TOWARD NATURAL SHORELINE INFRASTRUCTURE TO MANAGE COASTAL CHANGE IN CALIFORNIA

A Report for:

California's Fourth Climate Change Assessment

Prepared By:
Sarah Newkirk[1], Sam Veloz[2], Maya Hayden[2], Bob Battalio[3], Tiffany Cheng[3], Jenna Judge[4], Walter Heady[1], Kelly Leo[1], Mary Small[5]

1 The Nature Conservancy
2 Point Blue Conservation Science
3 Environmental Science Associates
4 National Oceanic and Atmospheric Administration
5 California State Coastal Conservancy

Edmund G. Brown, Jr. *Governor*

August 2018
CCCA4-CNRA-2018-011

ACKNOWLEDGEMENTS

This project was supported by many advisors, who were very generous with their time and expertise. Specifically: Andrea Pickart, *Humboldt Bay National Wildlife Refuge*; Brenda Goeden, *San Francisco Bay Conservation and Development Commission*; Michelle Orr, *Environmental Science Associates*; Damien Kunz, *Environmental Science Associates*; Eric Joliffe, *United States Army Corps of Engineers*; Christina McWhorter, *Hamilton Wetlands Plant Nursery*; Jeff Melby, *California State Coastal Conservancy*; Louis White, *Environmental Science Associates*; Paul Jenkin, *Surfrider Foundation*; Evyan Sloane, *California State Coastal Conservancy*; Rick Nye, *Seal Beach National Wildlife Refuge*; Marilyn Latta, *California State Coastal Conservancy*; Kathy Boyer, *San Francisco State University*; Su Corbaly, *California State Coastal Conservancy*; Elizabeth Gagneron, *California State Coastal Conservancy*; Mary Matella, *California Coastal Commission*; Jennifer Mattox, *State Lands Commission*; Laura Engeman, *San Diego Climate Collaborative*; Dani Boudreau, *Tijuana River National Estuarine Research Reserve*; Joel Gerwein, *California State Coastal Conservancy*; David Behar, *San Francisco Public Utility Commission*; Jack Liebster, *Marin County Planning*; Leslie Ewing, *California Coastal Commission*; Juliette Hart, *United States Geological Survey*; Amber Parais, *San Diego Climate Collaborative*; Sara Hutto, *Greater Farallones National Marine Sanctuary*; Natalie Cosentino-Manning, *National Oceanic and Atmospheric Administration National Marine Fisheries Service*; Jeremy Lowe, *San Francisco Estuary Institute*; Kif Scheuer, *Local Government Commission*; George Domurat, *U.S. Army Engineer Institute for Water Resources*; Ken Schreiber, *Land Use Planning Services, Inc.*; Bruce Bekkar, *City of Del Mar*; Joseph Tyburczy, *California Sea Grant Extension*; Brian Brennan, *Beach Erosion Authority for Clean Oceans and Nourishment*; Luisa Valiela, *Environmental Protection Agency*; Christina Toms, *San Francisco Bay Regional Water Quality Control Board*; John Rozum, *National Oceanic and Atmospheric Administration Office for Coastal Management*; Becky Lunde, *National Oceanic and Atmospheric Administration Office for Coastal Management*; Deborah Ruddock, *California State Coastal Conservancy*; Chris Williamson, *City of Oxnard*; Edward Curtis, *San Francisco State University*; Sergio Vargas, *Ventura County*; Dean Kubani, *City of Santa Monica*; Jenny Dugan, *University of California Santa Barbara*; Maren Farnum, *State Lands Commission*; Patrick Mulcahy, *State Lands Commission*; Madeline Kinsey, *California State Parks*; Andrew Gunther, *Center for Ecosystem Management and Restoration*; Kristen Goodrich, *Tijuana River National Estuarine Research Reserve*; Monique Myers, *California Sea Grant Extension*; Warner Chabot, *San Francisco Estuary Institute*; Alex Westhoff, *Marin County.*

PREFACE

California's Climate Change Assessments provide a scientific foundation for understanding climate-related vulnerability at the local scale and informing resilience actions. These Assessments contribute to the advancement of science-based policies, plans, and programs to promote effective climate leadership in California. In 2006, California released its First Climate Change Assessment, which shed light on the impacts of climate change on specific sectors in California and was instrumental in supporting the passage of the landmark legislation Assembly Bill 32 (Núñez, Chapter 488, Statutes of 2006), California's Global Warming Solutions Act. The Second Assessment concluded that adaptation is a crucial complement to reducing greenhouse gas emissions (2009), given that some changes to the climate are ongoing and inevitable, motivating and informing California's first Climate Adaptation Strategy released the same year. In 2012, California's Third Climate Change Assessment made substantial progress in projecting local impacts of climate change, investigating consequences to human and natural systems, and exploring barriers to adaptation.

Under the leadership of Governor Edmund G. Brown, Jr., a trio of state agencies jointly managed and supported California's Fourth Climate Change Assessment: California's Natural Resources Agency (CNRA), the Governor's Office of Planning and Research (OPR), and the California Energy Commission (Energy Commission). The Climate Action Team Research Working Group, through which more than 20 state agencies coordinate climate-related research, served as the steering committee, providing input for a multisector call for proposals, participating in selection of research teams, and offering technical guidance throughout the process.

California's Fourth Climate Change Assessment (Fourth Assessment) advances actionable science that serves the growing needs of state and local-level decision-makers from a variety of sectors. It includes research to develop rigorous, comprehensive climate change scenarios at a scale suitable for illuminating regional vulnerabilities and localized adaptation strategies in California; datasets and tools that improve integration of observed and projected knowledge about climate change into decision-making; and recommendations and information to directly inform vulnerability assessments and adaptation strategies for California's energy sector, water resources and management, oceans and coasts, forests, wildfires, agriculture, biodiversity and habitat, and public health.

The Fourth Assessment includes 44 technical reports to advance the scientific foundation for understanding climate-related risks and resilience options, nine regional reports plus an oceans and coast report to outline climate risks and adaptation options, reports on tribal and indigenous issues as well as climate justice, and a comprehensive statewide summary report. All research contributing to the Fourth Assessment was peer-reviewed to ensure scientific rigor and relevance to practitioners and stakeholders.

For the full suite of Fourth Assessment research products, please visit www.climateassessment.ca.gov. This report is intended to facilitate the use of Natural Shoreline Infrastructure along California's coast, improving the resilience of communities and habitats in the face of climate change.

ABSTRACT

Flooding and erosion caused by rising sea levels and powerful storms threaten property throughout coastal California. To protect against these climate-change related threats, landowners will certainly take action, and the default industry standard response has been to try to "hold the line" against the encroaching sea by constructing seawalls, dikes, levees and other forms of coastal armoring. While armoring may in some cases provide acceptable short-term protection, armoring also tends to accelerate shoreline erosion, exacerbating hazards to people and leading to the eventual loss of critical wildlife habitat and public beaches.

Natural Shoreline Infrastructure can be as effective as armoring, while having the added benefits of preserving coastal habitat and public access. Recognizing this, California agencies have mandated that decision-makers prioritize its use in planning and investment decisions. Yet, planners have encountered many stumbling blocks as they have tried to incorporate these approaches into coastal resilience plans. Major obstacles include: a lack of a common definition and shared terminology; lack of expertise; lack of precedent; and the absence of siting guidance and technical design standards.

Here, we set out to enable planners to adopt Natural Shoreline Infrastructure by filling in the missing information. With the input of dozens of coastal managers who served on our Technical Advisory Committee, we developed a definition and collected a list of case studies where Natural Shoreline Infrastructure has already been successfully deployed in California. Drawing from these and other projects, we collected into one place the first detailed technical guidance for implementation, including siting criteria and design thresholds. These criteria inform decisions about where and when to use six types of Natural Shoreline Infrastructure (e.g. sand dunes, seagrass beds). Using Monterey Bay and Ventura County projects as examples, we demonstrate how to use the technical guidance in tandem with spatial data to match a particular shoreline environment with appropriate Natural Shoreline Infrastructure options, creating "blueprints" for action.

The information in this report is intended to facilitate the use of Natural Shoreline Infrastructure along California's coast, improving the resilience of communities and habitats in the face of climate change.

Keywords: Natural Shoreline Infrastructure, living shorelines, green infrastructure, coastal protection, coastal resilience, sea level rise, coastal storms, flooding, erosion, coastal armoring, seawalls, hazard mitigation, case studies, vegetated dunes, wetlands, cobble berms, marsh sills, tidal benches, horizontal levee, oyster reefs, eelgrass beds, outer coast, estuaries, coastal ecosystems

Please use the following citation for this paper:

Newkirk, Sarah, Sam Veloz, Maya Hayden, Walter Heady, Kelly Leo, Jenna Judge, Robert Battalio, Tiffany Cheng, Tara Ursell, Mary Small. (The Nature Conservancy and Point Blue Conservation Science). 2018. ***Toward Natural Infrastructure to Manage Shoreline***

Change in California. California's Fourth Climate Change Assessment, California Natural Resources Agency. Publication number: CCCA4-CNRA-2018-011.

HIGHLIGHTS

- Coastal planners have faced many stumbling blocks when attempting to incorporate Natural Shoreline Infrastructure strategies into climate-change adaptation plans, and have instead often implemented short-term solutions like coastal armoring, and will continue to do so until significant hurdles to implementing other strategies can be overcome.
- Two major hurdles for planners are a lack of precedent and a dearth of technical guidance applicable to California's varied environmental settings. To begin to address the first, we've collected five detailed case studies where planners have already successfully implemented different types of Natural Shoreline Infrastructure.
- To address the second hurdle to implementation we provide detailed technical guidance information to direct planners in evaluating and deciding where, when, and how to use six types of Natural Shoreline Infrastructure (e.g. sand dunes, seagrass beds), for optimal results.
- Using Monterey Bay and Ventura County as examples, we demonstrate how to use this guidance in tandem with local spatial data to match a particular shoreline environment with appropriate Natural Shoreline Infrastructure options, creating "blueprints" for action.
- Going forward, state agencies and NGOs should support demonstration projects that include testing and monitoring, so that the community of practitioners may continue to improve upon Natural Shoreline Infrastructure approaches and so they can be applied on larger scales, to enhance resilience to climate-change related hazards and maintain public access to healthy shorelines long into the future.

WEB LINKS

http://coastalresilience.org/case-studies-of-natural-shoreline-infrastructure-in-coastal-california/

TABLE OF CONTENTS

1: Introduction

1.1 Purpose of This Study

This report aims to provide crucial information and guidance, so that in response to the threat of shoreline flooding and erosion—exacerbated by climate change—California planners can curtail their reliance on coastal armoring and can instead begin to more widely deploy Natural Shoreline Infrastructure solutions.

Currently, planners interested in using Natural Shoreline Infrastructure approaches face a host of obstacles (Caldwell et al. 2015). In consultation with our Technical Advisory Committee (Section 1.5, Appendix A), we identified four major obstacles that we could feasibly tackle and begin to overcome: (1) a lack of clarity over what Natural Shoreline Infrastructure entails; (2) a perceived lack of precedent for Natural Shoreline Infrastructure in California; (3) a lack of technical guidance for siting and design to help planners pinpoint which methods to use and where; (4) and a lack of examples demonstrating the application of siting guidelines to evaluate suitability of Natural Shoreline Infrastructure in specific locales.

Here, we address each of these challenges. First, we develop a shared definition of Natural Shoreline Infrastructure with stakeholders (Sections 1.4, 1.5). We then present five case studies where Natural Shoreline Infrastructure has been used successfully in California (Section 2, Appendix E). We also provide detailed technical guidance for deciding where, when and how to use Natural Shoreline Infrastructure approaches, according to local conditions (Section 3). Last, we demonstrate how the technical guidance can be applied using spatial data to evaluate suitability of these approaches in Monterey Bay and Ventura County (Section 4, Appendix F).

1.2 Overview

California's iconic coast links together thousands of miles of coastal habitats which are foundational to the high biodiversity unique to the coast and provide benefits to millions of people (Heady et al. 2018). Cliffs, dunes, wetlands, estuaries, and beaches provide critical habitat to fish, endangered plants, marine mammals, and birds travelling along the Pacific Flyway. (Neuman et al. 2008; Hughes et al. 2014; Heady et al. 2018).

It is impossible to overstate the importance and irreplaceability of these habitats, which serve as essential nursery, feeding and resting areas for both terrestrial and marine species. California's coastlines are also critical habitat for people. Millions flock to the coast annually, to fish, swim, surf, rest, honor sacred traditions and to be surrounded by nature (NOAA 2015, Heberger et al. 2009). Beach-goers in California spend approximately $3 billion annually, and the non-market benefits of coasts, when translated into dollar figures, are greater than $2 billion per year (Kildow and Colgan 2005).

Unfortunately, more than 90% of coastal wetlands, beaches, and estuarine intertidal lands have already been converted to agriculture or development (Dahl 1990, Zedler 1996). The remaining 10 % will likely continue to shrink from climate change-induced hazards. Coastal bluffs are already eroding at a rate of 0.30 m (1 ft) per year in many places, and that rate of change will likely increase over the coming decades as sea levels rise and Pacific storms intensify (Hapke and Reid 2007, Vitousek et al. 2017). By the turn of the century, projections of 1 to 2 m (3 to 6 ft) of sea level rise could eliminate up to two-thirds of Southern California beaches, unless measures are taken to curb this loss (Vitousek et al. 2017). Similarly, Heady et al. (2018) found that 55% of all coastal habitat area throughout California is highly vulnerable to five feet of sea level rise. These same forces also threaten to flood nearly $100 billion worth of property along the length of the California coast (Heberger et al. 2009).

1.3 Shoreline Protection Approaches

The magnitude of the looming ecological, social, and economic impacts described above guarantees that coastal landowners will act to protect their assets. There are two primary strategies to protect the shoreline and the communities that live along the coast: coastal armoring and natural infrastructure. Natural infrastructure, which for the purposes of this report we are calling “Natural Shoreline Infrastructure,” (see Section 1.5 for a more detailed account of the definition) offers many advantages over armoring, but it’s an approach that has been under-appreciated and under-utilized.

Coastal armoring typically entails the construction of seawalls, revetments, dikes and levees to “hold the line” and keep encroaching water and winds at bay. Coastal armoring has been the industry standard response to erosion for centuries, but it is an approach that has proven to be detrimental to its intended purpose in the long term, and it comes with many short-term consequences as well (Dugan 2008). Paradoxically, by attempting to control the dynamic nature of shorelines, coastal armoring tends to actually increase the risk of destruction of the very properties it was built to protect. Sea walls and other hard structures can accelerate the disappearance of beach in front of the wall and on neighboring properties by reflecting wave energy and interfering with natural sediment dynamics (USACE 1981). Sea walls also block beaches from naturally migrating landward (Figure 1; Melius and Caldwell 2015).

Armoring structures have other social consequences, such as limiting beach access, and inhibiting recreation and other human uses (USACE 1981, Dugan 2008, Griggs 2005). They can be expensive to install and require costly ongoing maintenance. Additionally, sea level rise will limit the practical life span of these structures. (A thorough exploration of economic costs and benefits is outside the scope of this paper, but for case study examples looking at relative costs and benefits of armoring see ENVIRON 2015 and Leo et al. 2017 Appendix F.) Thus, costly armoring investments ultimately undermine safety, ecological function, public access and long-term coastal resiliency.

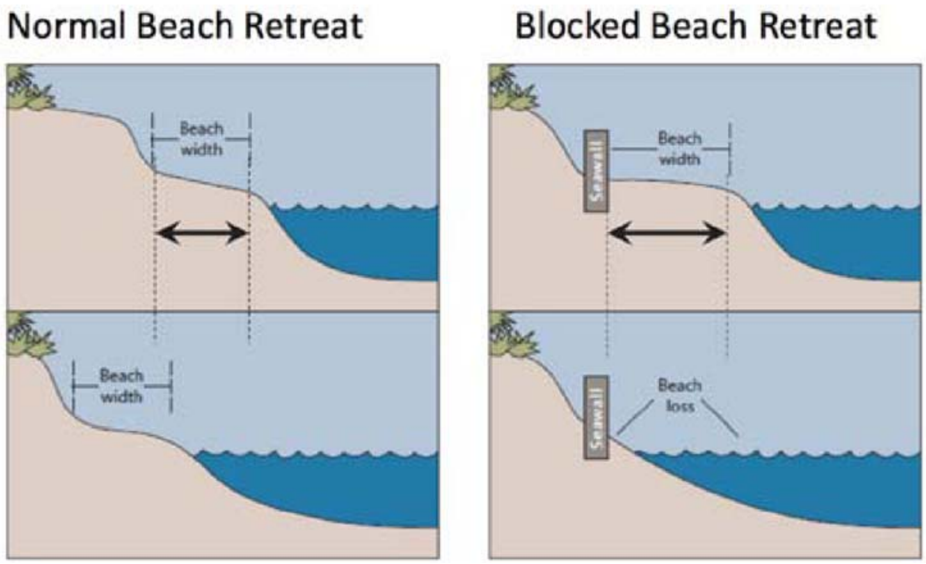

Figure 1: Diagram showing how armoring prevents beach migration and will result in the total loss of beach over time (Source: Melius and Caldwell 2015).

The other primary coastal protection approach is Natural Shoreline Infrastructure, which refers to the use of natural features to reduce the vulnerability of communities to hazards related to climate change, while also facilitating the ability of these systems to migrate landward rather than disappear under rising waters. It can take many forms, including restored sand dunes, marsh sills, oyster reefs and seagrass beds.

Natural Shoreline Infrastructure approaches allow coastal habitats to act as natural, self-sustaining buffers, providing protection from both storms and sea level rise (Barbier et al. 2011, ENVIRON 2015, Narayan et al. 2016, Leo et al. 2017). For instance, coastal habitats mitigate erosion by reducing the force of wave energy as waves approach the coast, primarily through the friction created by plant and sedentary animal material (Borsje et al. 2012, Moller et al. 2014, Narayan et al. 2016), such as seagrass beds and oyster reefs (BCDC & ESA 2013). Dunes also block waves that can't overtop their height, provide sand storage to buffer erosion during extreme events, and dissipating wave energy. These habitats currently protect much of the eastern seaboard and the Gulf of Mexico from storms and sea level rise (Arico et al. 2005, Arkema et al. 2013) as well as throughout California. In some places, even low dunes are considered to be protecting up to 300 m (984 ft) of lowlands behind them (Arkema et al. 2013).

When deployed appropriately, Natural Shoreline Infrastructure has been shown repeatedly to be equally or more effective than coastal armoring for mitigating risk of floods, allowing these features to gain elevation as sea levels rise. This approach also has the added advantages of continuing to provide public access, recreation opportunities, carbon sequestration, and biodiversity support (e.g., Arico et al. 2005, Barbier et al. 2011, Gedan et al. 2011, Moller et al. 1999, Moller and Spencer 2002, Narayan et al. 2016, Shepard et al. 2011, Wamsley et al. 2015). Natural Shoreline Infrastructure has also been shown to be more cost-effective and provide more economic benefits over the mid- to long-term (ENVIRON 2015 and Leo et al. 2017).

Nonetheless, armoring has been the industry standard for shoreline protection for a long time – and not just in California. The reason for this preference is multi-faceted. A recent study of the obstacles to deployment of Natural Shoreline Infrastructure in adaptation decision-making

(Caldwell et al. 2015) identified several significant obstacles, including (but not limited to) a lack of: awareness of the options and their efficacy, technical standards and deployment guidance, and funding.

1.4 Natural Infrastructure Defined and Codified into State Law

Although natural infrastructure (here, we are discussing the general usage of the term) has yet to be embraced among local coastal planners, policy-makers at the state-level are calling for more of these climate adaptation strategies. For instance, in 2015 California Public Resources codified "natural infrastructure" (both coastal and non-coastal applications) into law and defined the term:

> "*Natural infrastructure is the preservation and/or restoration of ecological systems, or utilization of engineered systems that use ecological processes, to increase resiliency to climate change and/or manage other environmental problems. This may include, but is not limited to, floodplain and wetland restoration or preservation, combining levees with restored ecological systems to reduce flood risk, and urban trees to mitigate high heat days.*" (Cal. Gov't Code § 65302 (g)(4)(C)(v) (SB 379)) (Appendix B).

Additional state-level plans that call for natural infrastructure include:

- The Safeguarding California Plan, California's climate change adaptation strategy developed by 38 agencies across state government, directs the state to prioritize green infrastructure solutions.
- California Coastal Commission's Sea Level Rise Policy Guidance, adopted August 12, 2015, highlights the utility of natural infrastructure for sea level rise planning in Local Coastal Programs.
- The Governor's Executive Order B-30-15 (2015) prioritizes the application of natural infrastructure in state agencies' planning and investments.
- The Governor's Office of Planning and Research also issued the Environmental Goals and Policy Report, which calls for the state to "[b]uild resilience into natural systems and prioritize natural and green infrastructure solutions."
- SB 379 (Jackson, 2015) created the requirement that the safety element of local General Plans be reviewed and updated to address climate adaptation and resiliency strategies, and requires that, where feasible, natural features and processes should be used in adaptation strategies.

1.5 Creating a Shared Definition of Natural Shoreline Infrastructure Among Stakeholders

In reviewing the growing collection of state reports that discuss "natural infrastructure" (Section 1.4), it became clear that its meaning varies from agency to agency, and often within agencies. The term has been used to describe diverse project types with diverse intentions, from the restoration of mangrove forests to measures placing a "bioveneer" of vegetation on top of built structural barriers. These and other approaches are also variously referred to as "green infrastructure," "nature-based solutions," or "ecosystem-based adaptation."

To increase the frequency and effectiveness of natural infrastructure projects in coastal California, we knew it was critical to first create a common understanding among diverse governance actors. In 2016, we engaged a Technical Advisory Committee of key stakeholders comprised of representatives from over two dozen coastal management organizations from local, state, and federal government agencies, non-governmental organizations and environmental consulting firms throughout California, particularly inviting people with expertise in the deployment of natural infrastructure.

With the committee, we reviewed relevant literature and distilled several principles essential to common perceptions of natural infrastructure:

- Natural infrastructure provides ecosystem services and benefits
- Natural infrastructure is/features a "healthy ecosystem"
- Natural infrastructure provides economic benefits and/or is cost-effective
- Natural infrastructure includes specific types of projects/features, including forests, saltmarsh, eelgrass beds, oyster reefs, beach and dunes, fish and wildlife habitat, etc.
- Natural infrastructure projects include preservation of biodiversity as a specific outcome

We also knew we needed a unifying definition specific to the coast, distinct from other forms of natural infrastructure, such as green infrastructure, which is often used to describe urban efforts to reduce stormwater runoff, for instance. We performed another literature search focusing on approaches related to shorelines (Appendix B). After substantial discussion, the committee developed this definition for natural infrastructure specific to coastal adaptation to climate change:

> *"For the purposes of this study, 'natural shoreline infrastructure for adaptation' means using natural ecological systems or processes to reduce vulnerability to climate change related hazards while increasing the long-term adaptive capacity of coastal areas by perpetuating or restoring ecosystem services."*

The authors of this report distilled the term even further, to "Natural Shoreline Infrastructure," using capitalization to underscore when we are referring specifically to the shared understanding and terminology created within the Technical Advisory Committee.

2: Case Studies

Most planners lack direct experience with Natural Shoreline Infrastructure projects. To be able to proceed with confidence, planners would like to at least be able to turn to well-documented precedents, specifically in areas with similar development and geographical profiles as their own (Caldwell et al. 2015). In California, this information has been scarce. Where case studies exist, relevant information has not previously been made accessible, except in technical reports that often are not geared to the information needs of planners.

To address the lack in familiarity among planners, we selected five projects where Natural Shoreline Infrastructure has been successfully implemented in California. These were narrowed down from a list developed with the input of our Technical Advisory Committee (Section 1.4, Appendix A), of 60 projects throughout the state in varying stages of planning, implementation, monitoring and completion. Most completed projects were originally intended as restoration projects, with the shoreline protection benefits occurring incidentally. However, these projects clearly serve as demonstration sites of how Natural Shoreline Infrastructure strategies have already benefited communities and improved coastal resilience throughout the state.

Below are short summaries of each project followed by key lessons (Section 2.6) that have been yielded thus far. For more technical details including permitting, planning, design, cost, implementation, and performance, *Case Studies of Natural Shoreline Infrastructure in California*, available at http://coastalresilience.org/case-studies-of-natural-shoreline-infrastructure-in-coastal-california/

Figure 2: Locations of Case Studies of Natural Shoreline Infrastructure in Coastal California

2.1 Seal Beach National Wildlife Refuge Thin-layer Salt Marsh Sediment Augmentation Pilot Project

Extensive sea level rise modeling by U.S. Geological Survey indicates that Seal Beach National Wildlife Refuge is an extremely vulnerable coastal marsh in California due to subsidence, a cut-off sediment supply, and sea level rise. The marsh is bounded by a Naval Weapons Base and cannot transgress landward, so U.S. Fish and Wildlife Service is piloting a method involving the application of a thin layer of dredge sediment on the surface of the marsh.

Tidal marsh habitats and the species within them have adapted to a changing coastline (Friedrichs and Perry 2001), but projected accelerated sea level rise threatens the persistence tidal marshes (Kirwan and Megonigal 2013). Tidal marshes are found within a narrow elevational range in the high intertidal zone. If wetland plants are inundated excessively, they drown. If inundated insufficiently, upland species will crowd them out. Many marshes have been able to keep relative pace with past rates of sea level rise, but continued resilience requires sufficient sediment supplies and/or robust rates of peat formation so that marsh elevation can track rising water levels in the future (Morris et al., 2002; Kirwan and Megonigal 2013). Reduced riverine sediment supplies and increased subsidence rates are key factors that can hamper marsh resilience (Morris et al. 2002; Day et al. 2008; Kirwan and Megonigal 2013).

Climate adaptation strategies can increase salt marsh resilience (Wigand et al., 2015). One such strategy is to raise the elevation of the marsh plain by adding sediment or soil, in order to maintain the marsh plant community relative to sea level. The term “thin-layer placement” describes sediment additions from approximately 1 cm (0.4 in) in depth to 50 cm (19.7 in) or more. Typical depths in existing project-scale applications are primarily in the 10-20 cm (3.9-7.9 in) range. One source of material is the beneficial re-use of dredged sediments from nearby harbors and navigation channels. Important evaluations for successful thin-layer placement include the appropriate depth of added soils so that marsh plants can grow through the overlying soil (or re-seed into that soil); soil quality in terms of toxicants and pollutants; and the frequent presence of sulfides in subaqueous soils which can oxidize into acid sulfate soils toxic to plants.

The goal at Seal Beach was to raise the elevation of the marsh to mitigate the impacts of subsidence and rising waters, and to enhance bird habitat. In early 2016 over the course of 4 months, the team used thin-layer placement to raise the site elevation by about 21.6 cm (8.5 in), and vegetation and channels are already developing on the site. Although monitoring is in its early stages, this is a promising approach for the most threatened Pacific Coast marshes where other strategies like reconnecting them to their sediment supplies are not available. (See Appendix E.1 for technical details).

2.2 Surfers’ Point Managed Shoreline Retreat Project

Surfers’ Point in Ventura County presents a case study of the combined adaptation strategies of habitat restoration, infrastructure realignment, and managed retreat.

In Surfers’ Point, strong community partnerships and a willingness to explore innovative engineering approaches led to a solution that worked with natural processes in ways that had not been attempted before. The project transformed an eroding parking lot and collapsing bike path into a cobble beach backed by dunes, in the process, restoring and widening the beach using native materials (cobble, sand) and dune planting. Infrastructure was relocated landward. It has since withstood strong El Niño storms and has protected the new bike path while providing continued public access to the beach. (See Appendix E.2 for more technical details.)

2.3 San Francisco Bay Living Shorelines: Nearshore Linkages Project

Living shorelines projects use natural habitats to protect the shoreline to achieve both physical and biological goals. The San Francisco Bay Living Shorelines project began in 2012 with the goal of examining how the creation of native ecosystems such as oyster reefs and eelgrass beds can protect the shoreline, minimize coastal erosion, and maintain coastal processes while enhancing natural habitat for fish and aquatic plants and wildlife. The project aims to create biologically rich and diverse subtidal and low intertidal habitats as part of a self-sustaining estuary system that restores ecological function and is resilient to changing environmental conditions. The project has so far demonstrated that oyster reefs and eelgrass beds can substantially increase habitat, food resources, and biodiversity as well as reduce wave energy by 30%.

In its next phase, the project will expand into the Giant Marsh Living Shorelines project, which will incorporate current lessons learned into a design with more habitat types to test a larger scale approach, linking eelgrass beds, oyster reefs, tidal marsh, and ecotone transition zones as a complete tidal system.

The San Francisco Bay Living Shorelines project raised awareness and built support and interest within the region, and there are now multiple public and private partnerships forming to support the development of other living shoreline projects. A project in San Rafael provided critical information and has led to additional living shorelines projects in San Diego Bay, Newport Bay, and Humboldt Bay, along with the growth of a statewide network of practitioners and robust exchange of ideas and lessons learned to help advance the use of Natural Shoreline Infrastructure throughout California and the Pacific Coast. (For a more detailed account, see Appendix E.3)

2.4 Hamilton Wetland Restoration Project

The Hamilton Wetland Restoration Project is exceptional in its restoration of a range of habitat types integrated with flood protection levees, and is one of the largest examples of beneficial reuse of dredge sediment on the Pacific Coast. It follows and improves upon the restoration of Sonoma Baylands, which also used dredged sediment to restore site elevation to marsh plain. The Hamilton Project included intertidal berms to slow down wind-generated waves, and allow suspended sediment carried into the site to deposit naturally. Accordingly, this project was an early example of a horizontal levee that provides ecological benefits, such as habitat for endangered species like the Ridgway's Rail and Salt Marsh Harvest Mouse. In addition, it is the first example of seasonal wetland construction on the Pacific Coast. Although the intertidal berms compacted more than expected, the site is vegetating well, and nesting shorebirds have been observed. (See Appendix E.4 for more detail.)

2.5 Humboldt Coastal Dune Vulnerability and Adaptation Climate Ready Project

There are 51 km (32 miles) of beach-dune systems near Eureka in Humboldt County that will be subject to sea level rise. This area includes four major barrier spits that protect the Humboldt Bay and Eel River estuaries as well as support rare coastal dune ecosystems, threatened and endangered species, and important archeological sites. In addition, critical infrastructure is located in some areas including the Humboldt Bay Municipal Water District pipeline and Manila Community Service District's wastewater treatment ponds. Evidence suggests that coastal dunes dominated by native plants are better able to move inland in response to sea level rise while maintaining their integrity and protecting inland habitats and land uses.

This project, led by the U.S. Fish and Wildlife Service's Humboldt Bay National Wildlife Refuge, uses demonstration sites to test adaptation strategies. Sediment movement and foredune morphology are being monitored at the scale of the littoral cell to better understand sediment dynamics in order to allow for the identification of areas of vulnerability due to factors such as sediment deficiency or subsidence. Dune vegetation management strategies are also tested at these demonstration sites to inform regional adaptation strategies to reduce vulnerability to sea level rise and coastal storms. (See Appendix E.5 for more detail).

2.6 Lessons Learned

While compiling the case studies and interviewing those who implemented the projects, we distilled a number of common principles and tips that could aid the establishment of future projects:

- Establish a multi-agency stakeholder process with long-term leadership to enhance buy-in and funding opportunities.
- Identify and engage champions of the project within partnering agencies.
- Coordinating with permitting agencies early in the design phase can make the process smoother. The permitting effort takes time, thoughtful discussion, and stepwise coordination, as there are multiple local, state, and federal regulations and species considerations at the land-sea interface.
- Engage with community groups to communicate the benefits of natural approaches and garner the support of local officials for approaches that improve public access and enjoyment of healthy ecosystems. Additionally, it is important to connect vulnerable communities with their shoreline, increasing understanding of risks and investment in preserving public access by using natural approaches.
- Engage volunteers to help with planting, monitoring, and removing invasive species, which reduces project costs in addition to being community ambassadors to support more projects like these in neighboring areas.
- California has extensive experience and lessons to learn from a long history of restoration. However, finding funding and accomplishing significant post-project monitoring to capture those lessons are consistent challenges for restoration and adaptation projects alike. Collectively, we should support demonstration projects that collect detailed monitoring information so that they can be improved upon, tested in other areas and applied on larger scales as part of an adaptation strategy to increase coastal resilience.

3: Technical Guidance on Natural Shoreline Infrastructure

3.1 Introduction and Appropriate Use

Although some Natural Shoreline Infrastructure projects have been implemented throughout California, guidance on appropriate siting and design has been severely limited.

But to meet funding requirements, planners often need to follow accepted technical standards. For example, FEMA requires hazard mitigation projects to be "technically feasible," which usually means that the project conforms to existing engineering standards; there are few such standards for Natural Shoreline Infrastructure.

This section begins to fill the gap by providing detailed guidance on a selection of six Natural Shoreline Infrastructure measures with a history of deployment in the state, organized by appropriate setting and backshore type. We've collected guidance for sand dunes, cobble berms, marsh sills, tidal benches, oyster reefs, and eelgrass beds. For each of the six types we developed technical guidance for the setting, design, construction, and monitoring. We consulted with geomorphological and ecological experts to characterize the conditions under which Natural Shoreline Infrastructure will be resilient to climate change and sea level rise over the next century. For each Natural Shoreline Infrastructure type, we evaluated the following parameters (at a minimum):

- Land Cover/Existing Development – to determine the need for, and suitability of, Natural Shoreline Infrastructure;
- Physical Context (wave environment, benthic geomorphology, shoreline geomorphology, space required to meet performance objectives, climate and/or marine conditions);
- Design specifications, criteria, and performance expectations of Natural Shoreline Infrastructure for erosion control, risk reduction, property protection; and
- Cost per hectare or linear kilometer. The actual cost of construction may be impacted by availability of construction crews and equipment and fluctuation of supply prices at the time work is bid. We make no warranty, expressed or implied, as to the accuracy of such opinions as compared to bids or actual costs.

Table 1 provides a summary of the six Natural Shoreline Infrastructure measures and their appropriateness in different coastal settings. Note that Table 1 is a simplification intended for guidance and planning purposes and is not intended to be prescriptive. Site-specific evaluations will be needed to confirm/verify information presented, and we recognize that the guidance is not a substitute for site-specific knowledge, analysis, and design.

Table 1: Suitability of Natural Shoreline Infrastructure measures for select wave exposure environments and backshore types. Green (or X) indicates that a type is suitable for the given environmental setting. Yellow (or /) indicates moderate suitability and red (or blank box) indicates that this type is not typically appropriate in this setting.

Backshore Type		Sand Dune	Cobble Berm	Marsh Sill	Tidal Bench	Oyster Reef	Eelgrass Bed
		Natural Shoreline Infrastructure Type					
Sheltered Water (wind-waves)	Beach	X	X	X	X	X	X
	Cliff		X	/	/	/	/
	Marsh			X	X	X	X
Open Coast (swell-exposed)	Beach	X	X				
	Cliff/Rocky Nearshore	/	X				
	River Mouth		X				
	Lagoon Estuary	X	X	X	X	X	X

3.2 Vegetated Dunes

Coastal sand dunes are natural shore form systems consisting of wind-blown sand and native plants located landward of the annual extreme wave runup zone along the beach. (Wave runup is defined as the uprush of water above the still water level resulting from wave action on the shore.) Sand dunes vary in extent from short distances to great expanses and act as coastal defense by both providing sand storage to buffer erosion during extreme events and dissipating wave energy. During storms, dunes are a supply of surplus sediment, which is transported offshore into a sand bar system. These sand bars induce wave breaking further out in the surf zone, thereby dissipating wave energy and destructive forces onshore. Sand bars, beaches and dunes work together in a dynamic equilibrium, cycling sediment while changing form and shape. By reducing wave overtopping events, dunes also inhibit saltwater intrusion into the backshore.

Vegetated dunes further enhance these physical processes and add additional ecological value. Vegetation acts to trap deposited sand particles and contribute to the overall growth of the dune. Established plants not only trap sand, but also wind-borne seeds to further enhance the vegetation of the dunes. Vegetation can also increase soil water content by intercepting fog and limiting evaporation from the surface through shading. Additionally, nitrogen fixing plants (e.g. yellow bush lupine (*Lupinus arboreous*) and chamisso bush lupine (*Lupinus chamissonis*)) increase the availability of nitrogen in the soil, a key limiting factor for newly formed dunes, which can facilitate the establishment and productivity of other plant species. Larger bushes provide shelter from the wind and sun, further facilitating the establishment and growth of seedlings.

Areas landward of the dune system, if vegetated, provide habitat and benefit from protection from salty and windy conditions.

Vegetated dunes also provide dynamic habitat for a diversity of wildlife. Established plants provide shelter from wind and sun for birds, mammals, reptiles, amphibians, and insects, many of which feed on nectar, seeds, or the plants themselves. Roots stabilize the sand for burrowing animals. Beaches and dunes together provide a range of habitats necessary for the foraging, resting, roosting and nesting of shorebirds.

Dunes provide excellent opportunities for nature viewing, including incredible displays of blooming native plants, and opportunities to see rare birds and animals. However, dunes are very fragile; inappropriate recreation can permanently damage dune systems. Thus, dedicated trails and boardwalks are best at providing recreational access while protecting the ecological function and services to people that dunes provide.

3.2.1 Setting

Dunes are found along the open coast and in bay environments and are generally found in areas with seasonally strong winds. Coastal sand dunes can be categorized into foredunes, dune fields and barrier dunes. The same settings and conditions that support natural dune systems can potentially support constructed dunes and can provide valuable reference sites to inform design of constructed dunes to address coastal hazards.

Foredunes are naturally created by windblown sand onto a vegetated part of the beach and are typically parallel to the shore. Surfers' Point Managed Retreat, Ventura is an example of constructed foredunes that have been successfully used as Natural Shoreline Infrastructure. Foredunes have also been proposed as Natural Shoreline Infrastructure at Ocean Beach, CA (Battalio 2016). Dune fields, another subcategory of coastal sand dunes, encompass both foredunes and mature dunes, which are located further inland. These can be found on both the open coast (e.g. Pacifica State Beach, Linda Mar, CA) and bay environments (Crissy Field, San Francisco, CA.)

Last, barrier dunes are sand embankments which form a barrier high enough to limit wave overtopping events and contain sufficient sand volume to withstand wave-induced erosion for a winter or several extreme events. These types of dunes are often either: (1) geologic remnant dunes with bare, slipping slopes at the angle of repose of loose sand (e.g. southern Monterey Bay); or (2) steeply sloping, high-relief engineered dunes with non-native vegetation (e.g. Ocean Beach, San Francisco, CA).

3.2.2 Design Guidance

3.2.2.1 Dune Geometry

Relevant design parameters for implementing dune systems as Natural Shoreline Infrastructure include:

- Seaward edge of the dune
- Landward limit of zone/space available for a dune field
- Appropriate alongshore length.

The seaward edge of the dune is defined by the location where: (1) total water level (top of ocean water level + wave runup) reaches infrequently (10 days per year or less); and (2) dry sand area during the summer is sufficient to supply wind-blown sand to rebuild dunes. If reference sites (e.g. an existing natural area nearby with a dune) are available, geometry parameters determined from these locations should be given priority, followed by historic conditions at the project site.

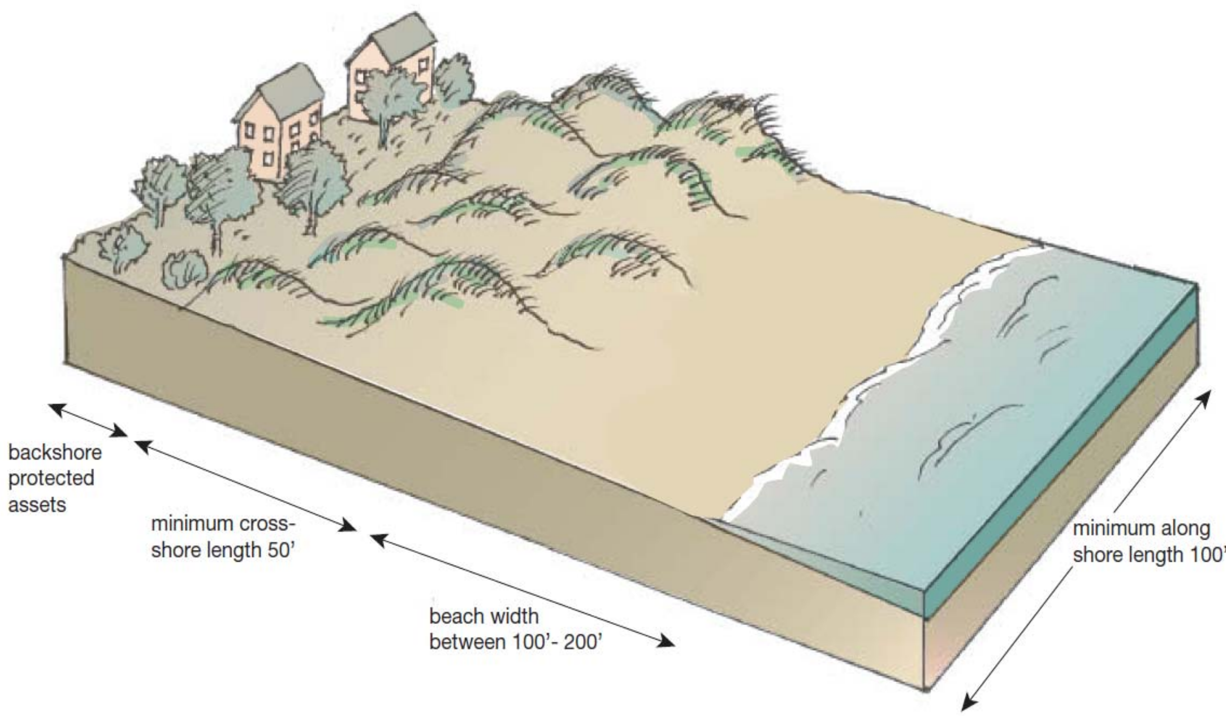

Figure 3: Oblique view of dune geometry thresholds

Sufficient space between development and the shoreline is required for sand dunes to be installed successfully and to function optimally (Figure 3). The available space should exceed the sum of total constructed dune footprint and a beach width between 30 m to 60 m (100 to 200 ft). The total constructed dune footprint is defined by the height of the dune above the beach, slope and crest width (Figure 4). The minimum alongshore length of a dune system is on the order of a hundred feet, while the maximum is set by the length of shore that satisfies the two conditions set forth for total water level and dry sand area. A higher cross-shore extent of dry beach will help limit wave attack and provide source of wind-blown sand onto the dunes from onshore winds.

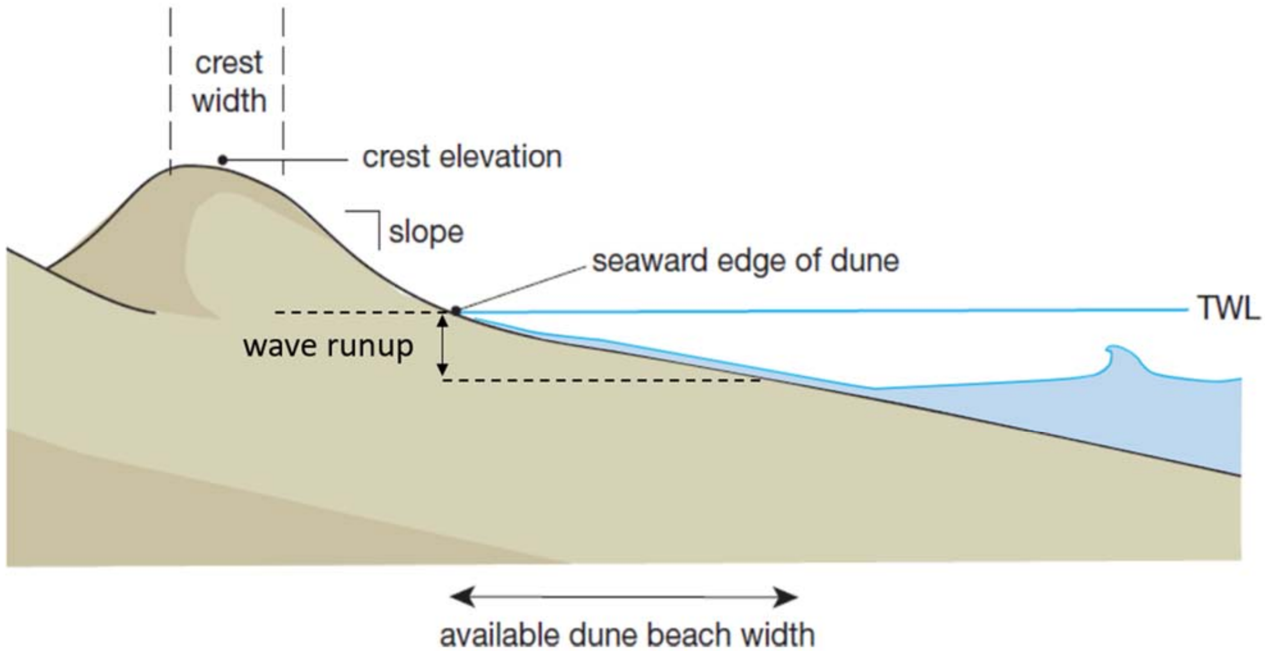

Figure 4. Profile view of dune geometry

The Coastal Engineering Manual (CEM) (USACE 2003) provides wave runup and total water level formulas. The reader is referred to the CEM as well for formulas quantifying wind-blown sand transport rate to get a better understanding of potential dune growth rate for their project site. Based off of historic wind for the project site, it is possible to estimate the sand transport rate across all directional bins. This may elucidate wind directions where sand loss due to aeolian (wind-driven) transport should be expected and inform short-term management actions to “trap” the sand. Further site-specific analysis will be necessary to determine exact quantities and cost estimates.

3.2.3 Dune Subtype and Vegetation

3.2.3.1 Foredunes

Foredunes require a constant backshore zone width with a dry sand fetch in order to foster multi-year growth of perennial vegetation. In other words, if the backshore zone is exposed to frequent disturbance by waves or does not have a long-lasting sand source, a stable foredune system will not be established.

Plants in the foredunes must be able to withstand a harsh environment. In particular, the plants must be able to withstand frequent disturbance from both wind and waves. In addition, foredune soils tend to have high salt content because of inputs from both waves and spray from the ocean. High winds can lead to the burial of vegetation and physical leaf damage from blowing sand. Given the frequent disturbance in the foredunes, plant cover tends to be very low resulting in less shade and therefore greater loss of soil water due to evaporation.

Planting is not necessarily required but is often employed to stabilize the dune geometry. Planting and other erosion control measures are particularly important in close proximity to development where strong sea-breezes occur. There are several methods to stabilize dunes from wind-blown transport. For example, the transport effectiveness of winds can be modified by punching dead plants, tree branches or straw into the sand and installing sand fences. Another method is to place coarse sand and or shell hash to armor the sand surface. These actions are often combined with planting.

If planting is included, seedling planting on foredunes usually takes place in the winter season. The optimal time for establishing natural foredune vegetation is between the peak winter storm periods and early spring, where seedlings benefit from low temperatures and high moisture from winter precipitation.

The foredune vegetation community varies from north to south in California with grass species more dominant in the north and forbs more dominant in the south. Dune vegetation also shifts from the dominance of herbaceous plants near the shore to the dominance of shrubs within a greater distance from the shore. A list of common, native plants is in Appendix C, to assist with design.

Two invasive plant species, European beach grass (*Ammophila arenaria*) and ice plant (*Carpobrotus edulis*) have become dominant in California coastal dune habitats and can have negative effects on the structure and function of dune ecosystems. Foredunes dominated by European beach grass tend to be taller and steeper, causing a loss of sand transport shoreward and disrupting the dynamics of sand supply between the dunes, beach and offshore sandbars. Ice plant similarly dominates dune plant communities limiting natural sand transport, limiting soil water availability and changing soil chemistry, thereby competitively excluding native plants. Ice plant also forms dense mats of vegetation, limiting sand movement. Both European beach grass and ice plant have high dispersal capabilities and thus nearby occurrences of these species can threaten the functioning of sand dune establishment and restoration projects.

3.2.3.4 Dune Fields and Barrier Dunes

Dune fields and barrier dunes occur landward of foredune communities. Both communities typically occur at higher relative elevations due to the positive feedback of the accumulation of wind-blown sand by the dune vegetation and also by remnant geologic features. Based on the higher elevation and greater distance from the shore, dune fields and barrier dunes receive less disturbance from both waves and wind resulting in a more favorable environment for plant establishment and growth. Vegetation in dune fields and barrier dunes are typically much more diverse and with greater plant cover than fore dune communities. Plants more adept at colonizing recently disturbed spaces, such as beach sagewort (*Artemisia pycnocephala*), will tend to be more dominant closer to the shore line while more woody species, such as chamisso bush lupine (*Lupinus chamissonis*) and lizard tail (*Eriophyllum staechadifolium*) dominate towards the rear of the dunes.

Restoration considerations: Many of the recommendations for restoring the foredune community apply to dune fields and barrier dunes. However, dune field and barrier dune plants are less able to establish in a completely disturbed environment because of excessive solar radiation and wind/sand scour. Sterile straw plugs or other temporary physical structures can be used to help native plants to establish in dunes where vegetation has been completely removed or has yet to establish. A list of common dune field and barrier dune vegetation in California is available at Appendix C, to assist with design.

3.2.4 Construction and Monitoring

Protecting the vegetation on a dune system is vital to the success of the dune system. Vegetation can be damaged by natural causes, such as storms, strong winds, fires, or human-related causes, like excessive foot traffic, vehicles, clearing, etc. A gap in vegetation cover could lead to a 'blowout' in the dune ridge, reducing its ability to act as a coastal buffer. Oftentimes, post or rope-based fences are recommended for delineating and protecting vegetated areas from human trampling, since they do not obstruct aeolian sand transport (Baye 2016). A 2 m (approx. 6.6 ft) minimum buffer of unvegetated sand behind the fence is recommended, since that is the approximate lateral spread rate of most foredune vegetation species.

Monitoring should focus on both the physical and ecological evolution of the dune. Vegetation extents, density and characteristics should be determined according to a monitoring plan using aerial photography (LiDAR – Light Detection and Ranging and/or photogrammetry) and ground truthing. Plant horizontal spread and vertical growth through sand accretion should be tracked each year. Regular surveys during the winter season and before/after extreme events of foredune topography is recommended, as well as determining sand accretion patterns and rates across the foredune profile. Monitoring of wildlife and human use of the foredune and fenced areas can help inform short-term management actions.

Based on previous project experience, the unit cost per acre for installing dunes is dependent on the type of dune constructed and other factors. For example, if volunteer labor for weeding and seeding over the course of dune evolution is available, costs are reduced. Dune vegetation management-focused projects with volunteer labor cost around $50 per square kilometer ($10,000/acre). For new dune hummock construction with imported sand and associated costs with the design-bid process, the unit cost per acre order of magnitude is around $500 per square kilometer ($100,000/acre). Last but not least, for a linear, sacrificial dune embankment type project, the unit cost per acre veers upwards towards $5,000 per square kilometer ($1,000,000/acre).

3.3 Cobble Berms

Cobble berms are mounds of rounded rock sorted and shaped by wave action (Allen et al. 2005; Everts et al. 2002; Lorang 1997; Bauer 1974). They are most prevalent at river and creek mouths but also form at the base of cliffs, whether as lag deposits (typically below sandy beach and exposed when the sand scours away) or as higher, well-developed berms that extend to higher levels of wave run-up. Cobble berms have been successfully installed as Natural Shoreline Infrastructure at both Surfers Point, Ventura, and Chula Vista Bayfront in San Diego Bay, to name just two of many examples. Where cobble deposits naturally occur, cobble is seasonally exposed or covered with a sand layer. Gravel-cobble systems, such as those found in Puget Sound (WA), are the higher latitude analogs to sand-cobble systems in central and southern CA (Pacifica State Beach and Surfer's Point Managed Retreat). In areas where cobble deposits are not naturally occurring, cobble berms are referred to as dynamic revetments. A few examples of where dynamic revetments have been successfully installed include: Ocean Beach (San Francisco, CA), Chula Vista Bayfront (San Diego Bay, CA) and Cape Lookout State Park (OR).

3.3.1 Setting

The use of cobble berms as Natural Shoreline Infrastructure is suitable on both open, swell-exposed coasts and sheltered waters. Cobble berms provide shore protection for the backshore (e.g. bluff, shoreward natural habitat or human infrastructure) by dissipating wave energy and reducing overtopping events. During extreme events or particularly erosive conditions, cobble berms can also serve as a “backstop” in terms of limiting the landward extent of erosion.

Cobble sediment size typically ranges from 15 to 61 cm (6 to 24 in.). Larger sediment sizes are associated with higher wave exposure, while smaller sizes, closer to gravel, can be used in berm formations for sheltered waters. The use of gravel on open coast environments would be considered more suitable for beach nourishment, rather than berm construction. The material is generally traversable and supports recreational access, both laterally and vertically.

Void space and permeability, which increases with larger cobble sizes, impacts the overall effectiveness of the cobble berm at dissipating wave energy. As water enters the berm on the uprush, wave backwash is reduced by the presence of the cobble. Increased wave action leads to the movement of cobble onshore, thus building the crest of the cobble berm and steepening the water-side slope. Sand sediment placed on top of cobble tends to move offshore and form offshore bars which also help with wave energy dissipation.

The ecological functions of cobble berms vary by whether cobble is native or non-native to a project site. Non-native cobble berms serve primarily as coastal defense mechanisms. Native cobble berms, however, provide habitat equivalency for marine invertebrates and other organisms while alluding to more natural landform. Salt grass can also establish by cobble berms (Figure 6). Traditional armored approaches, such as rock rip rap or solid seawalls, provide neither of these benefits.

(Photo Credit: Jenny Dugan)

Figure 6. Left: Salt grass established on cobble berm in Goleta, Santa Barbara County, CA. Right: Salt grass established on cobble berm at Arroyo Burro Beach, Santa Barbara County, CA.

3.3.2 Design Guidance

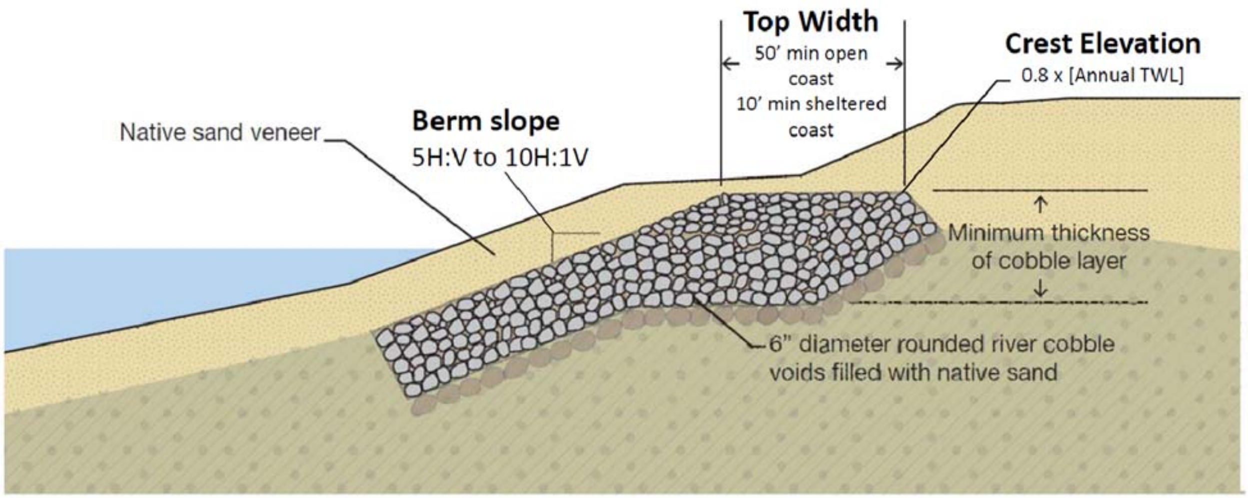

Figure 7. Profile view of cobble berm

Key design parameters a manager should determine for a cobble berm include: alongshore length of constructed berm, crest elevation, slope and layer thickness and volumes (Figure 7). The manager should also decide if the cobble berm will be the primary mechanism by which to achieve coastal defense or if it will be combined with another Natural Shoreline Infrastructure type and/or armoring element. For example, a cobble berm can be designed with a dune or natural boulder revetment in back.

The total space requirements for a cobble berm depends on its crest elevation and width and side slopes. If implemented alone, crest elevation of the cobble berm can be determined from calculating wave runup and, subsequently, total water levels (TWL) from extreme tides and storm waves for the project site. Approximately, the berm crest elevation can be estimated as 0.8 x TWL. If a cobble berm is installed in conjunction with artificial dunes, it is possible to reduce the crest elevation of the berm, since the dune crest would help prevent overtopping. The minimum crest widths for a cobble berm located in a sheltered wave environment and open coast are 3 m and 15 m (10 ft and 50 ft), respectively. Side slopes on the water side can range from 5H:1V to 10H:1V and 3H:1V or flatter on the upland side (Figure 7). The total cross-shore width can be determined from these parameters; at a minimum, the berm should span 24 m (80 ft) in the cross-shore direction in an exposed environment, and 13 m (45 ft) for sheltered coast.

To design and install a cobble berm successfully at a project site, the sizing/sorting of cobble with respect to the local wave climate must be determined. Managers should also consider the shoreline orientation of the project site to the predominant wave direction. Ideally, the predominant wave approach angle should be less than 20°. A strong angle of incidence (e.g. oblique waves) will lead to increased cobble transport. It is generally prudent to consider the evolution of the berm if the structure will be regularly exposed to oblique waves and its primary function is shore protection.

Finally, the extent of the cobble placement must be large enough to interact and respond to wave runup as a unified mass. At a minimum, the alongshore length of a constructed cobble berm should be at least 100 m (330 ft) or greater, depending on the extent of the backshore area a manager wants to protect. Roughly speaking, the nominal minimum thickness of a cobble berm on open coast would be around 1.2 m (4 ft). For sheltered coast, the minimum thickness is reduced to 0.91 m (3 ft).

3.3.3 Construction and Monitoring

Construction of cobble berms is markedly simple compared to that of a conventional revetment, due to drastically smaller sediment size. Based on previous experience, bid prices from similar projects and consultation with contractors and suppliers, the unit cost of a cobble berm is approximately $1,200 per linear foot. Managers are advised to conduct volumetric analyses, pre-and post-placement, as well as for extreme events to monitor profile redistribution and/or cobble loss over time. Determining the rate of sediment deficit and replacement and expected transport losses will assist managers in estimating the percentage of the initial placed volume that will remain in a "stable" configuration and thus, inform consequent decisions about maintenance.

3.4 Marsh Sills

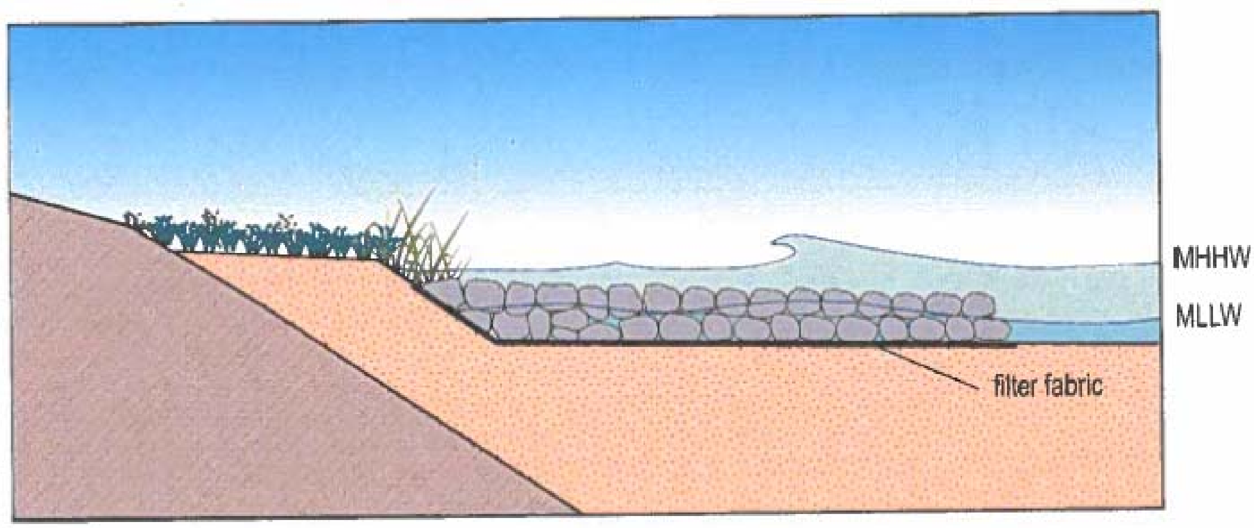

Figure 8. Section view of marsh sill in estuarine environment

A marsh sill is a low-profile stone structure, combined with a vegetated slope, constructed in water parallel to an existing shoreline (Figure 8). Sills can be constructed out of cobble or rock fragments. This Natural Shoreline Infrastructure type represents a midpoint on the green-grey continuum of living shorelines, since it combines engineered structures with natural vegetation.

Similar to a tidal bench, marsh sills encourage shoreline stabilization by allowing sand and sediment to accumulate between the sill and shoreline. Wave action is dissipated on the stone structure, rather than the natural shore. Sediment accretion and marsh growth potential of the site is enhanced due to the protection that the sill provides. Marsh vegetation and/or backshore development of the sill benefit from the added coastal defense.

As sea levels rise, the effectiveness of a marsh sill is gradually reduced since increased water levels allow larger waves to break further up the structure. Wave action higher up on the sill slope may potentially damage the sill and any infrastructure or vegetation behind the sill. Rapid submergence of the structure also renders it incapable of providing coastal defense. Therefore, a marsh sill should be sited in area with low to moderate tide ranges. When considering sill placement, the rate at which local water elevations will rise over the long-term (e.g. order of decades) should be considered in order to optimize design life.

3.4.1 Setting

Marsh sills are located on the water-side of emergent wetland vegetation (marsh), typically on the mudflat adjacent to or just offshore of the marsh scarp. The marsh scarp indicates an erosional marsh whereas a band of West Coast cordgrass (*Spartina spp*), or other vegetation, may indicate a stable or recently accreted shore. Ideally, marsh sills are located in the shallow flats above low water. If marsh sills are located below this elevation, they begin to resemble breakwaters and take on different design requirements.

Site specific suitability for a marsh sill is also affected by construction access limitations, shoreline orientation, and bottom type. The sediment bottom would need to be able to support the weight of a stone sill over a long period of time. Sill placement with respect to the marsh should maximize the marsh width.

3.4.2 Design Guidance

Once an appropriate site for a marsh sill has been determined, the resource manager will have to determine the following design parameters: shoreline slope, intertidal zone width and marsh zone width. According to Hardaway et al. (2010), slopes of 8H:1V to 10H:1V or milder in the intertidal zone have been identified as optimal for marsh development.

The width of the Greenbrae Boardwalk marsh sill was 4.5 m (15 ft) with a range of 3 to 6 m (10 to 20 ft) and a crest elevation of about 1.2 m (4 ft) above mean lower low water (MLLW), which is lower than the marsh plain elevation of approximately 1.5 to 2 m (5 to 6 ft) MLLW. This project has been monitored for 25 years, the results of which demonstrated that these design parameters provide adequate protection against locally generated wind-waves and boat wakes from ferry boats operating within speed restrictions (ESA 2017).

The total constructed sill footprint is defined by the elevation of the flat, crest width and extents of the side slopes. The minimum space for a marsh sill footprint is 3 m (10 ft) in the cross-shore direction and 9 m (30 ft) in the along-shore direction. Ideally, cross-shore widths of around 9 m (30 ft) are selected as desired dimensions for both the structural footprint and a transition before drop-off in slope to the channel. For "thin" sill sections of up to 1 m (3 ft) thick, the side slopes should not be steeper than 1.5H:1V. For placement lower on the profile (deeper water) and thicker rock section may be designed: For thicker sections up to 2 m (6 ft) thick, flatter slopes between 1.5H:1V to 3H:1V are recommended to estimate the minimum desired footprint of the structure.

Last but not least, marsh zone width (behind the sill structure) should be maximized as much as possible to increase the level of wave attenuation.

3.4.3 Construction and Monitoring

Factors for consideration in construction include type of access (land or water), construction access materials and mitigation for adverse construction effects. Water access may have lower impacts on the marsh environment. However, the shallow depths present a potential construction scheduling obstacle, requiring work at high tides and with a long-reach, shallow draft craft. Access by land likely requires special, low-ground pressure equipment and methods, and has the additional potential to adversely affect vegetated marsh that the marsh sills are expected to protect. Laborers will likely need timber sheets, planks and or fabric to provide footing in the work area.

There may be permitting issues if construction impacts mud / sand flat or other intertidal or subtidal benthic habitats. Mitigation is likely to be required, unless the overall project provides net benefit to these habitats. The foundation of the marsh sill should be disturbed to the minimum extent feasible to avoid reduction in the limited existing soil strength expected in wetland environments. Therefore, only excavation, and no earth fill is recommended. Excavation is typically limited to the minimum necessary to provide a relatively flat foundation for the sill structure and to compensate for the increased weight of the marsh sill. Bedding stone and/or filter fabric is required to spread the load of the rock mass and prevent shear failure in the subgrade. Loadings should be incremental with minimal acceleration and impact. The sill should not impede inundation of the marsh plain during higher tides and via tidal channels, hence limiting the sill crest elevation. Additionally, the sill should not be installed across channel mouths.

Monitoring of the marsh sill should focus on the stability of the sill structure and condition of the marsh behind the sill. Regular surveys should be conducted to check for settlement and any displaced rock, which may compromise sill stability. Biological surveys of indicator species should also be carried out to ensure that sill construction did not adversely impact habitat. Special attention should be paid to the ends of the sill structure. Coastal protection effectiveness, in terms of erosion prevention, is diminished at the end of the structure, resulting in “outflanking” (Figure 9), and occasionally at the seaward side (toe) of the structure.

With sea level rise, the increased water level will reduce the effectiveness of the sill as larger waves can propagate over the structure (wave heights in shallow water are limited by the water depth): The loss of effectiveness can be roughly approximated by the ratio of sea level rise to structure thickness (e.g. for a structure two feet thick, one foot of sea level rise would reduce its effectiveness by about 50% (50% = 0.5 = 0.3 m (1 ft.) sea level rise / 0.6 m (2 ft.) thick), and the structure would be largely ineffective with two feet of sea level rise (100% reduction in effectiveness, 1.0 = 0.6 m (2 ft). sea level rise / 0.6 m (2 ft.) thick). The effect of sea level rise can be mitigated by structural modification (adding more rock to raise the elevation) within practical limits.

Figure 9. Photograph showing "outflanking", or erosion at the end of a marsh sill, which is typical of coastal structures over their design life (ESA 2017). The wood post shows the distance between the eroded marsh edge and landward side of the sill.

3.5 Tidal Benches

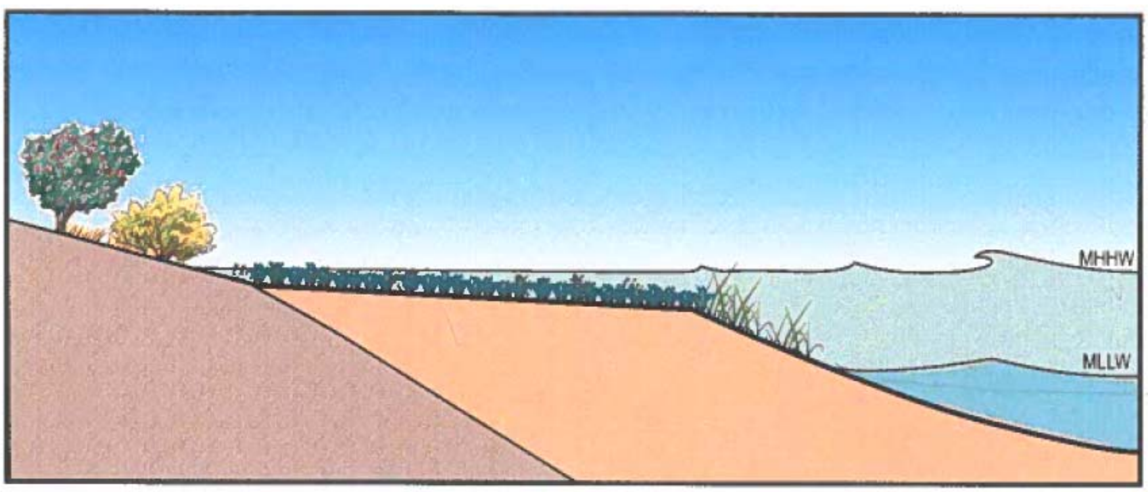

Figure 10. Profile view of tidal bench in estuarine environment (MHHW means mean higher high water, and MLLW means mean lower low water).

A tidal bench is a gently-sloping, dissipative bench extending from mean tide level (MTL) or lower to the backshore (Figure 10). Tidal benches act as wind-wave breaks and can be designed to define tidal watersheds, guide wind-driven circulation and influence the shape and location of an evolving tidal channel network. The slope is typically constructed with fill material and subsequently vegetated. This Natural Shoreline Infrastructure type is often used to create transitional habitat between a backshore barrier and the subtidal zone. Tidal benches are similar in concept to horizontal levees, although the latter extends above mean higher high water (MHHW) to include the upland transition zone. The Hamilton/Bel Marin Keys Wetland

Restoration is an example of a California Natural Shoreline Infrastructure project which has successfully implemented tidal benches into the project design.

Tidal benches offer a range of benefits when implemented correctly. They help to dissipate wave energy and reduce wave forcing on upland areas during extreme events. In contrast to rock armoring, tidal benches offer a greater area for habitat and recreation services, as well soil-based ecological functioning and ecosystem services. The bench provides a range of habitat values for a diversity of plants and animals including the potential for critical nesting habitat. Tidal benches also provide critical resting and feeding grounds for migratory birds along the Pacific Flyway. Incorporating a transitional zone above the bench provides further habitat diversity including a high tide refuge critical for many plants and animals. The dissipative slope encourages sediment accretion along the bench, which leads to shoreline stabilization and the potential for marsh growth and resilience to rising seas. Because of this accretion in combination with below ground plant biomass, tidal marshes have one of the highest per square meter rates of carbon sequestration. Tidal marshes are also excellent at cleaning nutrients and pollutants out of the water. Recreational benefits resulting from tidal benches include hiking, bird watching, fishing, and non-motorized boating.

3.5.1 Setting

Low-energy wave settings (e.g. estuarine environments) are most appropriate for tidal benches. Common installation sites include the inboard levee side of restored marshes or restored lagoon, sheltered bays and/or harbors. If exposed to high wave energy, tidal benches are susceptible to erosion and eventual scarping. Wetland vegetation may establish slowly or not at all. Horizontal space must be available to accommodate the bench slope, which is typically flatter than 7H:1V. Project site with surplus fill material or flexibility in shoreline location (e.g. ability of the landward edge to move inland) are also ideal.

3.5.2 Design Guidance

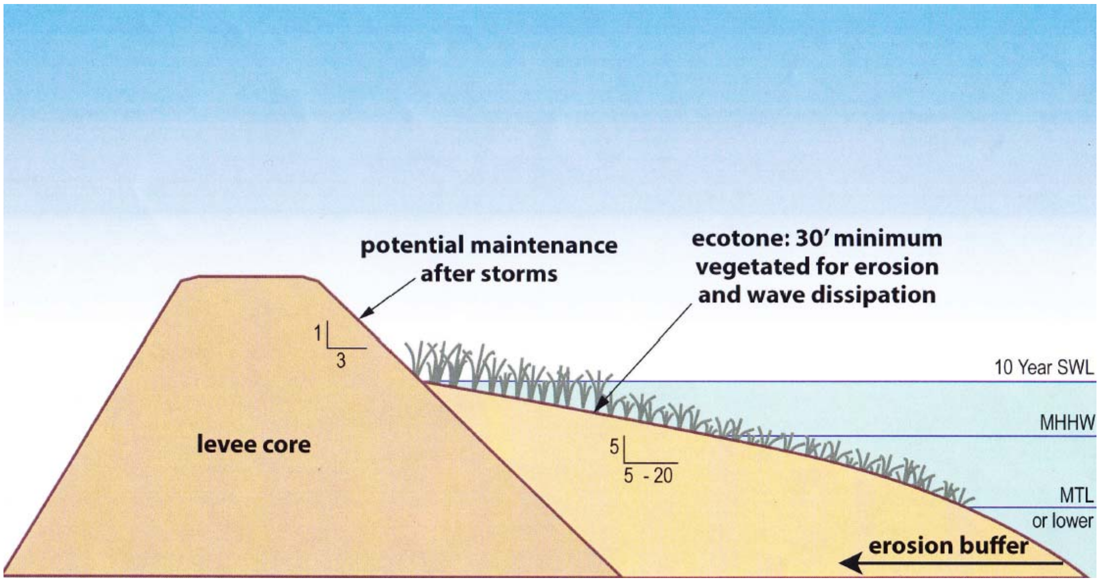

Figure 11. Tidal bench schematic showing slopes, bench width, erosion buffer and vertical datums

The design parameters that should be taken into account when considering using a tidal bench for a project site include the bench width, bench crest, shoreline slope, intertidal zone width, potential armoring and vegetation. If reference sites exist around the intended project site, the geometry from those natural systems (assuming similar physical conditions) should take precedence.

A 9 m (30 ft) minimum bench width is recommended for wave dissipation. Slopes from 10H:1V to 15H:1V have been shown to provide adequate wave dissipation (Knutson, 1990), although at a minimum, a 7H:1V slope is advised. A steeper bench slope will lead to a steeper erosion scarp, which would compromise the tidal bench's ability to provide coastal defense. Typically, the bench crest is set at the 10-year recurrence interval value for total water level, at a minimum, while the slope bottom would be at MLLW or site elevation, whichever is lower (Figure 11).

The width requirement can be considered in terms of the water level range and bench slope. Presuming the space for the bench is constrained, a slope on the steeper range is selected to be 10H:1V. For a water level range between a 10-year water level and mean tide level (MTL), the required width in Central San Francisco Bay is about 18 m (60 ft). Additional width may be added to provide a sacrificial buffer for severe storm erosion, which has been estimated to be up to 9 m (30 ft) horizontally in a mud levee (PWA, 1998). Often, the sacrificial erosion distance is considered redundant to the slope width. Extending the slope to a higher elevation provides ecological and flood protection benefits. This has been proposed as part of the South Bay Salt Ponds project but has not yet been constructed due to cost and space demands.

3.5.2.1 Vegetation

When choosing vegetation for a tidal bench, using a native plant palette according to elevation bands is encouraged (Figure 12). The dynamics and composition of native tidal marsh vegetation differs along these salinity gradients as well as among ecoregions (e.g. Northern, Central, and Southern California, and the San Francisco Bay). Therefore, reference sites used for selecting planting palettes should be chosen from as similar conditions as possible. A list common native plants in California marshes is available in Appendix C to provide guidance when selecting species, and tools are also available to ensure that tidal marsh transition zone restoration designs are resilient to climate change (Thalmayer, et al. 2016). Tidal marsh transition-zone planting may require maintenance which should be factored into construction and monitoring. Depending on the site, soil chemistry may prevent vegetation from becoming established, particularly for upper elevations in dry climates. Sites that incorporate bay fill or build upon existing levees may require a more saline-tolerant plant palette (Thalmayer, et al. 2016). Soil testing and amendments may be needed.

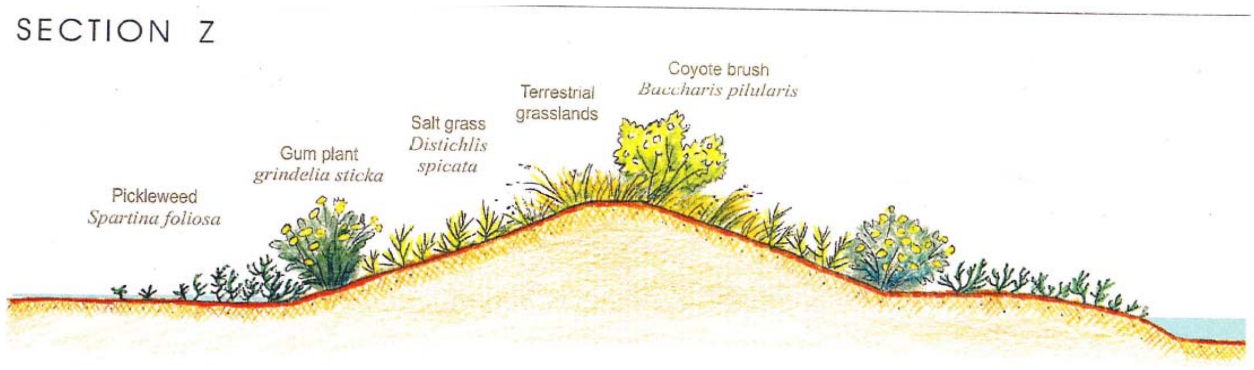

Figure 12. Native marsh vegetation by elevation bands

3.5.3 Construction and Monitoring

Creating a tidal bench primarily involves transport, compacting and grading of fill to the design slope and elevations. Large machinery for excavation and grading as well as areas for staging and stockpiling will be required. Since the costs for moving earth fill around the site are likely to constitute a major part of the total construction cost, it is recommended to optimize staging areas locations in the project site. Based on previous project experience, the unit cost for a tidal bench is approximately $4920 per linear meter ($1,500 per linear foot). The timing of the grading and subsequent planting should be planned accordingly with the seasons and optimal time windows for planting certain species. For example, in the Pacific Northwest, summertime grading minimizes excess sedimentation and runoff and lays the groundwork for planting in fall and early winter, thus decreasing need for irrigation (Johannessen et al. 2014). Adjustments to grade should be made after construction and before planting. Site conditions, such as the location of MLLW and MHHW, should be verified before and after construction of the bench.

Regular inspections of the tidal bench before and after extreme events and the winter season are recommended in order to gauge the bench response to higher, incoming wave energy. In particular, the development of scour or erosion hotspots should be monitored closely via cross-shore elevation surveys. Stability of surface soils and the sediment underneath should also be assessed. Other performance metrics for bench monitoring include vegetation establishment and sediment accretion.

3.6 Native Oyster Reef

Oyster reefs, also referred to as oyster beds, oyster bottoms, oyster banks and/or oyster bars are large aggregations of living oysters and oyster shells located in the intertidal and/or subtidal zones. A wide range of species have been used in coastal environments all over the United States: Eastern oyster *(Crassostrea virginica)* on the Atlantic and Gulf Coasts, Pacific/Japanese oyster *(Crassostrea gigas)* and native Pacific or Olympia oyster *(Ostrea lurida* or *Ostreola conchaphila)* on the West Coast. This guidance focuses on the use of native *Ostrea lurida* (referred to as 'oyster reefs' in the text), which can be found from Alaska to Baja California in intertidal habitats and subtidal beds in deeper embayments.

The geomorphic function of oyster reefs is two-fold: First, oyster reefs reduce bottom shear stress from waves and currents at lower tides and aid in sediment recruitment and retention. Second, the reefs help support vegetation growth in the low intertidal zone. When located in bays and estuaries, native oyster reefs are most effective at dissipating wave energy at mean tide and lower tide levels. Complete wave attenuation is generally not possible unless reefs are built well above typical elevations colonized by oysters.

Overall, a range of fauna benefit from the increased foraging opportunities and habitat space provided by this Natural Shoreline Infrastructure type. Oyster reefs create physical complexity (e.g. microcurrents) in mudflat topography, which influences the ecological value provided by the reef. They bolster the ecological function of a project site by increasing habitat diversity within the low intertidal and subtidal zones. Reefs also improve water clarity by filtering suspended particles (Reidenbach et al., 2013). Decreased turbidity encourages growth of submerged aquatic vegetation and subsequent habitat creation for crustaceans, fish and other organisms. Growth of successive generations of oysters contribute to structural irregularities and 'micro-habitat' creation within the reef. As biogenic - or living - structures, oyster reefs can adapt to rising sea levels thereby increasing the resilience of the Natural Shoreline Infrastructure and the many benefits it provides.

While oyster reefs alone do not provide distinct recreational benefits, reefs are easily implementable into a site design that does. Additionally, oyster reefs can be combined with other Natural Shoreline Infrastructure types, such as eelgrass beds, to provide more variety in function to a project site.

3.6.1 Setting

Oyster reefs perform well in sheltered waters such as bays and estuaries with short period wind-waves (Significant wave height, H_s < 10.9 m or (3 ft)). Open coast environments or areas exposed to primarily swell waves endanger the longevity of the reef. Impacts from strong vessel wakes have not been studied in detail. Reefs also require a saline environment; extended exposure to fresh water exceeding two weeks can kill oysters.

Successful reef placement also requires sediment (e.g. sand, silt, clay or mud) with sufficient strength to support the unit. Generally speaking, the sediment must be capable of supporting walking. Soft, unconsolidated mud not thicker than 0.303 m or (1.0 ft) may also be appropriate.

Wasson et al. (2014) provides an initial site assessment of 21 locations in Central California, with respect to environmental stressors such as: water temperature, chlorophyll content, salinity, predation, temperature, oxygen concentration and risk of low salinity events.

3.6.2 Design Guidance

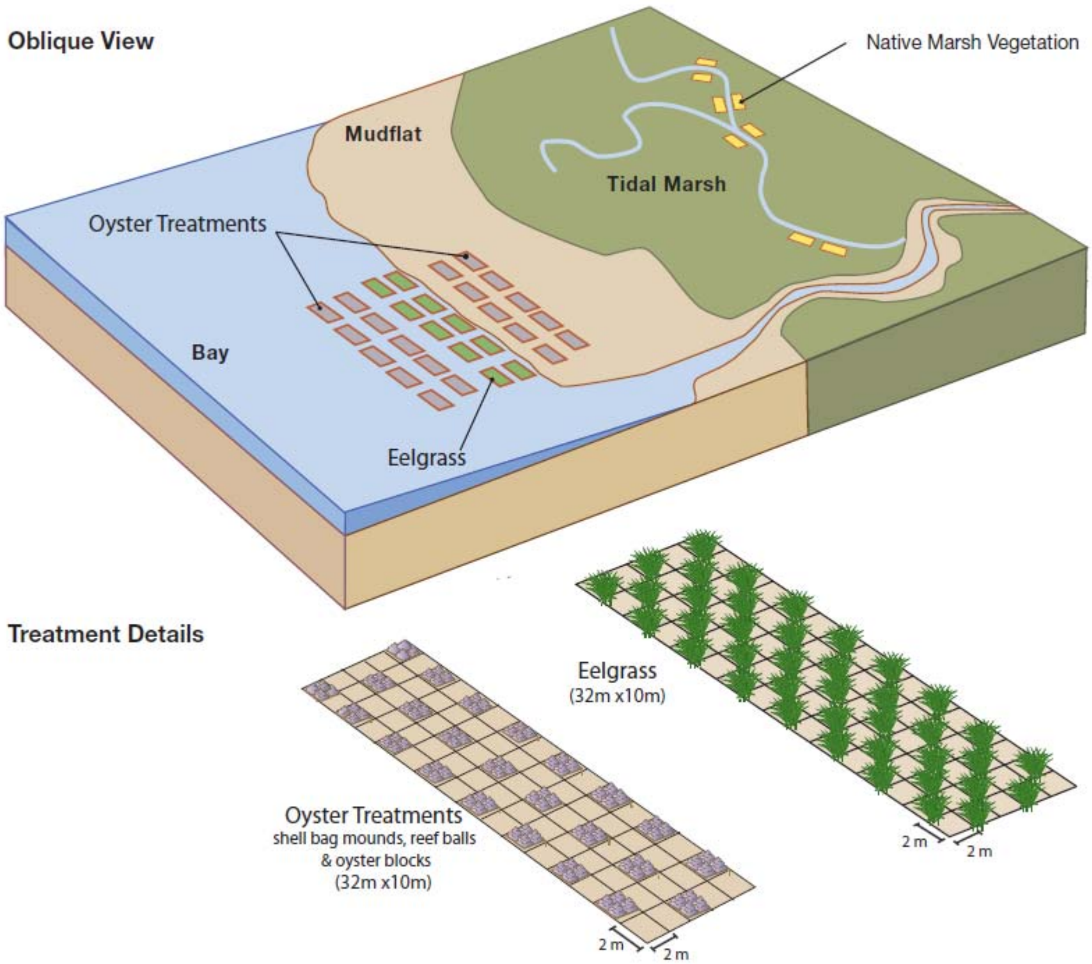

Figure 13. Schematic showing combined use of oyster reef (nearshore and offshore) and eelgrass beds to provide wave protection

The placement of oyster reefs along an estuarine profile enhances the level of coastal defense and geomorphic and ecological function provided by the shoreline. Constructed nearshore reefs, located in the low to mid-intertidal zone and near the shore, are intended to affect shoreline processes and thus yield fewer ecological benefits. Wave dissipation is present at the shore and erosion potential is reduced. In contrast, constructed offshore reefs located in deeper intertidal to subtidal zones are optimal for oyster recruitment and benefit mudflat processes and ecology. Zabin et al. (2016) found that there was no significant difference in live oyster abundance between cobble and muddy shoreline types. Offshore oyster reefs have been successfully installed at TNC San Rafael, ELER Eden Landing, Watershed Project Point Pinole and the Berkeley Marina (ESA PWA, 2012). Figure 13 shows the combined use of oyster reefs in the nearshore and offshore environments in conjunction with eelgrass beds to provide wave protection. The “offshore” distance from shore can be variable and is dependent upon the configuration of the nearshore bathymetry.

Oysters generally survive and thrive within a tidal elevation range of +/- 0.6 m (2 ft) of mean lower low water (MLLW). Reefs built outside of this range will have decreased recruitment and survival of native oysters. Oysters should remain submerged continually if they are to grow during low tide (Miller et al., 2015). Additionally, oyster reefs exposed to currents – as opposed to still water - uptake up to six times more oxygen, thus underlining the importance of initial site selection (Reidenbach et al., 2013). The timeframe and elevations for sea level rise at a project site should be taken into account when considering the desired design life of a constructed natural oyster reef. If water elevations change rapidly and effectively 'drown' the reef, then it will not be able to provide any coastal protection benefit.

Reefs are typically arranged in a linear or curvilinear fashion and follow the shape of natural bathymetric contours. In order to determine the optimal reef length corresponding to length of protection desired, two-dimensional wave modeling of typical and moderate storm events (approx. 2 to 10-year recurrence interval) should be undertaken for the project site. This will help determine the extent of wave attenuation and predicted impact on the shoreline, assuming a range of reef lengths. Where possible, the oyster reef should be oriented perpendicular to the predominant direction of approaching waves in order to provide maximal geomorphic function.

3.6.3 Construction and Monitoring

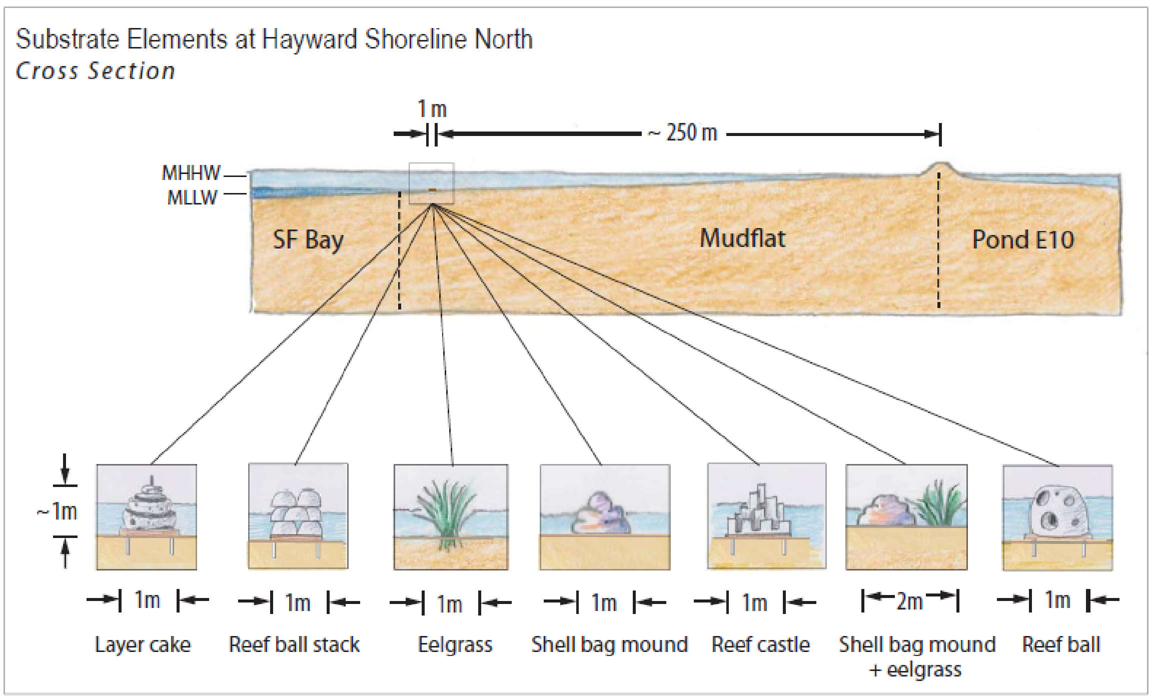

Figure 14. Types of substrate elements for oyster reefs (eelgrass shown as well) and approximate widths

Both natural (recycled shell, gravel) and manmade (aggregates, special concrete mixtures) materials are appropriate for oyster reef substrates and for constructing reef elements (Schulte et al., 2009) (Figure 14). Based off of previous oyster reef Natural Shoreline Infrastructure projects in San Francisco Bay, concrete "Reef Ball" types cost approximately $500 to $550 per linear foot in a single unit line and between $700 to $1,000 per linear foot when arranged in a multi-unit array. Commercial precast concrete domes (Reefballs) or precast concrete blocks that can be stacked together can also be used to form the reef. Granite and pelletized coal ash have also been used as substrate, with varying levels of success. Loose oyster shell is prone to movement from wave action. Thus, oyster shell is commonly gathered into biodegradable bags and stacked in order to reduce settling and scattering of the material. Concrete mixtures which incorporate native shell and aggregates have the additional benefit of providing rough textures and complexity, which make oyster success more feasible. Figure 14 shows the variety in substrate elements used for oyster reefs.

Construction methods for native oyster reefs require specialized floating equipment for work in shallow water. Installation timing and schedule should precede local oyster spat season (at which time larval oysters attach to substrate) by a month or two. Oyster reefs that are placed too early are susceptible to settlement of mussels and other organisms which are detrimental to oyster success.

Short-term monitoring for oyster reefs typically spans one to two years minimum and should include at least two recruitment phases. Mid-term monitoring (four to six years) is the recommended amount of time for monitoring oyster reef growth and health, since the longer time duration more readily captures impacts from inter-annual changes (Brumbaugh et al., 2006; Baggett et al., 2014). Where possible, constructed oyster reefs should be compared with control areas (unrestored) and natural (reference) reef sites to better determine 1) level of enhancement provided by this Natural Shoreline Infrastructure type and 2) health of constructed reef, respectively.

Wasson et al (2014) identified several attributes of sustainable oyster populations, including: high adult oyster density, high total oyster abundance, broad size distribution, recruitment rate, high juvenile growth and survival rate, and high larval contribution to region. The reader is referred to the Oyster Habitat Restoration Monitoring and Assessment Handbook (Baggett, et al., 2014) for further background on monitoring methodologies for the aforementioned attributes.

3.7 Eelgrass Beds

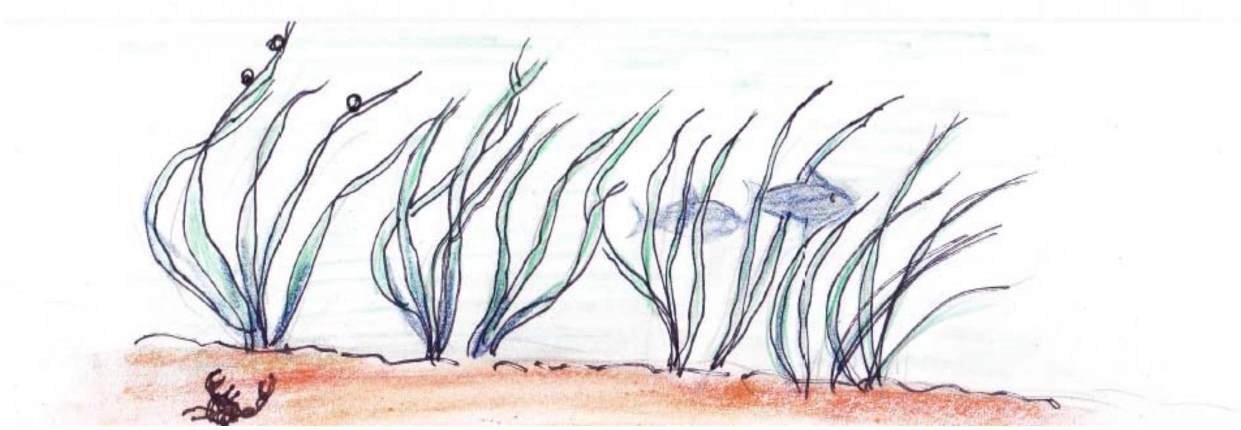

Figure 15. Eelgrass bed schematic

Eelgrass beds (Figure 15) dissipate wave energy and slow tidal currents, especially at low tide.

At low tide, eelgrass beds act to reduce bottom shear stress from waves and currents. They also increase sediment recruitment and retention, which leads to wave shoaling, where waves increase in height as they enter shallower depths. It is caused by the fact that the group velocity, which is also the wave-energy transport velocity, changes with water depth.

At low tide, stem flexion (eelgrass bending) dissipates wave energy and if the bed is dense enough, flows are blocked. However, no additional protection is afforded by eelgrass beds during storms at high tide. Therefore, eelgrass beds are not recommended as a primary mechanism for flood protection. They can be utilized with other Natural Shoreline Infrastructure types in a "layered" approach, reducing wave energy and erosion at common water levels so that landward Natural Shoreline Infrastructure (e.g. sand/cobble berms on the beach, marsh sills) are able to function optimally during extreme events.

Similar to oyster reefs, eelgrass beds also provide increased rearing and foraging opportunities for a range of aquatic species including nursery habitat for commercially important fisheries (Hughes et al. 2014), as well as water clarity improvements through enhanced sedimentation.

Pacific eelgrass has successfully been installed to provide low-level coastal defense in bays and estuaries at several project sites in San Francisco Bay and in southern California.

3.7.1 Setting

Typically found in the low intertidal to subtidal zones of sheltered waters (e.g. coastal estuaries), eelgrass beds thrive in softer, silty sediment on flatter bathymetry. Rapid accretion or frequently disturbed areas can smother the eelgrass. The upper range of suitable elevation is limited by heat stress and bottom disturbance by waves, while the lower range of elevation is dictated by light availability. Overly turbid environments, deep water, or areas fully in shade by higher vegetation or overwater structures prevent eelgrass from photosynthesizing.

Physical disturbances to seagrass beds from boat wakes and other human recreational activities should be considered when siting eelgrass beds. Boat wakes entrain sediment and potentially contribute to bed erosion. Scarring and mooring line "crop circles" have been observed in eelgrass beds located in portions of San Francisco Bay frequented by small vessels (Boyer and Willie-Echevarria 2010).

If eelgrass exists near the project site, physical conditions may generally be favorable for siting, barring site-specific limitations. If eelgrass does not exist nearby, the site may potentially still be suitable for planting. Previous guidance recommends undertaking a small-scale test plot (0.2 ha, or 0.5 acre or less) to determine best growing conditions for long-term eelgrass bed success. Larger-scale restoration projects would be on the order of 0.4 ha (1 acre) or greater.

3.7.2 Design Guidance & Implementation

Site selection is one of the most influential factors in successful seagrass restoration (Fonseca et al. 2001). Limited detailed guidance on typical design parameters for coastal Natural Shoreline Infrastructure, such as alongshore length and orientation, exists for eelgrass beds.

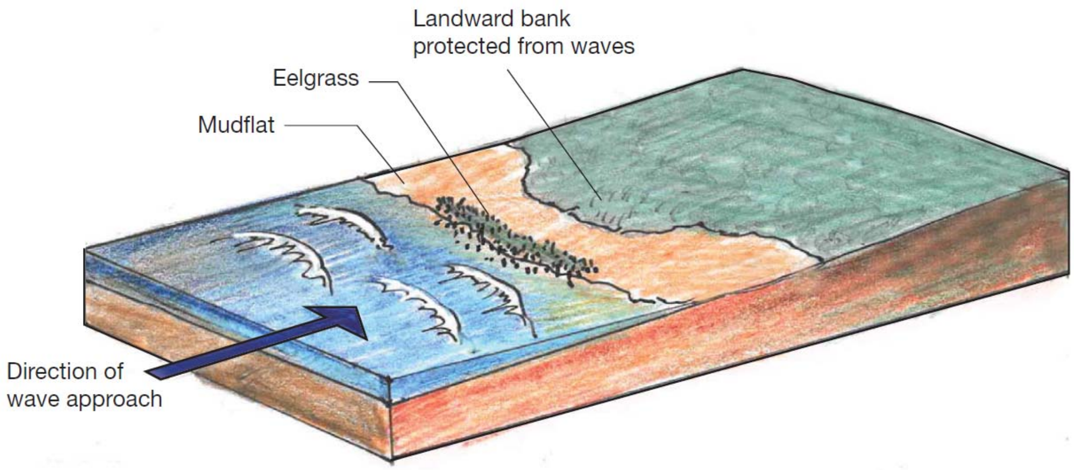

Figure 16. Oblique view of eelgrass bed located in estuarine environment

Similar to oyster reefs, eelgrass bed plantings should be situated perpendicular to the predominant direction from which waves arrive (Figure 16). The lateral extent of backshore coastal feature (e.g. stretch of bank actively eroding from wave attack) loosely dictates the width of the eelgrass bed. As a first step, a simple wave transformation model of the project site can be built to test for optimal design parameters: how far should eelgrass beds extend offshore to achieve the desired amount of wave attenuation? Will the eelgrass bed provide sufficient function through the year if the direction of wave approach changes seasonally?

Eelgrass bed plantings are typically made in dense groups, in order to maximize wave attenuation. The plantings are harvested from existing beds and transplanted by hands at low tide or by diving. New shoots are secured to the seabed using a small stick or straw embedded into the mud. Alternatively, eelgrass may be propagated by using so-called “seed buoys”, which are seeding eelgrass shoots that are harvested and subsequently used to distribute seed to a new location. Multiple re-plantings of eelgrass shoots may be required to fully establish new beds. Construction costs associated with collecting, preparing and planting eelgrass plugs are approximately $16/m2 ($62,700 per acre[1]), although total project costs can exceed five times that amount (Fonseca et al. 2001). Monitoring, which is conducted over a number of years after installation, typically contributes the bulk of costs. Boyer and Willie-Echevarria (2010) provide an overview of restoration techniques for eelgrass, for both whole shoot transplants and sods.

Common metrics for eelgrass bed success include shoot density, biomass and productivity rates. Shoot density and acreage estimates over seasons help indicate the health of the bed architecture and consequent habitat function. Biomass and productivity rates help ascertain ecological biodiversity (e.g. invertebrates, fishes) supported by the presence of the eelgrass. A minimum of five years has been recommended for project site monitoring, with comparisons to local reference sites, if they exist. Allotting personnel, time and resources to monitoring over

[1] An acre (0.4 ha) of seagrass restoration costs about $45,000 in 2001 dollars. Price above is escalated from 2001 dollars to present day.

this period of time will help assure that interannual factors which impact eelgrass performance can be captured.

The impacts of sea level rise on eelgrass beds include ecological stress from 1) increased salinity and 2) decreased light from increased water depths (Short and Neckles 1999). These impacts may be relevant to the overall long-term maintenance and use of eelgrass bed in a particular project site. Like other vegetation based Natural Shoreline Infrastructure types, eelgrass beds may accrete sediments to increase in elevation as well as move upslope in response to rising seas, thereby enhancing the resilience of the Natural Shoreline Infrastructure. The overall trend of sea level rise is such that suitable depths for eelgrass siting will move with the shoreline.

3.8 Other Considerations for Natural Shoreline Infrastructure

There are many considerations for selecting, implementing and maintaining Natural Shoreline Infrastructure, many of which are detailed above for each type. Other considerations are common across several or all types. Among these, managed retreat can provide more room, thereby enhancing the effectiveness and resilience of Natural Shoreline Infrastructure, and lagoon mouth management can be used to not only maximize the benefits of lagoons as habitats, but also ensure the resilience and effectiveness of Natural Shoreline Infrastructure.

A common consideration among Natural Shoreline Infrastructure types is the amount of space necessary to deploy the type and maintain its resilience as sea levels rise. In some situations, there is not enough space to deploy Natural Shoreline Infrastructure due to features in the built environment. If the work is all within one ownership, the owner may consider how critical the vulnerable feature is and weigh the costs and benefits of protecting it in place relative to removing it. Retreat may allow for functional and resilient Natural Shoreline Infrastructure to provide enhanced protective services to the other built features of the property, leading to an overall more resilient property. In our blueprints, we identify how much additional space afforded by retreat would be needed to enhance the suitability of a site for each given Natural Shoreline Infrastructure type.

Many of California’s estuaries are bar-built seasonally closing estuaries (Heady et al. 2014). These estuaries cycle between being open to the ocean and closed due to a sand bar forming isolating the estuary from the ocean. Subsequently, water elevations may vary dramatically. Natural estuarine marsh habitats have adapted to these extreme dynamics. Some bar-built estuaries are managed, meaning they are artificially breached and/or closed at certain time in the year or at certain threshold water elevations. Most often, this is done to prevent flooding of human assets, although mouth management for habitat value does occur. As we learn more about the detrimental effects of breaching to the habitats and species that rely on these unique estuaries, managers are favoring long-term mouth management over emergency breaching practices. Both natural dynamics and long-term mouth management plans should be considered when designing Natural Shoreline Infrastructure within bar-built estuaries.

4: Development of Blueprints for Deploying Natural Shoreline Infrastructure

4.1 Overview

Coastal California decision-makers and managers identified a lack of technical guidance as a major practical barrier to their ability to evaluate the suitability of Natural Shoreline Infrastructure options within specific coastal contexts (Caldwell et al. 2015; Technical Advisory Committee, Section 1.4). In Section 3, we begin to overcome this obstacle by providing detailed technical guidance for deciding when, where, and how to use six types of Natural Shoreline Infrastructure. But stakeholders also expressed a need for place-based examples that demonstrate how to apply technical guidance using locally-relevant information. Based on this feedback, our team developed a conceptual process which can be used to determine a suitable set of Natural Shoreline Infrastructure options given a specific set of environmental constraints (Figure 17). We then developed siting criteria distilled from the technical guidance (Section 3), to illustrate the broad suitability of six Natural Shoreline Infrastructure approaches: vegetated dunes, cobble berms, tidal benches, marsh sills, native oyster reefs, and eelgrass beds. Finally, we used a GIS-based multi-criteria analysis approach piloted in two regions where existing spatial data could be leveraged: Monterey Bay and Ventura County.

The tools we developed take advantage of spatial data to illustrate how to apply our technical guidance (Section 3) to evaluate the suitability of specific shoreline stretches using standard GIS techniques. The goal was to develop a practical approach that could be transferred to other regions, with the flexibility to be used with more precise and diverse site-specific data in the future and with the ability to refine siting criteria as we continue to learn from implemented projects. Our intent was that the broad-level screening approach and tools could be used to narrow the list of potential adaptation options that would then need to be assessed with more site-specific information.

A key assumption is that this screening tool would be used *after* a vulnerability assessment, so that Natural Shoreline Infrastructure solutions are matched to specific at-risk locations, assets, and the source of the hazard (e.g., erosion, coastal flooding, fluvial flooding). The intention is to facilitate the transition from a vulnerability assessment—identifying what, where, and why something is vulnerable, to adaptation planning—evaluating and prioritizing potential solutions to identified vulnerabilities.

4.2 Methods

We distilled the detailed technical guidance provided in Section 3 of this report into siting criteria that could be evaluated with spatial data using a GIS-based multi-criteria analysis approach (Greene et al. 2011; Appendix D). We developed thresholds for different criteria to assess the suitability of the environmental setting for six Natural Shoreline Infrastructure approaches. This included criteria for determining the appropriate environmental setting (e.g., wave exposure environment, foreshore and backshore characteristics, position within the tidal frame) and the necessary spatial footprint required for each Natural Shoreline Infrastructure type (e.g. cross-shore width, alongshore length) with thresholds to indicate low, medium and high suitability rankings for each Natural Shoreline Infrastructure approach.

We applied the thresholds for vegetated dune and cobble berm to the outer coast of Monterey Bay, extending approximately 110 km (68 miles) from the northern end of Santa Cruz County south to the Monterey Municipal Wharf, and to the outer coast of Ventura County (69 km; 43 miles). In areas of low and medium suitability, we calculated how much additional cross-shore space would be needed to achieve high suitability. This estimate of additionally needed space allows a user to consider potential opportunities for managed retreat.

We are in the process of finalizing the mapping of Natural Shoreline Infrastructure approaches suitable for sheltered/estuarine environments, including marsh sill, tidal bench, oyster, and eelgrass. We piloted the estuarine types in Elkhorn Slough in Monterey Bay and will extend the analysis to the smaller estuaries along the Ventura County coast. Detailed methods, including input data, criteria, thresholds, rationale, and GIS application are included in Appendix D, along with examples of preliminary mapping results for marsh sill, oyster, and eelgrass.

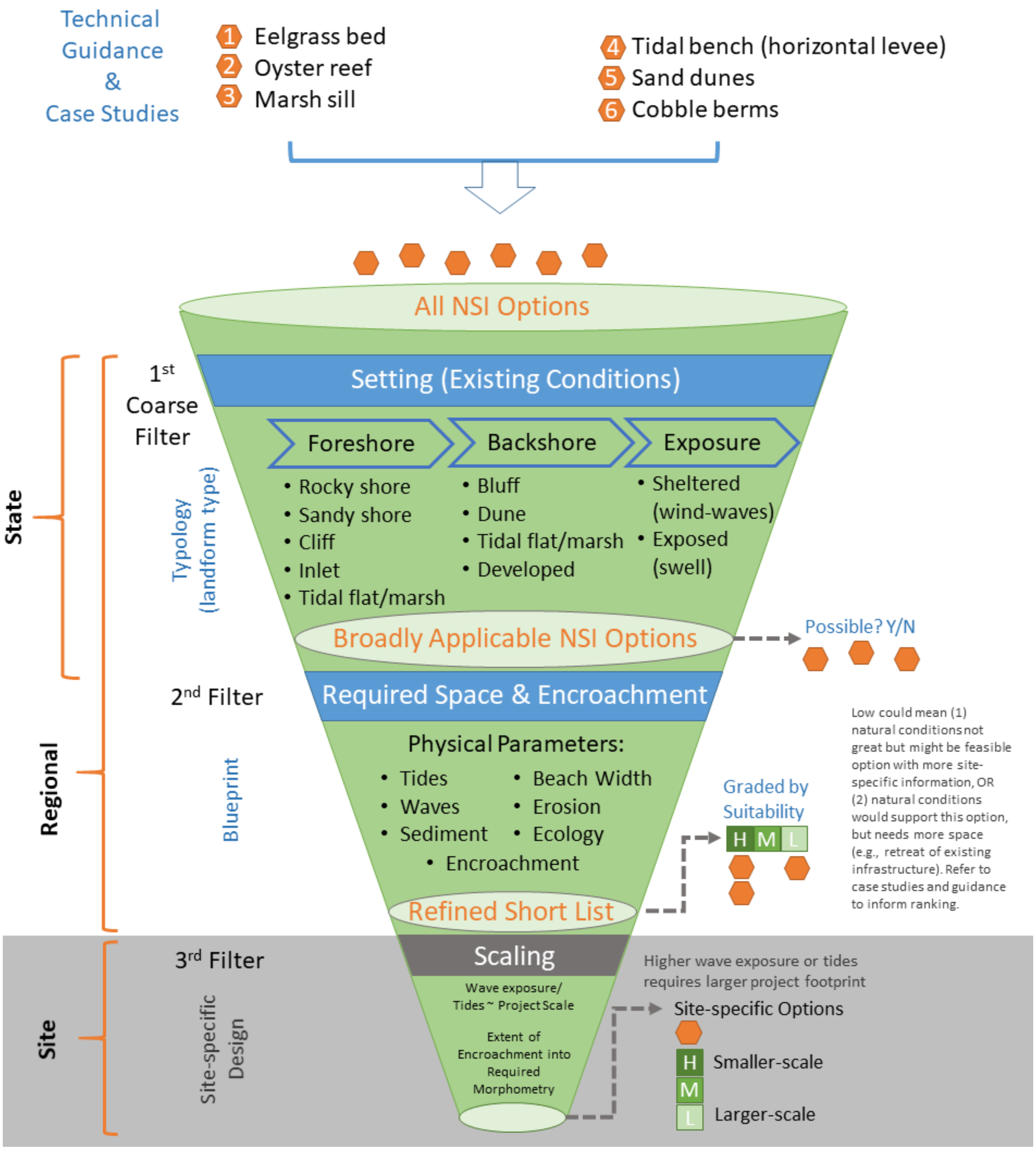

Figure 17. A conceptual process used to filter a suitable set of Natural Shoreline Infrastructure options given a specific set of environmental constraints. The filter starts out broad with the general foreshore, backshore and wave exposure environment. Data for this coarsest filter are available at the state and regional scale. More detailed information on shoreline width, tides, sediment etc provide a second filter to further screen options. Data for the second filter are typically only available at regional scales. A final filter would typically be applied at a site level where site-specific data would need to be collected to inform a specific project design.

4.3 Preliminary Results

4.3.1 Suitability of Vegetated Dunes in Monterey Bay and Ventura County

Based on foreshore typology, 66% of the 110-km outer coast of Monterey could potentially support vegetated dunes (Figure 18). The remaining 34%, concentrated in northern Santa Cruz County, is characterized by cliffs or rocky foreshore and was thus unsuitable for vegetated dunes. Including beach width criteria allowed us to further identify areas that could accommodate both the minimum footprint of a constructed dune, and a minimum buffer to dissipate wave energy (Appendix D). We determined that 8% of the 110-km (68-mile) outer coast of Monterey Bay is highly suitable for vegetated dunes, and an additional 11% could be highly suitable with 9 m (±4 m SD) (30 ft±13 SD) of additional cross-shore space. These high- and medium-suitability areas were located in pocket beaches of northern Santa Cruz County, or near the mouths of drainages along the long, westward-facing sandy beaches that dominate the Bay. 47% of the Monterey Bay outer coast had low suitability given the existing width of beach. These areas were typically wide enough to accommodate the minimum footprint of a constructed dune but lacked a sufficient buffer of dry beach needed to limit wave attack and provide a source of wind-blown sand. The suitability of these areas could be improved with 34 m (±12 m SD) of additional cross-shore space. In most places this would mean a doubling of the width of the existing beach.

The majority of the outer coast of Ventura County could support vegetated dunes (Figure 18), with only 9% unsuitable foreshore (rocky or an inlet area such as a harbor mouth). The best existing beach width conditions occurred along the wide beaches around Oxnard, from the mouth of the Santa Clara River south to Point Mugu. These high and medium suitability areas comprised 20% of the total 69-km (43-mile) shoreline. However, 71% of the shoreline had beaches that were too narrow (low suitability) and would require on average 4 times more cross-shore space to accommodate the wave dissipation buffering needed for longer-term sustainability.

4.3.2 Suitability of Cobble Berms in Monterey Bay and Ventura County

Based on foreshore typology, 87% of the 110-km outer coast of Monterey could potentially support cobble berms (Figure 18). The remaining 13% of the shoreline, scattered throughout northern Santa Cruz County, was characterized by cliffs or inlets and was thus unsuitable for cobble berms. Based on beach width, wider pocket beaches and beaches at the mouths of drainages tended to support high and medium suitability for cobble berms (5% and 6% of total shoreline length, respectively). 75% of the shoreline was considered low suitability given current beach width and would require on average 60m (±16m SD) of additional cross-shore space to be sustainable over the longer-term. In many places this would mean tripling the width of the existing beach.

The outer coast of Ventura County had similar results (Figure 18). While 97% of the foreshore typology could potentially support cobble berms, the majority of the shoreline (79%) was relatively narrow, leading to low suitability. Areas of high and medium suitability (12% and 6%) were concentrated around Oxnard, similar to the spatial distribution for vegetated dunes.

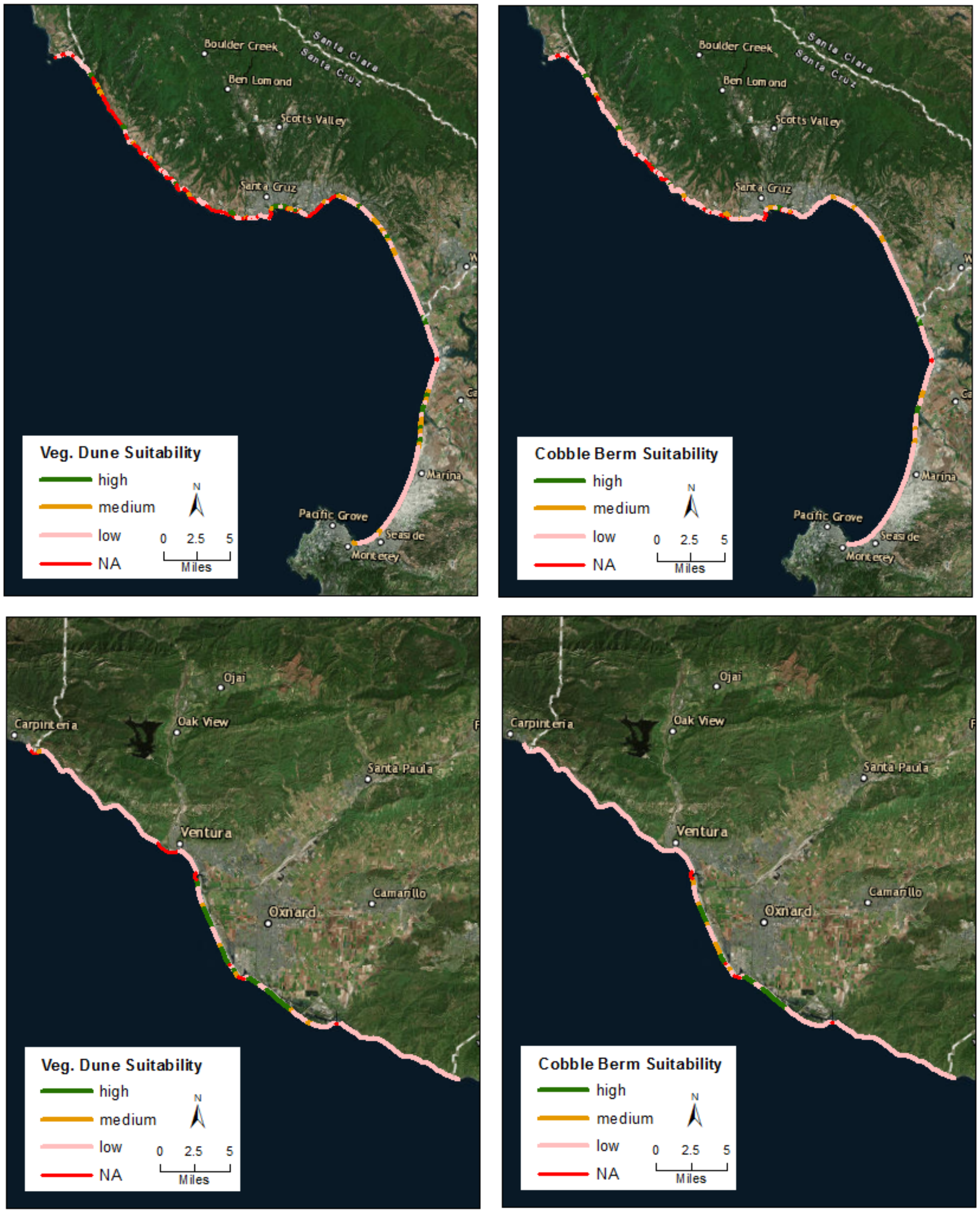

Figure 18: Suitability maps ("blueprints") for vegetated dunes and cobble berm as Natural Shoreline Infrastructure options along the Monterey Bay (top) and Ventura County (bottom).

4.4 Discussion and Anticipated Products

Our goal was to demonstrate a spatially-explicit application of our technical guidance (Section 3). This "blueprint" approach meets a specific need articulated by decision-makers, allowing them to see where opportunities exist to implement Natural Shoreline Infrastructure approaches for coastal adaptation. The intention was to provide a coarse-level screening tool that catalyzes further consideration of Natural Shoreline Infrastructure in appropriate places.

The final outputs for Monterey Bay and Ventura County, including additional mapping showing where marsh sills, oyster reefs, and eelgrass beds would be appropriate as coastal adaptation measures will be forthcoming in December 2018. These results will be made available as a map service on the Coastal Resilience decision-support tool (http://coastalresilience.org/). The maps will be color-coded to show in detail the degree of suitability of each geographic area for the deployment of a given Natural Shoreline Infrastructure option. The map service will also allow the user to define custom areas for analysis and comparatively evaluate different approaches within that area.

Importantly, this screening tool should be used in conjunction with a vulnerability assessment, matching specific at-risk locations, assets, and the source of the hazard (e.g., erosion, coastal flooding, fluvial flooding) with appropriate Natural Shoreline Infrastructure solutions. Thus, just because our mapping suggests a vegetated dune *could* be placed in a particular location does not mean it *should* be placed there. We recognize that other factors, both environmental and social, will further constrain the suitability of any given location, requiring the site-specific design filter described at the bottom of Figure 17. The GIS-based multi-criteria approach is flexible and can accommodate more detailed, site-specific data, updated criteria thresholds, or the addition of new criteria that can be screened with spatial data.

5: Conclusions and Future Directions

The implementation of Natural Shoreline Infrastructure adaptation measures along California's coasts will increase only if coastal decision makers become more familiar with the options available and have confidence in their understanding of the technical requirements needed for successful implementation. Projects already implemented will also need to demonstrate success in meeting coastal protection goals as well as other social and ecological values.

This report represents a major attempt to collate existing information and begin to close these gaps. Our engagement with stakeholders revealed how the different interests can lead to divergent desired outcomes. By participating on our Technical Advisory Committee and agreeing on a common definition, the stakeholders also agreed to a common understanding of what Natural Shoreline Infrastructure measures in California need to achieve. Ultimately this will lead to the implementation of measures that actually improve or enhance ecosystem function and ecosystem services, while also providing adaptation benefits in the face of climate change.

Although our case studies illustrate the breadth of Natural Shoreline Infrastructure approaches that have been implemented in California, our search for implementation examples highlighted the relative lack of actual implementation given the opportunities along the state's shoreline.

Funding should be prioritized for the implementation, monitoring and evaluation of new Natural Shoreline Infrastructure projects. Systematic monitoring and assessment of early Natural Shoreline Infrastructure projects will provide a better understanding of the risks and benefits associated with each option and will help improve the design of future projects. Additionally, the documentation of positive results will provide practitioners the confidence they need to deploy Natural Shoreline Infrastructure.

A common consideration among Natural Shoreline Infrastructure types is the amount of space necessary to deploy the type and maintain its resilience as sea levels rise. In some situations, there is not enough space to deploy Natural Shoreline Infrastructure due to built environment features. If the work is all within one ownership, the owner may consider how critical the vulnerable asset is, and weigh the costs and benefits of protecting it in place relative to removing it. Retreat may allow for resilient Natural Shoreline Infrastructure to provide enhanced protective services to the other built environment features of the property leading to overall enhanced property resilience. In our blueprints, we identify how much additional space afforded by retreat would be needed to enhance the suitability of a site for each given Natural Shoreline Infrastructure type.

The overall formula for coastal resilience in California will have aspects of armoring, Natural Shoreline Infrastructure, and hybrid approaches. It is critical to assess the coastal protection services provided by each of these approaches on a site-specific basis and to employ site-specific strategies in a way that improves overall coastal resilience statewide.

The technical guidance we provide should facilitate greater implementation of Natural Shoreline Infrastructure by lessening key barriers practitioners face when applying new approaches. Our application of the technical guidance, using spatial data to develop Natural Shoreline Infrastructure Blueprints for Monterey Bay and Ventura County highlights the suitability of Natural Shoreline Infrastructure options for these two geographies as well as the scalability of this screening approach. However, this effort also highlights the need for improved content, extent, and availability of spatial data to allow others to replicate this effort at both site and regional scales throughout the state. The creation of reliable spatial data identifying important opportunities and constraints on the siting of Natural Shoreline Infrastructure options would further enable a more widespread deployment of Natural Shoreline Infrastructure.

This work provides a first step to overcoming the obstacles of implementing Natural Shoreline Infrastructure. Future work is needed to provide even more detailed engineering specifications, comparative levels of protection, life expectancies, and costs/benefits to further facilitate the deployment of Natural Shoreline Infrastructure.

6: References

Allan, J. C., Geitgey, R., and Hart, R. (2005). Dynamic Revetments for Coastal Erosion in Oregon. Final Report SPR 620, prepared for Oregon Department of Transportation and Federal Highway Administration, August 2005.

M. Anderson, et al. (2011). Wave dissipation by vegetation, Retrieved from http://repository.tudelft.nl/view/hydro/uuid:17f2915f-bb57-47f9-8e85-67ff0c82510c/.

Arico, S. et al. (2005). Ecosystems and Human Well-Being. World Resources Institute.

Arkema, et al. (2013). Coastal habitats shield people and property from sea-level rise and storms. Nature Climate Change 3: 913–918. doi:10.1038/NCLIMATE1944.

Baggett, L.P., S.P. Powers, R. Brumbaugh, L.D. Coen, B. DeAngelis, J. Greene, B. Hancock, and S. Morlock (2014). Oyster habitat restoration monitoring and assessment handbook. The Nature Conservancy, Arlington, VA, USA., 96pp.

Barbier, E.B., et al. (2008). Coastal ecosystem-based management with nonlinear ecological functions and values. Science 319:5861.

Barbier, E. B., Hacker, S. D., Kennedy, C., Koch, E. W., Stier, A. C., & Silliman, B. R. 2011. The value of estuarine and coastal ecosystem services. Ecological Monographs, 81(2), 169–193. https://doi.org/10.1890/10-1510.1

Battalio, Bob, PE, ESA PWA (2012). Cobble Berms: A Brief Summary in Support of the Ocean Beach Master Plan, Appendix to the Ocean Beach Master Plan, prepared for SPUR and others.

Bauer, W. (1974). The Drift Sectors of Whatcom County Marine Shores: Their Shoreforms and Geo-Hydraulic Status. Report for Whatcom County Planning Commission. 74p.

Baye, Peter R. (2016). Preliminary conceptual designs and locations for Ocean Beach native foredune initiation [Memorandum]. Annapolis, CA.

Baye, Peter R. (2016). Practical short-term management objectives and methods for eolian (wind-related stabilization of Sloat/Great Highway artificial sand dike (berm); interim sand-stabilizing and trapping techniques for Ocean Beach [Memorandum]. Annapolis, CA.

Battalio, Bob. (2016). Pilot Project – Sand Dune [Memorandum]. San Francisco, CA: Environmental Science Associates (ESA).

BCDC, & ESA PWA, Corte Madera Baylands Conceptual Sea Level Rise Adaptation Strategy (2013). Retrieved from http://www.bcdc.ca.gov/planning/climate_change/CM final report_130731.pdf.

Behrens, D. Brennan, M. and B. Battalio (2015). A quantified conceptual model of inlet morphology and associated lagoon hydrology. Shore & Beach. Volume 83 No. 3.

Borsje, B. W., van Wesenbeeck, B. K., Dekker, F., Paalvast, P., Bouma, T. J., van Katwijk, M. M., & de Vries, M. B. (2011). How ecological engineering can serve in coastal protection. Ecological Engineering, 37(2), 113–122. doi:10.1016/j.ecoleng.2010.11.027

Boyer, K.E., Reynolds, L.K., & Wyllie-Echverria, S. (2007). Restoring the seagrass, Zostera marina L., in San Francisco Bay: experimental evaluation of a seeding technique. Final report to the NOAA Restoration Center Research Program.

Boyer, K. E., & Wyllie-Echeverria, S. (2010). Eelgrass Conservation and Restoration in San Francisco Bay: Opportunities and Constraints. Appendix 8–1, San Francisco Bay Subtidal Habitat Goals Project. 84 pp.

Bridges, T. S., Wagner, P. W., Burks-Copes, K. A., Bates, M. E., Collier, Z. A., Fischenich, C. J., ... & Wamsley, T. V. (2015). Use of Natural and Nature-Based Features (NNBF) for Coastal Resilience (No. ERDC-SR-15-1). ENGINEER RESEARCH AND DEVELOPMENT CENTER VICKSBURG MS ENVIRONMENTAL LAB file:///C:/Users/jadams/Downloads/3443.pdf

Brumbaugh, R. D., Beck, M. W., & Coen, L. (2006). A practitioners guide to the design and monitoring of shellfish restoration projects.

Byington, C. (2015). Natural Infrastructure: It's Not an Oxymoron. Retrieved from: http://blog.nature.org/science/2015/10/16/natural-infrastructure-its-not-an-oxymoron/

Caldwell, M.R., et al., Coastal Issues. In G. Garfin, A. Jardine, R. Merideth, M. Black, & S. LeRoy (Eds.) (2013), Assessment of Climate Change in the Southwest United States: A Report Prepared for the National Climate Assessment. Washington, DC: Island Press/Center for Resource Economics. doi:10.5822/978-1-61091-484-0.

Caldwell, M., Martinez, J., Siders, A., (2015). Stanford Law School Coastal Policy Lab Practicum, Local Barriers to Nature Based Strategies for Coastal Hazard Mitigation in California, available at: https://law.stanford.edu/education/only-at-sls/law-policy-lab/practicums-2014-2015/catalyzing-nature-based-coastal-flood-mitigation-and-adaptation/.

California Coastal Commission (2015). Sea Level Rise Policy Guidance: Interpretive Guidelines for Addressing Sea Level Rise in Local Coastal Programs and Coastal Development Permits.

Chapman, D. M. (1990). Aeolian sand transport—an optimized model. Earth Surface Processes and Landforms, 15(8), 751-760.

Cohen-Shacham, E., Walters, G., Janzen, C. and Maginnis, S. (eds) (2016). Nature-based Solutions to Address Global Societal Challenges. Gland, Switzerland: IUCN. Xiii+97pp.

Conservation International (2008). Economic Values of Coral Reefs, Mangroves, and Seagrasses, retrieved from http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.381.9603&rep=rep1&type=pdf.

Dahl, T. (1990). Wetlands Losses in the United States 1780's to 1980's. U.S. Department of the Interior, Fish and Wildlife Service, Washington, DC, 13 pp.

Day, J.W., R.R. Christian, D.M. Boesch et al. (2008). Consequences of climate change on the ecogeomorphology of coastal wetlands. Estuaries and Coasts 31:477-491.

Dugan, Jenifer E. et al. (2008), Ecological Effects of Coastal Armoring on Sandy Beaches, 29 PSZNI: Marine Ecology 160, 160-170.

ENVIRON International Corporation (2015). Economic Analysis of Nature-Based Adaptation to Climate Change Ventura County, California. Report prepared for The Nature Conservancy.

Everts, C. H., Eldon, C. D., and Moore, J. (2002). Performance of Cobble Berms in Southern California. Shore & Beach, 70(4).

ESA. (2013). Coastal Resilience Ventura: Technical Report for Sea Level Affecting Marshes Model (SLAMM) (prepared for The Nature Conservancy).

ESA (2015). Calleguas Creek - Climate Change Impacts to Fluvial and Coastal Flooding (prepared for The Nature Conservancy).

ESA (2017). Greenbrae Boardwalk, Marin County Shoreline Protection Project Year-25 Post-Construction Monitoring – Final Report (Including Public Comments & Response), Prepared for Golden Gate Bridge Highway and Transportation District.

ESA PWA. (2012). The San Francisco Bay Living Shorelines: Nearshore Linkages Project. Prepared for the Coastal Conservancy. San Francisco, CA, USA., 12pp.

ESA PWA, SPUR et al. (2015). COASTAL PROTECTION MEASURES & MANAGEMENT STRATEGY FOR SOUTH OCEAN BEACH Ocean Beach Master Plan: Coastal Management Framework Prepared for San Francisco Public Utilities Commission Under Contract to SPUR.

Federal Emergency Management Agency (2005). FEMA Final Draft Guidelines for Coastal Flood Hazard Analysis and Mapping for the Pacific Coast of the United States, Oakland Northwest Hydraulic Consultants Inc.

Federal Emergency Management Agency (2015). Federal Flood Risk Management Standard (FFRMS). Retrieved from http://www.fema.gov/media-library/assets/documents/101759

Fonseca, M. S., & Cahalan, J. A. (1992). A preliminary evaluation of wave attenuation by four species of seagrass. Estuarine, Coastal and Shelf Science, 35(6), 565-576.

Fonseca, M.S., Kenworthy, W.J., Julius, B.E., Shutler, S., & Fluke, S. (2001). Handbook of Ecologicla Restoration, Chapter 7: Seagrasses. Cambridge University Press, Cambridge.

Friedrichs, C.T., and Perry, J.E. 2001. Tidal salt marsh morphodynamics: a synthesis. Journal of Coastal Research 27: 7-37.

Gedan, K., et al. (2011). The present and future role of coastal wetland vegetation in protecting shorelines: answering recent challenges to the paradigm, Climatic Change, 106(1), 7–29. doi:10.1007/s10584-010-0003-7.

Greene, R., Devillers, R., Luther, J. E., & Eddy, B. G. (2011). GIS-Based Multiple-Criteria Decision Analysis. *Geography Compass*, *6*, 412–432. https://doi.org/10.1111/j.1749-8198.2011.00431.x

Griggs, G.B. (2005). The Impacts of Coastal Armoring, 73 Shore & Beach 13, 13-22 (2005).

Hale, L. Z., Meliane, I., Davidson, S., Sandwith, T., Beck, M., Hoekstra, J., and Hatziolos, M. (2009). Ecosystem-based adaptation in marine and coastal ecosystems. *Renewable Resources Journal*, *25*(4), 21-28. https://www.researchgate.net/profile/Nick_Davidson/publication/249231088_Ecosystem-based_adaptation_to_climate_change_in_coastal_and_marine_areas/links/56756e4808ae0ad265c0d126.pdf

Hanak, E. & G. Moreno (2008), California Coastal Management with a Changing Climate, Public Policy Institute of California, 11-12, available at http://www.ppic.org/content/pubs/report/R_1108GMR.pdf.

Hansen, J. C. (2013). The effects of waves and turbulence on sediment suspension and mixing within seagrass ecosystems. University of Virginia.

Hapke, C. J. and D. Reid (2007). National Assessment of Shoreline Change, Part 4: Historical Coastal Cliff Retreat along the California Coast: U.S. Geological Survey Open-file Report 2007-1133.

Hardaway, Jr. C.S. and K. Duhring (2010). Living Shoreline Design Guidelines for Shore Protection in Virginia's Estuarine Environments. Virginia Institute of Marine Science, College of William & Mary, Gloucester Point, VA. 123 pp.

Heady, W.N., K. O'Connor, J. Kassakian, K. Doiron, C. Endris, D. Hudgens, R. P. Clark, J. Carter, and M. G. Gleason. (2014). An Inventory and Classification of U.S. West Coast Estuaries. The Nature Conservancy, Arlington, VA. 81pp.

Heady, W. N., B. S. Cohen, M. G. Gleason, J. N. Morris, S. G. Newkirk, K. R. Klausmeyer, H. Walecka, E. Gagneron, M. Small. 2018. Conserving California's Coastal Habitats: A Legacy and a Future with Sea Level Rise. The Nature Conservancy, San Francisco, CA; California State Coastal Conservancy, Oakland, CA. 143pp

Heberger, M. et al. (2009), The Impacts of Sea-level rise on the California Coast, Cal. Climate Change Center, Pacific Inst., available at http://pacinst.org/wp-content/uploads/sites/21/2014/04/sea-level-rise.pdf.

Herr, D. and Galland, G.R. (2009). The Ocean and Climate Change. Tools and Guidelines for Action. IUCN, Gland, Switzerland. 72pp. http://environmentportal.in/files/the_ocean_and_climate_change.pdf

Holleman, R. C., and M. T. Stacey (2014). Coupling of Sea Level Rise, Tidal Amplification, and Inundation, Journal of Physical Oceanography 44:1439–1455.

Hughes, B. B., M. D. Levey, J. A. Brown, M. C. Fountain, A. B. Carlisle, S. Y. Litvin, C. M. Greene, W. N. Heady, and M. G. Gleason. 2014. Nursery Functions of U. S. West Coast Estuaries: The State of Knowledge for Juveniles of Focal Invertebrates and Fish Species. The Nature Conservancy, Arlington, VA. 168pp.

Hubbard, D. (2016). Surfer's Point Vegetation Monitoring Report. Santa Barbara, CA: Coastal Restoration Consultants, Inc.

Johannessen, J., A. MacLennan, A.Blue, J.Waggoner, S.Williams, W.Gerstel, R.Barnard, R.Carman, and H.Shipman (2014). Marine Shoreline Design Guidelines. Washington Department of Fish and Wildlife, Olympia, WA.

Jones, H. P., Hole, D. G., & Zavaleta, E. S. (2012). Harnessing nature to help people adapt to climate change. *Nature Climate Change*, *2*(7), 504-509. http://www.nature.com/nclimate/journal/v2/n7/full/nclimate1463.html

Jungerius & van der Meulen (1988), Erosion processes in a dune landscape along the Dutch coast, CATENA, 15(3-4): 217–228. doi:http://dx.doi.org/10.1016/0341-8162(88)90046-X.

Kildow, J. and C. S. Colgan (2005). California's Ocean Economy – A Report to the Resources Agency of California (Prepared by the National Ocean Economics Program). http://www.opc.ca.gov/webmaster/ftp/pdf/docs/Documents_Page/Reports/CA_Ocean_Econ_Report.pdf

Kirwan, M.L., and J.P. Megonigal. (2013). Tidal wetland stability in the face of human impacts and sea-level rise. Nature 504:53-60.

Knutson, Paul L., Allen, Hollis H., and Webb, James W. (1990). Guidelines for Vegetative Erosion Control on Wave-Impacted Coastal Dredged Material Sites. Technical Report D-90-13, US Army Engineering. Thyrment Station, Vicksburg, MS.

Koch, et al. (2009), Non-linearity in ecosystem services: temporal and spatial variability in coastal protection, Frontiers in Ecology and the Environment 7(1): 29–37, doi:10.1890/080126.

Langridge, S. M., Hartge, E. H., Clark, R., Arkema, K., Verutes, G. M., Prahler, E. E., ... & Ruckelshaus, M. (2014). Key lessons for incorporating natural infrastructure into regional climate adaptation planning. Ocean & Coastal Management, 95, 189-197. http://msp.naturalcapitalproject.org/msp_concierge_master/docs/Langridge_etal_2014_OCM.pdf

Leo, K., R. Battalio, W.N. Heady, P. King, A. McGregor, B. Cohen, J. Calil, E. Vandebroek, J. Jackson, F. DePaolis, D. Revell, R. Vaughn, J. Giliam, S. Newkirk. (2017). Economic Impacts of Climate Adaptation Strategies for Southern Monterey Bay. Technical Report prepared for the California State Coastal Conservancy by The Nature Conservancy. 2017/07. ClimateReadyGrant#13-107.

Levin, S. A., & Lubchenco, J. (2008). Resilience, robustness, and marine ecosystem-based management. *Bioscience*, *58*(1), 27-32. http://bioscience.oxfordjournals.org/content/58/1/27.full

Lorang, M. S. (1997). Wave Competence and Morphodynamics of Boulder and Gravel Beaches. PhD dissertation, Oregon State University, Corvallis, Oregon, 80 pp.

Lowe et al. (2013). Analysis of the Costs and Benefits of Using Tidal Marsh Restoration as a Sea Level Rise Adaptation Strategy in San Francisco Bay, Retrieved from http://www.bay.org/assets/FINAL D211228 Cost and Benefits of Marshes 022213.pdf.

Melius, Molly L. and Margaret R. Caldwell (2015). California Coastal Armoring Report: Managing Coastal Armoring and Climate Change Adaptation in the 21st Century, Stanford Law School: Environment and Natural Resources Law and Policy Program.

Mendez & Losada (2004). An empirical model to estimate the propagation of random breaking and nonbreaking waves over vegetation fields, Coastal Engineering 51(2): 103–118.

Miller, J., Rella, A., Williams, A., & Sproule, E. (2015). Living Shorelines Engineering Guidelines. Stevens institute of Technology.

Miller J.K., A. Rella, A. Williams and E. Sproule (2016). Living Shorelines Engineering Guideline. Stevens Institute of Technology and New Jersey Department of Environmental Protection, Hoboken, NJ. 102 pp

Moller, I., et al. (1999), Wave Transformation Over Salt Marshes: A Field and Numerical Modelling Study from North Norfolk, England, Estuarine, Coastal and Shelf Science, 49(3), 411–426. Retrieved from http://www.sciencedirect.com.proxy.miis.edu/science/article/pii/S0272771499905097.

Möller, I., & Spencer, T. (2002), Wave dissipation over macro-tidal saltmarshes: Effects of marsh edge typology and vegetation change. Journal of Coastal Research, 521(36), 506–521. Retrieved from http://www.science.ulst.ac.uk/ics2002/moller and spencer.pdf.

Möller, I., Kudella, M., Rupprecht, F., Spencer, T., Paul, M., Wesenbeeck, B. K. Van, … Schimmels, S. (2014). Wave attenuation over coastal salt marshes under storm surge conditions, 7(September), 727–731. https://doi.org/10.1038/NGEO2251.

Morris, J.T., P.V. Sundareshwar, C.T. Nietch et al. (2002). Responses of coastal wetlands to rising sea level. Ecology 83:2869-2877.

Munang, R., Thiaw, I., Alverson, K., Mumba, M., Liu, J., & Rivington, M. (2013). Climate change and Ecosystem-based Adaptation: a new pragmatic approach to buffering climate change impacts. *Current Opinion in Environmental Sustainability*, *5*(1), 67-71. http://www.seachangecop.org/sites/default/files/documents/2013%2001%20Climate%20change%20and%20Ecosystem-based%20Adaptation.pdf.

Narayan, S., Beck, M. W., Reguero, B. G., Losada, I. J., Van Wesenbeeck, B., Pontee, N., … Burks-Copes, K. A. (2016). The effectiveness, costs and coastal protection benefits of natural and nature-based defences. PLoS ONE, 11(5), 1–17. https://doi.org/10.1371/journal.pone.0154735.

NOAA Restoration Center and Puget Sound Restoration Fund (2010). West Coast native oyster restoration: 2010 workshop proceedings. U.S. Department of Commerce, NOAA Restoration Center. 49 pp.

NOAA (2010). Adapting to Climate Change : A Planning Guide for State Coastal Managers. Silver Spring.

Ozment, S., DiFrancesco, K., Gartner, T. (2015). The role of natural infrastructure in the water, energy and food nexus, Nexus Dialogue Synthesis Papers. Gland, Switzerland: IUCN http://www.iwa-network.org/wp-content/uploads/2015/12/1438066960-Natural-Infrastrucure-in-the-Nexus_Final-Dialogue-Synthesis-Paper-2015.pdf

Patrick, A. M., and M. A. Colwell (2014). Snowy Plovers select wide beaches for nesting, Wader Study Group Bulletin 121:17–20.

Philip Williams & Associates and LSA Associates (1998). Conceptual Design for Tidal Wetland Restoration for the Hamilton Army Airfield Focused Feasibility Study, Volume II: Technical Appendices. Prepared for the IT Corporation, by Philip Williams & Associates, Ltd., San Francisco, CA.

Philip Williams & Associates (PWA) and Phyllis M. Faber (2004). Design Guidelines for Tidal Wetland Restoration in San Francisco Bay. Prepared for The Bay Institute.

Philip Williams & Associates (PWA) (2006). Projecting the future evolution of Bolinas Lagoon. Prepared for Marin County Open Space.

Philip Williams & Associates (PWA) (2012). Evaluation of Erosion Mitigation Alternatives for Southern Monterey Bay. Prepared for the Monterey Bay Sanctuary Foundation and Southern Monterey Bay Erosion Control Workgroup. Prepared by ESA PWA with Dr. Ed Thornton, Meg Caldwell, J.D. Dr. Philip King, Aaron McGregor, PWA Project # 1972, May 20, 2012. Section 4.1.1 pp 67-73.

Pilkey, O.H. et al. (2012). Rethinking Living Shorelines, Program for the Study of Developed Shorelines, Western Carolina University, 3.

Pinsky, M., Guannel, G., & Arkema, K. (2013). Quantifying wave attenuation to inform coastal habitat conservation. Ecosphere, 4(August). Retrieved from http://www.esajournals.org/doi/abs/10.1890/ES13-00080.1; Renaud, F. G. S.-R. K. E. M. (Ed.). (2013). The Role of Ecosystems in Disaster Risk Reduction (p. 486). Tokyo: United Nations University;

Program for the Study of Developed Shorelines at Western Carolina University, Beach Nourishment Viewer, available at http://beachnourishment.wcu.edu/.

Reidenbach, M. A., Berg, P., Hume, A., Hansen, J. C., & Whitman, E. R. (2013). Hydrodynamics of intertidal oyster reefs: The influence of boundary layer flow processes on sediment and oxygen exchange. Limnology and Oceanography: Fluids and Environments, 3(1), 225-239.

Renaud, F. G. S.-R. K. E. M. (Ed.) (2013). The Role of Ecosystems in Disaster Risk Reduction (p. 486), Tokyo: United Nations University.

Rockefeller Foundation (2013). Vulnerable Natural Infrastructure in Urban Coastal Zones. Retrieved from https://www.rockefellerfoundation.org/app/uploads/Vulnerable-Natural-Infrastructure-in-Urban-Coastal-Zones.pdf

Schulte, D., G. Ray, and D. Shafer (2009). Use of alternative materials for oyster reef construction. EMRRP Technical Notes Collection (ERDC TN-EMRRP-ER-12). Vicksburg, MS: U.S. Army Engineer Research and Development Center.

Shepard, C. C., Crain, C. M., & Beck, M. W. (2011). The Protective Role of Coastal Marshes: Review and Meta-Analysis. doi101371journalpone0027374.

Short, F. T., & Neckles, H. A. (1999). The effects of global climate change on seagrasses. Aquatic Botany, 63(3), 169-196.

Sutton-Grier, A. E., Wowk, K., & Bamford, H. (2015). Future of our coasts: the potential for natural and hybrid infrastructure to enhance the resilience of our coastal communities, economies and ecosystems. *Environmental Science & Policy*, *51*, 137-148. http://www.sciencedirect.com/science/article/pii/S1462901115000799.

Temmerman, S., Meire, P., Bouma, T. J., Herman, P. M., Ysebaert, T., & De Vriend, H. J. (2013). Ecosystem-based coastal defense in the face of global change. *Nature*, *504*(7478), 79-83.

Thalmayer, I.M.*, T. Gardali, J. Wood, N.E. Seavy, L. Giambastiani, and J.J. Parodi. (2016). Marsh-Upland Transition Zone Climate-smart Restoration Tool User Guide. Point Blue Conservation Science www.pointblue.org/restorationtools

U.S. Army Corps of Engineers (1981). Technical Note CETN-III-8, Seawalls: Their Applications and Limitations.

U.S. Army Corps of Engineers (2003). Coastal Engineering Manual, Part. V. Coastal and Hydraulics Lab., US Army Engineer Research and Development Center, Vicksburg, Mississippi, USA

U.S. Fish and Wilife Service (2013). Recovery plan for tidal marsh ecosystems of Northern and Central California. Sacramento, CA.

U.S. National Research Council (2012). Informing Decisions in a Changing Climate Panel on Strategies and Methods for Climate-Related Decision Support. Washington DC: The National Academies Press.

Vignola, R., Locatelli, B., Martinez, C., & Imbach, P. (2009). Ecosystem-based adaptation to climate change: what role for policy-makers, society and scientists? *Mitigation and Adaptation Strategies for Global Change*, *14*(8), 691-696. http://repositorio.bibliotecaorton.catie.ac.cr:8080/bitstream/handle/11554/8088/Ecosystem_based_adaptation_to_climate.pdf?sequence=1&isAllowed=y

Vitousek S, Barnard PL, Limber P, et al. (2017). A model integrating longshore and cross-shore processes for predicting long-term shoreline response to climate change. J Geophys Res Earth Surf. doi: 10.1002/2016JF004065

Ward, L. G., Kemp, W. M., & Boynton, W. R. (1984). The influence of waves and seagrass communities on suspended particulates in an estuarine embayment. Marine Geology, 59(1-4), 85-103.

Wamsley T V., Cialone MA, Smith JM, et al (2010) The potential of wetlands in reducing storm surge. Ocean Eng 37:59–68. doi: 10.1016/j.oceaneng.2009.07.018

Warren Pinnacle Consulting, Inc. (2016), Sea Level Affecting Marshes Model, Version 6.7 beta, available at http://warrenpinnacle.com/prof/SLAMM6/SLAMM_6.7_Technical_Documentation.pdf

Wasson, K., Zabin, C., Bible, J., Ceballos, E., Chang, A., Deck, A., & Ferner, M. (2014). Guide to Olympia oyster Restoration and Conservation. Environmental conditions and sites that support sustainable populations in central California. San Francisco Bay National Estuarine Research Reserve.

Wasson, K., Zabin, C., Bible, J., Briley, S., Ceballos, E., Chang, A., ... & Latta, M. (2015). A guide to Olympia oyster restoration and conservation: environmental conditions and sites that support sustainable populations. Elkhorn Slough National Estuarine Research Reserve.

Wigand, C., T. Ardito, C. Chaffee, W. Ferguson, S. Paton, K. Raposa, C. Vandemoer, and E. Watson. (2015). A climate change adaptation strategy for management of coastal marsh systems. Estuaries and Coasts, DOI 10.1007/s12237-015-0003-y.

World Business Council for Sustainable Development (2016). Natural Infrastructure. Retrieved from http://www.wbcsd.org/naturalinfrastructure.aspx.

Zabin, C. J., Wasson, K., & Fork, S. (2016). Restoration of native oysters in a highly invaded estuary. Biological Conservation, 202, 78-87.

Zedler, J.B., 1996. Ecological issues in wetland and mitigation: an introduction to the forum. Ecol. Appl. 6, 33–37.

APPENDIX A: Technical Advisory Committee Membership

Joel Gerwein (California State Coastal Conservancy)

Michelle Iblings (Alameda County Flood Control)

David Behar (San Francisco Public Utilities Commission)

Jack Leibster (Marin County Planning Department)

Mary Small (California State Coastal Conservancy)

Leslie Ewing (California Coastal Commission)

Mary Matella (California Coastal Commission)

Juliette Hart (U.S. Geological Survey)

Amber Parais (San Diego Climate Collaborative)

Sara Hutto (Greater Farallons Sanctuary)

Marilyn Latta (California State Coastal Conservancy)

Natalie Cosentino Manning (NOAA Restoration Center)

Jeremy Lowe (San Francisco Estuary Institute)

Paul Jenkin (Ventura County Surfrider Foundation)

Elizabeth Russell (AMBAG)

Kif Scheuer (Local Government Commission)

Jennifer DeLeon (State Lands Commission)

Laura Engman (San Diego Region Climate Collaborative)

Dani Boudreau (Tijuana River National Estuarine Research Reserve)

George Domurat (Army Corps of Engineers)

Ken Schreiber (Land Use Planning Services, Inc.)

Bruce Bekkar (City of Del Mar)

Brenda Goeden (Bay Conservation and Development Commission)

Joseph Tyburczy (Sea Grant Extension Specialist)

Brian Brennan (BEACON)

Luisa Valiela (EPA, Region 9 Water Division)

Ben Livsey (San Francisco Estuary Partnership)

John Rozum (NOAA Office for Coastal Management)

Becky Lunde (NOAA Office for Coastal Management

APPENDIX B: Literature Defining Natural Shoreline Infrastructure

Source	Definition
California Government Code (Cal. Gov't Code § 65302 (g)(4)(C)(v) (SB 379))	Natural infrastructure is the preservation and/or restoration of ecological systems, or utilization of engineered systems that use ecological processes, to increase resiliency to climate change and/or manage other environmental problems. This may include, but is not limited to, floodplain and wetland restoration or preservation, combining levees with restored ecological systems to reduce flood risk, and urban trees to mitigate high heat days.
World Business Council for Sustainable Development (2015)	Natural (or "green") infrastructure is a term that refers to ecosystems providing services and benefits that can substitute gray physical infrastructure. Hybrid solutions involving an optimal combination of gray and natural infrastructure are also applicable where appropriate to ensure resilience and sustainability.
FEMA (2015)	Natural infrastructure (or nature-based) is the use of engineered features and restored natural features to mimic or restore natural processes that are created by human design. Examples include, but are not limited to, restored habitat for fish and wildlife, a constructed impounded wetland, or a beach and dune system site specifically engineered for coastal storm damage reduction. Nature-based approaches can be used in combination with or instead of new, existing, or other similar measures. A nature-based approach could also substitute for proposed actions, or could be used in combination with a proposed action.
US Army Corps of Engineers (Bridges et al., 2015)	Infrastructure that uses the natural environment and engineered systems [that mimic nature] to provide clean water, conserve ecosystem values and functions, and provide benefits to people and wildlife.
The Nature Conservancy (Byington 2015)	Natural alternatives to built infrastructure- healthy ecosystems that provide critical services.
Munang et al. (2013)	The use of natural capital by people to adapt to climate change impacts, which can also have multiple co-benefits for mitigation, protection of livelihoods and poverty alleviation.
Temmerman et al. (2013)	[Natural Shoreline Infrastructure] is applied at locations that have sufficient space between urbanized areas and the coastline to accommodate the creation of ecosystems.
Jones et al. (2012)	Ecosystem-based adaptation approaches provide flexible, cost-effective and broadly applicable alternatives for buffering the impacts of climate change, while overcoming many drawbacks of hard infrastructure.

Hale et al. (2009)	Preserve and restore natural ecosystems that can provide cost-effective protection against threats of climate change. Includes ecosystems like wetlands, mangroves, coral reefs, oyster reefs and barrier beaches.
IUCN (Herr and Galland 2009	Ecosystem-based Adaptation (EbA) uses "ecosystems as natural risk reduction mechanisms." "EbA is the sustainable management, conservation and restoration of ecosystems in order to ensure the continued provision of vital services that help people adapt to the adverse effects of climate change." Natural adaptation, natural systems- natural ecosystem structures as a form of soft engineering.

APPENDIX C: Common Native Plants for Restoration in California Coastal Habitats

Beach foredunes:

Beach wildrye or American dunegrass (*Elymus mollis*)
Beach-bur (*Ambrosia chamissoni*s)
Yellow sand-verbena (*Abronia latifoli*a)
Beach saltbush (*Atriplex leucophylla*)
Silvery beach pea (*Lathyrus littoralis*)
Beach morning-glory (*Calystegia soldanella*)

Dune field and barrier dunes:

Beach sagewort (Artemisia pycnocephala)
Lizard tail (Eriophyllum staechadifolium)
Chamisso bush lupine (Lupinus chamissonis)
Coast buckwheat (Eriogonum latifolium, Eriogonum parvifolium)
Mock Heather (Ericameria ericoides)
California Sage (Artemesia californica)

Low Marsh (Below Mean High Water)

Salt Marsh
California cordgrass (Spartina foliosa)
Annual pickleweed (Sarcocornia europea)
Brackish Marsh
Alkali-bulrush (Bolboschoenus maritimus)
Hardstem tule (Schoenoplectus acutus)
California tule (Schoenoplectus californicus)
Cattails (Typha species)

Middle Marsh (Between Mean High Water and Mean Higher High Water)

Salt Marsh
Pickleweed (Sarcocornia pacifica)
Salt Marsh dodder (Cuscutta salina)
Saltgrass (Distichlis spicata)
Alkali-heath (Frankenia salina)
Brackish Marsh
Bulrush (Schoenoplectus americanus, S. maitimus)
Rushes (Juncus arcticus ssp. balticus, J. lesueurii)
Sea-arrow grass (Triglochin maritima)

High Marsh (Mean High Water to upper elevation of spring tides or storm surges)

Marsh gumplant (Grindelia stricta var. angustifolia)

Saltgrass (Distichlis spicata)
Alkali-heath (Frankenia salina)
Pickleweed (Sarcocornia pacifica)
Alkali-weed (Cressa truxillensis)

APPENDIX D: Detailed Methods of Blueprints for Deploying Natural Shoreline Infrastructure

Table D-1. Thresholds used for ranking the suitability of Natural Shoreline Infrastructure measures.

Natural Shoreline Infrastructure Siting Guidelines	Low Ranking	Medium Ranking	High Ranking
Sand Dunes *Location*: Backshore (behind active beach) on sandy shores, ideally with sufficient dry beach to limit wave attack and provide source of wind-blown sand *Minimum Footprint:* Defined by crest elevation, crest width = **15 meters (49 ft) (cross-shore) by 30 meters (98 ft) (along-shore)**	Available space < Dune footprint + beach width of 30 m (49 ft) = 15 m (49 ft) + 30 m (98 ft) = 45 m (148 ft)	Available space > Dune footprint + beach width of 30 m (49 ft) = 15 m (49 ft) + 30 m (98 ft) = 45 m (148 ft)	Available space > Dune footprint + beach width of 60 m (197 ft).
Cobble & Gravel Berms *Location*: Shore and backshore, ideally on cobble substrate but potentially on sands *Minimum Footprint:* ● Berm Crest Elevation = 0.8 x Annual Total Water Level (TWL) ● Berm Crest Width = 15 m minimum for open coast. 3 m minimum for sheltered coast. ● Berm slopes = 5H:1V to 10H:1V on exposed (water) side. Can be 3H:1V or flatter on upland (land) side. ● Berm vertical thickness = 1.25 m minimum open coast, 1 m minimum sheltered coast ● Alongshore length MINIMUM of at least 100 m ● Wave approach angle should be less than 20˚ Total minimum cross-shore space requirement (plan-view): **25 m (82 ft) on exposed coast, 23 m (75 ft) on sheltered coast**	Available space < Berm footprint + beach width of 30 m (98 ft) = 25 m (82 ft) +30 m (98 ft) = 55 m (180 ft)	Available space > Berm footprint + beach width of 30 m (98 ft) = 25 m (82 ft) + 30 m (98 ft) = 55 m (180 ft)	Available space > Berm footprint + beach width of 85 m (279 ft) = 25 m (82 ft) + 60 m (197 ft)

Tidal Bench *<u>Location</u>*: Estuarine environment - intertidal zone *<u>Minimum Footprint</u>*: Based on bench width, bench crest, shoreline slope. ● Bench width = **10 m (33 ft) minimum bench width** recommended ● Bench Crest Elevation = 100-year recurrence value for Total Water Level ● Toe Elevation = MTL or site elevation, whichever is lower ● Alongshore length MINIMUM of at least 100 m.	Available cross-shore space < Bench footprint = 10 m (33 ft)	Available cross-shore space = Bench footprint between 10 m (33 ft) and 20 m (66 ft)	Available cross-shore space > Bench footprint = 20 m (66 ft)
Marsh Sill *<u>Location</u>*: Estuarine environment *<u>Minimum Footprint</u>*: Based on sill width, crest, rock slope. ● Marsh width behind slope = Minimum width between 9 m to 21 m (30 to 70 ft) for low-moderate energy sites ● Minimum shoreline slopes of 8H:1V to 10H:1V. Flatter slopes more ideal. ● Sill Crest Elevation = Minimum 0.3 m (1 ft) above MHW ● Sill Toe Elevation = MLLW ● Alongshore length MINIMUM of at least 10 m (33 ft). ● Cross-shore length MINIMUM of at least 3 m (10 ft)	Available cross-shore space < Sill footprint 3 m (10 ft) + Marsh width behind slope 10 m (33 ft)	Available cross-shore space = Sill footprint between 3 m (10 ft) and 10 m (33 ft) + Marsh width behind slope 10 m (33 ft)	Available cross-shore space > Sill footprint 10 m (33 ft) + Marsh width behind slope 10 m (33 ft)
Eelgrass Beds *<u>Location</u>*: Low intertidal to subtidal zone. Surveys in the San Francisco Estuary have found that eel grass beds occur between -3.00 and 0.40 m (-9.84 and 1.31 ft) MLLW, with 98 % of observations occurring between -1.77 and 0.40 m (-5.81 and 1.31 ft) MLLW, and 94 % between -1.60 and 0.00 m (-5.24 and 0.00 ft) MLLW (Boyer & Wyllie-Echeverria, 2010). *<u>Minimum Footprint:</u>* Appropriate siting requires knowledge of ecological factors in subtidal area.	The successful implementation of eelgrass beds depends on a number of ecological factors and not necessarily space availability. Factors include water clarity, light, sediment physical characteristics, nutrient availability, salinity, temperature, etc. These variables are best ascertained at the project site level. What may be helpful to the user is show where existing eelgrass projects/patches are located. Typically, existing or successful restoration of eelgrass in an adjacent area to the project site can provide a proxy for what conditions would foster the same at the project site. While eelgrass beds are not recommended for being a primary mechanism of coastal protection, the wave attenuation benefits they provide obviously increase as their width and overall extents increase. Boyer and Wyllie-Echeverria (2010) provide a rough estimate of ~2100 m^2 (0.5 acres) as a small-scale plot test, which is suggested for any site looking to implement eelgrass.		

For purposes of siting guidance we assume a MINIMUM of 30 m (98 ft) cross-shore width and a variable alongshore width. See notes.	
Oyster Reefs *Location*: Low to mid intertidal - constructed nearshore reefs. Low intertidal to subtidal - constructed offshore reefs. Oysters generally thrive within +/- 0.6 m (+/-2 ft) range of MLLW (Wasson 2014). *Minimum Footprint*: Appropriate siting requires knowledge of bed composition in intertidal / subtidal zones as well as water quality factors (e.g. salinity, temperature, dissolved oxygen content, etc.). See notes.	Similar to eelgrass beds, the applicability / appropriateness of oyster reefs as Natural Shoreline Infrastructure elements do not necessarily hinge on space constraints. Instead, the wave attenuation and ecological benefits they provide depend on the health of the oysters, affected by salinity, dissolved oxygen concentration, temperature, etc. See Olympia Oyster Restoration Guide for Central California (Wasson 2014). In this report, the authors identify 21 sites within San Francisco Bay and Elkhorn Slough and loosely rank them with respect to supportive factors and stressors.

D.1 Spatial Data Inputs

For the open coastal zones, we utilized spatial data for Monterey and Ventura counties in 500 m (1640 ft) alongshore block segment units. Each block unit was attributed with data condensed from previous GIS analysis (ESA 2013, 2015) on foreshore and backshore types, local and regional planform types, armoring information, 100-year total water levels (TWLs) and beach widths. Beach widths were calculated for Northern and Central Monterey following the methods of ESA (2015), because past analysis only covered Southern Monterey Bay (defined as south of Moss Landing).

For all open coast types, we determined that beach widths should be reflective of the minimum condition experienced at the site (i.e., wintertime conditions), to give a realistic estimate of suitability. The 2009-2011 California Coastal Conservancy Coastal LiDAR dataset and 1998 Airborne LiDAR Assessment of Coastal Erosion Project dataset was used for previous beach width calculations in Monterey Bay and Ventura. For the 2009-2011 LiDAR, data were collected in the Monterey Bay study area from May through October 2010, reflecting summer/fall beach profiles. The 1998 LiDAR dataset was taken in April 1998 after the 1997-1998 El Niño winter. Therefore, beach widths determined from the 1998 LiDAR were deemed to be more appropriate for the purpose of the Blueprint. For the Ventura area, data in the 2009-2011 California Coastal Conservancy Coastal LiDAR project were collected in November 2009. A storm erosion factor and seasonal change factor were applied to estimate the wintertime beach widths.

D.2 Application of Thresholds to Outer Coast Measures

Our rankings of Natural Shoreline Infrastructure measures for outer coast environments are based on the existing conditions within each of the shoreline blocks described above. This is an important consideration as our rankings do not consider alterations of the backshore adjacent to the shoreline blocks. For example, we would rank a shoreline block as low suitability for sand dunes if the existing beach width is < 45m (148 ft) (see below) even if the backshore consists of naturally occurring dunes. Our rationale is that it would not be suitable to construct new sand dunes at a site with a narrow beach even if sand dunes actually exist.

D.1.1 Sand Dunes

We first eliminated block units with a rocky, cliff, or inlet (e.g., river mouth or harbor entrance) foreshore type, which are environmental settings unsuitable to support a sand dune. We then used beach width for ranking the remaining shoreline blocks along the outer coast of Monterey Bay and Ventura County (see Table D-1). These criteria assume a minimum constructed dune width of 15m (49 ft) plus a minimum 30m (98 ft) buffer of fronting beach to dissipate wave energy. We also classified any block segment that had an alongshore length of <30 m (98 ft) as low suitability. We did not consider the wind and wave climates in our classification, but we do note that natural sand dune ecosystems occur within both Monterey Bay and Ventura County suggesting that in general the wave and wind patterns are within the range of suitability although site level conditions likely present constraints.

D.1.2 Cobble Berms

We first eliminated block units with a cliff or inlet foreshore type, which are environmental settings unsuitable to support a cobble berm. We then used beach width to rank the suitability of shoreline blocks for cobble berms within Monterey Bay and Ventura County (see Table D-1).

This assumes a minimum cross-shore space requirement of 25 m (82 ft) for the footprint of the cobble berm itself plus a 30 m (98 ft) buffer to dissipate wave energy. We also classified any block segment that had an alongshore length of <100 m (328 ft) as low suitability.

We did not consider the orientation of each shoreline block with respect to the predominant wave direction in our suitability classification.

D.1.3 Opportunities to Improve Location Suitability Through Managed Retreat

We used the difference between the beach width distance needed to attain a high suitability ranking and the existing beach width to help with assessing the feasibility of using managed retreat as part of a strategy to use Natural Shoreline Infrastructure measures where the existing space is insufficient. For example, just north of the Pajaro River mouth in Santa Cruz County, we classify the shoreline as low suitability for sand dunes because of a narrow beach width (Figure D-1).

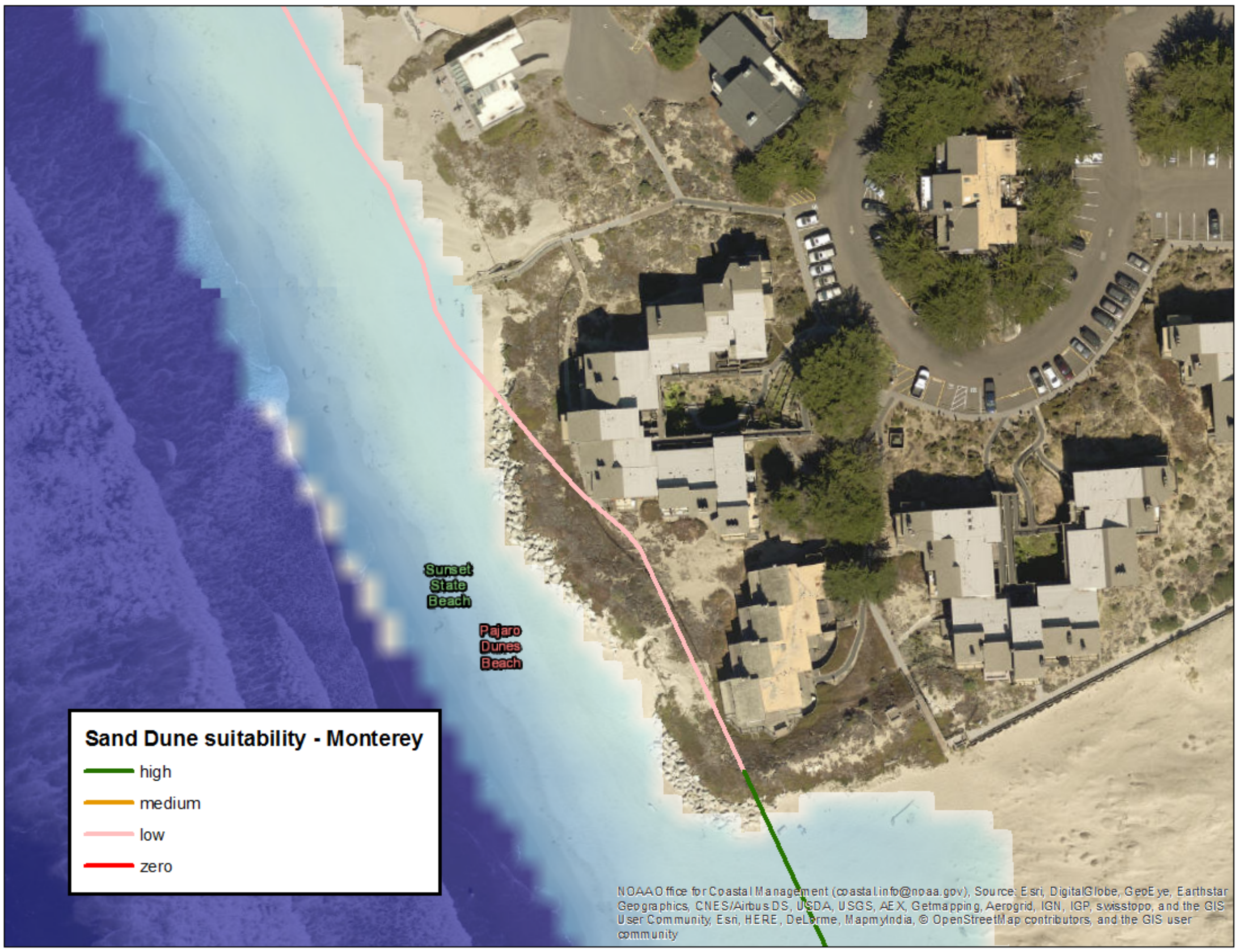

Figure D-1. Suitability for sand dune Natural Shoreline Infrastructure measures up coast of the Pajaro River mouth in Santa Cruz County. The blue shading indicates the inundation extent with six feet of sea level rise.

Our analysis indicates that creating 11 to 20 m (36 to 66 ft) of extra beach width along the shoreline could increase the suitability for sand dunes as Natural Shoreline Infrastructure adaptation measures (Figure D-2).

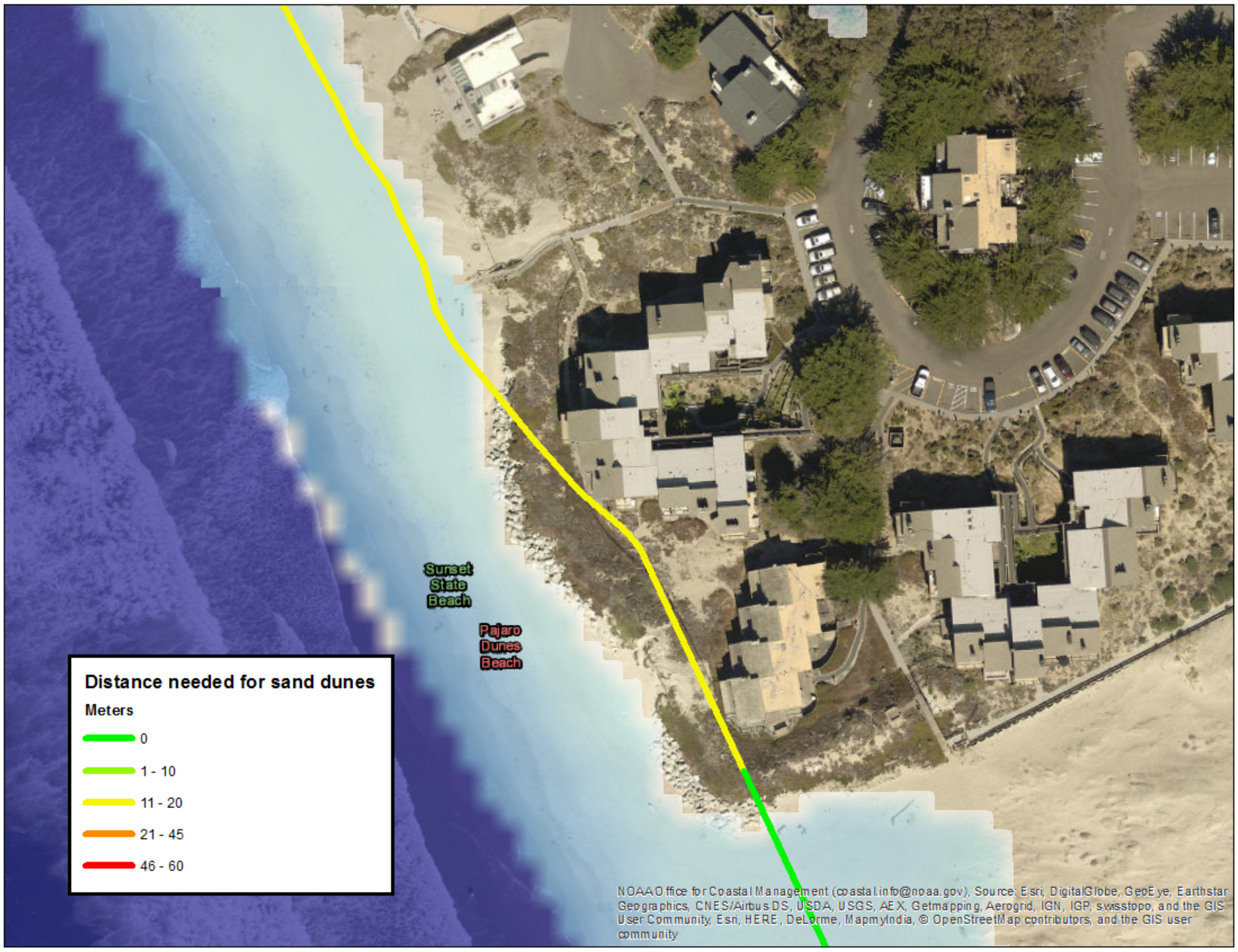

Figure D-2. The additional beach width needed to increase the suitability of sand dunes from low to high just up coast of the Pajaro River mouth in Santa Cruz County.

D.2 Application of Thresholds to Estuary Measures

D.2.1 Marsh Sill

As detailed in Section 3.4, marsh sills are low-profile structures located on the water-side of emergent wetland vegetation (marsh), typically on the mudflat adjacent to or just offshore of the marsh scarp. The design guidance specifies the minimum space for a marsh sill footprint as 3 m (9.84 ft) in the cross-shore direction and 10 m (32.8 ft) in the along-shore direction. Ideally, cross-shore widths of around 10 m (32.8 ft) would provide space for both the structural footprint and a transition before drop-off in slope to the channel. In addition, the vegetated marsh width upslope of the sill is recommended to be a minimum of 10 m (32.8 ft). To identify locations on the landscape that meet these criteria, we used high resolution habitat mapping available for Elkhorn Slough (2009), selected the saltmud habitat class, and generated transects every 10 m (32.8 ft) perpendicular to the centerline of the main slough channel to determine mudflat width. Transects were first screened for adjacency to a minimum of 10m of vegetated marsh. Then they were ranked based on available space for the sill footprint as “high” suitability if they were >10 m (32.8 ft) wide (across mudflat habitat type), “moderate” suitability if they were between 3-10 m (9.8-32.8 ft) wide, and “low” suitability if ≤3 m (9.8 ft).

D.2.2 Tidal Bench

Perhaps more than other Natural Shoreline Infrastructure options, tidal benches will be frequently utilized in conjunction with a more comprehensive tidal marsh restoration project. Ideally, a tidal bench would not be constructed on top of existing tidal marsh habitat, which would otherwise constitute the appropriate environmental setting, but rather the measure would be constructed on former marsh on the inboard side of an existing levee. Creating a tidal bench on top of existing marsh or mudflat would potentially destroy existing habitat and may not be possible given existing regulations and permit requirements. Additionally, the creation of the tidal bench requires mechanical shaping of the topography and thus the existing topography is less important for determining the ultimate suitability of a site for the approach. Mapping the potential suitability of the environmental suitability of tidal benches is not as straightforward as the other Natural Shoreline Infrastructure options considered in this report. Ultimately, we decided not to map the suitability for the tidal bench measure for this report.

D.2.3 Oyster Reefs and Eel Grass Beds

As stated above, oysters and eel grass are constrained by tolerances to biophysical conditions and ecological relationships and are less limited by space as compared to many of the other Natural Shoreline Infrastructure types covered in this report. Of all of the biophysical variables that may constrain the distribution of oysters and eelgrass within estuaries in California, we only had access to elevation layers. As noted in Table D-1, there are certain tidal elevation ranges that tend to support oysters and eelgrass beds.

We identified areas within these elevation bands as an initial screening for locations potentially suitable for oysters or eelgrass. We provide an example of the initial screening by elevation band for oysters in Figure D-3. The elevation criteria can serve to constrain the spatial extent where more detailed environmental data (e.g., salinity, dissolved oxygen, suspended sediment concentrations) would be needed for refining site suitability.

Conditions where oysters and eelgrass are already established within an estuary can help with identifying the suitable parameters for establishing populations at new sites.

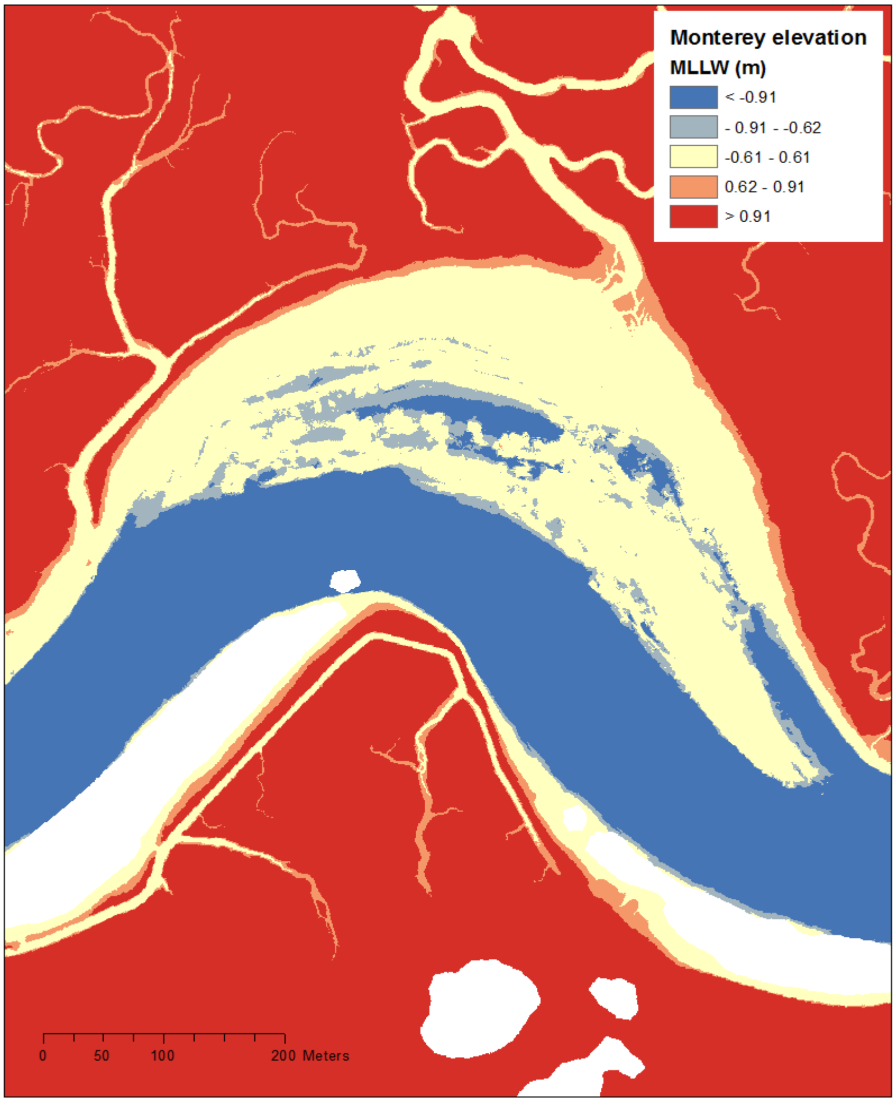

Figure D-3 Elevations suitable for Oyster persistence in Elkhorn Slough. Suitable elevations are between -0.61 and 0.61 m MLLW. Red areas in the map are too high for Oyster establishment and persistence and blue areas are too low.