TOWARD NATURAL INFRASTRUCTURE TO MANAGE SHORELINE CHANGE IN CALIFORNIA

DRAFT PAPER

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A Report for:

California's Fourth Climate Change Assessment

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PREFACE

The wording of the preface will come from the Fourth Assessment Management Team and will be one standard page for all technical reports.

ABSTRACT

Sea level rise and associated flooding already threatens property throughout coastal California, and the intensity of this threat will grow as sea level rises. There is no question that coastal landowners and planners will act to protect their assets from these losses. In the absence of compelling reasons to do otherwise, they will overwhelmingly default to the industry standard – specifically, the construction of coastal armoring (seawalls, revetments, dikes, and levees). While armoring may be the right choice in some locations, it has well-documented adverse consequences, including interrupting natural processes that leads to shrinking coastal habitat, increased erosion, and impacts to coastally-dependent species.

One alternative to coastal armoring is natural infrastructure, which has been shown to be a cost-effective approach to mitigating risk of floods, storms and sea level rise in many places. In this context, Natural Shoreline Infrastructure means using nature to reduce the vulnerability of coastal communities to climate change related hazards, and to increase the long-term adaptive capacity of coastal areas. Examples of Natural Shoreline Infrastructure include restored or engineered sand dunes, marsh sills, and oyster reefs. Natural Shoreline Infrastructure can also mean planning retreat from the coast. Natural infrastructure promotes the ability of systems to respond to sea level rise and migrate landward, ensuring their long-term persistence. In turn, these systems provide co-benefits for coastal communities: coastal ecosystems can serve as protective buffers against sea level rise and storm events while continuing to provide access, recreation opportunities, and other social benefits.

In spite of the well-known advantages of natural infrastructure, property owners continue to default to coastal armoring to protect their assets because of (1) lack of familiarity with how natural infrastructure works and how much these approaches cost, (2) lack of data-supported, technical standards for how to design and implement natural infrastructure projects that fit the specific needs of their communities, and (3) lack of technical siting guidance to identify where to most effectively deploy different natural infrastructure approaches.

The purpose of this project is to overcome these obstacles. This report and its associated products equip property owners, coastal managers and regulators with an understanding of what natural infrastructure is and how it works, including design and siting standards that can direct the appropriate deployment of natural infrastructure, and case studies of where and how natural infrastructure has been successfully used in California. We also present an approach to screening natural infrastructure options based on existing environmental conditions, piloted with mapping of suitable options in Monterey Bay and Ventura County using the siting guidance and available spatial environmental data.

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

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HIGHLIGHTS

- Natural infrastructure is a cost-effective approach to shoreline protection and sea level rise adaptation that promotes ecosystem function and delivers other benefits for coastal communities, while avoiding the adverse impacts of shoreline armoring.
- The delivery of explicit technical guidance for coastal natural infrastructure tailored to California's varied environmental settings fills an important information gap that should enable practitioners to evaluate a broader array of coastal adaptation measures.
- California has extensive experience and a long history of restoration, which provides reference points and lessons learned for the application of natural infrastructure. California should support demonstration projects that collect detailed monitoring information so that natural infrastructure approaches can be improved upon, tested in other areas, and applied on larger scales as part of an adaptation strategy to increase coastal resilience.

WEB LINKS

http://coastalresilience.org/california/natural-infrastructure

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

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1: Introduction

1.1 Coastal Change in California

California's iconic coast links together thousands of miles of coastal habitats - cliffs, dunes, wetlands, estuaries, and beaches – that provide critical habitat to fish, endangered plants and marine mammals, and birds travelling along the Pacific Flyway. It is impossible to overstate the importance and irreplaceability of these habitats; the coast is where land, rivers and the ocean intersect, and it regulates how things move between them – freshwater, salt, wave energy, nutrients, and even the creatures themselves. Unfortunately, more than 90% of coastal wetlands and marine and estuarine intertidal lands, which once provided essential nursery, feeding and resting areas for a diverse suite of both terrestrial and marine species, have already been converted to agriculture or development (Dahl 1990, Zedler 1996). This habitat loss will be exacerbated as rising seas convert existing coastal habitats into open water.

California's shores are also naturally eroding, and sea-level rise and more frequent, intense storms will make this erosion much worse. Coastal bluffs are eroding at a rate of one foot per year in many places, and that number will likely increase over the coming decades as climate change accelerates sea-level rise and intensifies Pacific storms (Hapke and Reid 2007). Vitousek et al. (2017) project that 3 to 6 feet of sea-level rise could eliminate 31 to 67 percent of Southern California beaches by the turn of the century, unless measures are taken to curb this loss. California's beaches are a significant source of recreational and economic value. Market expenditures by beach-goers reach approximately $3 billion annually, and California beaches produce non-market economic benefits that are likely to be significantly greater than $2 billion annually (Kildow and Colgan 2005). Loss of beach width can significantly impact these uses and values.

1.2 Shoreline Protection

In addition to the impacts described above, sea-level rise and associated flooding will threaten nearly $100 billion worth of property along the California coast by 2100 (Heberger et al. 2009), and the magnitude of this looming economic impact guarantees that coastal landowners and planners will act to protect their assets from these losses. In the absence of compelling reasons to do otherwise, they will overwhelmingly default to the industry standard – specifically, the construction of coastal armoring (seawalls, revetments, dikes, and levees).

Armoring structures are often used to protect property from encroachment by the sea, however armoring ultimately undermines its intended purpose by accelerating the loss of beaches and coastal habitats and ultimately bringing the sea closer to the property seeking protection (Figure 1) (Melius and Caldwell 2015)). Coastal armoring is rarely a permanent solution and sea level rise may further shorten the usable life of these structures. Over time, armoring structures cause loss of public beach seaward of the structure, limit beach access, and inhibit recreation in the area influenced by the shoreline armoring (USACE 1981, Dugan 2008, Griggs 2005). In addition, armoring structures are often expensive to install, require costly ongoing maintenance, and can exacerbate flood risk by disrupting natural coastal geomorphic processes. Because seawalls cause increased erosion on neighboring properties, the construction of one seawall will often lead to the need for others.

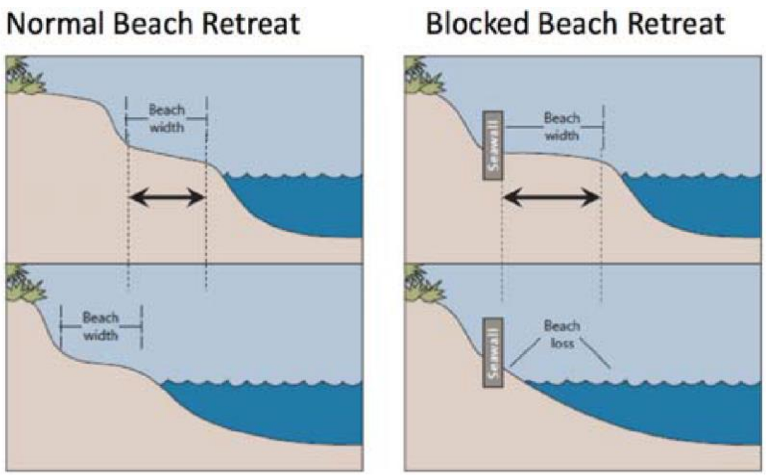

Figure 1: Diagram showing how armoring prevents beach migration and will result in the total loss of beach over time (Source: California Coastal Commission).

The alternative to coastal armoring is natural infrastructure, which has been shown to be a cost-effective approach to mitigating risk of floods, storms and sea-level rise in many places (Barbier et al. 2011, ENVIRON 2015, Narayan et al. 2016, Leo et al. 2017). In this context, Natural Shoreline Infrastructure means using nature to reduce the vulnerability of coastal communities to climate change related hazards, and to increase the long-term adaptive capacity of coastal areas. Examples of Natural Shoreline Infrastructure include restored sand dunes, marsh sills, and oyster reefs. Natural Shoreline Infrastructure can also mean planning retreat from the coast. Natural infrastructure promotes the ability of natural systems to respond to sea level rise and migrate landward, ensuring their survival. In turn, these systems provide co-benefits for coastal communities: coastal ecosystems can serve as protective buffers against sea-level rise and storm events while continuing to provide access, recreation opportunities, and other social benefits. These benefits have been well documented (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).

Nonetheless, armoring has been the industry standard for shoreline protection for centuries – not just in California but well beyond. The reason for this preference is multi-faceted. A recent study of the obstacles to deployment of natural infrastructure in adaptation decision-making (Standford Law School Policy Lab Practicum 2015) found several significant obstacles:

(1) *Awareness*: Although planners may be aware of natural infrastructure adaptation approaches, they are far more familiar with armoring strategies and therefore have a tendency to "do what they know." This lack of familiarity causes decision-makers to view natural infrastructure as an unproven course of action. Planners highlighted the lack of precedent for deployment of natural infrastructure, not only in general but specifically in areas with similar development or geographical profiles as their own. Planners specifically

cited the need for a toolkit that would explain how natural infrastructure works and how much these approaches cost.

(2) *Lack of data/funding*: Many planners cited a lack of data-supported, scientific standards for how to deploy natural infrastructure projects that fit the specific needs of their communities. Planners rely heavily on data about their community's risk profile, so it is unrealistic to believe that officials will entrust their coastlines and infrastructure to newer, innovative solutions without a full picture of how they will impact both the natural and built environments. This will result in more of the same approaches landowners have relied on for years: armoring approaches.

(3) *Lack of technical standards*: In addition to needing data on where to most effectively deploy natural infrastructure, planners require technical standards for how to design and implement these approaches. 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 infrastructure. Lacking technical standards, planners view nature-based adaptation solutions as "risky" and untested alternatives to seawalls and levees.

In the words of one planner:

> "We're asking the Public Works people to make these decisions, and they like to build things that work, so they know how to design a seawall and the life expectancy. They don't know how to do managed retreat and beach nourishment and don't know that [those approaches] have the same level of certainty that needs to happen to make the mayor and everyone else happy…. We don't have the expertise for these [nature-based] strategies."

1.3 General Principles of Coastal Protection by Natural Infrastructure

1.3.1 Wave attenuation and dissipation by natural infrastructure

Wave attenuation by natural infrastructure mitigates coastal erosion by reducing the energy impacting the coast, and is a function of various sources of friction (Borsje et al. 2012, Moller et al. 2014, Narayan et al. 2016). These include plant and sedentary animal material, such as oyster reefs, as well as bottom friction (BCDC & ESA 2013). Other factors that contribute to wave attenuation include bathymetry, geomorphology, sediment characteristics, width of intertidal and shallow subtidal vegetation, and wave characteristics (Koch et al. 2009, Narayan et al. 2016, Lowe et al. 2013). Waves lose energy as they pass over or through vegetation and other physical characteristics of coastal habitats that increase friction in opposition to the wave propagation (Moller et al. 2014).

In addition to attenuating waves, dunes and other coastal habitats provide protection from storms by blocking waves that can't overtop their height. As such, 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 cases, dunes are considered to protect 300 m of lowlands behind them, regardless of classification as either high or low dunes (Arkema et al. 2013).

1.4 How We Define Natural Shoreline Infrastructure

Natural infrastructure is a popular buzzword today, and it may mean different things to different people. For many, the term conjures images of mangrove forests or oyster reefs. For others, it may mean structural barriers topped off with a layer of vegetation to create a sort of "bioveneer." Still others question whether managed retreat can result in the creation of natural infrastructure.

There is a fairly extensive literature on natural infrastructure that runs the gamut from science blogs and federal organization workplans to peer-reviewed literature. Appendix B shows the range of definitions of natural infrastructure resulting from a literature search for "natural coastal infrastructure" and "natural infrastructure for sea-level rise."

Importantly, the California legislature has created a definition of natural infrastructure in statute. Under California state law (AB 1482 (Gordon) and SB 379 (Jackson) 2015), 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."

In order to increase the accessibility of coastal natural infrastructure in California, it is critical to create a common language and understanding across the public and diverse governance actors. We needed a unifying definition specific to coastal natural infrastructure to guide other aspects of this project, but more importantly to align the community of practitioners in California around a common definition. We engaged the TAC, as representatives of the community of practitioners, to help us arrive at a definition that could meet these needs.

We began with the California Government Code definition of natural infrastructure as a starting point for discussion. However, our review of the literature related to natural and green infrastructure, as well as ecosystem-based adaptation, indicated that other principles may be essential to a complete understanding of natural infrastructure:

- Natural infrastructure provides ecosystem services and benefits;
- 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/ecosystem-based adaptation projects include preservation of biodiversity as a specific outcome;
- Natural infrastructure is/features a "healthy ecosystem;"
- Natural infrastructure definition remains broad or is specific to coastal resiliency.

After substantial discussion, the TAC arrived at the following definition:

> *"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."*

1.5 Practical and Policy Considerations related to Natural Infrastructure

The overall formula for coastal resilience in California will have aspects of armoring, natural 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. For example, neither beach nourishment nor living shorelines approaches are effective in areas subject to high-energy wave action, as experienced along much of California's ocean coastline. Thus, in many places in California, there will be few hybrid options, leaving selective, thoughtful relocation or retreat as the only natural infrastructure alternative (Figure 2).

The concept of Natural Infrastructure is codified in state law. The California Public Resources code defines "Natural Infrastructure" as:

> [T]he preservation or restoration of ecological systems or the utilization of engineered systems that use ecological processes to increase resiliency to climate change, manage other environmental hazards, or both. This may include, but need not be limited to, flood plain and wetlands restoration or preservation, combining levees with restored natural systems to reduce flood risk, and urban tree planting to mitigate high heat days.

Cal. Pub. Res. Code § 71154 (c)(3) (AB 1482) and Cal. Gov't Code § 65302 (g)(4)(C)(v) (SB 379)

Natural Infrastructure is also included in state policy and planning. For example, the 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 prioritizes the application of natural infrastructure in state agencies' planning and investments. SB 379 (Jackson) created the requirement that the safety element of local General Plans be reviewed and updated as necessary to address climate adaptation and resiliency strategies applicable to that city or county, and requires that natural features and processes should be used in adaptation strategies, where feasible. The Safeguarding California Plan is California's climate change adaptation strategy and directs the state to prioritize green infrastructure solutions. The Governor's Office of Planning and Research created 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."

Figure 2: Strategic retreat in California. Removal of the Officers' Club at Fort Ord allowed the removal of a rock revetment and the restoration of the adjacent beach.

1.6 Economic benefits of natural infrastructure

Recent work by The Nature Conservancy (TNC) and partners has demonstrated that natural infrastructure approaches are more economically beneficial when applied on a regional basis than coastal armoring approaches. An economic analysis of two responses to sea level rise in Ventura County, CA – an engineered management scenario and a natural infrastructure scenario – showed that both of the two adaptation scenarios reduce damages significantly (Figure 3); but the natural infrastructure approach provides additional ecosystem service benefits in terms of preserving or restoring the natural functions of the ecosystem (i.e. water storage and treatment, production and protection of wildlife, prevention of beach erosion, and other natural ecosystem services) (ENVIRON 2015). This is in direct contrast to the engineered management solution, which ensures the eventual loss of coastal habitat and access throughout most of the County. This research demonstrates that a natural infrastructure alternative may be economically preferable, depending on the value assigned to the ecosystem services, which is complex and will depend on a number of site-specific variables, including community value and preference.

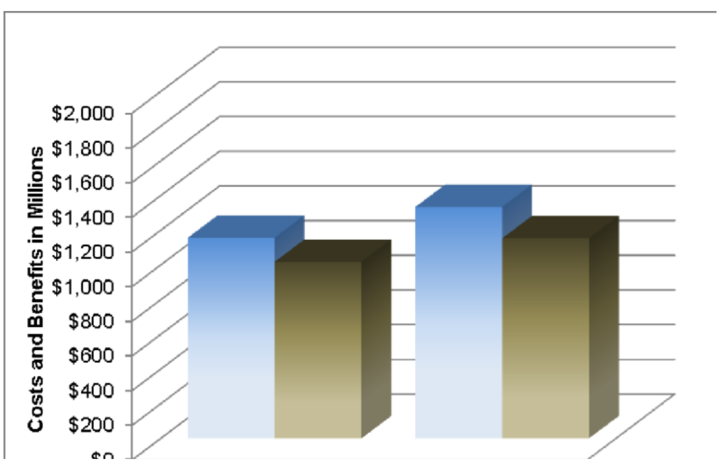

Figure 3: Net Present Value of Costs and Benefits of a Coastal Armoring approach to shoreline management (CAA) and a Nature-Based approach (NBA) from 2014 to 2100, excluding ecosystem services (ENVIRON 2015)

The Nature Conservancy and partners also evaluated the economic impact of a suite of climate adaptation strategies - both engineering based and nature based as well as hybrid solutions – in the Southern Monterey Bay area. Results of this work indicate that over the mid- to long-term, non-armoring approaches provide greater economic net benefits. Indeed, for all timeframes except 2030, shoreline armoring is the worst option (Leo et al. 2017).

1.7 Purpose of This Study

The purpose of this project is to provide a suite of tools to begin to overcome the obstacles to broader use of natural infrastructure. In order for natural infrastructure to be considered a realistic, practical and beneficial alternative to coastal armoring, managers need: (a) a clear definition of natural infrastructure, and a thorough understanding of how it functions as an alternative to coastal armoring; (b) technical guidance relating to the design and implementation of natural infrastructure in California coastal environments; (c) information on how and where natural infrastructure can be deployed to maximize its risk reduction value and its ability to deliver ecological, recreational and economic benefits ("blueprints"); and (d) case studies to illustrate demonstrated benefits and lessons learned. With a clear understanding of each of the above, property owners, coastal managers and regulators can begin to understand, design and deploy natural infrastructure in their own work and – in so doing – enhance the overall resilience of the coastline they manage.

However, this report is only the first step. The products described below are limited by a shortage of practical examples in California, and limited data on the physical and ecological environments in our study area. In addition, these tools do not supplant the need for engineering studies and long-term monitoring at the site-level.

This report is intended for a savvy, but largely non-technical audience: planners, local government, etc., although the technical guidance section will probably be useful for a more technical audience (public works, etc.). There are also many permitting challenges for these approaches that need to be resolved.

1.7.1 Stakeholder Engagement on Natural Infrastructure

We established a Technical Advisory Committee (TAC) to guide the project, with representatives from key coastal management organizations throughout CA, as well as those with expertise in the deployment of natural infrastructure. This TAC provided us with a more thorough understanding of the obstacles managers face and the information needs they experience. Together with the TAC, we developed a shared understanding of the term Natural Infrastructure in the coastal adaptation context. This included a definition of the term, a uniform set of objectives or outcomes that natural infrastructure projects are expected to produce, and a list of natural infrastructure projects that have been planned and/or implemented in California to serve as case studies for the other tasks in this project. The TAC membership and affiliations are listed in Appendix 1.

1.5.2 Technical Requirements for Natural Infrastructure

We selected 6 types of natural infrastructure with a history of deployment in California: sand dunes, cobble berm, marsh sill, tidal bench, oyster reef, and eelgrass beds. For each of the six types we developed technical guidance for the setting, design, construction, and monitoring. Additionally, we researched the application of managed retreat and lagoon mouth management as practices to enhance the resilience of human assets, and potentially improve the effectiveness of natural infrastructure approaches. We consulted with geomorphological and ecological experts to characterize the conditions under which natural infrastructure will be resilient to climate change and sea level rise over the next century. For each natural infrastructure type we evaluated the following parameters (at a minimum):

- Land Cover/Existing Development – to determine the need for and suitability of natural 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 infrastructure for erosion control, risk reduction, property protection; and
- Cost per hectare or linear kilometer.[1]

Full details of the setting, design guidance, and construction and monitoring for each of the 6 natural infrastructure types, as well as considerations for managed retreat and lagoon mouth management can be found in Section 3: Technical Guidance on Natural Shoreline Infrastructure.

1.7.3 Blueprints for Natural Infrastructure Deployment

We assembled available geospatial data based on suitability criteria identified in the technical requirements, and used it to develop a blueprint of high-, medium-, and low-suitability of several types of natural infrastructure in two pilot study areas: Ventura County, and Monterey Bay. We vetted the approach and preliminary maps with representatives from the TAC and other local stakeholders, and adjusted based on feedback. Importantly, in developing the blueprints we determined that there are substantial gaps in statewide data. Future funding directed to the creation of statewide spatial data that addresses the technical requirements of coastal infrastructure could facilitate the assessment and implementation of natural infrastructure.

The methodology and preliminary blueprints are available in Appendix E.

The final blueprints will be forthcoming in summer 2018, and will take the form of a map service on the Coastal Resilience decision-support tool (http://coastalresilience.org/), including color-coded maps detailing the degree of suitability of each geographic area for the deployment of a given natural infrastructure type. The map service will also allow the user to define custom areas for analysis and comparatively evaluate different approaches within that area.

1.7.4 Case Studies of Coastal Natural Infrastructure

From a list of planned/implemented natural infrastructure projects generated by the TAC, we selected five completed in California from which to develop detailed case studies,

[1] Please note that in providing estimates of probable construction costs, the Core Team has no control over the actual costs at the time of construction. 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.

including analysis of the design, cost, and performance. The project team consulted project proponents from the TAC and beyond to synthesize the background, permitting, planning, implementation, performance, and key lessons learned from each project in order to provide the critical information needed to implement successful adaptation strategies to address coastal issues, and inspire other communities by highlighting the lessons learned.

The case studies were compiled and published in a separate report, entitled *Case Studies of Natural Shoreline Infrastructure in California*, which is available at http://coastalresilience.org/case-studies-of-natural-shoreline-infrastructure-in-coastal-california/. The report is excerpted at Appendix F.

2: Technical Guidance on Natural Shoreline Infrastructure

2.1 Introduction and Appropriate Use

Natural infrastructure projects have been successfully implemented throughout California, but guidance on appropriate siting and design is limited relative to traditional shore armoring projects. This section begins to fill the gap in technical understanding related to siting and design constraints for natural infrastructure, by providing detailed guidance on a selection of six natural infrastructure measures and two broader natural infrastructure strategies with a history of deployment in California, organized by appropriate setting and backshore type.

Table 1 provides a summary of the six different natural infrastructure measures and their appropriateness in different coastal settings. In addition to the six measures listed, we also provide guidance for broader strategies of Managed Retreat, as a means to increase natural infrastructure feasibility, and Lagoon Mouth Management, where the wave-built beach and mechanical breaching affect water elevations. Note that Table 1 is a simplification intended for guidance, and is not intended to be prescriptive.

The guidance presented below is intended to be used for planning purposes only. 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.

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

Table 1: Suitability of coastal natural infrastructure measures for select wave exposure environments and backshore types. Green indicates that a natural infrastructure type is suitable for the given environmental setting. Yellow indicates moderate suitability and red indicates that the natural infrastructure type is not typically appropriate in this setting. Note that this is a simplification intended for guidance, and is not intended to be prescriptive.

2.2 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. Sand dunes vary in extent from short distances to great expanses. Dunes act as coastal defense by providing sand storage to buffer erosion during extreme events and dissipating wave energy. During storms, dunes are a supply of sacrificial 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 physical processes and add ecological value. Vegetation acts to trap deposited sand particles and contribute to growth of the dune. Established plants not only trap sand, but also wind-born seeds to further enhance the vegetation of the dunes. Dune vegetation can also increase soil water content by intercepting fog and by limiting evaporation from the surface through shading. Additionally, nitrogen fixing dune plants (e.g yellow bush lupine (*Lupinus arboreous*), chamisso bush lupine (*Lupinus chamissonis*) increase the availability of nitrogen in the soil, a key limiting factor in 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 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.

2.2.1 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 as well and natural dune systems 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 infrastructure. Foredunes have also been proposed as natural infrastructure at Ocean Beach, CA (Battalio, 2016). Dune fields 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.) 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, slough-ing 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).

2.2.2 Design Guidance

2.2.2.1 Dune Geometry

Relevant design parameters for implementing dune systems as natural 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 (wave runup + top of ocean water level) 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.

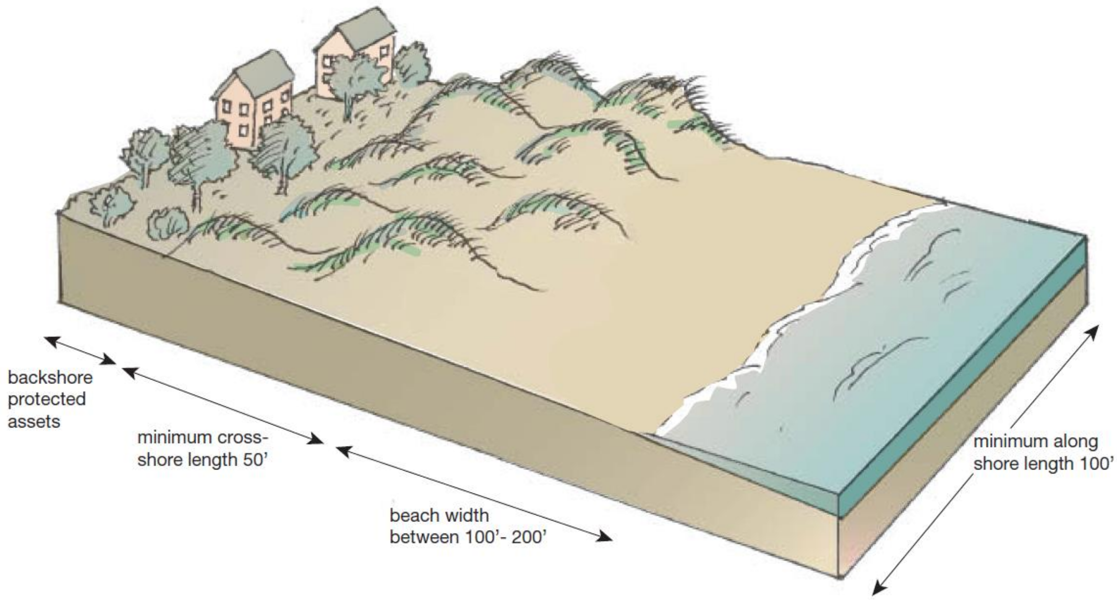

Figure 4: Oblique view of dune geometry thresholds

Sufficient space between development and the shoreline is required for sand dunes to be installed successfully and to function optimally (Figure 4). The available space should exceed the sum of total constructed dune footprint and a beach width between 100 to 200 feet. The total constructed dune footprint is defined by the height of the dune above the beach, slope and crest width (Figure 5). 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 offshore winds.

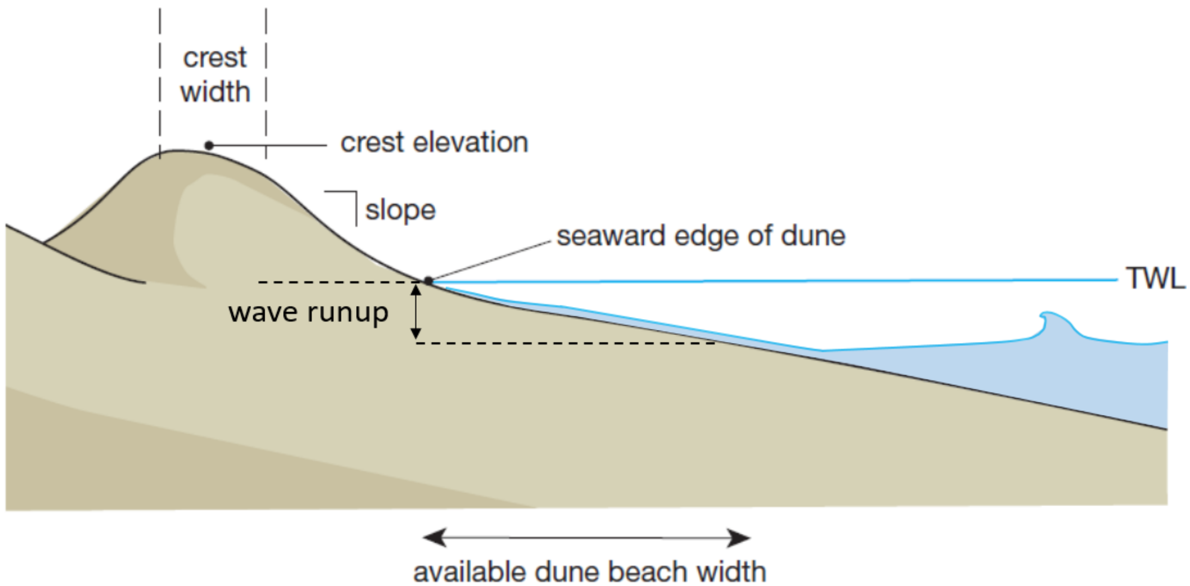

Figure 5. Profile view of dune geometry.

The Coastal Engineering Manual (CEM) (USACE, 2002) 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 roses 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 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.

2.2.3 Dune Subtype and Vegetation

2.2.3.1 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, fore dune 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 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 plant or straw into the sand, tree branches and 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 with 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 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.

2.2.3.4 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 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.

2.2.4 Construction and Monitoring

Protecting the vegetation on a dune system is vital to the success of the dune system. Therefore, monitoring is focused on both the physical and ecological evolution of the dune. 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). As vegetation spreads along the dune system, these fences would be extended. A 2 m minimum buffer of unvegetated sand behind the fence is recommended, since that is the approximate lateral spread rate of most foredune vegetation species.

Vegetation extents, density and characteristics should be determined according to a monitoring plan using aerial photography (LiDAR 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.

2.3 Cobble Berms


Figure 6. Left: Cobble berm in Goleta, Santa Barbara County, CA March 8, 2017. Note deposition of wrack on berm crest, indicating extent of wave runup and physical process supporting ecological function (Photo: Everett Lipman). Right: Cobble berm at Prisoner's Harbor (Photo Credit: Jenny Dugan).

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 (Figure 6). 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).

2.3.1 Setting

The use of cobble berms as natural 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 6- 24 inches. 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 oysters, crabs and other organisms while alluding to more natural landform. Salt grass can also establish by cobble berms (Figure 7). Traditional armored approaches, such as rock rip rap or solid seawalls, provide neither of these benefits.

Figure 7. 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. Photos: Jenny Dugan

2.3.2 Design Guidance

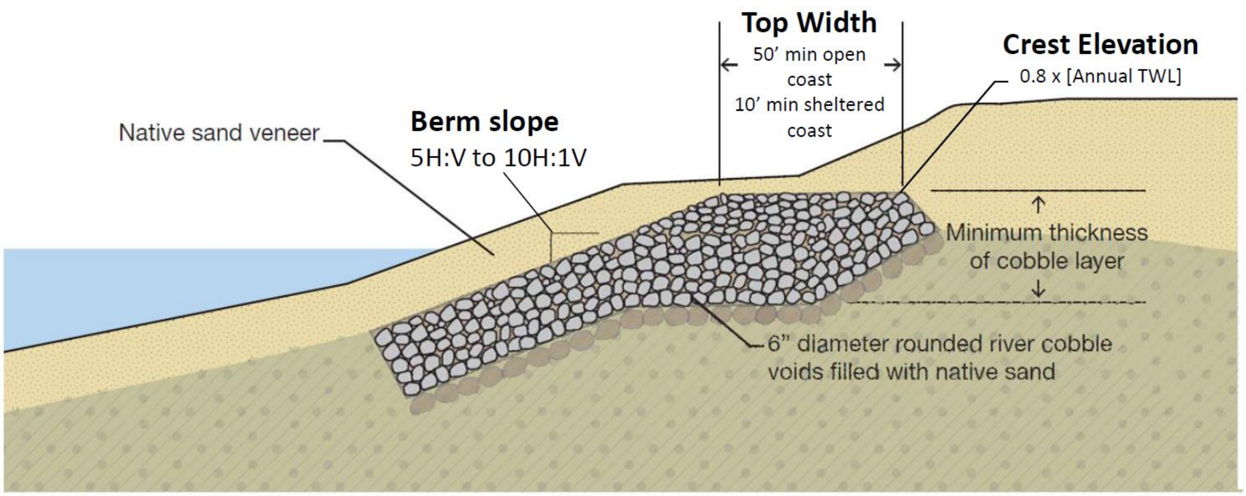

Figure 8. Profile view of cobble berm

Key design parameters a beach manager should determine for a cobble berm include: alongshore length of constructed berm, crest elevation, slope and layer thickness and volumes (Figures 8). The beach 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 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 10 feet and 50 feet, 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 8). The total cross-shore width can be determined from these parameters; at a minimum, the berm should span 80 feet in the cross-shore direction in an exposed environment, and 75 feet 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. Beach 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 planview evolution of the berm if the structure will be regularly exposed to oblique waves and its primary function is shore protection.

Last but not least, 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 330 feet or greater, depending on the extent of the backshore area a beach manager wants to protect. Roughly speaking, the nominal minimum thickness of a cobble berm on open coast would be around 4 feet. For sheltered coast, the minimum thickness is reduced to 3 feet.

2.3.3 Construction and Monitoring

Construction of cobble berms is markedly simpler 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. Beach 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 beach managers in estimating the percentage of the initial placed volume that remains in a “stable” configuration and thus, consequent decisions about maintenance.

2.4 Marsh Sills

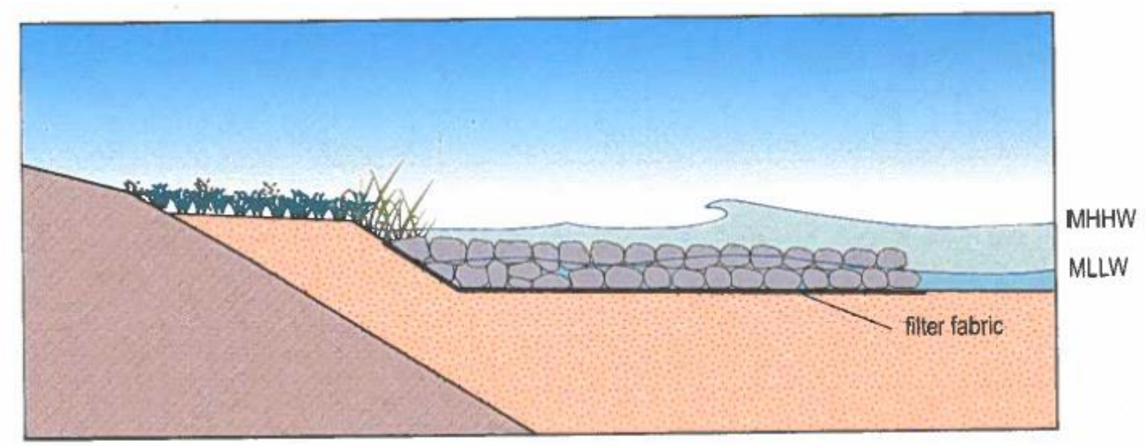

Figure 9. Section view of marsh sill in estuarine environment

A marsh sill is a low-profile stone structure, combined with a vegetated slope, constructed in water parallel to an existing shoreline (Figure 9). Sills can be constructed out of cobble or rock fragments. This natural 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.

2.4.1 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, 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.

2.4.2 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.

Based off of experience gained at the Greenbrae Boardwalk marsh sill, which has been monitored for 25 years show that the design parameters used in this project provided adequate protection against locally generated wind-waves and boat wakes from ferry boats with operational (speed) restrictions (ESA 2017). The nominal width of the Greenbrae marsh sill was 15' with a range of 10' to 20' and a crest elevation of about 4.0' MLLW, which is lower than the marsh plain elevation of approx.. 5'-6' MLLW.

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 10 feet in the cross-shore direction and 30 feet in the along-shore direction. Ideally, cross-shore widths of around 30' 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 3' 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 6' 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.

2.4.3 Construction and Monitoring

Factors for consideration in construction include type of access (land or water), construction access materials and mitigation for adverse construction effects. Construction access to the project site may be by water or land. 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 habitat. 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 shall not impede inundation of the marsh plain during higher tides and via tidal channels, hence limiting the sill crest elevation. Additionally, the sill shall 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 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 10), 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 = 1’ sea-level rise / 2’ thick), and the structure would be largely ineffective with two feet of sea level rise (100% reduction in effectiveness, 1.0 = 2 ‘ sea-level rise / 2’ thick). The effect of sea-level rise can be mitigated by structural modification (adding more rock to raise the elevation) within practical limits.

Figure 10. Photograph showing "outflanking", or erosion at the end of a marsh sill, which is typical of coastal structures over their design life (ESA, 2017).

2.5 Tidal Benches

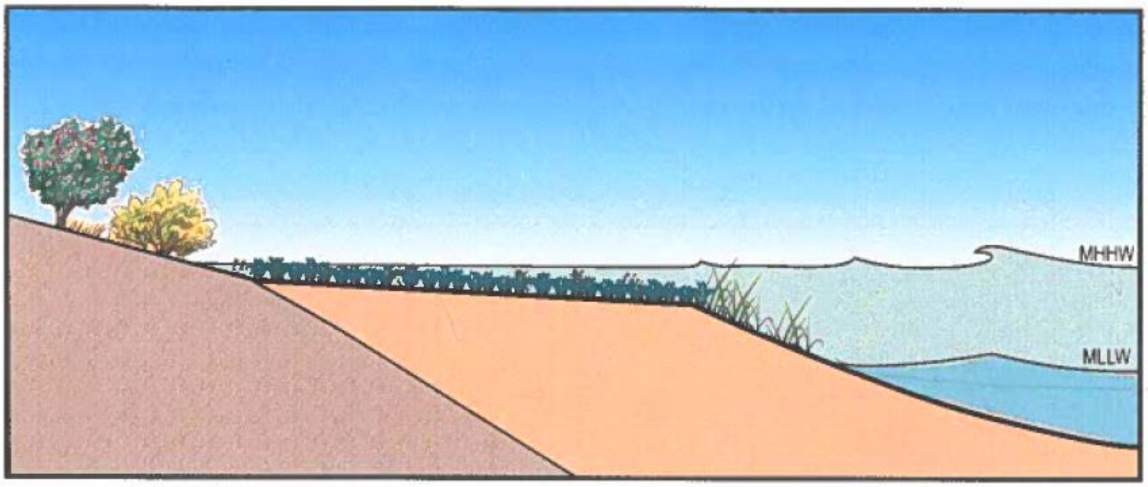

Figure 11. Profile view of tidal bench in estuarine environment

A tidal bench is a gently-sloping, dissipative bench extending from mean tide level (MTL) or lower to the backshore (Figure 11). 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 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 CA natural infrastructure project which have 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 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. Because of this accretion in combination with below ground plant biomass tidal marshes have one of the highest per acre 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.

2.5.1 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. can the landward limit be set back?) are also ideal.

2.5.2 Design Guidance

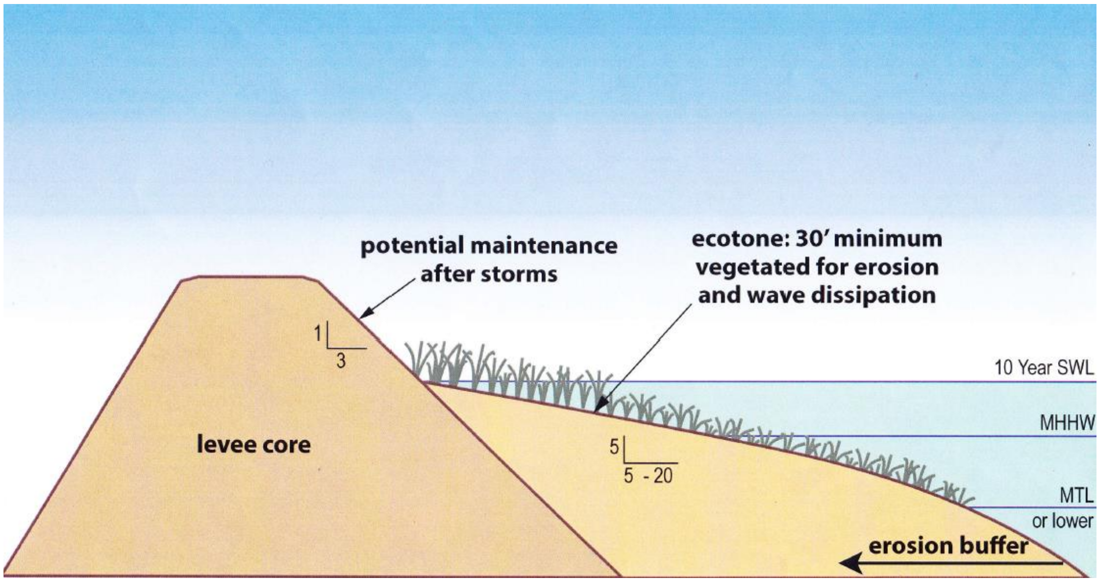

Figure 12. Tidal bench schematic showing slopes, bench width, erosion buffer and vertical datums

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 30-foot 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 12).

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 60'. Additional width may be added to provide a sacrificial buffer for severe storm erosion, which has been estimated to be up to 30 feet horizontally in a mud levee (PWA, 1998). Often times, 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.

2.5.2.1 Vegetation

When choosing vegetation for a tidal bench, using a native plant palette according to elevation bands is encouraged (Figure 13). 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 including which should be factored into construction and monitoring. Depending on the site, soil chemistry may prevent vegetation establishment, 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.

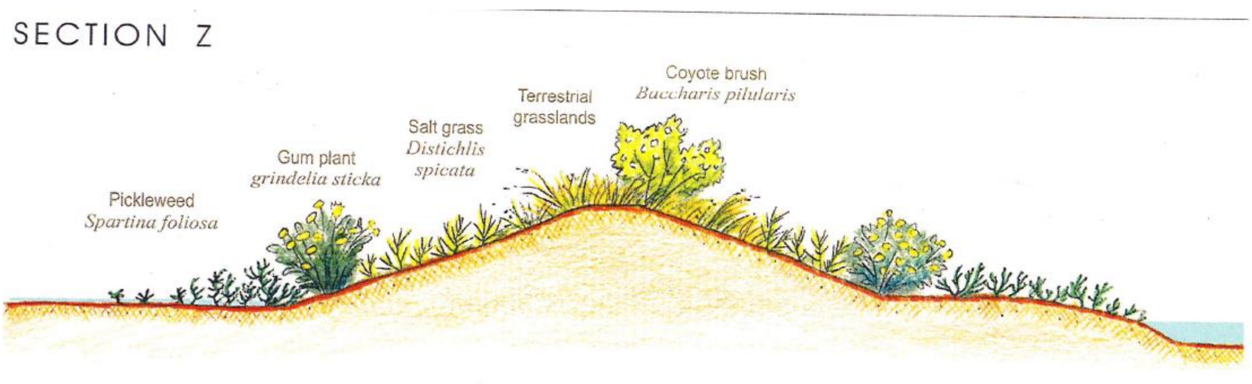

Figure 13. Native marsh vegetation by elevation bands

2.5.3 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 $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 before planting and after construction. 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.

2.6 Native Oyster Reef

Oyster reefs, also referred to as oyster beds, oyster bottoms, oyster banks, 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: Crassostrea virginica (Eastern oyster) in the Atlantic and Gulf Coasts, Crassostrea gigas (Pacific/Japanese oyster) and Ostrea lurida or Ostreola conchaphila (native Pacific or Olympia oyster) in 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. Oyster reefs reduce bottom shear stress from waves and currents at lower tides and aid in sediment recruitment and retention. 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 if reefs are built well above typical elevations colonized by oysters. They reduce shoreline erosion potential and support vegetation growth in the low intertidal zone. Reefs create physical complexity (e.g. microcurrents) in mudflat topography, which influences the ecological value provided by the reef.

Oyster reefs bolster the ecological function of a project site by increasing habitat diversity within the low intertidal and subtidal zones and improving water clarity through filtration of 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. Overall, a range of fauna benefit from the increased foraging opportunities and habitat space provided by this natural infrastructure type.

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 infrastructure types, for example, eelgrass beds, to provide more variety in function to a project site.

2.6.1 Setting

Oyster reefs perform well in sheltered waters such as bays and estuaries with short period wind-waves (H_s < 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 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. The reader is referred to this matrix for additional background material specific to the CA coast.

2.6.2 Design Guidance

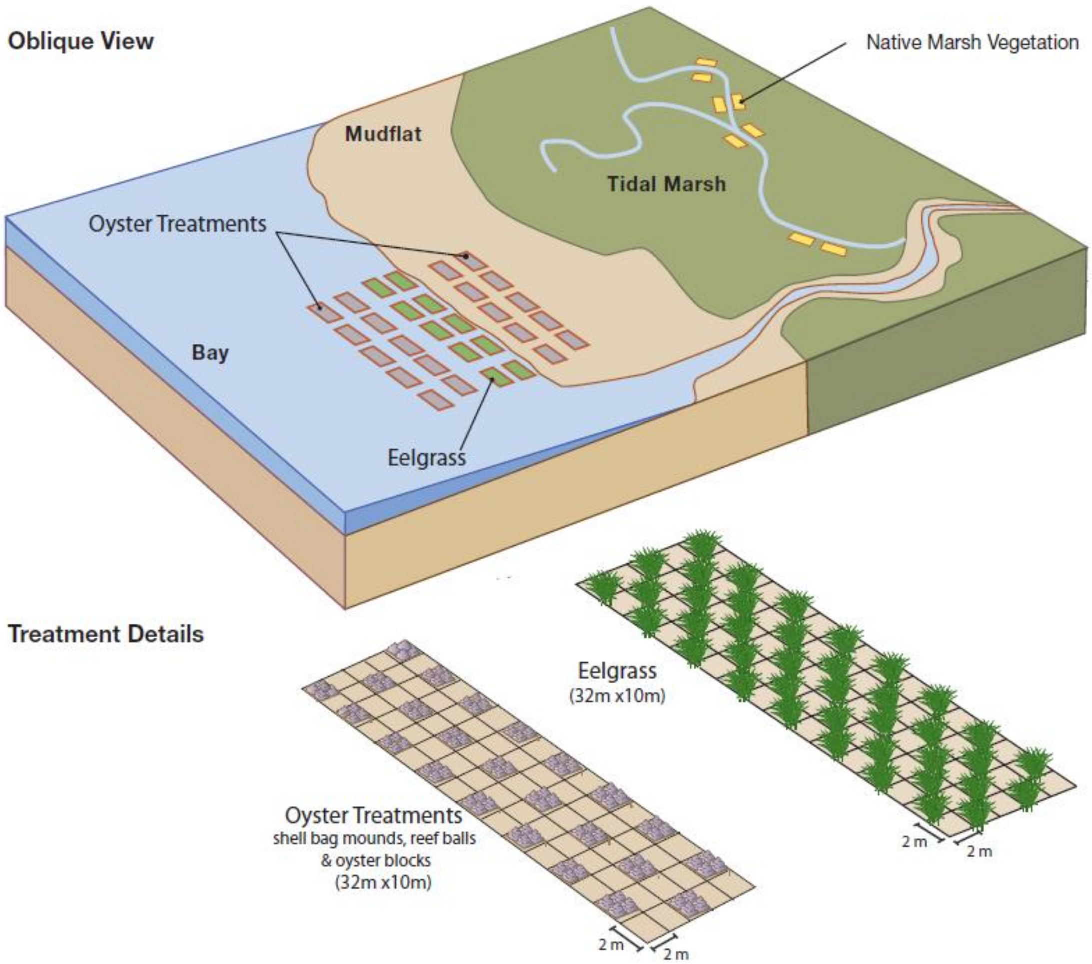

Figure 14. Schematic showing combined use of oyster reef (nearshore and offshore) and eelgrass beds to provide wave protection

The placement of oyster reefs along an estuarine profile enhances the level of coastal defense, geomorphic and ecological function provided. Constructed nearshore reefs, which are located in the low to mid-intertidal zone, near the shore, are intended to affect shoreline processes and yield less ecological benefit. 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. Examples of successful implementation of offshore oyster reefs include those installed at TNC San Rafael, ELER Eden Landing, Watershed Project Point Pinole and the Berkeley Marina (ESA PWA, 2012). Figure 14 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 +/- 2 ft of mean lower low water (MLLW). Reefs built outside of this range will have decreased recruitment and survival of native oysters. It is recommended that oysters remain submerged continually if they are to grow during low tide (Miller et al., 2015). Additionally, oyster reef studies have shown that reefs exposed to ambient velocities a majority of the time rather than stillwater 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, to provide maximal geomorphic function.

2.6.3 Construction and Monitoring

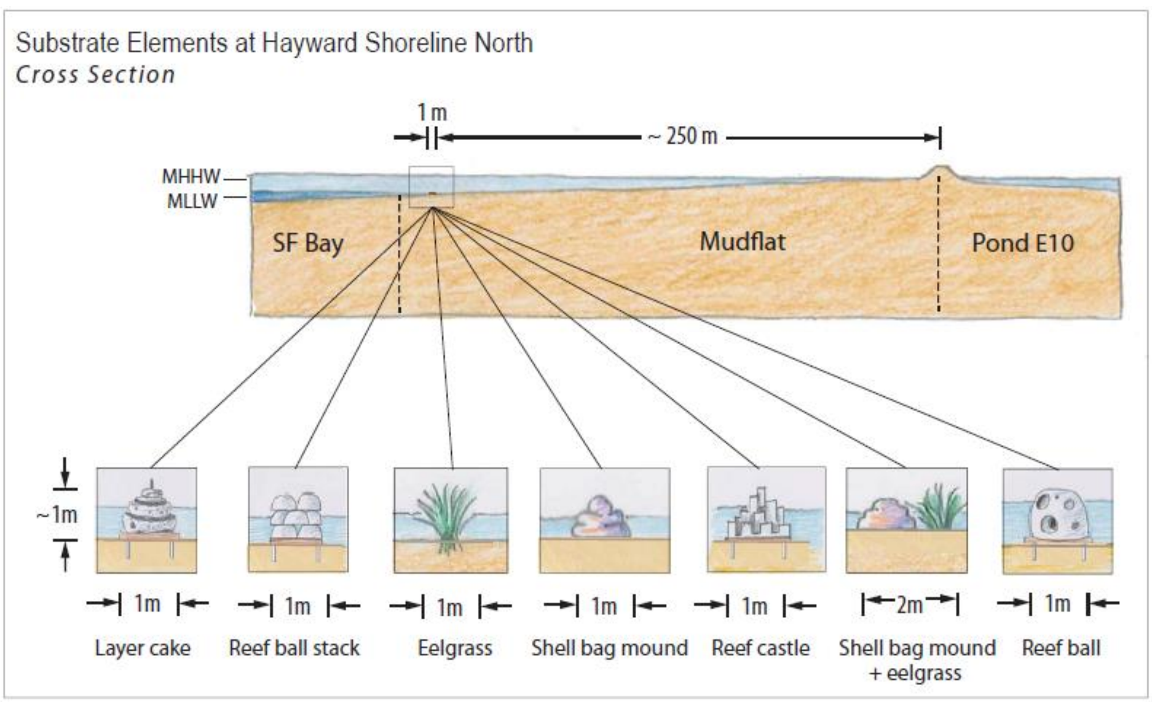

Figure 15. Types of substrate elements for oyster reefs (eelgrass shown as well) and approximate widths

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). Based off of previous oyster reef natural 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. Figure 15 shows the variety in substrate elements used for oyster reefs. 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. Commercial precast concrete domes (Reefballs) or precast concrete blocks that can be stacked together can also be used to form the reef. Concrete mixtures which incorporate native shell and aggregates have the additional benefit of providing rough textures and complexity, which make oyster success more feasible.

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 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 interannual 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 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 104 Oyster Habitat Restoration Monitoring and Assessment Handbook for further background on monitoring methodologies for the aforementioned attributes.

2.7 Eelgrass Beds

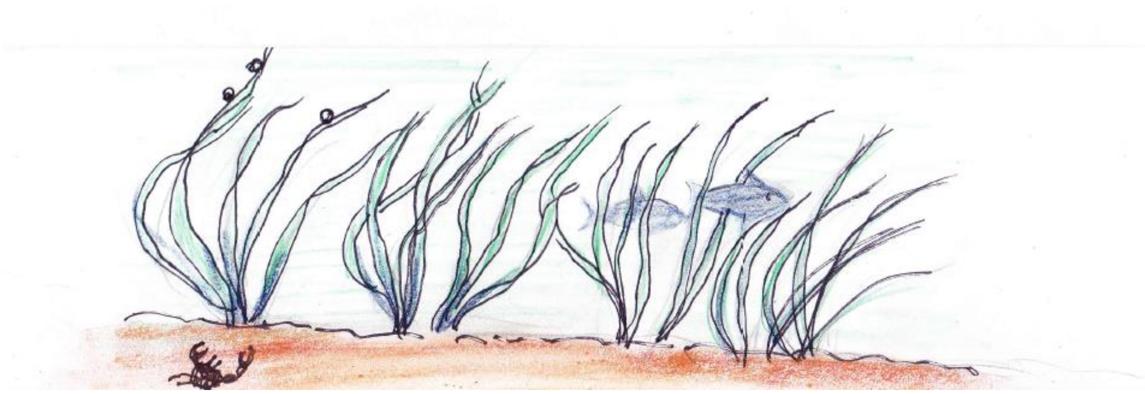

Figure 16. Eelgrass bed schematic

Eelgrass beds (Figure 16) can be implemented as natural infrastructure in bays and estuaries for low-level coastal defense. Pacific Eelgrass has been successfully installed through several project sites in San Francisco Bay and Southern California: TNC San Rafael, ELER Eden Landing, Marin Rod and Gun Club Restoration Site, and Morro Bay San Diego. The beds help to dissipate wave energy and slow tidal currents, compared to bare mudflats alone, at mean tide and lower tide levels. Its primary geomorphic function is 1) to reduce bottom shear stress from waves and currents at low tide and 2) increase sediment recruitment and retention, which leads to wave shoaling. At low tide, stem flexion 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 infrastructure types in a “layered” approach, reducing wave energy and erosion at common water levels so that landward natural infrastructure (e.g. sand/cobble berm on beach, marsh sill) are able to function optimally during extreme events. Similar to oyster reefs, eelgrass beds provide increased rearing and foraging opportunities for a range of aquatic species and water clarity improvements through enhanced sedimentation.

2.7.1 Setting

Typically found in the low intertidal to subtidal zones of sheltered waters (e.g. coastal estuaries), eelgrass beds thrive on softer, silty sediment on flatter bathymetry. Rapid accretion or frequently disturbed areas can smother the eelgrass. The upper range in suitable elevation is limited by heat stress and bottom disturbance by waves, while the lower range in 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 disturbance 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 nearby to 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 (0.5 acre or less) to determine best growing conditions for long-term eelgrass bed success. Larger-scale restoration projects would be on the order of 1 acre or greater.

2.7.2 Design Guidance & Implementation

Limited detailed guidance on typical design parameters for coastal natural infrastructure, such as alongshore length and orientation, exists for eelgrass beds. This is due to site variability worldwide and within those regions, the overarching importance of site selection. Fonseca et al. (2001) cites site selection as one of the most influential factors in successful seagrass restoration.

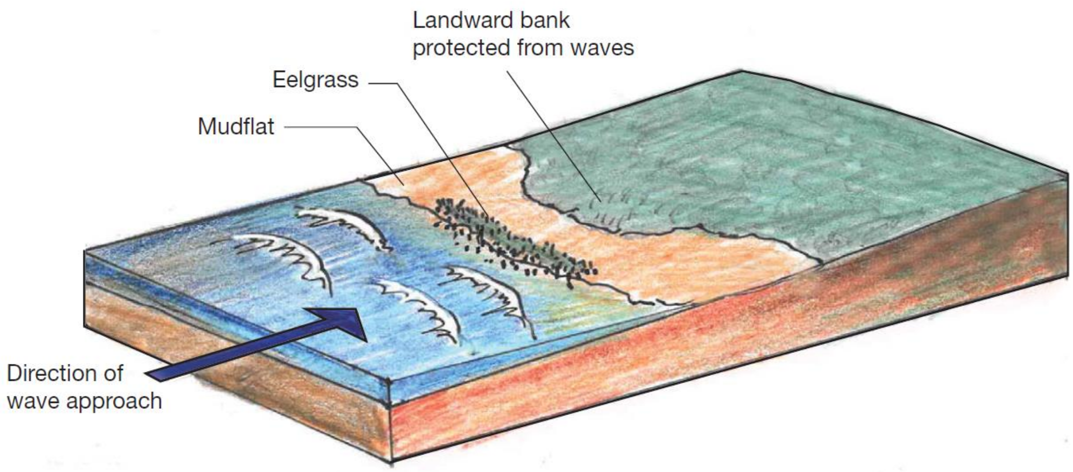

Figure 17. Oblique view of eelgrass bed located in estuarine environment

Similar to oyster reefs, eelgrass bed plantings should be situated perpendicular to the predominant direction where waves arrive from (Figure 17). The lateral extent of backshore coastal feature (e.g. stretch of bank actively eroding from wave attack) would loosely dictate the width of the eelgrass bed. As a first cut, 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 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 beds. Construction costs associated with collecting, preparing and planting eelgrass plugs are approximately $62,700 per acre[2], although total project costs can exceed more than five times that amount (Fonseca et al., 2001). Monitoring, which is conducted over a number of years after installation, typically contributes to 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 eelgrass presence. 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 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). While these effects may not be factored into present decisionmaking, they are relevant to the overall long-term maintenance and use of eelgrass bed in a particular project site. The overall trend of sea level rise is such that suitable depths for eelgrass siting will move with the shoreline.

2.8 Lagoon Mouth Management

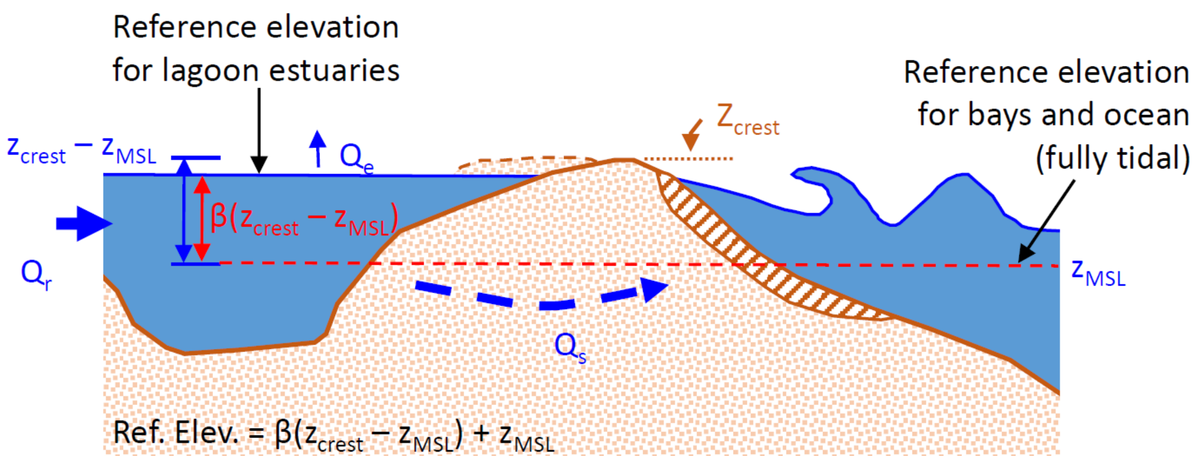

Figure 18. Schematic representation of the lagoon conceptual model in SLAMM

The purpose of this section is to inform the use of the estuarine natural infrastructure guidance for lagoon estuaries. Lagoon estuary water levels are different and typically higher than ocean water levels (Figure 18). The water levels in lagoon estuaries are affected by mouth management, which is typically done to lower water levels for flood

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

control. Hence, lagoon mouth management and resulting water levels need to be understood when considering implementing natural infrastructure or other management actions.

Lagoon estuaries in California cover a range of tidal inlet states, water levels and salinity. As defined by Heady et al. (2014), lagoon estuaries are the most prevalent type of estuary in California and experience mouth closures ranging from days, to months, and potentially years. The mouths of California lagoon estuaries are typically affected by the presence of a barrier beach, which are built by sand and water transport processes in the lagoon-beach system (Figure 19). The barrier beaches mute or completely block tidal propagation into the estuary as well as fluvial discharge from the estuary into the ocean. Thus, lagoon water levels behind the barrier are elevated above the ocean tide range and affect vegetation elevations and wetland habitats. ESA assisted with the development of CA-SLAMM, the update to the model, SLAMM (Sea Level Affecting Marsh Model) for estuaries perched behind beaches. The user is referred to the SLAMM 6.7 Technical Documentation for further instruction on determining the elevation framing for a particular lagoon estuary. Understanding the elevation framing of a lagoon estuary, such as the inundation range, can inform the use of estuarine natural infrastructure within these environments.

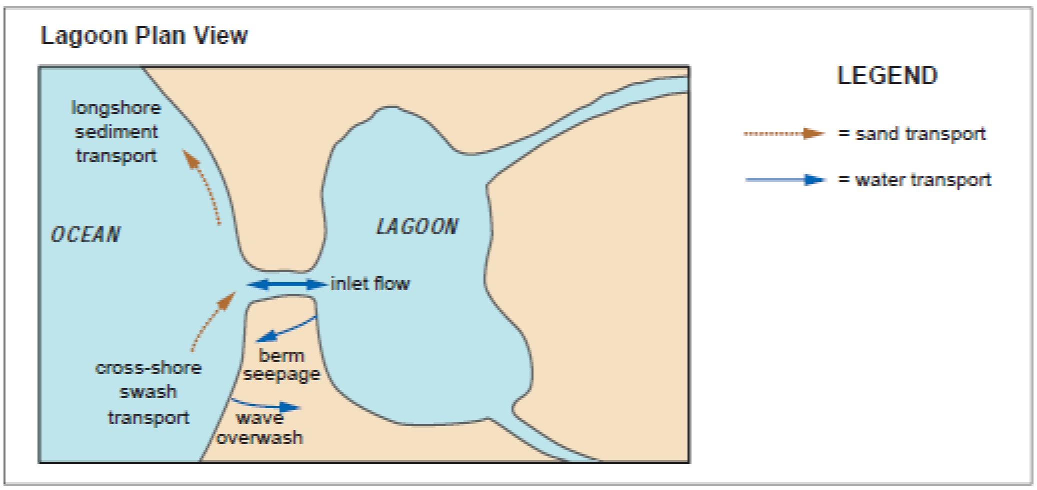

Figure 19. Plan-view schematic showing sand and water transport processes present in a lagoon-beach system

Previous work by Behrens et al., 2015 classifies lagoon estuaries into four subtypes, from greatest to least tidal connectivity: embayment, predominantly open, predominantly closed and drainage outlet. Increased tidal connectivity means higher salinity and lower water levels that are close to or within the oceanic tidal range. Decreased tidal connectivity indicates lower salinity and water levels exceeding the oceanic tidal range. Examples of embayment estuaries, where the tidal range within the embayment is only slightly less than the oceanic tidal range, include Elkhorn Slough and Bolinas Lagoon. Predominantly open lagoon estuaries (e.g. Russian River Estuary, Goleta Slough) close at least once per year for a few weeks to a little over a month. Alternately, predominantly closed lagoon estuaries (e.g. Santa Ynez River Estuary, Carmel River Estuary) have a closed inlet for the majority of the year and open due to an extreme fluvial discharge event or extreme wave overtopping event. Last but not least, the drainage outlet type of lagoon estuary experiences uni-directional flow towards the ocean, since the estuary is perched well above high tides. Examples of this lagoon estuary type include Scott Creek and Laguna Creek.

The conceptual model outlined in the SLAMM technical documentation focuses on the two primary physical processes of inlet dynamics and estuary water balance for open and closed lagoon states (Figure 20). Water levels within the lagoon estuary are affected by tides, fluvial discharge, wave overwash, groundwater seepage and evaporation. Tides impact the lagoon water level disproportionately during open inlet conditions while other factors dominate during closed conditions. The largest outflow component is typically groundwater seepage through the barrier beach or berm.

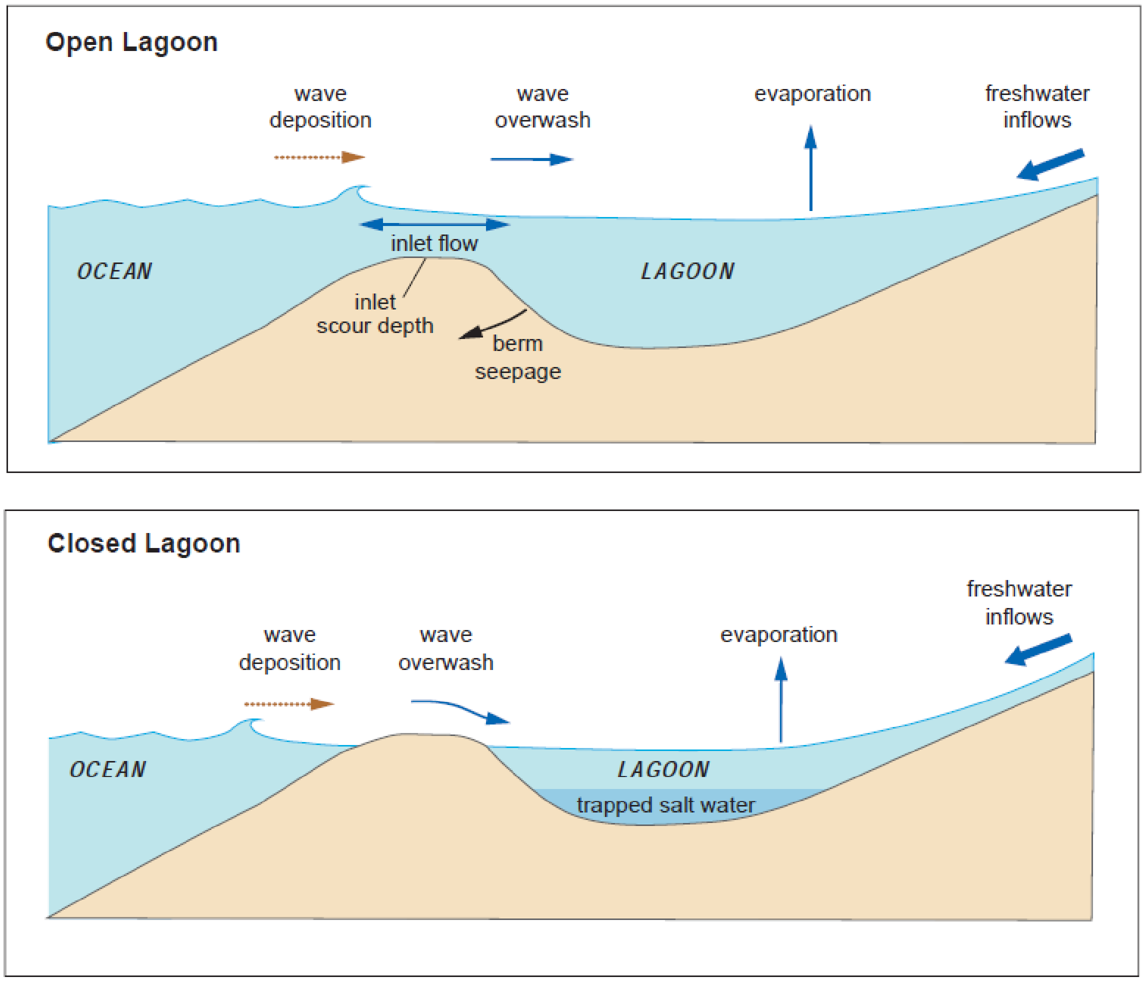

Figure 20. Profile views of physical processes in open (top) and closed (bottom) lagoon systems.

In Figure 18, a value "beta", β , is used to indicate the location of the estuary mean sea level (MSL) above the ocean MSL. β is multiplied by the height of the beach berm above ocean MSL. The resulting elevation can then be applied to inundation range parameters (MLLW, MHHW and the salt boundary, defined as the 30-day high water mark). This elevation can also be estimated by the elevation of vegetation in the estuary (and also bypass the need for estimating β). Similarly, β can be derived from water level measurements in the estuary. In the absence of better information, the SLAMM technical documentation can be used to estimate the value of β (Warren Pinnacle Consulting, Inc. 2016). Note that areas with low water supply and or high losses due to extraction or evaporation may have betas that are lower reference water levels (lower β values) closer to oceanic values. Lower than oceanic values are possible, but these systems are typically hypersaline flats/pannes which are not addressed in this guidance document.

Evaluating the elevation frame using the lagoon conceptual model in CA-SLAMM is meant to help users determine the relevant elevations for implementing the other types of natural infrastructure outlined in the technical guidance in a lagoon estuary environment. These datum Future areas of improvement for CA-SLAMM include, but are not limited to: 1) increased flexibility of lagoon water levels, which may not move in a linear relationship with sea level rise and 2) changes in inlet dynamics due to an increase in inundation range.

2.9 Managed Retreat

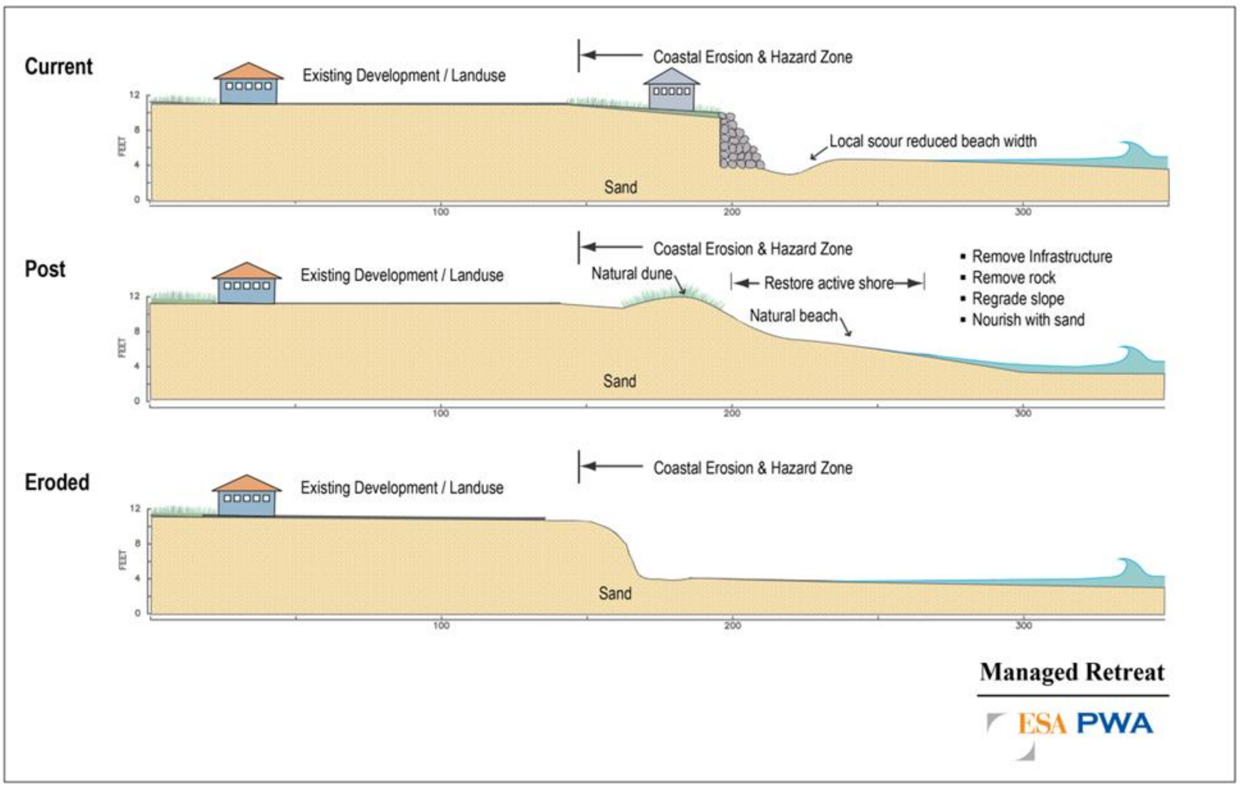

Figure 21. Managed retreat in its simplest form consists primarily of backshore restoration by removal of built assets. (ESA PWA, 2012)

Managed Retreat and Realignment is a coastal zone management strategy applied primarily where development is located within coastal hazards zones. Therefore, managed retreat can be thought of as a "landward realignment" of developed assets and land uses. Managed retreat can also be thought of as a "coastal restoration" of the natural coastal flood plain, akin to restoration of tidal wetlands previously diked for agriculture or filled for development. The concept of Managed Retreat is depicted in Figure 21. Figures 22 and 23 describe more nuanced version of managed retreat developed to adapt to sea-level rise.

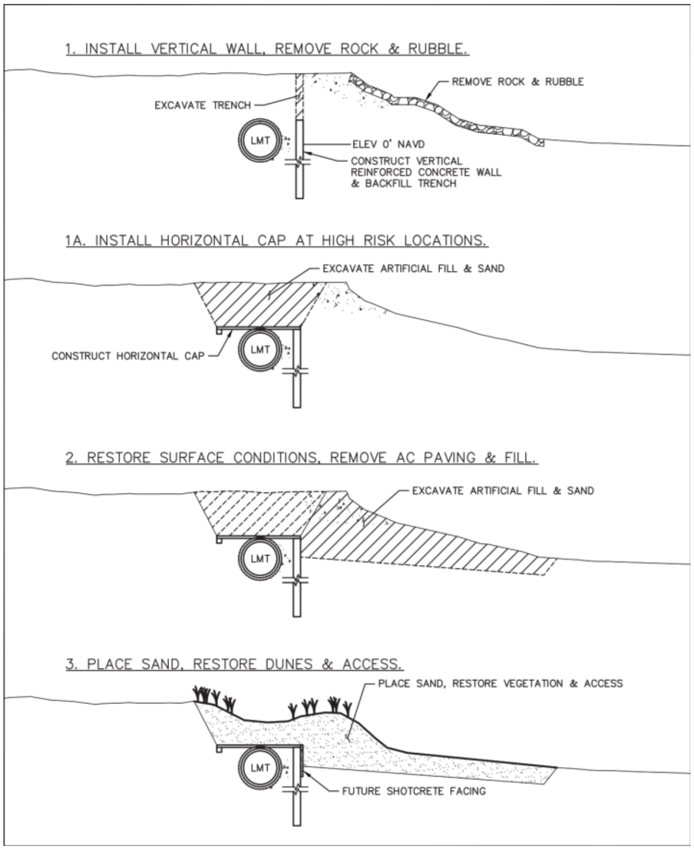

Figure 22. The Ocean Beach Master Plan (San Francisco, California) uses a Managed Retreat strategy with a "hybrid" of adaptation measures (armoring, armoring removal, sand placement, restoration) to maintain the functions of a critical wastewater element (Lake Merced Transport tunnel, "LMT" in the figure) while achieving multiple other objectives. (ESA PWA and SPUR, 2015)

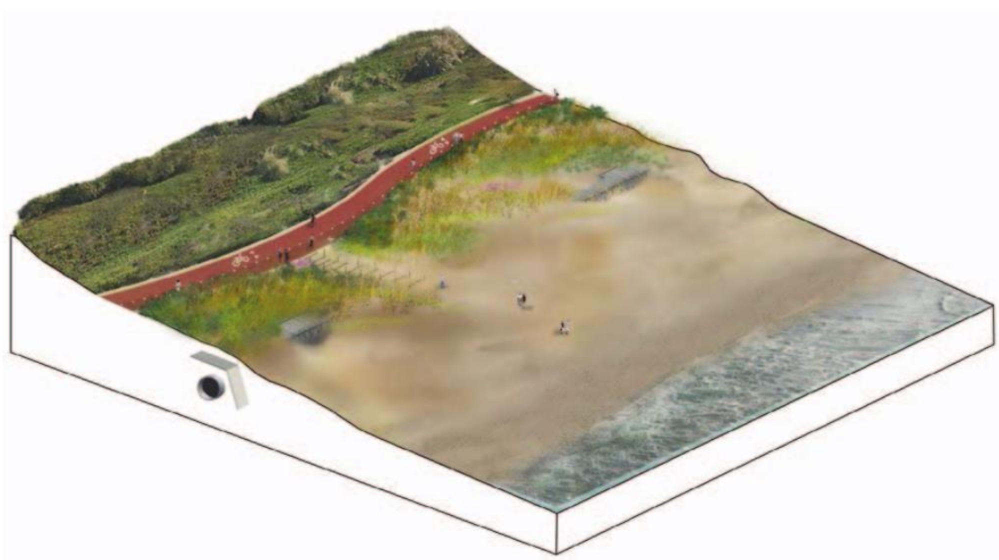

Figure 23. A rendering of the enhanced Ocean Beach shore showing the wastewater tunnel and armoring (see Figure 21) overlain by a restored shore. Graphics by AECOM.

With highly accelerated sea-level rise, it is possible that natural processes such as coastal erosion may not be sufficient to maintain the existing shore form (e.g. beach, marsh), and mechanical conversion of the back shore, whether the backshore is developed or not, may be desirable. Indeed, most contemporary coastal restoration projects are providing space to accommodate future sea levels. Planning and construction cost estimates for a managed retreat project vary depending on the land value, extent of development and infrastructure present; therefore, no estimate per hectare is provided in the managed retreat technical guidance. The reader is referred to the Surfers' Point Managed Retreat Case Study to gain an idea of costs associated with a managed retreat project of that size and scope.

In most cases, however, we're interested in managed retreat as a means of reducing risk through landward relocation of assets and establishment of natural infrastructure benefits of flood and erosion protection of our assets. Consequently, the concept of "necessary space" for the shore arises. By definition, managed retreat is pursued when the available space is less than the space necessary to achieve natural functions: in other words, development has encroached upon the shore to the point that risks are not acceptable. For a "stable" shore, one that is not migrating landward, the damage risk may be due to temporary conditions that are short lived and reversible: For example, the landward reach of waves and erosion during extreme events such as during "El Niño winters" when the cumulative effect of elevated water levels and waves narrow the beach and wave runup reaches farther landward. For these stable shores, the asset retreat distance is defined by the anticipated landward extent of seasonal shore migration (e.g. the beach typically narrows in the winter in response to more energetic waves), the additional shore migration that occurs during a single or series of storms, plus the landward extent of wave runup propagating overland. For a shore that is migrating (aka "eroding"), the required space stays the same, but the coastal hazard zone of erosion and wave action migrates landward at the erosion rate. Hence, relative to the fixed line of development, the required retreat distance increases with time for eroding shores. Finally, sea-level rise can cause a landward migration of the shore and therefore increases the required set-back distance for both stable and migrating shores. The California Coastal Commission and others have provided guidance on computing the required "setbacks" to provide adequate space for natural shores (California Coastal Commission, 2015).

Of course, the problem is that the "required" space is often not only larger than the available space, but it is also larger than the space which can be generated via consensus, given substantial investments and expectations associated with built assets and property. Managed Retreat is a strategy by which benefits can be achieved without complete restoration of the shore. Further, Managed Retreat is predicated upon adaptation, resulting in the appropriate level or risk and rate of adjustment for a community. Also, Managed Retreat can be accomplished with one or more other hazard mitigation measures including shore armoring which may be needed to "buy time" for planning, design, funding, etc. needed result in retreat. Often, therefore, the actual retreat is in "steps" that are greatly influenced by anthropogenic factors such as property lines, ownership, land uses and governance.

For the purposes of these natural infrastructure guidelines, managed retreat is most pertinent when the available space between the shore and development reduces the feasibility of a natural infrastructure type that is otherwise attractive to the community. In this situation, providing more space for natural infrastructure will increase the potential feasibility of the typology. These guidelines are therefore focused on assisting the user with assessing the amount of retreat needed to increase the feasibility of a natural infrastructure type for a given location.

Additional considerations related to designing a managed retreat strategy are outlined in Appendix D.

3: Conclusions and Future Directions

The implementation of coastal natural infrastructure adaptation measures along California's coasts will only increase if coastal decision makers and managers become more familiar with both the options available and the technical requirements needed for successful implementation. This report represents a major attempt to collate existing information in a way that effectively closes this familiarity gap.

Although defining the term "natural infrastructure" is a seemingly a simple task. Our engagement with a diverse set of stakeholders illustrated how the mandates and specific interests of the stakeholders leads to a focus on different aspects of the costs and benefits of natural infrastructure approaches. By agreeing on a common definition, the stakeholders also agree to a common understanding of what the natural infrastructure measures need to achieve. Ultimately this will lead to the implementation of adaptation measures that actually improve or enhance ecosystem function while also providing sea level rise and flooding adaptation benefits.

Although are case studies illustrate the breadth of coastal natural 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. The technical guidance we provide should facilitate greater implementation by lessening the barriers practitioners face when applying new approaches. However, our attempts to make the technical guidance spatial through the blueprints demonstrates that there is a lack of spatial data available that can be used to adequately evaluate the suitability of all adaptation measures at the site level. The creation of reliable spatial data representing important constraints on the siting of natural infrastructure options would enable more refined estimates of where natural infrastructure measures are appropriate and thus ultimately more implementation. Finally, as implementation of natural infrastructure increase, it will be important to monitor the success of implemented measures and disseminate the results so that practitioners can learn from early adopters.

4: 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-stabilizaing 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.

California Coastal Commission (2015). Sea Level Rise Policy Guidance: Interpretive Guidelines for Addressign 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.

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.

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.

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.

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.

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

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 (2015).

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.

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.

Stanford Law School Coastal Policy Lab Practicum (2015), 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/.

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.

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

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APPENDIX B:
Literature Defining Natural Infrastructure

Source	Definition
The Nature Conservancy (Byington 2015)	Natural alternatives to built infrastructure- healthy ecosystems that provide critical services.
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.
IUCN (Ozment et al., 2015)	The networks of land and water that provide services to people.
Rockefeller Foundation (2013)	The interconnected network of natural and undeveloped areas needed to maintain and support the ecosystems that provide a wide array of environmental, health, and economic benefits, including but not limited to mitigating climate change impacts and sustaining clean air and water (US EPA).
IUCN (Cohen-Shacham et al., 2016)	Approach seen as restoring structure, function and composition of ecosystems to deliver ecosystem services. Used only at a landscape scale.
Temmerman et al. (2013)	It is applied at locations that have sufficient space between urbanized areas and the coastline to accommodate the creation of ecosystems.
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.
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.
Sutton-Grier et al. (2015)	Healthy ecosystems
Langridge et al. (2014)	"coastal ecosystems"
IUCN (Herr and Galland 2009	EbA is "ecosystems as natural risk reduction mechanisms" "Ecosystem-based Adaptation (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.

Munang et al. (2013)	EbA is 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. It is an approach that is applicable across both developed and developing countries. Ecosystem-based approaches address the crucial links between climate change, biodiversity and sustainable resource management and, by preserving and enhancing ecosystems, enable society to better mitigate and adapt to climate change [2]. Hence the key tenet is the need to protect the ecosystems that provide the essential 'life support systems' (ecosystem services) that we all depend on.
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.
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."
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.
Vignola et al. (2009)	The adaptation policies and measures that take into account the role of ecosystem services in reducing the vulnerability of society to climate change, in a multi-sectoral and multiscale approach. EBA involves national and regional governments, local communities, private companies and NGOs in addressing the different pressures on ecosystem services, including land use change and climate change, and managing ecosystems to increase the resilence of people and economic sectors to climate change.

Levin and Lubchenco (2008)	EBM for the oceans is the application of ecological principles to achieve integrated management of key activities affecting the marine environment. EBM explicitly considers the interdependence of all ecosystem components, including species both human and nonhuman, and the environments in which they live. The goal of marine EBM is to protect, maintain, and restore ecosystem functioning in order to achieve long-term sustainability of marine ecosystems and the human communities that depend on them.

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:

Additional Considerations in Designing a Managed Retreat Strategy

The dynamic coastal zone can conflict with structures, habitation, and facilities and the associated risk is related to proximity. Therefore, a direct way to reduce risk is to realign landward (retreat). Sea level rise will increase this "proximity risk" over time as the shore attempts to move landward. There is a fundamental conflict between fixed property / infrastructure and migrating shore: Traditional approaches (armoring – "holding the line") have net detriments over the longer term by progressive encroachment of assets into the natural shore, as well as increased loadings and damage potential, including catastrophic damages.

The managed retreat strategy includes the following characteristics:

- Removes development to protect public safety and to reduce the risk of damages
- Maintains natural shores and their ecologic, recreational, and aesthetic attributes
- Allows implementation over time, consistent with practical needs and priorities of communities
- Can employ all other coastal zone management measures, including development setbacks, conservation and rolling easements, armoring and beach nourishment and can include combinations of these measures over time and located where needed
- Is based on coastal processes and projection of future conditions
- Requires community involvement
- Is innovative relative to traditional property ownership laws, planning practice, and general government practice

The following steps are used to establish an appropriate retreat distance:

1. Estimate the "natural" shore condition
2. Define coastal hazard zones (flood and erosion); for existing and future conditions; consider
    a. sediment budget
    b. sea level rise / climate change.
3. Assess asset vulnerability and identify priorities
4. Assess feasibility (ownership, costs, benefits, alternatives)
5. Develop a Managed shore retreat / realignment plan (aka Adaptation Plan)
6. Phased project implementation, and
7. Monitoring and adaptive management.

For the purposes of these guidelines and application of the Blueprint, the following steps are recommended:

1. Review the feasibility ranking provided for the selected natural infrastructure type at your location: If the feasibly ranking is lower than desired (eg. Low or moderate), you may wish to consider managed retreat;
2. Look at the required distances for a higher feasibility ranking, also provided by the blueprint: Can you achieve these retreat distances?
   a. If yes, then you may wish to further evaluate the natural infrastructure type within the context of landward realignment / managed retreat.
   b. If no, or you're not sure, you may still want to consider how much retreat is potentially feasible, recognizing that incremental natural infrastructure benefits may exceed the incremental costs associated with the limited retreat.

APPENDIX E:

Development of Blueprints for Deploying Natural Shoreline Infrastructure

E.1 Background and Purpose

Coastal California decision makers and managers identified an important gap in their understanding specifically around identifying suitable locations for different types of coastal natural infrastructure (Stanford Law School Coastal Policy Lab 2015). Stakeholders expressed a demand for spatially explicit examples of where natural infrastructure could be implemented, demonstrating how to apply the technical guidance provided in Section 3. However, the stakeholders also indicated that they are not necessarily looking for the single adaptation approach for any given stretch of coast and that the development of adaptation strategies would need to rely on locally-collected data and site-specific models and plans. Based on this feedback, our team developed a set of screening criteria that illustrate the broad suitability of the coastal natural infrastructure approaches we presented in section 3 (Figure E1), and then applied the criteria in two pilot regions where we could leverage existing spatial data: Monterey Bay and Ventura County.

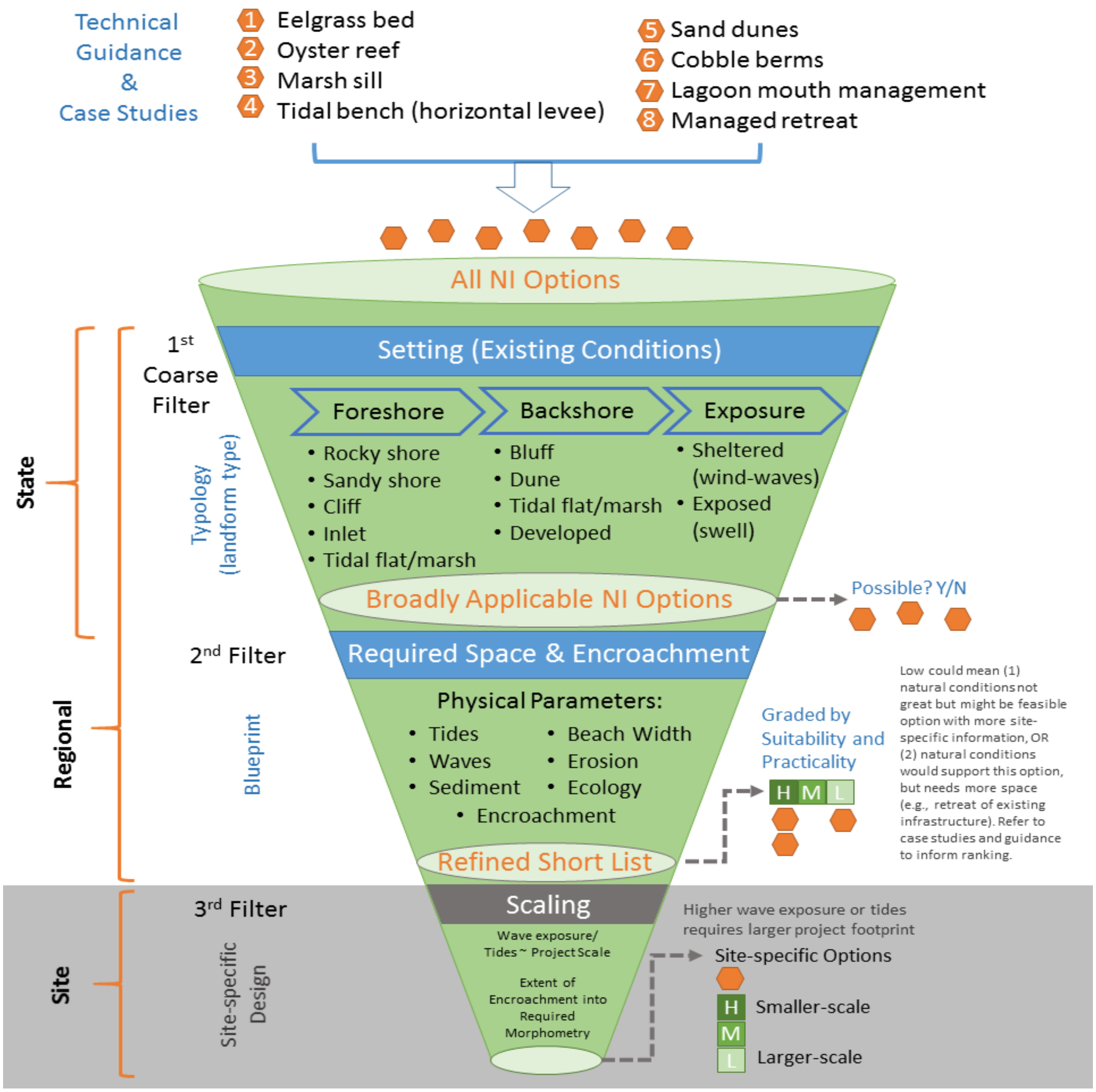

Figure E-1. A conceptual process used to filter a suitable set of coastal natural infrastructure options given a specific set of environmental constraints. The filter starts out broad starting with the general foreshore, backshore and wave exposure type. Data for this level is available at the state and regional level. 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 project specific data will need to be collected to support a specific project design.

We distilled the detailed technical guidance provided in Section 2 of this report into criteria that could be evaluated and mapped with existing spatial data. 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 infrastructure type (e.g. cross-shore width, alongshore length) with thresholds to indicate low, medium and high suitability rankings for each natural infrastructure type.

The tools we developed take advantage of existing data to illustrate how to apply our technical guidance to evaluate the site suitability of individual shoreline stretches. The goal was to develop an 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. Our intent was that the broad level screening tools can be used to narrow the list of potential adaptation options that would then be assessed with more site-specific information.

For the open coastal zones, we utilized spatial data for Monterey and Ventura counties in 500m alongshore block segment units. Each block unit was attributed with data on foreshore and backshore types, local and regional planform types, armoring information, 100-year TWLs and beach widths. These data were condensed from previous GIS analysis conducted by ESA (2013) and ESA (2015). 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.

E.2 Natural Infrastructure Siting Thresholds

Based on the technical guidance in Section 2, we developed thresholds for different parameters to assess the suitability of the environmental setting for five of the natural infrastructure elements we considered (Table E-1).

Table E-1. Thresholds used for ranking the suitability of natural infrastructure measures.

Natural 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 (cross-shore) by 30 meters (along-shore)**	Available space < Dune footprint + beach width of 30 meters = 15 m + 30 m = 45 m	Available space > Dune footprint + beach width of 30 meters = 15 m + 30 m = 45 m	Available space > Dune footprint + beach width of 60 meters.
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 on exposed coast, 23 m on sheltered coast**	Available space < Berm footprint + beach width of 30 m = 25 m +30 m = 55 m	Available space > Berm footprint + beach width of 30 m = 25 m + 30 m = 55 m	Available space > Berm footprint + beach width of 85 m = 25 m + 60 m
Tidal Bench *Location*: Estuarine environment - intertidal zone *Minimum Footprint*: Based on bench width, bench crest, shoreline slope. ● Bench width = **10 m 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	Available cross-shore space = Bench footprint between 10 m and 20 m	Available cross-shore space > Bench footprint = 20 m

<table>
<tr><th>Natural Infrastructure Siting Guidelines</th><th>Low Ranking</th><th>Medium Ranking</th><th>High Ranking</th></tr>
<tr><td>Marsh Sill
Location: Estuarine environment
Minimum Footprint: Based on sill width, crest, rock slope.
Marsh width behind slope = Minimum width between 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 1' above MHW
Sill Toe Elevation = MLLW
Alongshore length MINIMUM of at least 10 m.
Cross-shore length MINIMUM of at least 3 m</td><td>Available cross-shore space < Sill footprint (3 m) + Marsh width behind slope (10 m)</td><td>Available cross-shore space = Sill footprint between 3 m and 10 m + Marsh width behind slope (10 m)</td><td>Available cross-shore space > Sill footprint (10 m) + Marsh width behind slope (10 m)</td></tr>
<tr><td>Eelgrass Beds
Location: Low intertidal to subtidal zone.
Minimum Footprint: Appropriate siting requires knowledge of ecological factors in subtidal area. For purposes of siting guidance we assume a MINIMUM of 30 m cross-shore width and a variable alongshore width. See notes.</td><td colspan="3">The successful implementation of eelgrass beds depends on a number of ecological factors, 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 instead to the user may be to show where existing eelgrass projects/patches are located in Monterey and Ventura Counties. 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 0.5 acres (or ~2100 square meters) as a small-scale plot test, which is suggested for any site looking to implement eelgrass.</td></tr>
<tr><td>Oyster Reefs
Location: Low to mid-intertidal - constructed nearshore reefs. Low intertidal to subtidal - constructed offshore reefs.
Minimum Footprint: Appropriate siting requires knowledge of bed composition in intertidal / subtidal zones as well as water quality factors (e.g. salinity, tempearture, dissolved oxygen content, etc.). Oysters generally thrive within +/- 2 ft range of MLLW. See notes.</td><td colspan="3">Similar to eelgrass beds, the applicability / appropriateness of oyster reefs as natural 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.</td></tr>
<tr><td>Lagoon Mouth Management
Location: Lagoon-beach system.</td><td colspan="3"></td></tr>
</table>

Natural Infrastructure Siting Guidelines	Low Ranking	Medium Ranking	High Ranking
Managed Retreat See notes.	These are broader strategies or more a set of techniques rather than an measure that has a 'footprint'.		

E.3 Application of Thresholds to Outer Coast Measures

Our rankings of natural 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 (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.

E.3.1 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. We classified shoreline blocks with beach widths of ≤ 45 m as low suitability, beach widths > 45 m < 60 m moderate suitability and beach widths ≥ 60 m as high suitability. These criteria assume a minimum constructed dune width of 15m plus a minimum 30m buffer of fronting beach to dissipate wave energy. We also classified any block segment that had an alongshore length of <30 m 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.

E.3.2 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. We classified shoreline segments as: low if existing beach width was ≤ 55m; as moderate where existing beach width > 55 m < 85 m; and high where existing beach width was ≥ 85 m. This assumes a minimum cross-shore space requirement of 25m for the footprint of the cobble berm itself plus a 30m buffer to dissipate wave energy. We also classified any block segment that had an alongshore length of <100 m as low suitability.

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

E.3.3 Managed Retreat Outer Coast

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 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 E2).

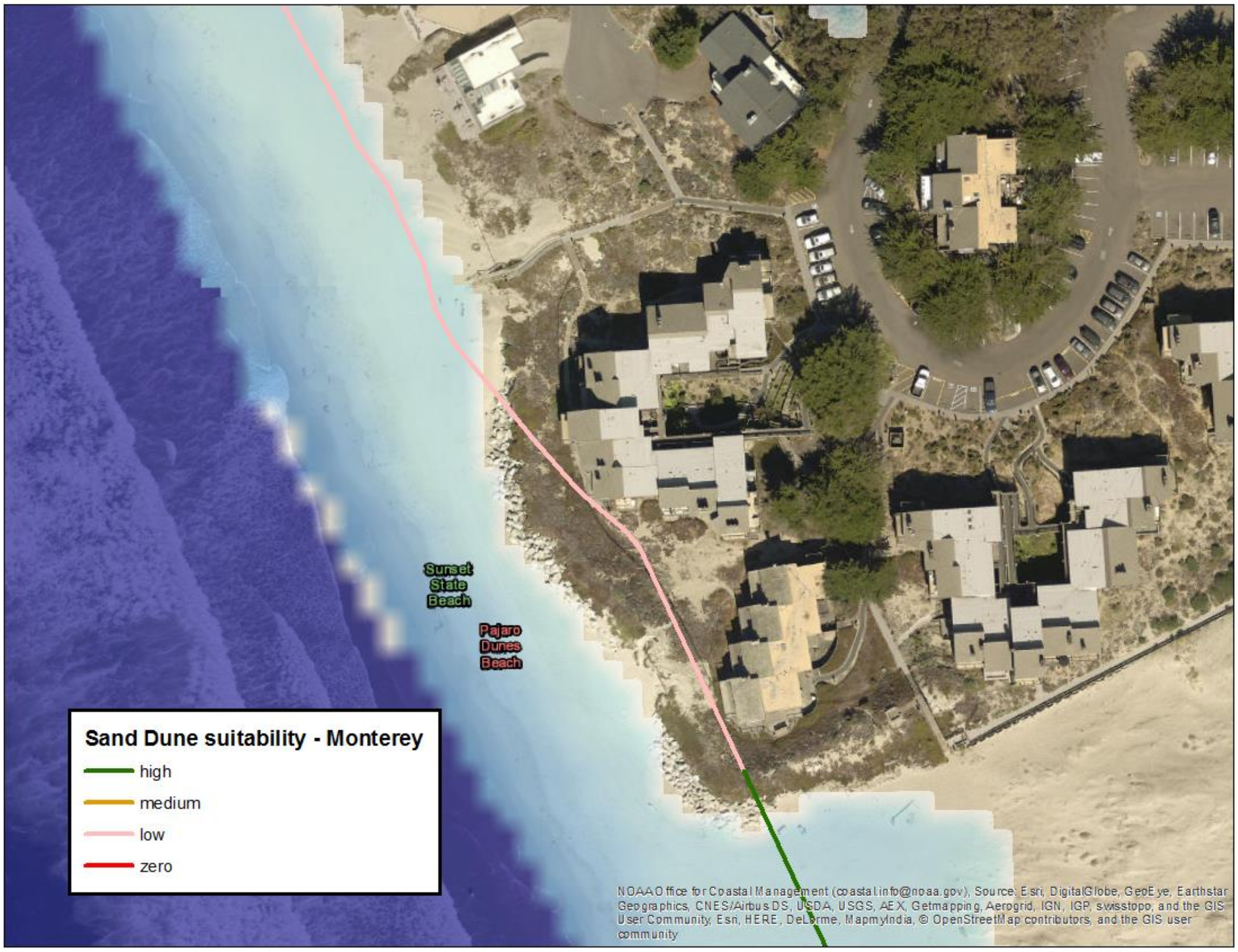

Figure E-2. Suitability for sand dune natural infrastructure measures up coast of the Pajaro river mouth in Santa Cruz County. The blue shading indicates the inundation extent with six feet of sea level rise.

Our analysis indicates that creating 11 – 20 m of extra beach width along the shoreline could increase the suitability for sand dunes as natural infrastructure adaptation measures (Figure E3).

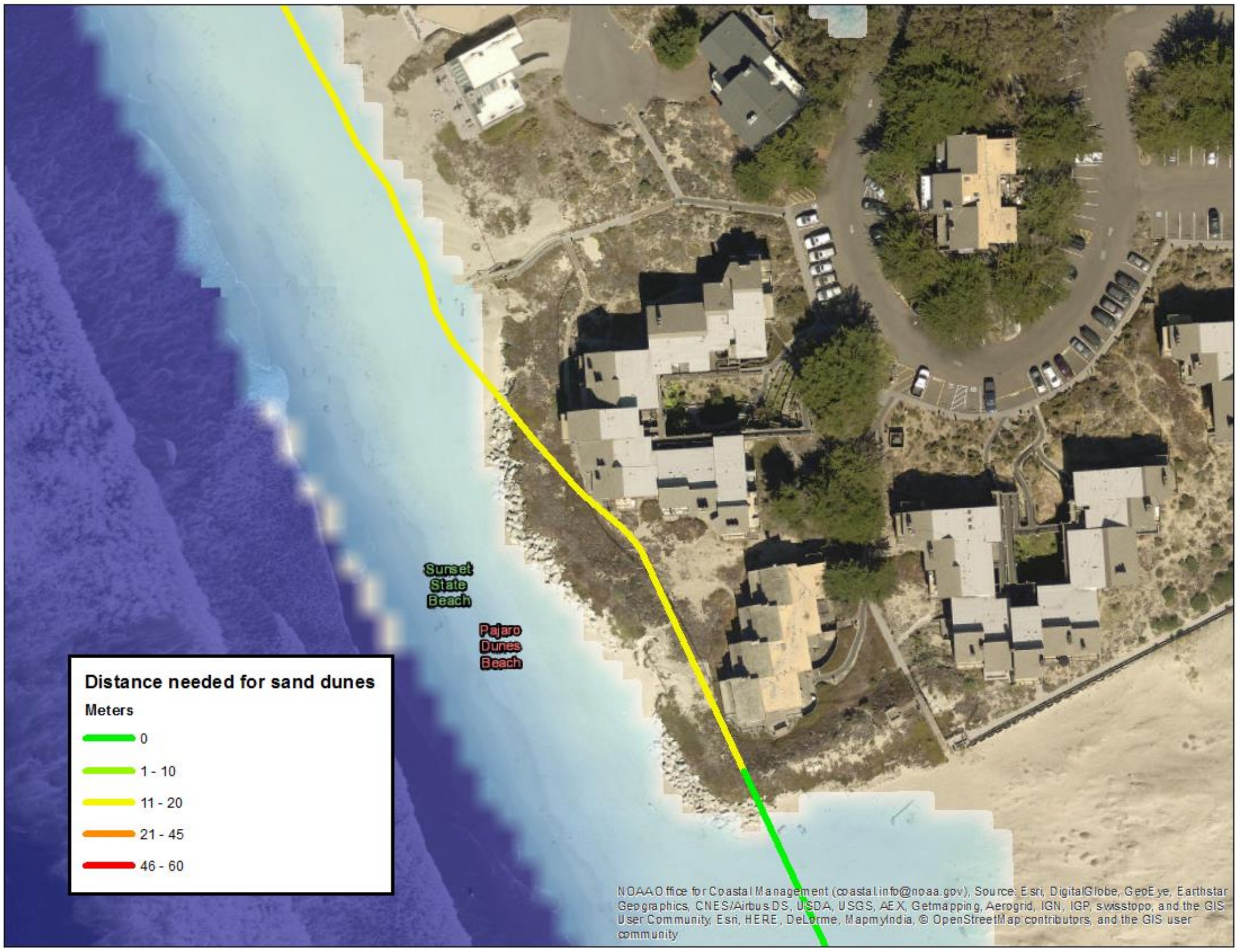

Figure E-3. The additional beach width needed to increase the suitability of sand dunes from low to high just up coast of the Pajaro river mouth in Santa Cruz County.

E.4 Application of Natural Infrastructure Thresholds to Estuary Measures

E.4.1 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 3m in the cross-shore direction and 10m in the along-shore direction. Ideally, cross-shore widths of around 10m 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 10m. 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 10m 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 >10m wide (across mudflat habitat type), “moderate” suitability if they were between 3-10m wide, and “low” suitability if ≤3m.

E.4.2 Tidal Bench

Perhaps more than other natural 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 infrastructure options considered in this report. We ultimately decided not to map the suitability for the tidal bench measure for this report.

E.4.3 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 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.

Wasson et al. (2014) identified a zone of oyster suitability at elevations between -0.61 and 0.61 m MLLW as suitable for the persistence of Oysters (Figure E4). We indicate declining suitability from -0.61- -0.91 m MLLW and 0.61 – 0.91 m MLLW and then unsuitable habitat with elevations < - -0.91 m MLLW and > 0.91 m MLLW.

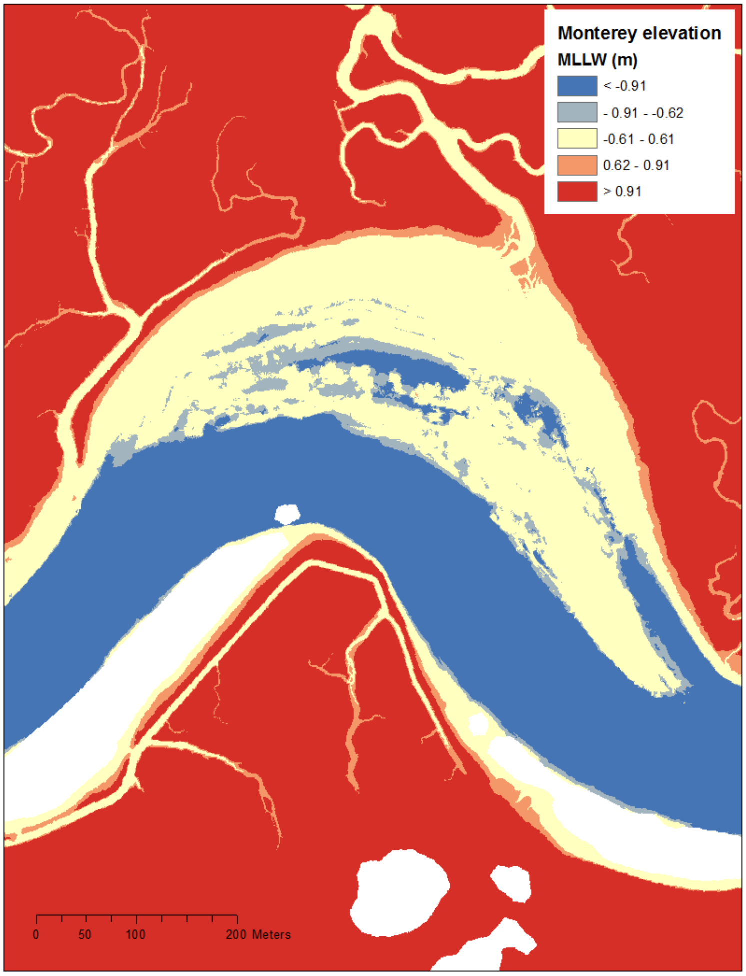

Figure E-4 Elevations suitable for Oyster persistence in Elkhorn Slough. Suitable elevations are between -0.61 and 0.61 m MLLW. Red areas in the map are too high for Oyster establishment and persistence and blue areas are too low.

Surveys in the San Francisco Estuary have found that eel grass beds occur between -3.00 and 0.40 m MLLW (Boyer & Wyllie-Echeverria, 2010). However, surveys have recorded most (98 %) eel grass in the estuary occurring between -1.77 and 0.40 m MLLW (Boyer & Wyllie-Echeverria, 2010). Further, 94 % of observations found eel grass beds between -1.60 and 0.00 m MLLW (Boyer & Wyllie-Echeverria, 2010). We used this zones to map out suitable elevations for eel grass beds (Figure E5).

If data are available, a next step would be to further constrain the mapped suitable conditions by salinity, dissolved oxygen, or suspended sediment concentrations. Conditions where oysters and eel grass are established within an estuary can help with identifying the suitable parameters for establishing populations at new sites.

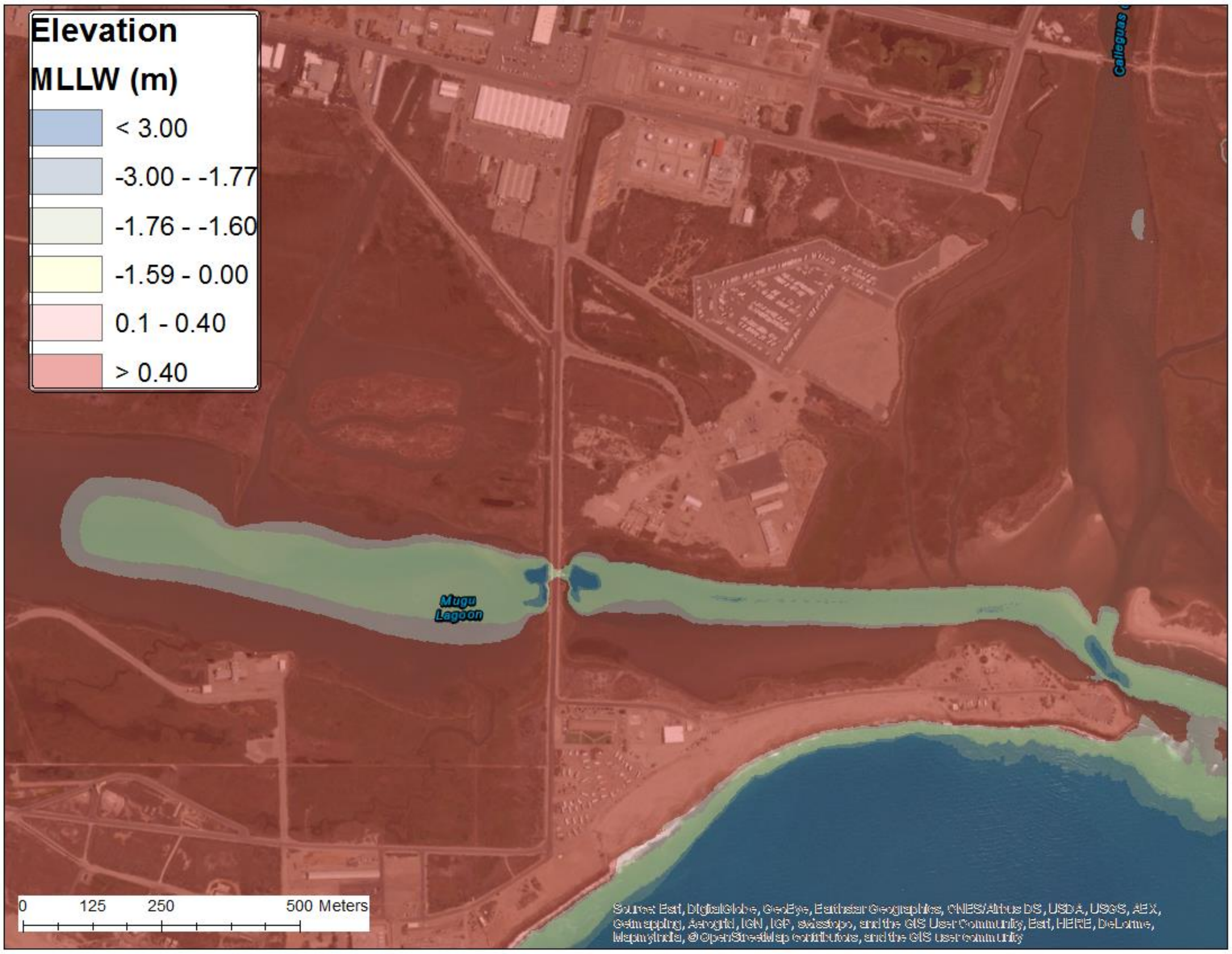

Figure E-5. Elevations surrounding Magu Lagoon in Ventura County. Eel grass beds can occur between -3.00 and 0.4 m MLLW. We assume the highest suitability for eel grass beds to be between -1.59 and 0 m MLLW. Red areas in the map are too high for eel grass bed establishment and persistence and blue areas are too low.

APPENDIX F:

Case Studies of Natural Shoreline Infrastructure

This Appendix is excerpted from the full report *Case Studies of Natural Shoreline Infrastructure in California,* available at http://coastalresilience.org/case-studies-of-natural-shoreline-infrastructure-in-coastal-california/.

F.1 Background and Purpose

To address the gap in familiarity with natural infrastructure and the lack of technical guidance to aid decision-makers and engineers in the appropriate application of different strategies for different situations, this report summarizes natural infrastructure projects for a range of settings in coastal California. Each case study covers the background, permitting, planning, implementation, performance, and key lessons learned from each project in order to provide the critical information needed to implement successful adaptation strategies to address coastal issues, and inspire other communities by highlighting the lessons learned.

F.2 Case Studies Selection

A Technical Advisory Committee was charged with selecting a set of projects to highlight as case studies of natural shoreline infrastructure, and was composed of 34 representatives from local, state, and federal government agencies, non-governmental organizations (NGOs), and environmental consulting firms. Collectively, a list of 60 projects in varying stages of planning, implementation, monitoring and completion addressing a wide range of issues was compiled (Appendix 1). Most completed projects were properly categorized as restoration projects that had shoreline protection benefits; in other words, most of the projects were not driven primarily by shoreline protection objectives. However, it made sense to take shoreline management lessons from innovative restoration strategies, many of which can and should be incorporated into plans for regional coastal resilience.

Five projects that spanned the California coast and represented different coastal settings and corresponding approaches were selected for the purposes of this report. From South to North these include:

- Seal Beach National Wildlife Refuge Thin-layer Salt Marsh
- Sediment Augmentation Pilot Project,
- Surfers' Point Managed Shoreline Retreat Project,
- San Francisco Bay Living Shorelines: Nearshore Linkages
- Project,
- Hamilton Wetland Restoration Project, and
- Humboldt Coastal Dune Vulnerability and Adaptation Climate Ready Project.

These case studies were designed to be useful examples for coastal planners, local governments, and others working on solutions and making decisions regarding climate-related coastal hazards. Summaries, key lessons learned, and project details can be found at the beginning of each case study, making it simple for readers to decide if they want to read further for a more in-depth account of project processes and outcomes. The Technical Guidance component of the Identification of Natural Infrastructure Options for Adapting to Sea Level Rise report is a useful companion to these case studies, and provides additional guidance and technical details to inform site selection and implementation of the strategies highlighted here.

Figure F-1: Five projects were selected to highlight a range of settings and natural shoreline infrastructure approaches in coastal California.

F.3 Lessons Learned

A number of overarching lessons were identified through the process of developing the case studies and interviewing those who implemented the 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.
- Volunteers can 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, funding and accomplishing significant post-project monitoring to capture and learn from 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.

F.4 Seal Beach National Wildlife Refuge Thin-layer Salt Marsh Sediment Augmentation Pilot Project

F.4.1 Summary

Coastal marshes are important natural buffers to storms, high tides, and rising sea level and provide many additional benefits to numerous native and endemic species including threatened or endangered species. Extensive sea level rise modeling by U.S. Geological Survey (USGS) indicates that Seal Beach National Wildlife Refuge (Fig. F-2) 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 (USFWS) is piloting a method involving the application of a thin layer of dredge sediment on the surface of the marsh. The goal 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 raised the site elevation by about 8.5 inches, 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.

Figure F-2: The project site is located at the Seal Beach National Wildlife Refuge in Orange County.

F.4.2 Site History

The mission of the Seal Beach National Wildlife Refuge (SBNWR) is the conservation and recovery of endangered species, migratory birds, and their habitat. Specifically, SBNWR supports the federally endangered California least tern (*Sternula antillarum browni*), light-footed Ridgway's rail (*Rallus obsoletus levipes*), and federally threatened Western snowy plover (*Charadrius alexandrinus nivosis*).

Due to subsidence from oil and water extraction and natural tectonics, lack of sediment accretion and rising sea levels, the marsh—including all available nest space—is now regularly flooded at high tides (Fig. F-3). High rates of inundation and exposure to high salinity water stunts the growth of Spartina, the primary habitat-providing plant. Additionally, the Refuge is surrounded on all landward sides by roads necessary for Naval base operations, preventing migration of the marsh to higher ground. SBNWR is experiencing relative sea level rise at a rate three times higher (6.23 mm/yr) than similar Southern California coastal marshes that are not experiencing subsidence.

Figure F-3: Refuge before sediment augmentation at mid-tide (left) and high tide (right) showing complete tidal flooding of nesting habitat for endangered bird species. Photo credit: Rick Nye.

F.4.3 Objective

The goal of this pilot project was to test the effectiveness of thin layer deposition of sediment to reduce inundation and improve marsh habitat at SBNWR, with the possibility of expanding to other Pacific Coast marshes. This is part of a broader effort by wetland managers, agencies, and scientists to evaluate the effectiveness of thin-layer sediment augmentation to ensure long-term sustainability of coastal marshes along the Pacific Coast. Metrics of success include: (1) achieve at least 3 inches increased elevation of the marsh plain after 2 years, (2) increase cordgrass (*Spartina*) height, (3) prevent soil carbon loss, (4) promote a biodiverse and abundant invertebrate community, and (5) increase foraging and nesting resources for Ridgway's Rails and other species of interest.

F.4.4 Design

Within the 565-acre intertidal marsh at the refuge, a 16-acre site was selected, on which the team planned to place 10,000-13,500 cubic yards of sediment to raise the site by 10 inches. The 6 acres not receiving sediment were designated as buffer zone and hay bales and other sediment capture materials were placed at the border of the 10-acre site. However, the plan was modified midway through because a sediment shortage prevented application to the full 10 acres. The available sediment was enough to apply 16,875 cubic yards to raise 7.87 acres by about 9 inches (see Implementation section). The sediment source was a maintenance-dredging project in the Sunset/Huntington Harbor conducted by Orange County Parks from which sediment was hydraulically pumped to the project site (Fig. F-4). Pre-sediment application monitoring was conducted to document the existing biological and physical conditions on the site and five years of post-sediment application monitoring. The project team hypothesized that vegetation would reestablish itself by dispersal or vegetatively from buried rhizomes, and no active planting would be necessary. Additionally, the refuge installed field cameras to produce time-lapse documentation of the site. All activities required coordination between Refuge staff, the U.S. Navy, the County, and the sediment augmentation contractor Curtin Maritime, in addition to the researchers accessing the site for monitoring.

Figure F-4: Pipeline route from dredge site to augmentation site at the Refuge. The Nearshore Sediment Placement site was used in the larger dredging project and not the Seal Beach project.

F.4.5 Implementation

The parties completed pre-augmentation monitoring and surveying between October and December 2015. The site was prepared prior to sediment application by placing hay bales secured with rebar and wooden stakes around the edges of the augmentation site with a 50-foot buffer edge. The hay bales were a precaution meant to contain sediment in the intended location and reduce runoff into channels to protect water quality, especially in areas where there is eelgrass. Wooden grade stakes were placed across the site in a 10m by 10m grid, and each was marked at 10 inches above the starting grade to act as a guide for sediment depth. The Refuge sourced sediment from a nearby Orange County Parks channel-dredging project. Sediment application began in January 2016 with an 8-inch diameter dredge and the sediment contractor tested several nozzle types within the test area, including round, round with deflector, oval, and spoon shaped. The sediment slurry turned out to have a much lower silt to sand ratio (expected 45% sand, 43% silt and 12% clay and got 84% sand, 8% silt, and 8% clay) than initial grain size analysis indicated. The slurry ended up filling the site like a bathtub, resulting in thicker areas where there had been dips or ponds and resulting in not enough dredge sediment to cover the entire 10-acre site. Accordingly, the team reduced the overall size to 7.87 acres, prioritizing areas that contained research plots, and applying 16,875 yd^3 of sediment in total. The hay bales worked well to contain sediment except in places near channels where scouring was observed and additional measures were taken to contain sediment using sand bags, and geotextile fabric. An air horn and cracker shells were used to encourage birds to leave the spray zone, however they tended to return to forage on invertebrates in the sediment slurry and were not harmed. The last day of sediment application was April 4, 2016, although there was a considerable amount of garbage transferred along with the dredge spoils, which needed to be cleaned up. Post-construction monitoring began on June 1, 2016.

Figure F-5: Augmentation site after completion of sediment augmentation. Photo credit: Kirk Gilligan, USFWS.

F.4.6 Performance

On April 7, the applied sediment measured 10” +/- 2” over the 7.87 acres of the originally designated 10-acre site. After about 2 months, the elevation decreased to an average of 8.5 inches due to compaction, as expected by the research team (Fig. F-5). Although there was some damage to nearby eelgrass beds within the Refuge, monitoring has shown it to be recovering. On the augmentation site, pickleweed (*Salicornia*) and cordgrass (*Spartina foliosa*) are beginning to grow in patches. Most of the pickleweed is growing due to seed dispersal and most of the cordgrass present is growing from rhizomes of cordgrass that survived sediment placement. Additionally, tidal channels are beginning to form at the site. The Refuge staff and science teams continue to monitor elevation, accretion/erosion, sediment flux, carbon flux, and vegetation/animals. Although the site is evolving as expected, it is too early to know whether the marsh will be sustainable in the face of future sea level rise without a continued supply of sediment. The university-led research teams have produced more detailed reports, and a lessons learned report is being prepared by the SBNWR, which will be available on their website.

F.5 Surfers’ Point Managed Shoreline Retreat Project

F.5.1 Summary

Surfers’ Point presents a case study of the combined adaptation strategies of habitat restoration, infrastructure realignment, and managed retreat in California. 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 that has withstood strong El Niño storms and has protected the new bike path while providing continued public access to the beach. The project restored and widened the beach using native materials (cobble, sand) and dune planting by relocating infrastructure landward.

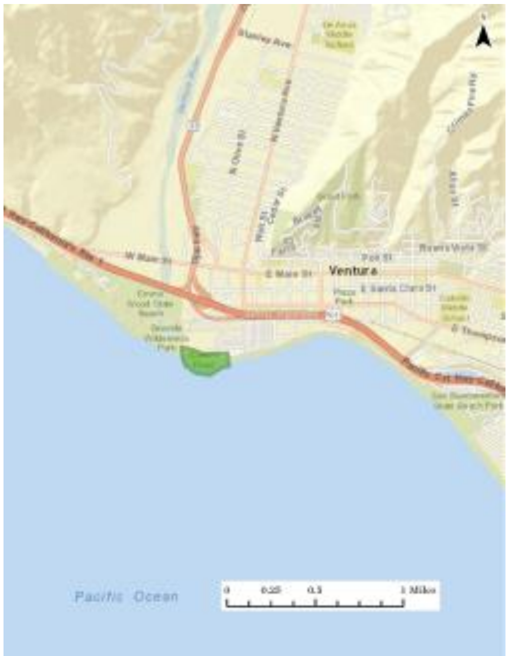

Figure F-6: The project site is located at Surfers' Point in Ventura, just East of the mouth of the Ventura River. Emma Wood State Beach was the natural reference site for the project.

F.5.2 Site History

The project site is a river delta, with wetlands and a cobble and sand beach backed by dunes. The estuary wetlands to the east were filled and developed, and are presently used as Ventura County Fairgrounds, while the estuary to the west of the river is part of Emma Wood State Beach (Fig. F-6). A railway crosses the river delta, running roughly parallel to the shore and inland of the project site. In the 1940's a levee was constructed along the southeast bank of the Ventura River in response to major flooding of the City's west side. This levee constrains the river delta and wetlands from encroaching on the County Fairgrounds and associated development, much of which has been incrementally filled over the decades. The backshore was improved for public access by installation of a bike path, roadway and public parking in 1989-1990. The improvements were constructed close to the shore on imported earth and debris fill. Severe erosion and collapse of the bike path and fairground parking lot (constructed in 1989 and eroded in 1992), caused portions of it to be unusable until the managed retreat project was implemented 18 years later (Fig. F-7). A rock revetment was placed to limit further erosion of the backshore near the river jetty, in the location shown in. This rock revetment was largely removed although some rocks remain and are visible, particularly during the winter when the shore recedes.

Figure F-7: Project site before (left) and after (right) landward realignment of built infrastructure and restoration of the dunes and beach. The bike path and parking lot were built on fill in 1989 and eroded within 2 years. Photo credit: Paul Jenkin.

F.5.3 Objective

The primary goals of the project were to relocate the damaged parking lot and bike path to limit exposure to erosion and wave overtopping, provide resilience and offset risk from sea level rise and storms for 50 years, and maintain access and other coastal resources without building hard structures such as seawalls. Although enhancing ecosystem function was not an explicit goal of this project, the chosen approach included restoring a natural beach backed by vegetated dunes, which inherently provides more ecosystem functionality and associated services than a seawall alternative. The project was largely driven by surfers who emphasized that natural shore conditions are more consistent with surfing and access, while armoring (e.g., seawalls) has counter-productive effects. Therefore, this is a natural infrastructure project that occurred before the term 'natural infrastructure' was widely used.

F.5.4 Design

Important design elements were landward realignment of infrastructure to provide adequate space for restoration of the back-shore using native materials (i.e., cobble, sand) and dune planting. The reconstruction of the back-shore provided space for dissipation of waves with less wave reflection and scour, and accommodated the largely 'reversible' shore dynamics driven by the seasonal wave climate and less-regular river discharge of sediment. The setback of shore also accommodates future migration of the shore landward due to the regional sediment deficit and future sea-level rise. The landward realignment of infrastructure and back-shore restoration differs from traditional beach nourishment projects, which attempt to build the shore seaward without providing adequate space landward to achieve a more natural wave-shaped shore; hence, the setback is more resilient with less sediment placement. The second difference from a traditional beach nourishment project is the use of coarse sediment (cobble) as well as sand, and construction of dunes. Described more succinctly, the Surfers' Point project restored natural shore morphology, including materials, structure, and processes; while traditional beach nourishment is a more engineered approach, which requires higher maintenance, does not require restoration of the backshore, and is not as desirable ecologically.
Infrastructure design included regrading with an associated drainage system to mitigate existing water quality concerns. A bioswale and pump/filter system were incorporated to capture and/or filter parking lot runoff before discharging into the rivermouth. A new concrete bike path was designed to connect with the Ventura River Trail along the levee at the rivermouth and estuary. The California Coastal Commission issued a Coastal Development Permit to the City of Ventura to implement the project, and required a monitoring plan. The monitoring plan included identification of maintenance triggers: points along the shore that if eroded would require placement of additional cobble to maintain the protective functions of this space from wave run-up. The water-side engineering team (ESA) used a natural reference site and performed wave run-up studies and other analyses to inform their design of the project. The landside improvements (hard-scape) were designed by RRM Design Group.

Emma Wood State Beach, just west of the site on the other side of the Ventura River mouth, was the reference site used to inform the elevations, slopes, and morphology of the cobble berm and back-beach design.

Completed in 2005, the preliminary engineering design of the project included 0.5 feet of sea level rise, which translated to an additional 15 feet of setback landward of the calculated wave runup limits. The original setback distance of 65 feet was negotiated during the environmental review process as a balance between restoration of the shore and impact to existing land uses, which included Fairgrounds property. The City of Ventura hired ESA (then PWA) to evaluate the negotiated setback distance based on projections of existing and future runup limits to confirm that risk of damage to the new bike trail, parking and roadway would be acceptable. The analysis indicated that additional setback was needed on the western side, near the river, and this change was adopted by the City, the Fairgrounds and stakeholders, and subsequently permitted by the California Coastal Commission. This design was completed years before the State of California's interim (2010) and updated guidance (2013) and policies regarding sea-level rise, but the project design did consider sea-level rise consistent with expectations of California Coastal Commission staff, along with long-term shore recession, storm-induced erosion, and high wave runup.

F.5.5 Implementation

Initially, the project was designed to move the fairgrounds parking lot and bike path landward and restore cobble beach and dunes for the 1,800 feet of shoreline east of the Ventura River mouth. However, due to funding limitations, the City decided to implement the project in two phases, the first of which was constructed in 2010-2011. Phase 2 has not been constructed due to funding limitations and need for stakeholder consensus. Dunes were graded and seeded in fall/winter 2012 primarily relying on City crews for grading, and volunteers led by the Surfrider Foundation to implement planting and seeding of native dune vegetation. The City acquired the dune sand through beneficial reuse of sand that accumulated at the Pierpont Dunes, where sand was impacting residences constructed adjacent to sand dunes.

Construction began in fall of 2010 with removal of the eroding edge of the parking lot and collapsed bike path and underlying fill. The contractor excavated test pits to confirm the depth of the fill layer and to test methods for charging the cobble voids with sand. Cobble sourced from Santa Paula Creek and sand sourced from Calleguas Creek were placed on the site and some hydroseeding was done. Ultimately, the beach was widened by over 60 feet. By June 2011 the new parking lot and bike path behind the restored cobble beach were completed marking the end of Phase 1. However, by February 2012, there had been significant windblown sand transport over the flat, restored beach, causing sand build-up on the new parking lot and bike path. (Figure 14) To remedy this problem, dunes were constructed using sand from Pierpont Dunes. Contractors first placed imported dune sand in linear 4-foot high berms in April 2012 and then spread the sand in May when they installed sand fencing and additional sand from Pierpont Dunes. The sand transport issue continued, requiring maintenance to remove sand from the parking lot and bike path. In November 2012, the dunes were graded into a natural hummocky pattern with more sand from Pierpont Dunes. The dune restoration was implemented during a multiple year drought 2012-2015, led by Dave Hubbard of Coastal Restoration Consultants, Inc. The dunes were planted using seeds collected from Emma Wood State Beach in December (primarily beach bur, sand verbena and beach saltbush), and no irrigation was used, saving $200k in project costs. Several methods were used to stabilize sand in the short-term while plants became established. Surfrider Foundation and City of Ventura volunteers continue to weed the site each spring to remove primarily sea rocket (Cakile spp.) and ice plant, which is mostly eradicated but spreads quickly if not removed.

Figure F-8: Successful construction and vegetation of dunes, 2014. Photo credit: Louis White.

F.5.6 Performance

This project has performed as designed, and prevented erosion and accommodated erosion during strong El Niño storms, and has become the most visited beach in Ventura County. (Figure 16) Staff from the City of Ventura performed the beach profile monitoring, maintenance trigger points have not been reached, and the beach is behaving similarly to the reference site. While the western-most end of the site experiences greater winter erosion due to the continued presence of the Ventura River Levee and Army Corps spur groin, the summer beach profile returns due to the site's downcoast proximity to the rivermouth. Overall, the community-based volunteer project has been successful in establishing vegetated dunes with native plants and relatively low weeds, all without irrigation during drought years (Fig. F-8).

The areas of the beach backed by dunes have vegetated quickly and performed the job of protecting the space behind them from flooding during large storms. Of interest, during high wave conditions in the 2015-2016 winter while other shore areas were damaged, no damage was experienced at the Surfers' Point Retreat project, and wave runup was documented to reach the bike path only where dunes were absent, in the area left flat to facilitate kite surfer activity (ESA 2016). In contrast, significant damages occurred elsewhere in the region due to these storms, including damage to Ventura Pier, erosion damage and emergency revetment at the promenade, and significant wave run-up east of the project site including overtopping and inundation in the Pierpont neighborhood.

F.6 San Francisco Bay Living Shorelines: Nearshore Linkages Project

F.6.1 Summary

The multi-objective 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 objective is to create biologically rich and diverse subtidal and low intertidal habitats, including eelgrass and oyster reefs, as part of a self-sustaining estuary system that restores ecological function and is resilient to changing environmental conditions. The project demonstrated that oyster reefs and eelgrass beds can substantially increase habitat, food resources, and biodiversity as well as reduce wave energy by 30%.

As its next phase, the Giant Marsh Living Shorelines project 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 SF Bay Living Shorelines project raised awareness and built support and interest within the San Francisco Bay Area for living shorelines projects, and there are now multiple public and private partnerships forming to support the development of other living shoreline projects (i.e., using natural habitats to soften and protect the shoreline, and achieve both physical and biological goals). The 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.

Figure F-9: The subtidal project site is about 1 acre in size and is located about 200 feet offshore, along the San Rafael shoreline.

F.6.2 Site History

Native Olympia oysters (*Ostrea lurida*) and eelgrass (*Zostera marina*) were once abundant in San Francisco Bay and the San Francisco Bay Subtidal Habitat Goals Report (2010) recommended protection and restoration of 8,000 acres of oyster habitat and 8,000 acres of eelgrass beds. To reach this goal, pilot studies are needed and the site offshore from the San Rafael shoreline was chosen as the first test site for larger scale restoration strategies (Fig. F-9). The shoreline is lined with rip-rap, a loose stone barrier which limits the interface of terrestrial and bay habitats, but does provide some habitat for Olympia oysters and other shoreline invertebrates and plants. The offshore areas of the site are shallow mudflats that are semi-protected from wave action by the Marin Islands National Wildlife Refuge. The shoreline is affected by wakes from ship traffic, wind wave energy, and tides and currents in the bay. In addition to the natural presence of native oysters in the intertidal, eelgrass test plots planted in 2006 were successful. These factors together, along with The Nature Conservancy being a willing landowner, meant this was a unique site and opportunity to test restoration approaches and their benefits for shoreline protection and ecosystem benefits.

F.6.3 Objective

The San Francisco Bay Living Shorelines: Near-shore Linkages Project is a pilot project designed in a thoughtful, experimental framework to answer priority science and restoration questions and meant to inform the design of larger-scale restoration projects at additional sites in San Francisco Bay or statewide in the future. The project was designed to implement key recommendations and test techniques in the Subtidal Goals Report, the San Francisco Baylands Habitat Goals Science Update (Coastal Conservancy 2015) and other regional planning documents including the San Francisco Estuary Comprehensive Conservation and Management Plan. This project aimed to test methods of eelgrass and oyster bed restoration and their effects on fostering biologically diverse invertebrate, fish, and bird communities while providing shoreline protection benefits such as increased wave attenuation and increased sediment accretion in the nearshore area. These physical benefits are increasingly important to buffer shorelines against sea level rise and increased storm surge and frequency projected for San Francisco Bay.

F.6.4 Design

The State Coastal Conservancy is the lead on the project, including the lead agency on CEQA/NEPA and permitting, and provides both funding and project management. A complete package of permit application submittals, including the Joint Aquatic Resources Project Application to the agencies listed above, with Project Design, a Biological Assessment, Wetlands Delineation, Cultural Resources Report, and a detailed Monitoring Plan were submitted to regulatory agencies. There were several limitations on the project, including a lack of data (as this approach was new to the Pacific Coast), limitations on the type and amount of fill permitted, a need to plan access to the site around sensitive species windows such as salmon migration, and other site and regulatory constraints. Ultimately, the permitting agencies and landowner supported experimentation and testing of innovative new living shorelines concepts with this project, and supported it because of the habitat enhancement potential, and conservation measures and high frequency monitoring that will provide valuable data for future efforts.

To test both the biological and physical effects of oyster reefs and eelgrass beds, and the interactions between them, the design included a large experiment of four 32m by 10m plots placed roughly 200m offshore from the San Rafael shoreline, just south of the mouth of the San Rafael Canal. These plots compared the effects of placing Pacific oyster shell-bag mounds, planting eelgrass, interspersing both together, and a treatment control plot. The team compared biodiversity, wave attenuation, and other attributes between experimental plots and a control plot. A small experiment was also included, to assess different substrates for oyster recruitment success. These included reef balls, mini reef ball stacks, oyster blocks, and layer cakes composed of 'baycrete', a mixture of cement, sand, shell, and rock. This material was designed to include natural materials from the bay and be more biodegradable, and is easier to permit than full concrete fill. See Figure 20 for a design schematic of both large and small experiments.

F.6.5 Implementation

Installation of eelgrass and oyster reef plots was completed from July to early August 2012 according to the design plans prepared by the main project team (State Coastal Conservancy, SFSU, UCD, USGS, ESA). The sourcing of materials included clean Pacific oyster half shell from Drakes Bay Oyster Company, shell and sand mined from the bay and provided by Jericho Products, and preparation of the baycrete oyster elements ahead of time by California Wildlife Foundation, Drakes Bay Oyster Company, Dixon Marine

Services, and Reef Innovations. Unfortunately, permitting and construction were delayed by six weeks, resulting in late season mid-late August eelgrass plantings, as the plants had to be installed after the oyster elements were placed in July-August. The initial eelgrass planting was not successful, potentially due to this late timing and less ideal tide cycles and light availability for eelgrass. The team replanted the site in April 2013. High frequency monitoring of eelgrass survival and density; oyster recruitment, survival, and density; invertebrate use, fish, and bird use; and physical parameters including bathymetry surveys, water quality monitoring, and wave monitoring was completed by the main project team from fall 2012-spring 2017 and the fifth year of required monitoring will be completed in December 2017. The project team plans to continue to monitor the project less frequently over the next five years and in the long-term.

F.6.6 Performance

Due to a rigorous monitoring program, many lessons were learned about the process of eelgrass bed and oyster reef design, construction, monitoring, and the resulting habitat and coastal protection benefits of the project. The 2014 and 2016 hydrographic surveys revealed higher rates of erosion on the bayward side of the plots and increased accretion on the shoreward sides of the plots. According to wave modeling conducted for the project, for waves immediately offshore of the plots, the oyster–eelgrass plot dissipated approximately 30% more wave energy than the control at mean tide level. This reduction added to the wave attenuation benefits of the broad offshore mudflat, which extracted substantial energy before waves reached the plots.

Olympia oysters recruited quickly to both shell bag mounds and the baycrete structures, with an estimated peak of more than three million recruits in spring 2013, followed by a decline in recruitment and survival over the next three years to approximately 350,000 by fall 2016. Control tiles on the shoreline documented a similar decline reflecting the same patterns of declines at control areas as well as the treatments. Native oyster populations are known to fluctuate over time and can be quite ephemeral, as can eelgrass populations, with fluctuating numbers both within and between years. The shell bag mounds recruited more oysters than the baycrete structures likely due to their larger size and surface area amongst and between the shells. Deeper portions of the elements and vertical surfaces tended to recruit higher densities than horizontal surfaces, potentially due to mitigation of heat stress at low tides. Although there was some initial sinking (10 cm) and sediment accumulation around the bottom of the oyster shell bags, the bags were stable after 5 months.

Eelgrass density reached 200% above initial planted densities when planted alone and just under 100% density when planted amongst oyster shell mounds, which can be abrasive to shoots and restricted the available space where eelgrass could expand. The project team still recommends restoring oyster and eelgrass habitat together in the same design for highest biodiversity, but to include more space between them to allow for maximum eelgrass bed expansion. The source of the eelgrass had a minor effect on success of planting and the team recommends choosing a source site with similar sediments and habitat conditions to the planting site.

The invertebrate communities in eelgrass and oyster plots were significantly different from the control plot and attracted species that prefer a structured environment. While there has been an increase of more than ten taxa on the reefs and in the sediments, as of 2016, the community composition had not completely aligned with natural mature eelgrass beds in the bay, with the native isopod (*Idotea resecata*) being absent, and native sea hare (*Phyllaplysia taylorii)* being very rare (only two individuals found). Sediment core sampling of infaunal invertebrates showed a significant increase in density where eelgrass and oyster bags were installed, potentially due to the detritus and biological material coming off the reefs and enhancing food resources for species in benthic sediments. Fish trapping, seining and acoustic monitoring indicated an increased occurrence of certain fish species, including early recruitment of eelgrass specialists such as bay pipefish (*Syngnathus leptorhynchus*). Densities of American black oystercatcher (*Haematopus bachmani*) increased in the treatment area in comparison to pre-installation and control densities, and Forster's terns (*Sterna forsteri*) and wading birds (herons and egrets) began using the treatment area after installation. Birds used the treatment area for foraging at low tide more than adjacent areas and used the oyster structures for resting or preening at high tide.

F.7 Hamilton Wetland Restoration Project

F.7.1 Summary

The Hamilton Wetland Restoration Project is exceptional in its restoration of a range of habitat types integrated with flood protection levees, in addition to being 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.

Figure F-10: The project site is located east of Novato, along the northwest shoreline of San Francisco Bay.

F.7.2 Site History

The 994-acre project area (Fig. F-10) was formerly a tidal marsh that was diked and drained in the 1800s for agriculture, then subsequently converted to an Army airfield in the 1930s. Over decades there was subsidence amounting to about 8-15 feet below mean lower low water. PCBs, DDT, and toxic metals had contaminated a relatively small portion of the soils (50,000 yards). In 1994, the airfield was closed through a Base Realignment and Closure process and cleaned up to Comprehensive Environmental Response, Compensation, and Liability Act standards. Over the following decade, plans were developed to restore the site to tidal marsh, seasonal wetlands, and improved levees that incorporated tidal marsh to upland transition zone habitat along the north side of the project site (Figure 23). This represented one of the earliest on-the-ground examples of the horizontal levee concept.

F.7.3 Objective

The project planned to restore a former airfield to tidal and seasonal wetlands and improve the southern flood protection levee between the adjacent neighborhood and the restoration site by raising the existing levee and incorporating a 300-foot wide sloping wildlife corridor without the use of rock armoring. This approach has more recently been referred to as a horizontal levee. The northern levee protects a sanitary district outfall pipe and 1600 acres of agricultural land that are proposed for restoration to wetlands as the Bel Marin Keys Unit V Restoration project. Once natural processes have fully restored the site, the project will have restored approximately 924 acres of tidal wetlands and seasonal wetlands, and 70 acres of transitional habitat (including the wildlife corridor) and created 2.66 miles of public access trails to this ecologically sensitive part of the San Francisco estuary. Due to the proximity to housing, agriculture, and wastewater treatment assets, this restoration project sought to integrate several approaches that would result in a healthy ecosystem while enhancing flood protection and recreational opportunities for the nearby communities. Lessons learned from the project will be applied to restoring the adjacent 1600-acre Bel Marin Keys property as a continuous landscape, incorporating many of the same habitat features.

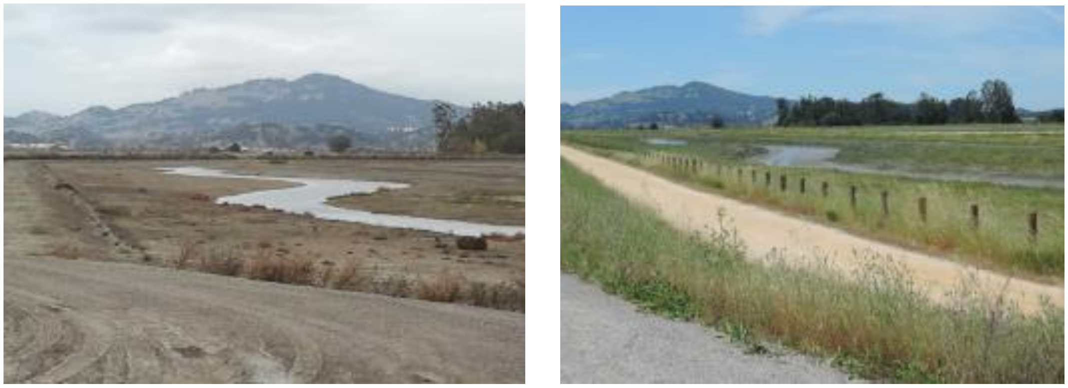

Figure F-11: Tidal channel entering the northern seasonal wetlands looking north in November 2012 (left) and May 2017 (right). Photo credit: Christina McWhorter.

F.7.4 Design

The project design incorporated several approaches, including (1) beneficial reuse of clean dredge sediment to raise the elevation of the site for marsh restoration, (2) realignment of flood control levees to protect housing and agricultural lands while allowing space for restored wetlands and natural tidal processes, (3) incorporation of tidal berms to break up wave energy and provide bird habitat, (4) a gently sloping wildlife corridor to support a range of vegetation types and (5) seasonal wetlands. The project design incorporated feedback from a large planning committee including representation from 80 stakeholders, environmental groups, residents, and agencies. Project leaders from the Army Corps of Engineers and the State Coastal Conservancy partnered with the Bay Conservation and Development Commission, a key permitting agency in the San Francisco Bay Area, to develop permit applications.

The use of dredged sediment was key to the success of the project as there is no faster way to restore a subsided site to a functional tidal marsh. This project also provided an opportunity for beneficial reuse of sediment dredged from the Bay for navigation, making use of a valuable natural resource that otherwise would have been disposed of. To allow tidal waters onto the site, the perimeter levees needed to be raised and strengthened to provide the level of flood protection required by the Federal Emergency Management Agency. During the base realignment, the adjacent community of Hamilton was developed by the City of Novato. The Hamilton Levee (formerly known as the New Hamilton Partnership levee) protects this community and lies on the western edge of the project site. Along this edge, the site design included a flatter, vegetated area transitioning from the top of the flood protection levee with a 100:1 slope. This shallow slope reduced the need to armor the levee with rip-rap. Along the northern levee, a subtidal bench was added to the toe of the levee designed to reduce wave action on the levee itself. Another important feature of the site was the addition of several intertidal berms set just below marsh plain elevation. These berms were added to the site design to reduce wind waves created on site by the long wave fetch created by the strong north bay winds and to help guide channel development. The subtidal bench and intertidal berms were designed to erode naturally over time, adding to the site sediment. The design team was also interested in providing habitat connectivity between the open land on either side, so a 300-foot wildlife corridor was incorporated to accommodate the shallow slope of the transitional habitat and provide wildlife access to land from the south and along Pacheco Pond to the north.

F.7.5 Implementation

The majority of the project site was restored to tidal marsh with a mosaic of upland transition zones, tidal pannes, and seasonal wetlands. This process included raising the elevation of the site with clean dredge sediment and constructing intertidal berms that would serve as wind breaks as the marsh developed. It required approximately 6 million cubic yards of sediment, most of which was sourced from the Port of Oakland's Harbor Deepening Project from 2007-2013 and pumped onto the site as it was available. Placement of the sediment required a dredged sediment offloader anchored in the Bay at depths most dredge scows could use, and construction of a 5-mile pipe and pumps to transport dredge material to the site. After constructing the perimeter levees, intertidal berms, wildlife corridor, habitat levee, and public access trail, the sediment was pumped on site and allowed to settle. The plan was to raise the site elevation to 1-1.5 feet below Mean Higher High Water (marsh plain elevation) and let natural sediments fill the site and support creation of tidal channels and sloughs after the levee breach. However, there was not enough sediment to fill the site to the desired height, and it ended up being approximately 2 feet lower than planned, thus the site will take longer than originally projected to reach an elevation that can support marsh vegetation.

The site also includes two seasonal wetlands, one in the northern panhandle, and one on the southern end of the site. A dedicated nursery was built onsite from a repurposed water treatment building to grow native plants, with a dedicated nursery manager and botanist in charge of plant production, planting, and invasive plant control. The south seasonal wetlands were not planted.

On April 25, 2014 the bayside levee was breached, restoring tidal action to the site and supporting natural sediment accretion, colonization of marsh vegetation, and use of the site by invertebrates, birds, and fish (Fig. F-11). The USACE leads an adaptive management and monitoring plan and group. The nursery manager performs vegetation monitoring; bird, fish, invertebrate, sediment, wind conditions, and water drainage are monitored by ESA; and structural performance of the perimeter levee is monitored by USACE. The site is expected to reach full maturity between 2030 and 2050, although factors such as sea level rise and low levels of natural sediment accretion could delay or prevent the site from becoming fully restored.

F.7.6 Community Engagement

A substantial public outreach component included the planting of 35,000 plants as of summer 2017 in the north-ern seasonal wetland, and wildlife corridor areas. The nursery manager handles all the plant related efforts on site as well as the public outreach effort. A

Point Blue program called Students and Teachers Restoring a Watershed (STRAW), with funding from the State Coastal Conservancy, engages local school groups and pairs them with Point Blue and USACE biologists to participate in the planting. Approximately 3,600 total hours contributed to the planting effort to establish native vegetation at the site, including 1,100 hours by community volunteers of all ages, and 2,500 hours by an AmeriCorps National Civilian Community Corps team.

F.7.7 Performance

The Hamilton Wetland Restoration Project site is on track for full restoration of natural tidal marsh processes, according to monitoring results after the first year following the levee breach. Accretion of sediment on the future marsh plain, tidal drainage and species richness for birds, fish and invertebrates are all positive signs of the project's success. There has been a 50-75% survival rate of planted vegetation, a positive and expected result. However, the height of the berms and the perimeter levee are lower than specified, due to compaction of both the sediments underlying dredge sediment and the placed dredge sediment itself. This has resulted in erosion of the vegetated tidal bench where it ties in with the levee, especially during recent king tides and storms. The project team is determining whether the level of erosion is problematic and, if it is, will perform necessary repairs. Additionally, some areas do not fully drain when the tide goes out, but this should improve as tidal channels develop. In general, it is too early to fully assess the physical performance of the site.

F.8 Humboldt Coastal Dune Vulnerability and Adaptation Climate Ready Project

F.8.1 Summary

The 32 miles of beach-dune systems along the Eureka littoral cell in Humboldt County include four major barrier spits that protect the Humboldt Bay and Eel River estuaries and will be subject to sea-level rise and inland migration (Fig. F-12). These barrier systems 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 is both a science project and tests adaptation strategies at demonstration sites and is led by the U.S. Fish and Wildlife Service Humboldt Bay National Wildlife Refuge (the refuge). The science component is monitoring sediment movement and foredune morphology at the scale of the littoral cell to better understand sediment dynamics to allow for the identification of areas of vulnerability due to factors such as sediment deficiency or subsidence. Dune vegetation management strategies are tested at demonstration sites to inform regional adaptation strategies to reduce vulnerability to sea level rise and coastal storms. The current Climate Ready project will provide additional insights into the best adaptation strategies to maximize the resilience of dunes, which are the primary coastal defense infrastructure for the human communities living along Humboldt Bay.

Figure F-12: The project is studying sediment dynamics throughout the Eureka Littoral Cell and has two demonstration projects at the Lanphere Dunes and the mouth of the Eel River.

F.8.2 Site History

The coastal barriers that enclose Humboldt Bay and the Eel River Estuary have historically supported expansive and diverse dune habitats. Much of the area was degraded by the intentional introduction and subsequent spread of non-native, invasive European beachgrass (*Ammophila arenaria*) and other species that overstabilize the dunes and crowd out native plants and animals. Beginning in the 1990s with the Lanphere dune restoration, land managers began collaborating to restore the dune ecosystems by removing non-native grass and, to a lesser extent, planting the native dune-building grass species. Extensive dune restoration projects and monitoring have continued throughout this area since that time. To date, over 6 km of shoreline has been restored along the North and South Spits. This effort has returned the native dune species assemblage and restored dune system functions.

Since 2012, land managers have begun exploring the benefits of past restoration efforts beyond ecological benefits such as biodiversity, to determine whether restoration plays a role in promoting resilience to sea level rise and extreme events. A three-year study at Humboldt Bay National Wildlife Refuge funded by USFWS Region 8 Inventory and Monitoring program was carried out by refuge staff in collaboration with the USFWS Coastal Program. Twelve transects were established to measure changes in dune elevation and vegetation along 3 miles of coastline. Preliminary analysis of the 3-year data set revealed that invasive vegetation trapped sand strictly at the foredune seaward face, while native vegetation permitted more sand to crest and overtop the foredune, suggesting that restoration may increase resilience to sea level rise. The preliminary study was the basis for developing a demonstration adaptation project to examine different plant morphologies as a means of increasing resilience. Sediment budgets are a major determinant of resilience; however, the study was too geographically limited to assess sediment budgets beyond a very localized scale. The study has since been expanded and extended as part of the Dunes Climate Ready project.

F.8.3 Objective

The primary goal of the project is to prepare for climate-change-related vulnerabilities of coastal dunes and beaches along the 32-mile Eureka littoral cell (Fig. F-12). The USFWS have taken the scientific lead on this project with multiple partners. The study measures dune morphology changes in relation to vegetation and sediment supply using both historical imagery and collection of new data in the field. To test sea-level adaptation strategies, demonstration sites at the Lanphere Dunes are being used to compare beachgrass-dominated dunes to restored dunes to determine the vegetation scenario that optimizes sediment transport and facilitates landward and upward migration of an intact foredune. In addition, foredune-building will be tested in a second adaptation site at the Eel River mouth where sediment deficits exist. The scientific sediment supply project and adaptation demonstration projects form the basis for the vulnerability assessment and adaptation strategies in the Humboldt area.

Figure F-13: European beachgrass being removed from dunes (left) to allow native vegetation and natural dynamics to return (right). Photo credit: Andrea Pickart.

F.8.4 Design

- *Creation and monitoring of two adaptation projects*
    - The Lanphere Dunes adaptation site will help determine the desirable planting composition that optimizes sand transport and facilitates landward and upward migration of an intact foredune (a desirable response to sea-level rise). This site compares European beachgrass (*Ammophila)*-dominated foredunes with foredunes that are restored and planted with different assemblages of native plants after removal of *Ammophila.* Native plant comparison plots included 3 treatments: American dunegrass (*Elymus mollis),* a mixture of dune mat species, and *Elymus* planted with dune mat species.
    - The mouth of the Eel River adaptation site used a combination of native plants and driftwood to promote and monitor natural recovery of a foredune following an over-wash event.
- *Monitoring Dune Dynamics*
    - Topographic data is being collected using RTK-GPS technology, each winter and summer, over the entire Eureka littoral cell. The data is being analyzed to

better understand long and short-term beach-dune dynamics. Together with the analysis of historic shoreline changes based on air photo records, this information will be used to predict effects of sea level rise and extreme events, and to analyze vulnerabilities.

- *Native dune grass propagation site*
  - A native dune grass propagation site has been established on the North Spit to analyze how native grass plantings affect sand movement from the beach, and to assist in future dune restoration projects along the North Spit.

F.8.5 Implementation

The project covers a large area between all the components and involves a high level of collaboration and participation from landowners (primarily staff from California State Parks, BLM, CDFW, and The Wildlands Conservancy), refuge staff, hired research assistants (RA), academic scientists, graduate students, and volunteers recruited by Friends of the Dunes. Each component informs the others and will inform the regional vulnerability assessment and adaptation planning. Andrea Pickart is a USFWS ecologist with the refuge who oversees the work at the adaptation sites and organizes teams for the surveys.

F.8.6 Adaptation Projects

The Lanphere Dunes sea level rise adaptation site had vegetation removed in fall 2015, and was planted with native vegetation in winter 2017. The California Conservation Corps (CCC) were contracted to do the beachgrass removal, assisted by CDFW and by partners and volunteers (Fig. F-13). Planting was done by CDFW, CCC donated time, RAs, USFWS staff and volunteers. Vegetation monitoring is done by USFWS staff and RAs. USFWS staff conducts aerial kite surveys of the adaptation site. Vegetation monitoring through May 2017 showed high survivorship of native dune grass, with more variable success of native dune mat species. Additional planting is scheduled for fall 2017/winter 2018, however, native dune mat species have volunteered on the site in large numbers.

Geomorphic monitoring through October 2016 showed that sediment flux was greatest in the beach (generally true of beach/foredune systems) with large erosive events in winter 2016 and 2017 causing vertical scarping (cliffing) of the foredune and significant loss of elevation in the beach. Beach elevation after the first scarping interval recovered during the more depositional conditions of summer (response to winter 2017 not yet analyzed). The foredune retained volume and height in restored areas after the first year, with some translation of foredune crests eastward. Analysis of second year data is in progress, and monitoring will continue as plants become better established. All geomorphic monitoring is done by University of Victoria (now Arizona State University) students under Dr. Ian Walker's direction and with help from RAs and USFWS staff.

Work at the Eel River adaptation site has been done almost exclusively with in-kind match using labor from the landowner (The Wildlands Conservancy) and CDFW. The Eel River adaptation site (characterized by sediment deficit) experienced additional over-wash in the two subsequent winters, and is now being reevaluated as to the need to test a less passive adaptation methodology through foredune recontouring prior to planting and wood placement.

F.8.7 Dune Dynamics

Andrea Pickart oversees two to three funded local RAs and they are joined by up to a dozen agency partners and volunteers each season to complete the beach/dune transect surveys. The teams deploy three RTK-GPS base-station/rover pairs (provided by Dr. Ian Walker) to complete three different transects each field day. Teams are composed of a crew leader who runs the GPS, and 'veg sampler' who takes vegetation measurements. The vegetation samplers include scientists from different disciplines among refuge partners (ranging from botanists to engineers to fishery biologists), who take a vegetation sampling training before each survey. Crews generally walk to sites carrying equipment in backpacks due to the major access logistics for ATVs. During the surveys, the crews work 40-hour weeks in the field. Everyone really seems to enjoy this work, getting out and seeing the dunes. The partners enjoy working in the dune system and can really understand what the project is doing by participating.

Three surveys have been completed (winter 2016, summer 2015, winter 2017) and a fourth is in progress (summer 2017). Funding for two additional surveys has been secured (winter 2018 and summer 2018). Survey results have not been quantitatively analyzed, but show a trend of beach-dune recovery throughout much of the littoral cell following two extreme winters (2016 El Niño and 2017 characterized by extreme high water events). In the southern portion of the littoral cell, where a sediment deficit was presumed, recovery has not been observed, suggesting greater vulnerability.

The historic shoreline analysis is near completion, and preliminary results indicate a relatively stable to accretionary shoreline along most the littoral cell, except for an erosional hot spot north of the North Jetty of Humboldt Bay and along the entire length of the Eel River south spit. Significant accretionary trends have been exhibited over time south of the Little River, along a portion of the North and South Spits of Humboldt Bay, and the north spit of the Eel River. These data will inform the vulnerability assessment and together with the semiannual transect data will allow exploration of littoral cell dynamics and potential impacts of removal of dredge material outside of the littoral cell.

F.8.8 Community Engagement

This project included over a dozen partners ranging from federal, state, and local agencies to universities, NGOs, tribes, special districts, a consulting firm and even private landowners. Landowners and agencies that manage land worked together along the 32-mile dune system and in the process broadened their perspective and understanding of the entire ecosystem. In addition to engaging a high diversity of partners in the actual work, the public is actively engaged through Friends of the Dunes. Friends of the Dunes maintains a page on their website to keep the public updated quarterly about the project (http://www.friendsofthedunes.org/science/climate-ready/). They have also sponsored public presentations and field trips to provide opportunities for dialogue between the public, scientists, and land managers.