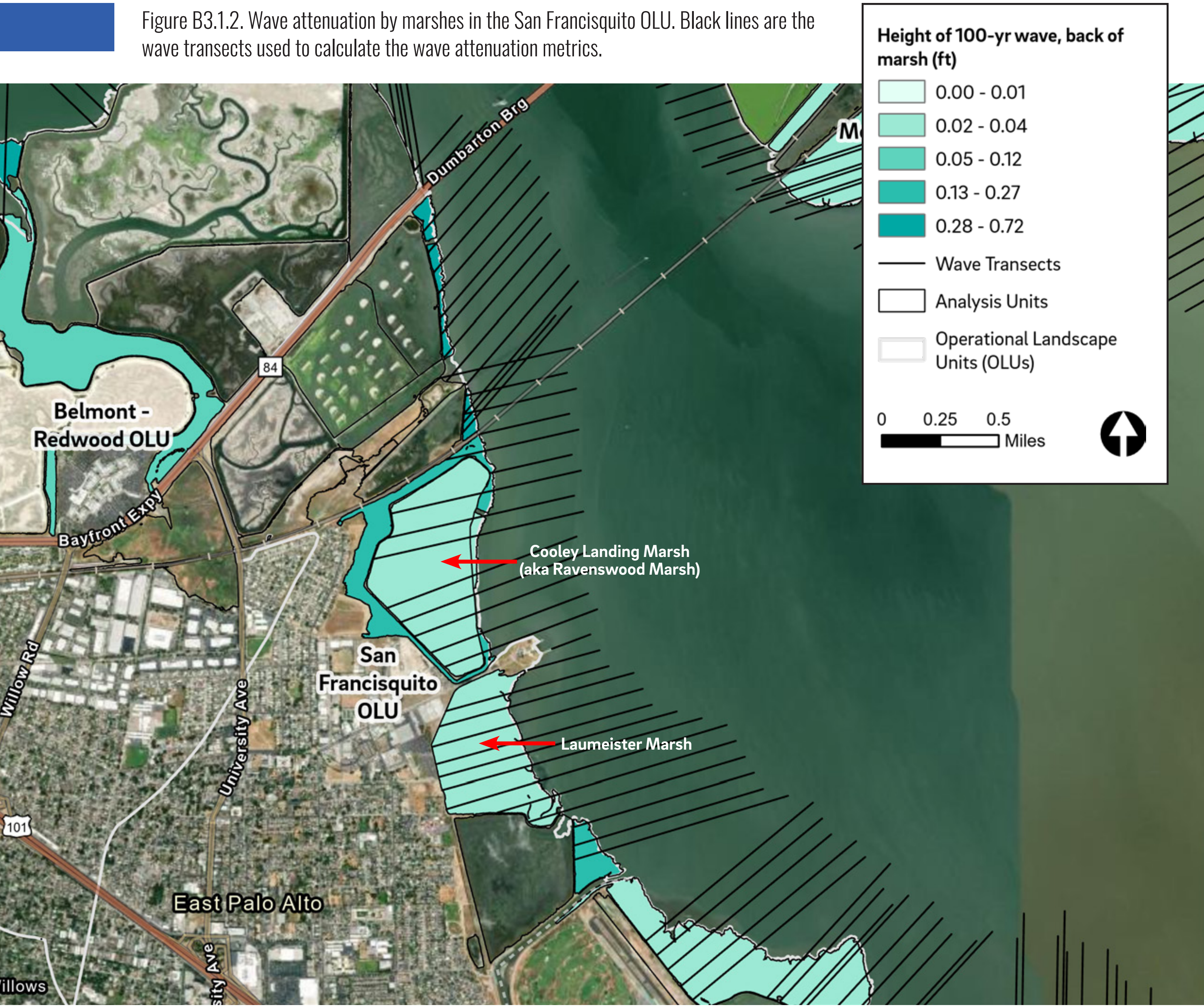
We provide several outputs from the wave attenuation model, described briefly here. These values are an average across all the wave transects for a given unit.

- **Height of 100 year wave (ft).** The maximum height of waves with a 100-year recurrence interval.
- **Height of 100 year wave at back of mudflat (ft).** Mudflats contribute to wave attenuation; this metric describes the contribution of the mudflat to attenuating waves before they reach the marsh.
- **Height of 100 year wave at back of marsh (ft)**: wave height at back of marsh after attenuation by both mudflat and marsh.
- **Average marsh width (ft)**: provided as context for the following output.
- **Difference in marsh width needed to attenuate 100 year wave to 1 ft**: Indicates how much wider the marsh would need to be to attenuate the 100 year wave to a height of 1 ft, or how much narrower it can get before it is unable to do so. Negative values indicate a wider marsh is needed to attenuate to 1 ft.

EXAMPLE

Differences in marsh width, marsh elevation and vegetation affect the degree to which waves are attenuated before reaching levees in the San Francisquito OLU (Figure B3.1.2). Laumeister Marsh, one of the oldest marshes in the South Bay, sits higher in the tidal frame and is more completely vegetated than Cooley Landing Marsh (aka Ravenswood Marsh), which was operated as a salt pond until 1981 and restored to tidal marsh in 2000 (H.T. Harvey & Associates 2023). However, both of these marshes are relatively wide, and attenuate 100-year waves (about 2-2.5 feet high in this area) to less than an inch high by the time they reach the back of the marsh. Narrower fringing marshes south of the Dumbarton Bridge are somewhat less effective but still attenuate waves down to a few inches in height by the time they reach the back of the marsh. Understanding the existing contributions of marshes to wave attenuation can inform adaptation actions (including sediment placement) where preservation of wave attenuation is desired or an increase in wave attenuation is needed to prevent erosion of levees or other shoreline structures. Wave attenuation benefits are likely to be of most importance where waves are highest—along the East Bay shoreline—though there are other places around the Bay where wave attenuation by marshes and mudflats provides erosion prevention benefits.

Figure B3.1.2. Wave attenuation by marshes in the San Francisquito OLU. Black lines are the wave transects used to calculate the wave attenuation metrics.



METHOD

To evaluate the contribution of intertidal and subtidal habitats in reducing wave heights, we employed a 1-D transect model to determine wave reduction based on elevation, width, and relevant friction coefficients. We adapted the model from the WATTE toolbox (Foster-Martinez et al. 2020) to incorporate elevation data and built additional functionality for enhanced refinements. Starting wave heights originated from a regional modeling effort (DHI 2011, 2013) initiated as part of the most recent update to the Bay Area's FEMA flood maps. We limited our analysis to marshes that are adjacent to the open bay (i.e., not marshes located in inner estuaries where wind waves are unlikely to propagate). At these marshes, we built shore-normal transects and created points where the transects intersected the edge of each habitat type (marsh and mudflat). Next, we assigned elevation, slope, and friction coefficients (based on Baylands Habitat Map 2020 classification) to each section of the transect. For more information about the formulas and parameters employed in the model, refer to Appendix A: Expanded Methods. Future iterations of this model can be improved by employing refined local parameters (e.g., for vegetation height and roughness), improved topobathymetric data, and including additional habitats (e.g., oyster reefs, eelgrass). Additional model outputs, such as wave heights including runup, are available upon request.

C PLACEMENT FEASIBILITY METRICS

The wildlife support and flood attenuation metrics are focused on the resilience of bayland ecosystem services. In contrast, the placement feasibility metrics are focused on logistical considerations of placing sediment in different ways. This regional analysis provides a high-level view of the relative feasibility considerations associated with placement sites. Each potential sediment placement site will have its own unique set of logistical constraints to consider at a detailed, site-specific level.

In general, large, deeply subsided sites with wide mudflats will be more challenging and expensive to fill with dredged sediment than smaller sites closer to deep water. Sites closer to boat-accessible channels will be more efficient to fill than sites far from navigation channels. In combination with the wildlife support and flood attenuation metrics, these types of high-level considerations can help identify suitable sites for the placement of dredged sediment. Table C.1 lists the placement feasibility metrics developed to date.

Table B1. Placement feasibility metrics.

Metric
C1. Volume
C2. Distance to Placement Site
C3. Distance to Feasible Shallow Water Placement Location
C4. Site Considerations

C1

PLACEMENT FEASIBILITY METRICS

VOLUME

SUMMARY OF METRIC

Understanding the volume of sediment required to maintain the elevation of existing marshes and to fill subsided diked baylands to marsh elevation will be useful for weighing feasibility considerations of pursuing placement projects.

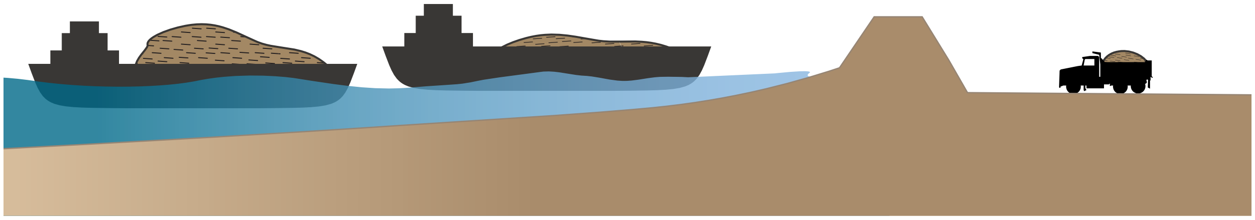


Figure C1.1. One of the volume metrics we report summarizes fill volumes by the number of trips required by fully-loaded scows, light-loaded scows, and trucks. Light-loaded scows can access shallower water than fully loaded scows; however, more trips will be required.

APPLICATION

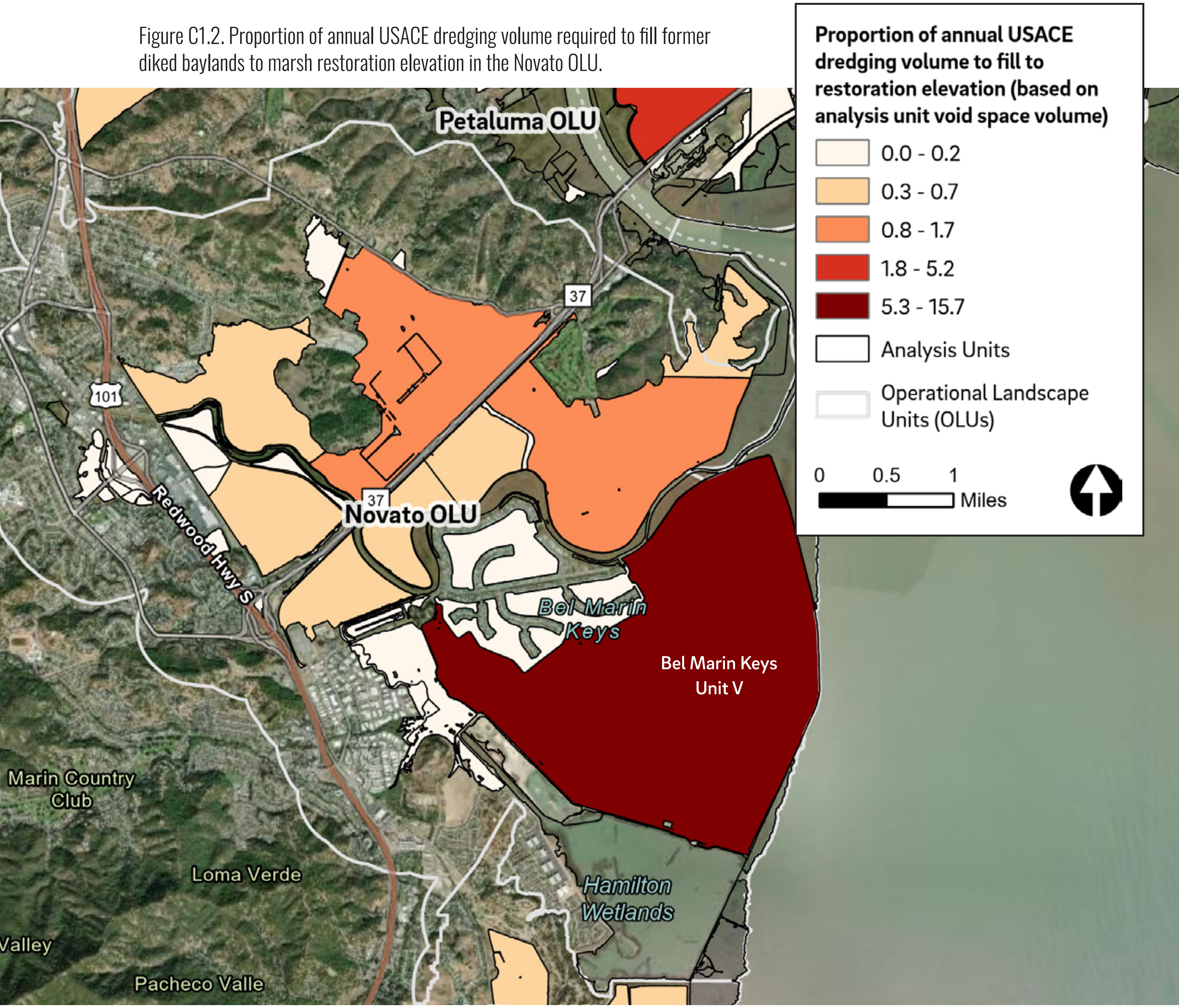
The volume of fill required is an important factor to consider when selecting beneficial use placement sites. Cubic yards is a standard way to report volume, but other volume metrics can be derived to provide ways to visualize the time and logistical requirements associated with filling sites. By normalizing volumes of fill to the total dredging volume in a single season, we allow comparison of the number of years it will take to fill various sites around the Bay with dredged material. This provides a sense of the length of investment required to commit to a particular site, although this does not allow for compaction of the placed material and the number of years will likely be an underestimate. Some of the possible placement sites are so large and subsided that they will require multiple seasons of dredging to fill. Others are small and multiple sites could be filled in one season.

We also present volume of fill in terms of scow-loads and truck-loads to provide a sense of the logistical requirements associated with filling each site (Figure C1.1). These are rough estimates only and are meant to aid in assessing the feasibility of various placement approaches as well as providing a relevant unit for understanding the level of effort required to fill smaller and larger sites. These numbers are underestimates as we did not account for the changing bulk density of dredged material as it makes its way from a Bay channel to the scow to the placement site. In reality, much of the volume of each scow-load is taken up by water, requiring more trips to achieve the target volume of sediment. For more information on changes in bulk density at each stage in the beneficial reuse process refer to McKnight et al. 2020.

EXAMPLE

The diked baylands of the Novato OLU are subsided to different degrees and will require varying amounts of sediment to fill to restoration elevation, should this strategy be pursued as part of restoration plans (Figure C1.2). Only part of the analysis unit that includes the Bel Marin Keys Unit V restoration will be restored to tidal marsh. Construction of the new levee dividing the parcel occurred in 2020, after the development of the Shoreline Inventory (SFEI 2016), illustrating the importance of regularly updating these data. However, this unit is still one of the highest-volume diked baylands in the region, due to its low elevation as well as its size, and filling even part of it will require committing multiple seasons of dredged material to the project.

Figure C1.2. Proportion of annual USACE dredging volume required to fill former diked baylands to marsh restoration elevation in the Novato OLU.



METHOD

For marsh units, we calculated the volume to fill to marsh plain elevation, based on a digital elevation model compiled from the latest available LiDAR. We used 0.1 ft (0.03 m) above MHW as the average marsh plain elevation in the Bay (Takekawa et al. 2013). For diked bayland units, we calculated the volume to fill to one foot below marsh plain elevation, the recommended fill elevation determined to be most beneficial for natural accretion and channel development (PWA and Faber 2004). All volumes reported are void space volumes and do not account for compaction; these additional volume considerations, including the influence of varying bulk densities of sediment placed (McKnight et al. 2020), will need to be determined at a later stage of planning.

To determine the percent of annual dredge volume as well as the volume per load, we used the following values:

- Volume of sediment removed from federal navigation channels in one dredging season: 2,575,060 cubic yards, the value for the 2020 dredging season (USACE 2021).
- Volume of sediment transported in a light-loaded scow, which has better access to shallow water: 900 cubic yards. This was the value used as an estimate for planning the Eden Landing shallow water placement pilot project, which allowed a scow to draft at 9-10 feet (USACE San Francisco District 2023). Though not assessed here, there are also smaller 300 cubic yard scows that can access even shallower water.
- Volume of sediment transported in a fully-loaded scow: 1,450 cubic yards (based on input from USACE)
- Volume of sediment transported in a truck: 8 cubic yards (based on input from USACE)

C2

PLACEMENT FEASIBILITY METRICS

DISTANCE TO PLACEMENT SITE

SUMMARY OF METRIC

For the placement of dredged material there are two key elements of distance to consider: the distance from the dredging location to the offloading location, and the distance from the offloading location, often across shallow water and mudflat, to the desired placement site. In the future, we may extend this analysis to cover upland source locations delivered by trucks.

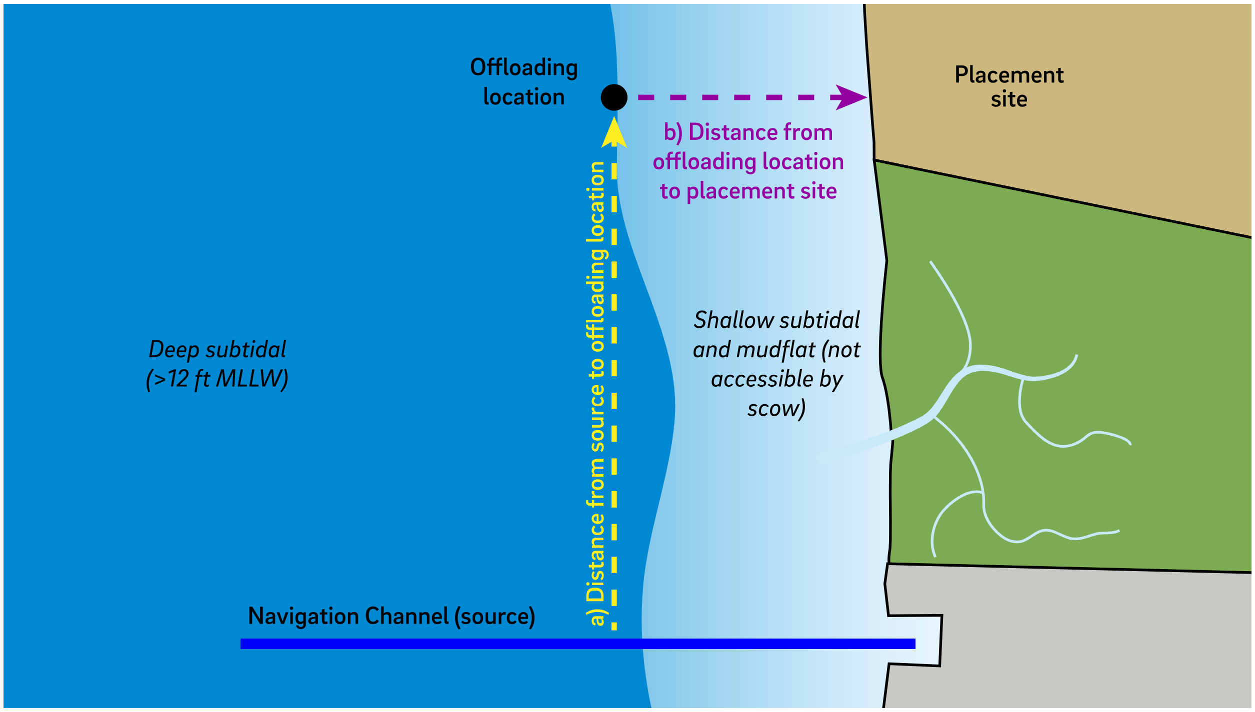


Figure C2.1. Two key distance metrics are: (a) the distance from the source location (such as a navigation channel where dredging occurs) to the offloading location (determined by water depth at MLLW) and (b) the distance from the offloading location to the placement site.

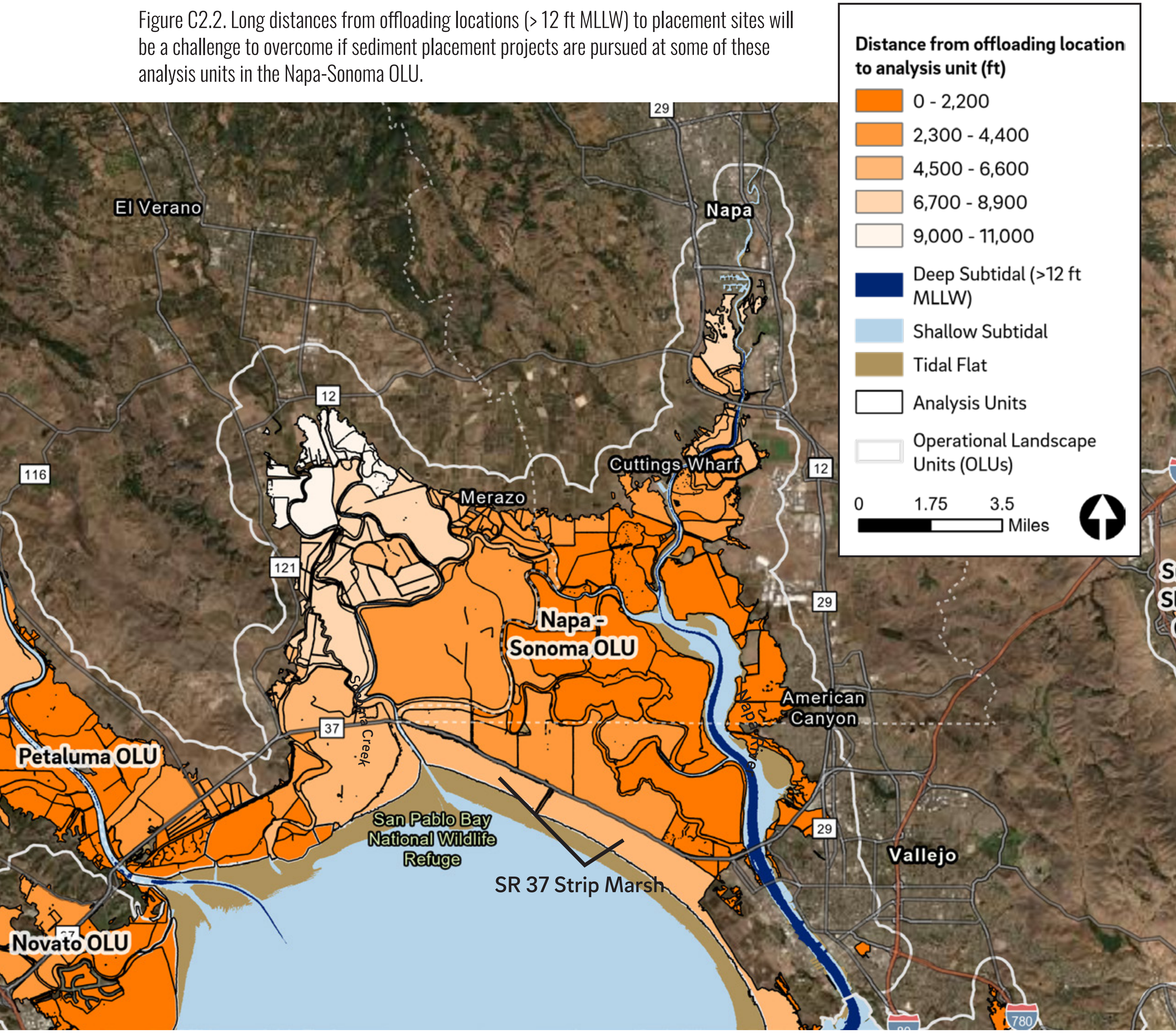
APPLICATION

Placement sites that are closer to dredging locations (such as navigation channels) are economically and environmentally preferable because of reduced fuel use and greenhouse gas emissions and optimized turnaround times (Figure C2.1). A major constraint of both direct and strategic placement is transporting material from the offloading location to the placement site (distance (b) in Figure C2.1). Restoration sites that are closer to viable offloading locations may be preferable to reduce pumping distance and the need for a complex offloading facility. For this analysis, we assume the specific placement method and associated constraints will be determined at a later stage; this analysis is meant to provide a rough estimate of the accessibility of sites.

EXAMPLE

In regions with wide shallows and tidal flats, like northern San Pablo Bay (Napa-Sonoma OLU) (Figure C2.2), transporting material to sites from offloading locations may add difficulty and cost to sediment placement projects. In the Sonoma Creek baylands, wide mudflats and shallow waters fronting the State Route 37 strip marsh limit the approach of scows. Access from the Napa River side of the OLU may be more feasible than access from Sonoma Creek.

Figure C2.2. Long distances from offloading locations (> 12 ft MLLW) to placement sites will be a challenge to overcome if sediment placement projects are pursued at some of these analysis units in the Napa-Sonoma OLU.



METHOD

To calculate the distance from the source to the nearest offloading location (distance (a) in Figure C2.1) we created a distance accumulation raster from each USACE navigation channel within the limits of navigation of a fully-loaded scow (depths less than 12 feet at MLLW). Each raster cell contains a distance from the nearest navigation channel. Raster cells farther from a navigation channel received higher distance values. We then selected the closest raster cell to each placement site and assigned that navigation channel distance value to the offloading site.

To calculate the distance from the offloading location to the placement site location (distance (b) in Figure C2.1), we calculated the distance from the nearest edge of each placement site (marsh or diked bayland unit) to the 12 ft MLLW depth polygon (the "deep subtidal" category of the Baylands Habitat Map 2020).

C3

PLACEMENT FEASIBILITY METRICS

DISTANCE TO FEASIBLE SHALLOW WATER PLACEMENT LOCATION

SUMMARY OF METRIC

Shallow water placement projects drop sediment offshore to be carried by natural processes to mudflats and marshes. This metric identifies the distance from each marsh unit to the nearest potential shallow water placement location.

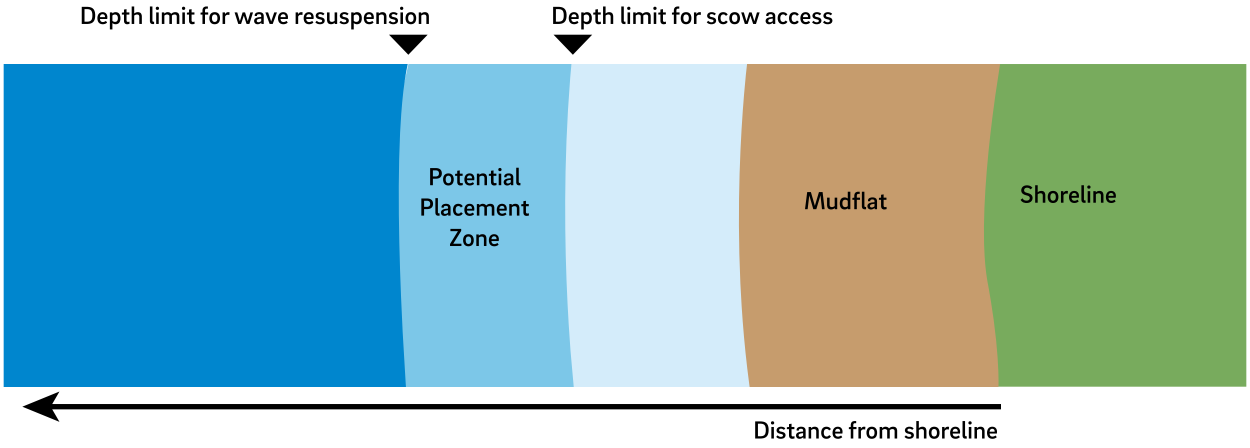


Figure C3.1. The "potential placement zone" for shallow water placement. Adapted from Figure 3-10 from the Strategic Placement Framework (USACE et al. 2017).

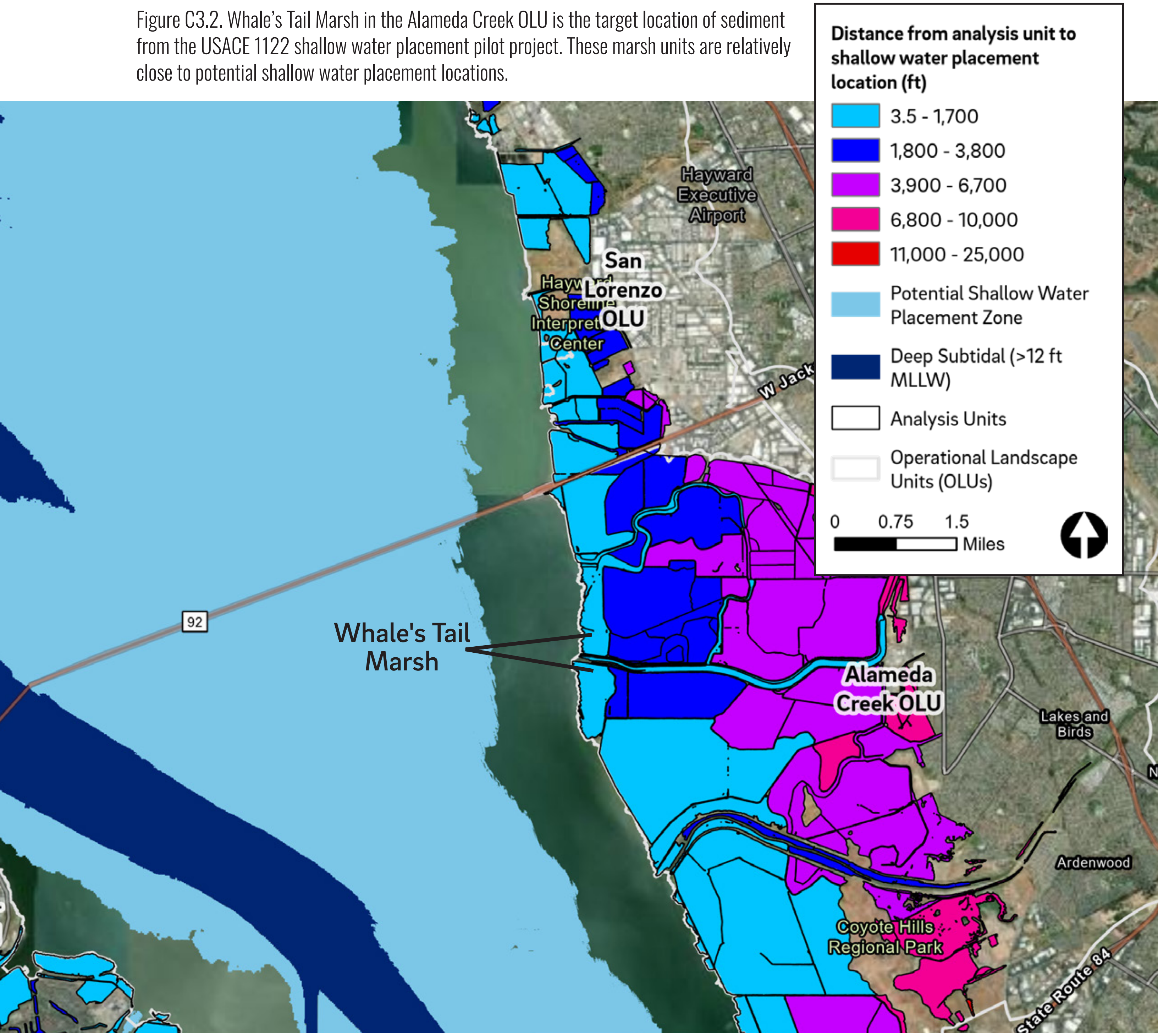
APPLICATION

For shallow water placement, there is a limited band of area that is deep enough for scows to access and offload, yet shallow enough that wave action is sufficient to resuspend sediment and transport it by tidal currents onto the target marshes (Figure C3.1). Pairing this metric with marsh and mudflat elevation metrics allows identification of shallow water placement project locations that a) require supplemental sediment due to low elevations and b) are close enough to a potential placement zone that shallow water placement is feasible. While the distance from the potential shallow water placement locations to the marsh edge is not the only factor affecting how much sediment reaches the marsh, it is a useful proxy for placement suitability. Placement locations nearer the marsh edge are likely to result in higher rates of sediment accretion on the marsh than placement sites far from the marsh edge. This analysis provides a rough estimate of potential offloading locations for shallow water placement. A more detailed consideration of feasible depths will be needed at the site scale. Additional information on depths is also available from the companion Sediment Transport Modeling study being conducted for the RDMMP.

EXAMPLE

The Alameda Creek and San Lorenzo OLUs have numerous marsh and diked bayland units relatively close to potential shallow water placement locations (Figure C3.2). The USACE pilot project at Whale's Tail Marsh is testing the feasibility of shallow water placement as a beneficial reuse strategy to build elevation at the marsh as well as the breached ponds behind the marsh. This metric can be paired with results from that pilot study, as well as sediment transport modeling, to help identify future locations that may be suitable for shallow water placement.

Figure C3.2. Whale's Tail Marsh in the Alameda Creek OLU is the target location of sediment from the USACE 1122 shallow water placement pilot project. These marsh units are relatively close to potential shallow water placement locations.



METHOD

We define the possible shallow water placement zone as the area where the zone of wave-driven sediment resuspension intersects with the feasible offloading area for scows. A 9-foot MLLW depth is used as the minimum depth limit for a light-loaded scow based on analyses conducted for the shallow water placement pilot project at Eden Landing (USACE 2023). Sediment resuspension is dependent on wave shear stress, which depends on water depth, wave height, and surface roughness. We used a relationship between wave height and critical depth of resuspension identified for an experimental field site south of the San Mateo Bridge (Brand et al. 2010). Wave heights were derived from the Our Coast Our Future - Coastal Storm Modeling System (CoSMoS) developed for San Francisco Bay (Barnard et al. 2014); we used annual wave heights from the model to determine the estimated depth of wave resuspension. By using known relationships between wave height and the maximum water depth at which sediment resuspension occurs in the Bay (Brand et al. 2010) and by assuming a constant bed surface roughness typical of mudflats (also from Brand et al. 2010), we were able to calculate the maximum depth of sediment resuspension associated with the annual wave height. By subtracting this depth from the elevation of the water surface at MLLW, we were then able to calculate the minimum depth elevation at which sediment resuspension is likely to occur. Finally, we calculate the distance from each marsh unit to the nearest potential shallow water placement location where sediment resuspension is likely to occur.

C4

PLACEMENT FEASIBILITY METRICS

SITE CONSIDERATIONS

SUMMARY OF METRIC

We identify a range of site characteristics that can help hone placement strategies and feasibility, including public versus private ownership, wet versus dry conditions, breached restoration sites, and proportion of each site within marsh spraying distance.

APPLICATION

The additional site considerations assessed here will help determine appropriate placement strategies. These considerations can help planners hone in on which sites may be suitable for different placement strategies, and which sites may be more or less feasible to restore based on their characteristics. We analyzed the following site considerations:

- **Ownership.** Sediment placement projects are more feasible to pursue in the near-term at sites that are already under public ownership.
- **“Wet versus dry” condition.** It may be easier to truck sediment in across a dry site (e.g., a diked bayland), while spraying may be a more effective strategy in a wet site (e.g., a former salt pond). In managed ponds, it may be necessary to construct berms to allow truck access for placement in all parts of the site.
- **Breached restoration sites.** These may be better locations for water column seeding. They tend to have few entrance points and may have higher velocities, constricted flows, and high turbulence in the water column, all of which can lead to more sediment in the water column that is delivered onto the marsh surface (USACE et al. 2017). Sites where breach locations are close to scow-accessible locations may be more optimal for water column seeding.
- **Proportion of site within marsh spraying distance.** Marsh spraying (thin layer placement) equipment cannot easily be placed within existing marshes (or there will be major feasibility and permitting hurdles to do so). Therefore, marsh spraying is more likely to be feasible in smaller marshes where most of the area is accessible from the edges (e.g, from levees, uplands, or open water). This metric, which describes how much “edge access” a site has, may also be useful for exploring other placement methods beyond marsh spraying.

EXAMPLE

A high proportion of the baylands in the Novato OLU are already owned by public entities (Figure C4.1a), making this a potentially more feasible area to pursue near-term restoration projects than places where most parcels are privately owned. Some of these parcels are used for agriculture and kept dry year-round, while others are seasonal wetlands or managed ponds (Figure C4.1b). Of the marshes in the Novato OLU, fringing marshes along the Bay near the Hamilton Wetlands and Novato Creek have the highest proportion of area within marsh spraying distance (100 meters) (Figure C4.1c). Understanding practical considerations like ownership, management status, and site configuration can help determine appropriate sediment placement strategies.

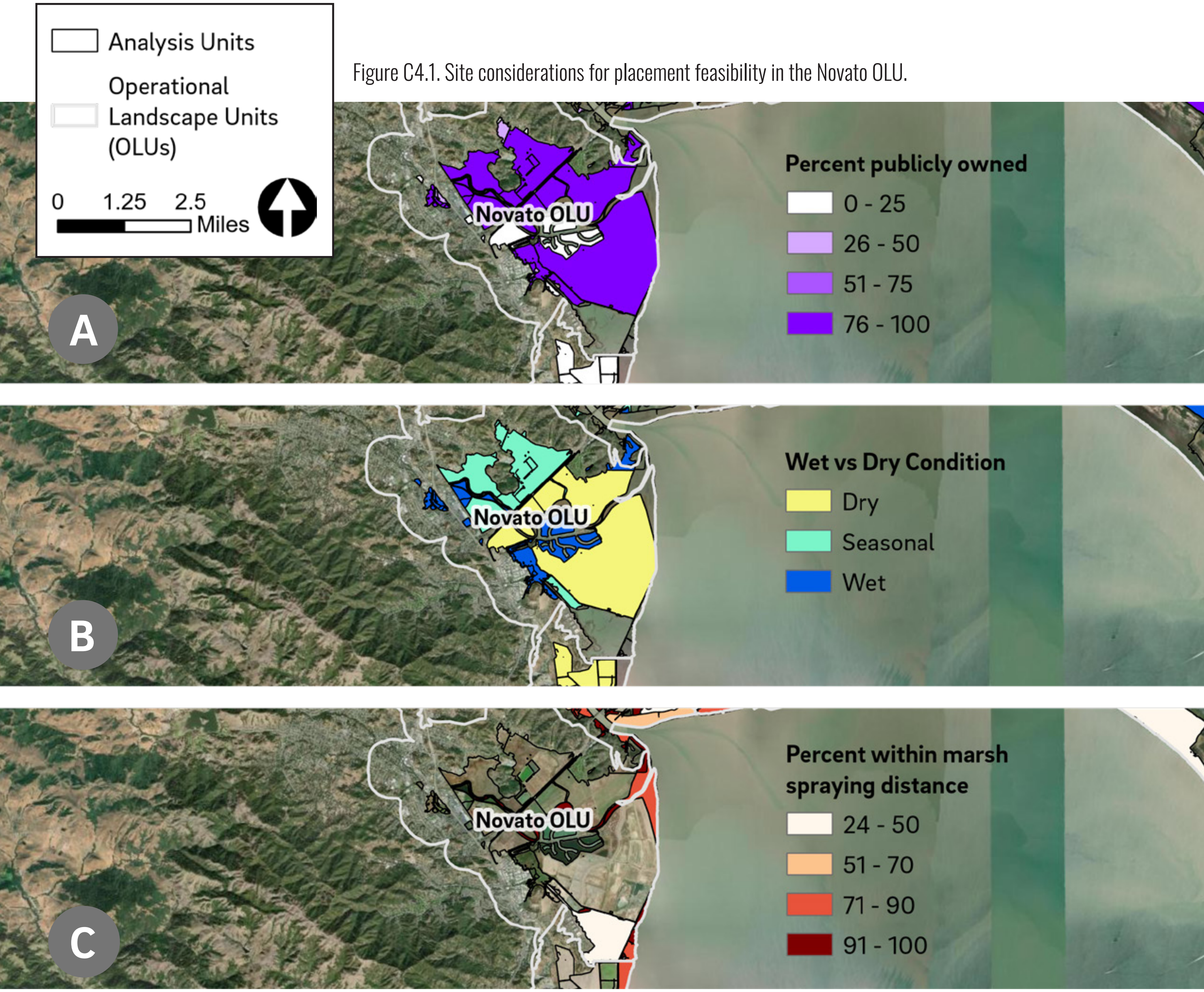


Figure C4.1. Site considerations for placement feasibility in the Novato OLU.

METHOD

There are numerous site considerations that may inform the development of a suitable sediment placement strategy. Here, we describe four relevant considerations to start to tackle the suite of relevant opportunities and constraints.

- **Ownership.** We used CALFIRE's California Land Ownership file to identify sites that are publicly owned.
- **"Wet versus dry" condition.** We used Baylands Habitat Map 2020 data to separate wet, dry, and seasonally wet diked baylands. "Wet" classes include managed ponds, wastewater ponds, and salt ponds. "Dry" classes include non-aquatic diked baylands and agriculture. "Seasonally wet" classes include managed marshes and undetermined other marshes.
- **Breached restoration sites.** A recent effort in collaboration with the Baylands Habitat Map 2020 map was undertaken to improve understanding of breach years and locations to better track restoration progress across the region. We used the results of this analysis to identify breached restoration sites.
- **Proportion of site within marsh spraying distance.** The range of marsh spraying is about 330 ft (100 meters) (USACE et al. 2017), so the proportion of the site that is within 100 meters of the edge is a useful first-pass metric to explore the feasibility of spraying. This metric does not explore how accessible any edge is from land or from sea; it assumes all edges are accessible, which is a major caveat to the analysis. We created an internal buffer of 100 meters for each analysis unit and calculated the proportion of the unit that fell within that buffer.

NEXT STEPS

The metrics developed in this study serve as tools for informing decision-making and quantifying benefits associated with beneficial reuse of dredged sediment from San Francisco Bay's navigation channels. As the Baylands Resilience Framework effort progresses, we will continue to update and refine these metrics, incorporating data from the WRMP to validate metrics, ground-truth model parameters, and add additional metrics. Our next steps include 1) developing additional metrics, particularly related to channel networks and fish habitat, and 2) developing materials explaining how the metrics can be combined to describe marsh resilience and adaptation opportunities at both regional and OLU scales. For example, combining metrics related to transition zone connectivity, marsh elevation, and mudflat elevation can help describe the range of opportunities for increasing marsh resilience, whether through upland migration or sediment placement. Integrating placement feasibility metrics such as distance and volume offers insights into the opportunities, constraints, and costs of placement projects.

Beyond informing the work of the USACE San Francisco District, we anticipate broader utility for these metrics for the San Francisco Bay restoration and adaptation community. The WRMP intends to adapt a subset of the wildlife support metrics as indicators. The Bay Adapt program plans to incorporate resilience metrics into its Regional Shoreline Adaptation Plan mapping tools. The San Francisco Bay Restoration Authority could leverage these metrics to inform funding strategies and evaluate the effectiveness of their investments. Though developed with sediment placement in mind, these metrics have value beyond the Regional Dredged Material Management Plan, providing insights to a diverse range of planning efforts within the Bay.

REFERENCES

Ahern, J. 2011. From fail-safe to safe-to-fail: Sustainability and resilience in the new urban world. Landscape and Urban Planning 100:341–343.

Anchor QEA. 2021. Lower Coyote Creek Realignment Hydraulic Modeling Report. Prepared for Marin County Flood Control District by Anchor QEA, LLC.

Baker, W. L., and Y. Cai. 1992. The r.le programs for multiscale analysis of landscape structure using the GRASS geographical information system. Landscape Ecology 7:291–302.

Barnard, P. L., M. Van Ormondt, L. H. Erikson, J. Eshleman, C. Hapke, P. Ruggiero, P. N. Adams, and A. C. Foxgrover. 2014. Development of the Coastal Storm Modeling System (CoSMoS) for predicting the impact of storms on high-energy, active-margin coasts. Natural Hazards 74:1095–1125.

BCDC. 2016. SF Bay Tidal Datums. https://data-bcdc.opendata.arcgis.com/datasets/BCDC::sf-bay-tidal-datums-2016/about.

Beller, E., A. Robinson, R. Grossinger, and L. Grenier. 2015. Landscape Resilience Framework: Operationalizing ecological resilience at the landscape scale. Publication #752. Prepared for Google Ecology Program. A Report of SFEI-ASC's Resilient Landscapes Program, San Francisco Estuary Institute, Richmond, CA.

Boyer, K., C. Zabin, S. D. L. Cruz, E. Grosholz, M. Orr, J. Lowe, M. Latta, J. Miller, S. Kiriakopolos, C. Pinnell, D. Kunz, J. Moderan, K. Stockmann, G. Ayala, R. Abbott, and R. Obernolte. 2017. San Francisco Bay Living Shorelines: Restoring Eelgrass and Olympia Oysters for Habitat and Shore Protection. Page Living Shorelines. CRC Press.

Brand, A., J. R. Lacy, K. Hsu, D. Hoover, S. Gladding, and M. T. Stacey. 2010. Wind-enhanced resuspension in the shallow waters of South San Francisco Bay: Mechanisms and potential implications for cohesive sediment transport. Journal of Geophysical Research 115:C11024.

Bridges, T., J. King, J. Simm, M. Beck, G. Collins, Q. Lodder, and R. Mohan. 2021. International Guidelines on Natural and Nature-Based Features for Flood Risk Management. USACE Engineer Research and Development Center.

Buffington, K. J., C. N. Janousek, B. D. Dugger, J. C. Callaway, L. M. Schile-Beers, E. Borgnis Sloane, and K. M. Thorne. 2021. Incorporation of uncertainty to improve projections of tidal wetland elevation and carbon accumulation with sea-level rise. PLOS ONE 16:e0256707.

Buffington, K. J., and K. M. Thorne. 2019. LEAN-corrected San Francisco Bay Digital Elevation Model. U.S. Geological Survey data release.

California Sea-level rise Guidance. 2024. DRAFT: State of California Sea-level rise Guidance: 2024 Science and Policy Update. California Sea-level rise Science Task Force, California Ocean Protection Council, California Ocean Science Trust.

Callaway, J. C., E. L. Borgnis, R. E. Turner, and C. S. Milan. 2012. Carbon Sequestration and Sediment Accretion in San Francisco Bay Tidal Wetlands. Estuaries and Coasts 35:1163–1181.

Collins, J., and R. Grossinger. 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. 308. San Francisco Estuary Institute, Oakland, CA.

Culberson, S. D., T. C. Foin, and J. N. Collins. 2004. The Role of Sedimentation in Estuarine Marsh Development within the San Francisco Estuary, California, USA. Journal of Coastal Research 2004:970–979.

CWMW, C. W. M. W. 2013. California Rapid Assessment Method (CRAM) for Wetlands User's Manual. Page 67. 6.1.

DHI. 2011. Regional Coastal Hazard Modeling Study for North and Central San Francisco Bay. Prepared by DHI for Alameda County Flood Control District and FEMA Region IX.

DHI. 2013. Regional Coastal Hazard Modeling Study for South San Francisco Bay: Final Draft Report. Prepared by DHI for Alameda County Flood Control District and FEMA Region IX.

Drouet, S., P. Decottignies, V. Turpin, B. Ismail, V. Méléder, B. Cognie, L. Godet, and R. Cosson. 2013. Spatial distribution of shorebirds on an intertidal mudflat colonized by microphytobenthos biofilm.

ESA. 2020. Sonoma Creek Baylands Strategy Hydrodynamic Modeling Appendix. Prepared by Environmental Science Associates for Sonoma Land Trust.

Ferreira, J. C. T., J. R. Lacy, S. C. Mcgill, L. T. WinklerPrins, D. J. Nowacki, A. W. Stevens, and A. C. Tan. 2023. Hydrodynamic and sediment transport data from Whale's Tail marsh and adjacent waters in South San Francisco Bay, California 2021-2022.

Folke, C., G. P. Kofinas, and F. S. Chapin, editors. 2009. Principles of Ecosystem Stewardship: Resilience-Based Natural Resource Management in a Changing World. Springer, New York, NY.

Forman, R. T. T. 1995. Some general principles of landscape and regional ecology. Landscape Ecology 10:133–142.

Foster-Martinez, M. R., K. Alizad, and S. C. Hagen. 2020. Estimating wave attenuation at the coastal land margin with a GIS toolbox. Environmental Modelling & Software 132:104788.

Fulfrost, B. 2018. San Francisco Bay Joint Venture (SFBJV) Baseline Transition Zone for SF, San Pablo and Suisun bays: GIS and White paper. GIS datasets and white paper developed for and funded by San Francisco Bay Joint Venture.

Ganju, N. K. 2019. Marshes Are the New Beaches: Integrating Sediment Transport into Restoration Planning. Estuaries and Coasts 42:917–926.

Ganju, N. K., Z. Defne, M. L. Kirwan, S. Fagherazzi, A. D'Alpaos, and L. Carniello. 2017. Spatially integrative metrics reveal hidden vulnerability of microtidal salt marshes. Nature Communications 8:14156.

Gedan, K. B., M. L. Kirwan, E. Wolanski, E. B. Barbier, and B. R. Silliman. 2011. The present and future role of coastal wetland vegetation in protecting shorelines: answering recent challenges to the paradigm. Climatic Change 106:7–29.

Goals Project. 1999. Baylands Ecosystem Habitat Goals. U.S. Environmental Protection Agency and S.F. Bay Regional Water Quality Control Board, San Francisco and Oakland, CA.

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, Oakland, CA.

H.T. Harvey & Associates. 2023. SAFER Bay Project High Tide Refugial Habitat Assessment and Resulting Salt Marsh-Upland Transition Zone Configuration Recommendations, North and South of Bay Road, East Palo Alto. Prepared by H.T. Harvey & Associates for San Francisquito Joint Powers Authority, Menlo Park, CA.

Jaffe, B. E., R. E. Smith, and A. C. Foxgrover. 2007. Anthropogenic influence on sedimentation and intertidal mudflat change in San Pablo Bay, California: 1856–1983. Estuarine, Coastal and Shelf Science 73:175–187.

Kamman Hydrology & Engineering, Inc. 2016. Novato Creek Hydraulic Study: Analysis of Alternatives. Prepared by Kamman Hydrology & Engineering, Inc. in association with WRECO for County of Marin Department of Public Works, San Rafael, CA.

Kearney, M. S., R. E. Grace, and J. C. Stevenson. 1988. Marsh Loss in Nanticoke Estuary, Chesapeake Bay. Geographical Review 78:205.

Kellner, C. 2014. Comments for the State Wildlife Plan – Salt Marshes of the San Francisco Bay Area.

Koch, M. S., and I. A. Mendelssohn. 1989. Sulphide as a Soil Phytotoxin: Differential Responses in Two Marsh Species. Journal of Ecology 77:565–578.

Lacy, J. R., M. R. Foster-Martinez, R. M. Allen, M. C. Ferner, and J. C. Callaway. 2020. Seasonal Variation in Sediment Delivery Across the Bay-Marsh Interface of an Estuarine Salt Marsh. Journal of Geophysical Research: Oceans 125:e2019JC015268.

Lacy, J. R., and D. Hoover. 2011. Wave Exposure of Corte Madera Marsh, Marin County, California—a Field Investigation. Page 28. 2011–1183. Open-File Report.

Lowe, J., and J. Bourgeois. 2015. Science Foundation Chapter 1: The Dynamic Workings of the Baylands. Baylands Ecosystem Habitat Goals Science Update.

Mariotti, G. 2016. Revisiting salt marsh resilience to sea-level rise: Are ponds responsible for permanent land loss? Journal of Geophysical Research: Earth Surface 121:1391–1407.

Mariotti, G., and S. Fagherazzi. 2013. Critical width of tidal flats triggers marsh collapse in the absence of sea-level rise. Proceedings of the National Academy of Sciences 110:5353–5356.

McKnight, K., A. Braud, S. Dusterhoff, L. Grenier, S. Shaw, J. Lowe, M. Foley, and L. McKee. 2023. Conceptual Understanding of Fine Sediment Transport in San Francisco Bay. SFEI Contribution #1114. San Francisco Estuary Institute, Richmond, CA.

McKnight, K., J. Lowe, and E. Plane. 2020. Special Study on Bulk Density. SFEI Contribution # 975. San Francisco Estuary Institute, Richmond, CA.

Morris, J. T., J. Z. Drexler, L. J. S. Vaughn, and A. H. Robinson. 2022. An assessment of future tidal marsh resilience in the San Francisco Estuary through modeling and quantifiable metrics of sustainability. Frontiers in Environmental Science 10.

Morris, J. T., P. V. Sundareshwar, C. T. Nietch, B. R. Kjerfve, and D. R. Cahoon. 2002. Responses of Coastal Wetlands to Rising Sea Level 83.

Narayan, S., M. W. Beck, B. G. Reguero, I. J. Losada, B. Van Wesenbeeck, N. Pontee, J. N. Sanchirico, J. C. Ingram, G.-M. Lange, and K. A. Burks-Copes. 2016. The Effectiveness, Costs and Coastal Protection Benefits of Natural and Nature-Based Defences. PLOS ONE 11:e0154735.

Nederhoff, K., R. Saleh, B. Tehranirad, L. Herdman, L. Erikson, P. L. Barnard, and M. Van Der Wegen. 2021. Drivers of extreme water levels in a large, urban, high-energy coastal estuary – A case study of the San Francisco Bay. Coastal Engineering 170:103984.

NOAA. 2022. NOAA/NOS Vertical Datums Transformation. https://vdatum.noaa.gov/.

Nowacki, D. J., and N. K. Ganju. 2019. Simple Metrics Predict Salt-Marsh Sediment Fluxes. Geophysical Research Letters 46:12250–12257.

Nyström, M. 2006. Redundancy and Response Diversity of Functional Groups: Implications for the Resilience of Coral Reefs. Ambio 35:30–35.

Overton, C. T., J. Y. Takekawa, M. L. Casazza, T. D. Bui, M. Holyoak, and D. R. Strong. 2015. Sea-level rise and refuge habitats for tidal marsh species: Can artificial islands save the California Ridgway’s rail? Ecological Engineering 74:337–344.

Overton, C., and J. Wood. 2015. Science Foundation Chapter 5 Appendix 5.1 – Case Study California Ridgway’s Rail (Rallus obseoletus obsoletus).

Parker, V. T., and K. E. Boyer. 2019. Sea-Level Rise and Climate Change Impacts on an Urbanized Pacific Coast Estuary. Wetlands 39:1219–1232.

Piercy, C. D., N. Pontee, S. Narayan, J. Davis, and T. Meckley. 2021. Chapter 10: Coastal Wetlands and Tidal Flats. Page *in* T. S. Bridges, J. K. King, J. D. Simm, M. W. Beck, G. Collins, Q. Lodder, and R. K. Mohan, editors. International Guidelines on Natural and Nature-Based Features for Flood Risk Management. U.S. Army Engineer Research and Development Center (U.S.), Vicksburg, MS.

Plane, E., and K. Iknayan. 2021. Ecotone levees and wildlife connectivity: A technical update to the Adaptation Atlas. SFEI Contribution #1037. San Francisco Estuary Institute, Richmond, CA.

PWA, and P. M. Faber. 2004. Design Guidelines for Tidal Wetland Restoration in San Francisco Bay. Page 83. The Bay Institute and California State Coastal Conservancy, Oakland, CA.

Raposa, K. B., K. Wasson, E. Smith, J. A. Crooks, P. Delgado, S. H. Fernald, M. C. Ferner, A. Helms, L. A. Hice, J. W. Mora, B. Puckett, D. Sanger, S. Shull, L. Spurrier, R. Stevens, and S. Lerberg. 2016. Assessing tidal marsh resilience to sea-level rise at broad geographic scales with multi-metric indices. Biological Conservation 204:263–275.

Robinson, A. 2018. Appendix 9: Transition Zone Background & Methodology. Southern California Wetlands Recovery Project, San Francisco Estuary Institute and California State Coastal Conservancy.

Robinson, A., B. Fulfrost, J. Lowe, H. Nutters, and J. Bradt. 2017a. Transition Zone Mapping Methodology: Integrating the Bay Margin and Upper Boundary Methods. San Francisco Estuary Partnership, San Francisco Estuary Institute.

Saura, S., and L. Pascual-Hortal. 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 83:91–103.

Saura, S., and L. Rubio. 2010. A common currency for the different ways in which patches and links can contribute to habitat availability and connectivity in the landscape. Ecography 33: 523-537.

Schile, L. M., J. C. Callaway, J. T. Morris, D. Stralberg, V. T. Parker, and M. Kelly. 2014. Modeling Tidal Marsh Distribution with Sea-Level Rise: Evaluating the Role of Vegetation, Sediment, and Upland Habitat in Marsh Resiliency. PLOS ONE 9:e88760.

SFEI. 1998. Bay Area EcoAtlas: Geographic Information System of wetland habitats past and present.

SFEI. 2016. San Francisco Bay Shore Inventory. SFEI Contribution #779. San Francisco Estuary Institute, Richmond, CA.

SFEI. 2023a. Baylands Resilience Framework for San Francisco Bay: Wildlife Support. SFEI Contribution #1115. San Francisco Estuary Institute, Richmond, CA.

SFEI. 2023b. Where creeks meet baylands: Opportunities to re-establish freshwater and sediment delivery to the baylands of San Francisco Bay. SFEI Contribution #1150. San Francisco Estuary Institute, Richmond, CA.

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, Richmond, CA.

SFEP. 2011. The State of San Francisco Bay 2011. San Francisco Estuary Partnership.

SFEP. 2015. State of the Estuary 2015. San Francisco Estuary Partnership.

Shellhammer, H., and L. Barthman-Thompson. 2015. Science Foundation Chapter 5 Appendix 5.1 – Case Study Salt Marsh Harvest Mouse (Reithrodontomys raviventris). Baylands Ecosystem Habitat Goals Science Update.

Shepard, C. C., C. M. Crain, and M. W. Beck. 2011. The Protective Role of Coastal Marshes: A Systematic Review and Meta-analysis. PLoS ONE 6:e27374.

Smith, K. R., M. K. Riley, L. Barthman–Thompson, I. Woo, M. J. Statham, S. Estrella, and D. A. Kelt. 2018a. Toward salt marsh harvest mouse recovery: A review. San Francisco Estuary and Watershed Science 16.

Smith, K. R., M. K. Riley, California Department of Fish and Wildlife, L. Barthman–Thompson, California Department of Fish and Wildlife, I. Woo, U.S. Geological Survey, M. J. Statham, University of California, Davis, S. Estrella, California Department of Fish and Wildlife, D. A. Kelt, and University of California, Davis. 2018b. Towards Salt Marsh Harvest Mouse Recovery: A Review. San Francisco Estuary and Watershed Science 16.

Sonoma Land Trust and partners. 2020. Sonoma Creek Baylands Strategy. Prepared by Sonoma Land Trust, San Francisco Estuary Institute, Point Blue Conservation Science, Environmental Science Associates, Ducks Unlimited, U.S. Fish and Wildlife Service.

Statham, M. J., S. Aamoth, L. Barthman-Thompson, S. Estrella, S. Fresquez, L. D. Hernandez, R. Tertes, and B. N. Sacks. 2016. Conservation genetics of the endangered San Francisco Bay endemic salt marsh harvest mouse (Reithrodontomys raviventris). Conservation Genetics 17:1055–1066.

Statham, M. J., and B. N. Sacks. 2019. Salt marsh harvest mouse landscape genetics and connectivity within the Suisun Bay Area Recovery Unit. Report to the California Dept. of Water Resources. Page 39.

Stralberg, D., M. Brennan, J. C. Callaway, J. K. Wood, L. M. Schile, D. Jongsomjit, M. Kelly, V. T. Parker, and S. Crooks. 2011. Evaluating tidal marsh sustainability in the face of sea-level rise: a hybrid modeling approach applied to San Francisco Bay. PloS One 6:e27388.

Takekawa, J. Y., K. M. Thorne, K. J. Buffington, K. A. Spragens, K. M. Swanson, J. Z. Drexler, D. H. Schoellhamer, C. T. Overton, and M. L. Casazza. 2013. Final report for sea-level rise response modeling for San Francisco Bay estuary tidal marshes. Page 171. 2013–1081. USGS Numbered Series, U.S. Geological Survey, Reston, VA.

Takekawa, J. Y., I. Woo, U.S. Geological Survey, R. Gardiner, U.S. Geological Survey, M. Casazza, U.S. Geological Survey, J. T. Ackerman, U.S. Geological Survey, N. Nur, PRBO Conservation Science, L. Liu, and PRBO Conservation Science. 2011. Avian Communities in Tidal Salt Marshes of San Francisco Bay: A Review of Functional Groups by Foraging Guild and Habitat Association. San Francisco Estuary and Watershed Science 9.

Taylor, P. D., L. Fahrig, K. Henein, and G. Merriam. 1993. Connectivity is a vital element of landscape structure. Oikos:571–573.

Taylor-Burns, R., K. Nederhoff, J. R. Lacy, and P. L. Barnard. 2023. The influence of vegetated marshes on wave transformation in sheltered estuaries. Coastal Engineering 184:104346.

Thorne, K., G. MacDonald, G. Guntenspergen, R. Ambrose, K. Buffington, B. Dugger, C. Freeman, C. Janousek, L. Brown, J. Rosencranz, J. Holmquist, J. Smol, K. Hargan, and J. Takekawa. 2018. U.S. Pacific coastal wetland resilience and vulnerability to sea-level rise. Science Advances 4:eaao3270.

USACE. 2021. Dredged Material Management Office (DMMO) Dredging and Placement of Dredged Material in San Francisco Bay: January-December 2020 Report.

USACE. 2023. Environmental Assessment (with Draft FONSI) and 404 (b)(1) Analysis & Initial Study (with Draft Mitigated Negative Declaration): San Francisco Bay Strategic Shallow-Water Placement Pilot Project.

USACE San Francisco District. 2023, June 2. Regional Dredge Material Management Plan. https://www.spn.usace.army.mil/Missions/Projects-and-Programs/Regional-Dredge-Material-Management-Plan/.

USACE, Stantec, and SFEI. 2017, February. Strategic Placement of Dredged Sediment to Naturally Accrete in Salt Marsh Systems: Key Stakeholder Draft Not For Public Distribution.

USFWS. 2013. Recovery plan for tidal marsh ecosystems of northern and central California. Page 434. U.S. Fish & Wildlife Service, Sacramento, CA.

Veloz, S., M. Fitzgibbon, S. Stralberg, D. Michaile, D. Jongsomjit, D. Moody, N. Nur, L. Salas, J. Wood, M. Elrod, and G. Ballard. 2014. Future San Francisco Bay Tidal Marshes: A climate-smart planning tool. [web application].

Wasson, K., N. K. Ganju, Z. Defne, C. Endris, T. Elsey-Quirk, K. M. Thorne, C. M. Freeman, G. Guntenspergen, D. J. Nowacki, and K. B. Raposa. 2019. Understanding tidal marsh trajectories: evaluation of multiple indicators of marsh persistence. Environmental Research Letters 14:124073.

Woltz, V. L., C. L. Stagg, K. B. Byrd, L. Windham-Myers, A. S. Rovai, and Z. Zhu. 2023. Biomass Carbon Stock and Net Primary Productivity in Tidal Herbaceous Wetlands of the Conterminous United States. U.S. Geological Survey data release.

Wood, D. A., T.-V. D. Bui, C. T. Overton, A. G. Vandergast, M. L. Casazza, J. M. Hull, and J. Y. Takekawa. 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 18:131–146.