550 Kearny Street
Suite 800
San Francisco, CA 94108
415.896.5900 phone
415.896.0332 fax

esassoc.com

Stinson Beach Nature-Based Adaptation Feasibility Study

Study Memorandum 3

date	May 14, 2021
to	Marin County CDA
from	ESA Project Team
subject	Stinson Beach Adaptation Alternatives Development and Evaluation Task 3 Deliverable for Stinson Beach Nature-Based Adaptation Feasibility Study

This memorandum describes the development and evaluation of adaptation alternatives for the Stinson Beach Nature-Based Adaptation Feasibility Study (study). The alternatives development builds upon prior work describing existing conditions (Study Memorandum 1, ESA 2020a), climate scenarios and adaptation thresholds (Study Memorandum 2, ESA 2020b). The process for developing and selecting adaptation alternatives is documented (study Task 3.1) followed by a description of evaluation methods and results (study Task 3.2). This memorandum is the deliverable for Task 3 of ESA's scope of work for the Marin County Community Development Agency (CDA).

Table of Contents

1. Introduction 2
2. Description of Nature-Based Infrastructure Types 3
3. Suitability of Nature-based Infrastructure at Stinson Beach 11
4. Adaptation Alternatives Development 17
5. Adaptation Alternatives Cross Section and Planview Detail 23
6. Adaptation Alternatives Evaluation 29
7. Long-term Adaptation Pathways for Stinson Beach 61
8. Conclusions and Next Steps 63
9. References 66

1. Introduction

The nature-based adaptation alternatives proposed for Stinson Beach build upon the adaptation strategies presented in the C-SMART Adaptation Report (Marin County 2018). A range of near-term adaptation alternatives were developed in this study based on existing conditions along the shoreline, seasonal shoreline changes and potential storm impacts (see Chapter 3 and Study Memorandum 1, ESA 2020a). Long-term adaptation pathways consistent with the near-term alternatives analyzed in this study are also discussed to facilitate integrated adaptation planning for the greater Stinson-Seadrift community. The following nature-based infrastructure types were considered for application:

1. **Foredunes** – natural Pacific Coast sand dune geometry with native perennial vegetation and low-relief hummocks, typically found on the landward side of a beach, and sometimes fronting larger mature dunes.
2. **Foredunes and cobble-gravel berm** – foredunes with buried cobble-gravel berm for erosion protection.
3. **Dune embankment** – linear sand embankment that is landscaped to form a protective barrier to wave run-up and erosion during extreme events. A dune embankment is a compressed (narrower footprint) version of mature dunes that are often in the form a wide "dune field". Dune embankments are taller and narrower than foredunes and can be widened or combined with foredunes, if space allows.
4. **Dune with cobble-gravel berm** – a dune embankment with a buried cobble-gravel berm for increased erosion protection.
5. **Cobble-gravel berm** – buried cobble-gravel (c-g) berm without dune cover. The c-g berm is a mass of rounded rock in a layer placed in the upper tide range just below dry beach elevations, seasonally buried by sand and exposed during high surf conditions. The c-g berm is also called a "dynamic revetment" because it provides flood and erosion protection to landward areas, but is more malleable than traditionally engineered rock revetments during elevated wave breaking and runup. A variant is a "lag deposit" geometry which is a wider, lower elevation cobble apron that is only exposed during extensive beach scour or erosion typically associated with rare events. This variant applies to all the nature-based infrastructure types that include a cobble-gravel berm, but is included primarily to accommodate drainages from inland, such as Easkoot Creek flood flows at the Stinson Beach National Park facility.

Two adaptation alternatives are proposed for analysis for four of the five reaches – Seadrift East, Patios, Calles, and NPS. Based on the existing narrow beaches and existing armoring along the western Seadrift Reach and proximity to the Bolinas Lagoon mouth, only one alternative was analyzed (cobble berm). See Figure 22 and Figure 23 that show plan view schematics of nature-based adaptation alternatives 1 and 2.

The five nature-based infrastructure types are described in Chapter 2. Chapter 3 describes which nature-based infrastructure types are suitable by reach, based on the existing conditions. The full range of natural infrastructure types are screened and the adaptation alternatives selected in Chapter 4. Chapter 5 presents diagrams of the adaptation alternatives by reach. Chapter 6 documents the evaluation of adaptation alternatives. Long-term potential adaptation pathways comprised of additional adaptation strategies are described in general terms in Chapter 7: these strategies include sand placement to widen beaches (beach nourishment), shore armoring, raising buildings on piles, and other actions that accommodate or retreat landward/upward. Chapter 8 presents our salient conclusions of the evaluation and next steps toward implementing natural infrastructure at Stinson Beach.

2. Description of Nature-Based Infrastructure Types

Nature-based shore infrastructure for adaptation -- sometimes referred to as natural infrastructure, natural adaptation measures, and living shorelines -- refers to using natural physical features to mitigate coastal hazards. The following definition was recently developed as part of California's Fourth Climate Assessment (Newkirk and others 2018) which also includes descriptions of various nature-based shore infrastructure projects:

"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."

Examples of nature-based shore infrastructure are provided in terms of Case Studies in a related report (Judge and others 2018), and descriptions of nature-based and other adaptation measures are provided in the C-SMART Adaptation Report (Marin County 2018), including Appendix B (ESA 2016). Shore infrastructure types applicable to this study are summarized below along with natural and built examples in California.

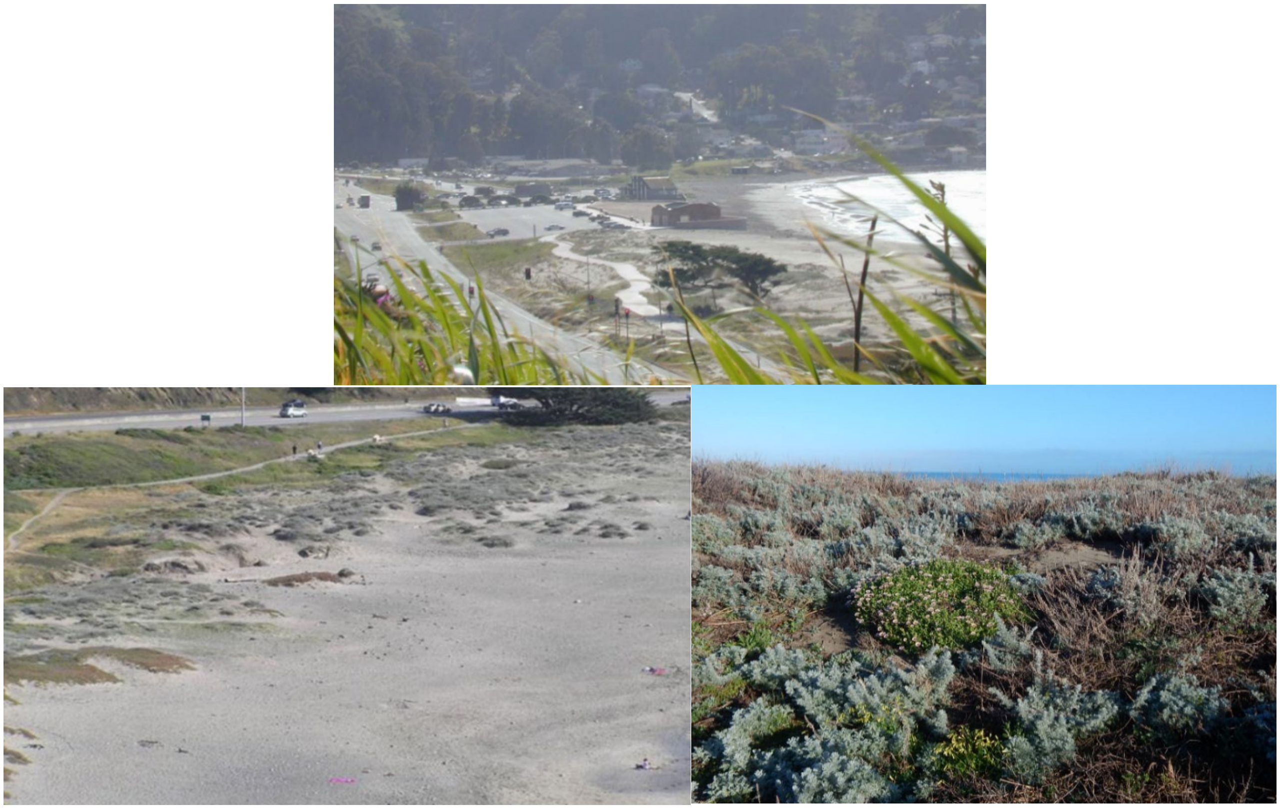
2.1. Foredunes

Foredunes are low-relief landforms resulting from the interaction of onshore wind-blown sand transport and native plants. The dunes are not barriers but rather dissipate wave run-up gradually, while being resilient. Figure 1 shows the restored foredunes at Surfers Point, Ventura CA. An example of a more natural dune system that also provides flood and erosion protection can be found at Pacifica State Beach in the Linda Mar District of Pacifica (Figure 2). It consists of a young dune field and foredunes, seaward of road embankment and ditch where space is limited by Highway One. Figure 3 is a photograph of a naturally formed foredune providing significant flood protection, where European beachgrass was removed, and the dune was revegetated with native Northern California dune plants, located between the ocean and Humboldt Bay, California (Judge and others 2017). Figure 4 shows foredunes established at the NPS reach. These types of dunes can be established within a few years following minor earthwork and native plantings, and vegetation maintenance. The dune field dissipates wave run-up via roughness and porosity over the relatively flat zone with limited scour. Sand deposition can occur with wave run-up as well as wind-blown transport.

SOURCE: Louis White

Stinson Beach Nature-Based Adaptation Feasibility Study . 171009.00

Figure 1
Foredunes at Surfers Point, Ventura, CA (Judge and others 2017)



SOURCE: City of Pacifica (top); Peter Baye (bottom)

Stinson Beach Nature-Based Adaptation Feasibility Study . 171009.00

Figure 2
Dunes at Pacifica State Beach, Linda Mar, Pacifica, CA.

SOURCE: Andrea Pickart

Stinson Beach Nature-Based Adaptation Feasibility Study . 171009.00

Figure 3
Seaward edge of restored and revegetated young foredunes, Humboldt Dunes (Judge and others 2017)

SOURCE: Peter Bave

Stinson Beach Nature-Based Adaptation Feasibility Study . 171009.00

Figure 4
Foredunes at NPS Stinson Beach

2.2. Dune Embankment

A dune embankment is an engineered version of a natural mature dune, compressed into a contiguous linear embankment, acting as an erodible levee or dike. Dune embankments are sometimes referred to as linear dunes and sand embankments. An example is found at Ocean Beach, San Francisco (Figure 5) and at the NPS reach of Stinson Beach (Figure 6). Note that the vegetation and dune geometry of dune embankments are typically not native to this area, but provide a pleasant natural appearance. However, native plants could be incorporated into dune embankment designs. Twentieth century dune stabilization along the entire Pacific Coast was based on the planting and subsequent natural spread (invasion) of the European marram or beachgrass, which has sand-trapping and binding capacity that far exceeds all native Pacific Coast dune plant species. Marram's stiff, erect, dense, tall broom-like vegetation builds steep, high foredunes where rates of onshore wind transport of sand are sufficient. In comparison, native dune grasses such as beach wildrye build gentler foredune slopes because of their inherently more open, spreading growth habit.

The dune embankment is a barrier to wave run-up and overtopping when intact. During extreme conditions, waves erode the dune and the eroded sand migrates to the beach and surf zone, conceptually dissipating the wave power and reducing the landward extent of the erosion event. Reconstruction is required after erosion. Planting is required to maintain the dune shape and limit wind-blown transport landward. Controlled access across the dune is recommended to maintain vegetation where the embankment crosses heavily used lateral access points (Calles, NPS reaches).

Where there isn't much beach width available to implement natural infrastructure, dune embankments are sometimes placed within the available space on a shore such as on exposed cobble berms or over rock revetments. A local example of a smaller sand embankment is Seadrift (Figure 7) where a rock revetment was constructed and then buried with beach sand in the 1980s. Some of the rock revetment is still buried under vegetated foredunes in the center of the Seadrift reach (which is the widest beach in Seadrift reach), while other areas are exposed but protect the remaining foredunes landward of the structure. Another example is at South Ocean Beach, San Francisco where a sand embankment is placed every 1 to 3 years to mitigate bluff and beach erosion in critical areas (Figure 8). These "dunes" are temporary and presumed to have little ecological value. Where space is available, dune embankments may be combined with foredunes to more closely resemble a natural dune field.

SOURCE: : SPUR 2012

Stinson Beach Nature-Based Adaptation Feasibility Study . 171009.00

Figure 5
Dune Embankment at Ocean Beach, San Francisco, CA

SOURCE: Bob Battalio Aug 2018

Stinson Beach Nature-Based Adaptation Feasibility Study . 171009.00

Figure 6
Dunes at National Park Service Beach
Stinson Beach, CA

SOURCE: James Jackson 2019

Stinson Beach Nature-Based Adaptation Feasibility Study . 171009.00

Figure 7
Seadrift dune embankment covering rock revetment (left) and eroded with rock exposed (right) Seadrift, CA

SOURCE: Louis White Dec 2016

Stinson Beach Nature-Based Adaptation Feasibility Study . 171009.00

Figure 8
Sacrificial sand embankment, South Ocean Beach, San Francisco, CA

2.3. Foredunes and Dune Embankments with Cobble-Gravel Berms

Dunes behind cobble-gravel berms are typically found near river mouths and other sources of coarse sediment in California. In a nature-based infrastructure context, constructed cobble-gravel berms can be combined with foredunes and dune embankments to provide a more resilient, erosion-resistant shore form. The cobble-gravel berm may be buried by the dune feature for most of the year, but exposed seasonally following large wave events.

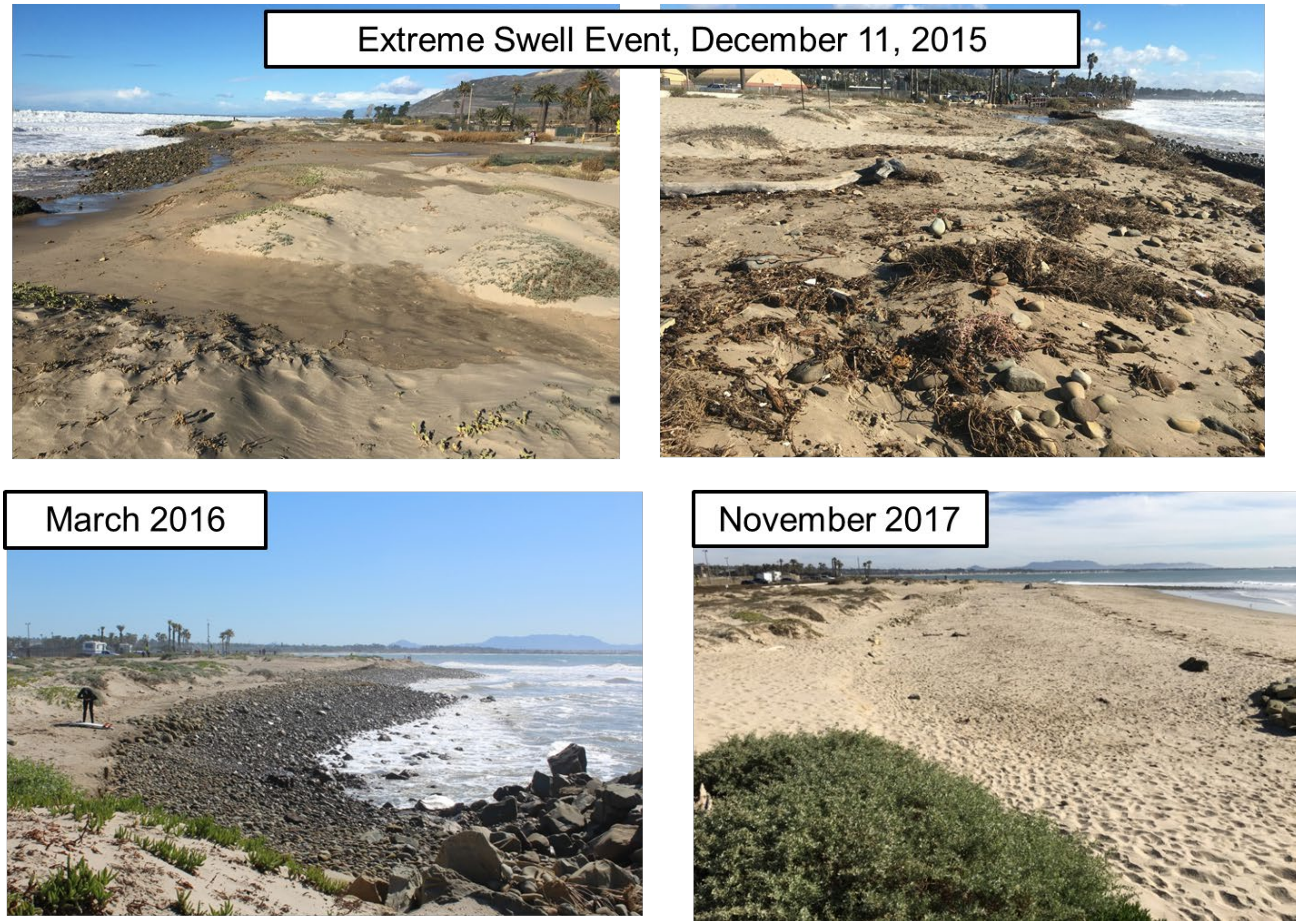
Natural cobble-gravel berms are typically below a sandy beach with sufficient dry sand to feed dune growth via wind, augmented by vegetation trapping and growth. Where there is adequate sand supply, the cobble is typically covered by sand, but exposed during extreme high wave events in the winter season. Where the shore is eroding, the cobble may be exposed at all times. The cobble and gravel tend to be moved onshore by waves and hence the exposed cobble-gravel berms slow but do not stop shore migration. The outcome of this process of migrating shore is depicted in Figure 9 at Emma Wood State Beach in Ventura, CA, near the Ventura River Mouth.

SOURCE: Bob Battalio early 2000s

Stinson Beach Nature-Based Adaptation Feasibility Study . 171009.00

Figure 9
Emma Wood State Park. Migrating cobble berm backed by vegetation and fronted by sand. The trees on the beach were behind the cobble berm and beach prior to the shore migrating landward.

Figure 10 shows the extent of wave run-up at the Surfers Point dunes during an extreme swell event that caused damages in other parts of Ventura but did not damage the dunes or adjacent backshore. The cobble and dunes dissipated the large wave run-up. The sand beach was eroded, exposing the cobble berm. The sand beach recovered the following summer. Note that the dunes are located landward of the cobble berm face, and are protected by the cobble berm. As shown in Figure 10, the foredunes were flooded slightly but remained intact over the extreme 2015-2016 El Nino.



SOURCE: ESA 2017

Stinson Beach Nature-Based Adaptation Feasibility Study . 171009.00

Figure 10
Post event performance and recovery of cobble and dune shore in Ventura, CA

2.4. Cobble-Gravel Berm

Cobble-gravel berms refer to coastal sediment deposits that are coarser (larger particle diameter) than sand, and can include sizes ranging from gravel to boulder. Cobble berms are most prevalent at river and creek mouths but also form at the base of cliffs, whether as lag deposits buried under sandy beaches (only exposed seasonally and/or during storms) or as higher, well developed berms that extend to higher levels of wave run-up. Cobble-gravel berms and lag deposits are essentially natural rock revetments, sometimes referred to as “dynamic revetments” in the coastal engineering literature because the rocks move in response to waves and wave run-up. Rock movement results from the smaller, more rounded rocks, as compared to the rocks used in traditionally designed rock revetment shore armoring, which consist of larger, “rough, angular” stone generated at rock quarries which tend to “lock together” with a small foot print if placed carefully. The cobble-gravel berms tend to have flatter slopes and a larger footprint than traditional rock revetments, which increases dissipation of waves and wave run-up with less wave reflection and scour. These characteristics facilitate sandy beach recovery. The cobble-gravel deposits are also easier to traverse and likely provide better ecology than traditional shore armor.

These coarser sediments tend to move onshore if mobilized by waves due to the asymmetric power of waves coming to shore versus receding back to sea. Coarse sediment movement on the shore is greatest when waves accelerate onshore during run-up; coarse sediment movement is lower when waves recede (down-rush) via infiltration of run-up water into the porous sediment mass and steep angle of repose of the larger particles (stability of the piled berm) (Everts and others 2002). In other words, the waves expend most energy as they run-up on the shore and move large sediments, some of the water seeps into the berm while the rest flows back to sea, leaving most of the coarse sediment in place as a berm. The crest of the cobble-gravel berm is, like sandy beaches, related to wave run-up elevations (Lorang 2002).

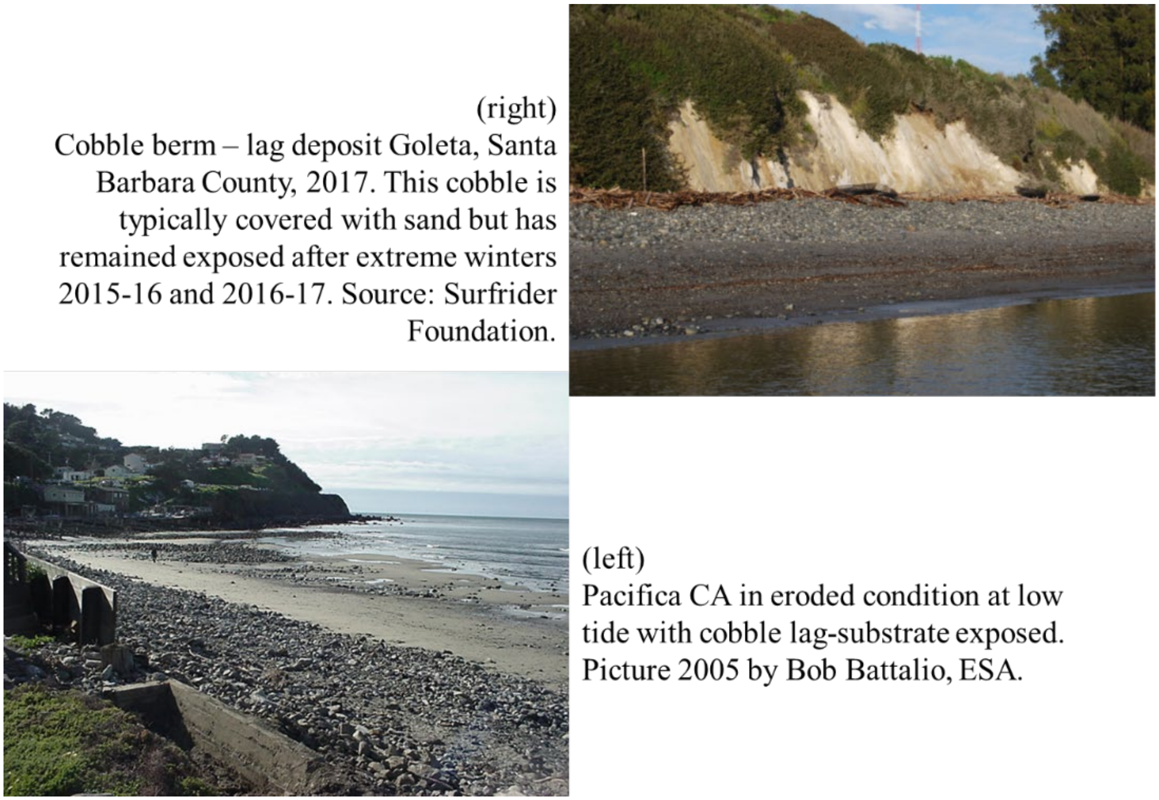
If the coarse sediment supply is not sufficient to form a large enough mass or is too large for the waves to move inland and upslope, the sediment will accumulate in a lower, thinner deposit called a “lag deposit”. Cobble-boulder-gravel lag deposits are typically found at the base of coastal bluffs where coarse material accumulates on wave-cut shore platforms and is buried by sand much of the time, but exposed during extreme winters. A local example cobble berm exists east of Stinson in the cove below Steep Ravine. Examples of cobble-gravel berms and lag deposits elsewhere in California are shown in Figure 11 and Figure 12.

(right)
Cobble Berm, 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. Source: Surfrider Foundation.

(left)
Cobble berm at Prisoner’s Harbor, Santa Cruz Island, CA. Photograph by Jenny Dugan.

Stinson Beach Nature-Based Adaptation Feasibility Study . 171009.00

Figure 11
Cobble-Gravel berms in California



(right)
Cobble berm – lag deposit Goleta, Santa Barbara County, 2017. This cobble is typically covered with sand but has remained exposed after extreme winters 2015-16 and 2016-17. Source: Surfrider Foundation.

(left)
Pacifica CA in eroded condition at low tide with cobble lag-substrate exposed. Picture 2005 by Bob Battalio, ESA.

Stinson Beach Nature-Based Adaptation Feasibility Study . 171009.00

Figure 12
Cobble / gravel / boulder lag deposits

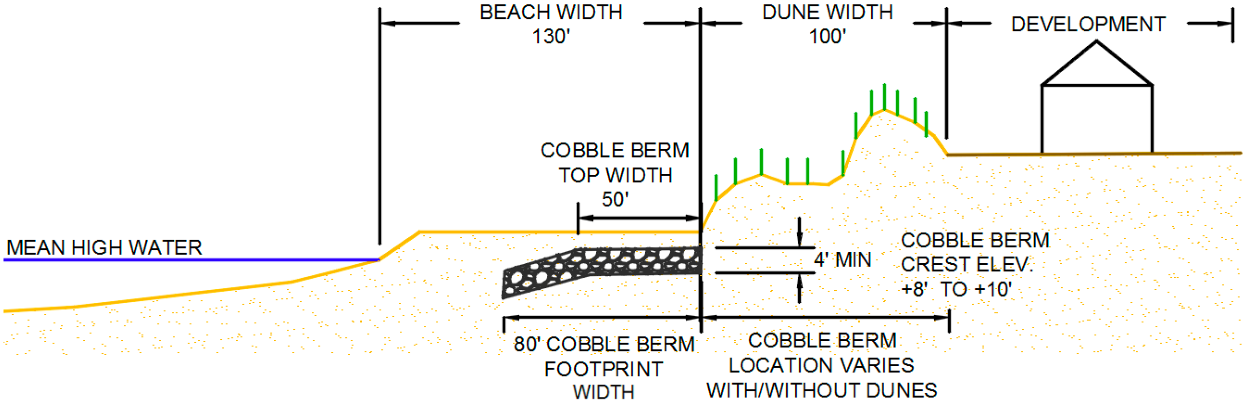
3. Suitability of Nature-based Infrastructure at Stinson Beach

ESA developed an initial range of nature-based infrastructure types that could be implemented at each study reach. General suitability of different types is based on a comparison of desired space for natural infrastructure function and the available space along Stinson Beach defined as the distance seaward of existing development to the shoreline. The desired and available space metric is generically called “shore width” that includes beaches and existing dunes where present. The shore widths available by reach (Section 3.2) are based on historic and existing conditions described in Study Memorandum 1 (ESA 2020a) and the minimum desired shore widths for nature-based infrastructure types are summarized in Section 3.1 and further described in Study Memorandum 2 (ESA 2020b). Section 3.3 discusses the suitability of different natural infrastructure types in each reach.

3.1. Minimum Natural Infrastructure Width Requirements

The desired cross-shore width dimensions for beaches, dunes and cobble-gravel berms were previously developed based on a review of site conditions, reference sites and natural infrastructure guidelines (Study Memorandum 1, ESA 2020a). These dimensions are shown schematically in Figure 13. These dimensions are desired minimums to result in morphologic and ecologic functions, and are provided for screening of alternatives as well as providing an indication of the benefit of development setbacks to increase available space and performance of nature-based approaches.

Given the limited space available in the study area, minimum dimensions somewhat less than the desired dimensions are considered for this study. The minimum space requirements for each nature-based infrastructure type were determined from the C-SMART analysis and Natural Infrastructure Guidelines (TNC and others 2018) and compared to the existing space available along the shoreline (see Existing Conditions, ESA 2020a). The minimum dune width is 50 feet (foredune and dune embankment features). The minimum top width for cobble berm is 50 feet, while the minimum overall cobble berm footprint is 80 feet including the seaward sloping face. The minimum beach width is 100 feet from either the 50 feet of dunes or the 50 feet of cobble-gravel berm top width.



SOURCE: ESA 2020

Stinson Beach Nature-Based Adaptation Feasibility Study . 171009.00

Figure 13
Conceptual Desired Dimensions for Natural Infrastructure Elements at Stinson Beach

3.2. Available Shore Width by Reach

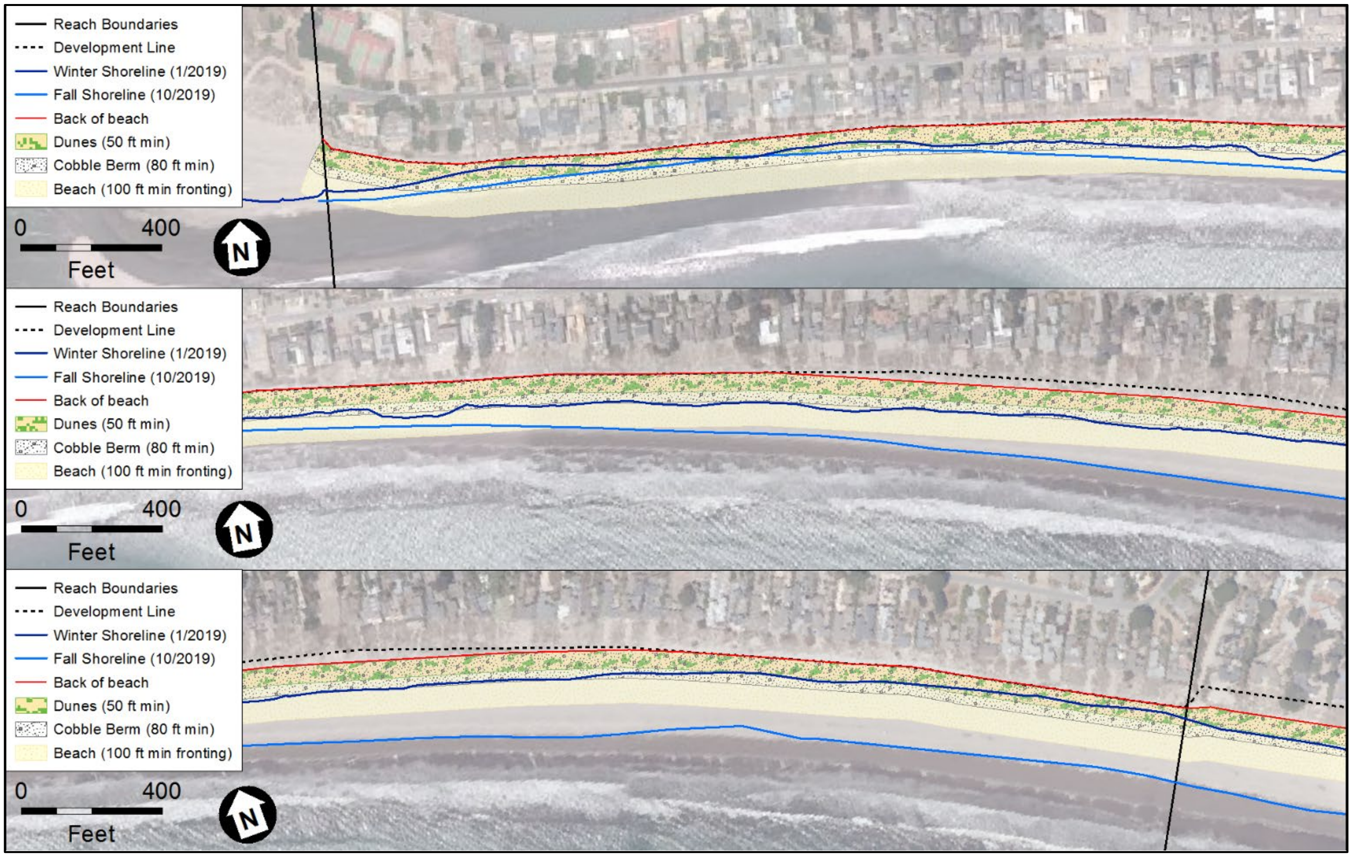
Minimum feature widths for dunes, cobble-gravel berms and optimum fronting beach widths are superimposed on aerial photographs of the study area in Figure 14 and Figure 15. Minimum feature widths are measured from the "back of beach" red line, which represents the current transition of the beach to upland features or structures such as dune toe (back of dune), coastal armor or homes. The blue lines represent the location of the mean high water (MHW) shoreline surveyed in October 2019 (light blue) and the same shoreline extracted from January 2019 County LiDAR. The area between the "back of beach" and the MHW shoreline is considered the space available for nature-based infrastructure. A "development line" is added where built assets are landward of the "back of beach" line used to locate the alternatives. Development includes the Seadrift rock revetment (some of which is buried behind foredunes), homes in the Patios and Calles reaches, and buildings/parking lots in the NPS reach. These lines are approximate and schematic but adequate for the purposes of this alternatives screening analysis. Note that the October 2019 beach was abnormally wide compared to recent aerial imagery and shoreline data, and represents the maximum available space under existing conditions. The January 2019 beach is representative of a recent minimum for the study area based on collected shorelines.

Available beach width by reach based on recent survey data and LiDAR

- Seadrift (Figure 14) is discussed as two reaches due to the varying beach width alongshore. Western Seadrift does not have adequate space for nature-based infrastructure given the relatively narrow beach and the existing shore armor (rock revetment) which is covered by vegetated sand in some locations.

Seadrift East has a wider beach adequate to meet the minimum dimensions of nature-based infrastructure. Note that the back of beach is located at the exposed rock revetment along most of Seadrift except in the center of the reach where the revetment is buried by foredunes.

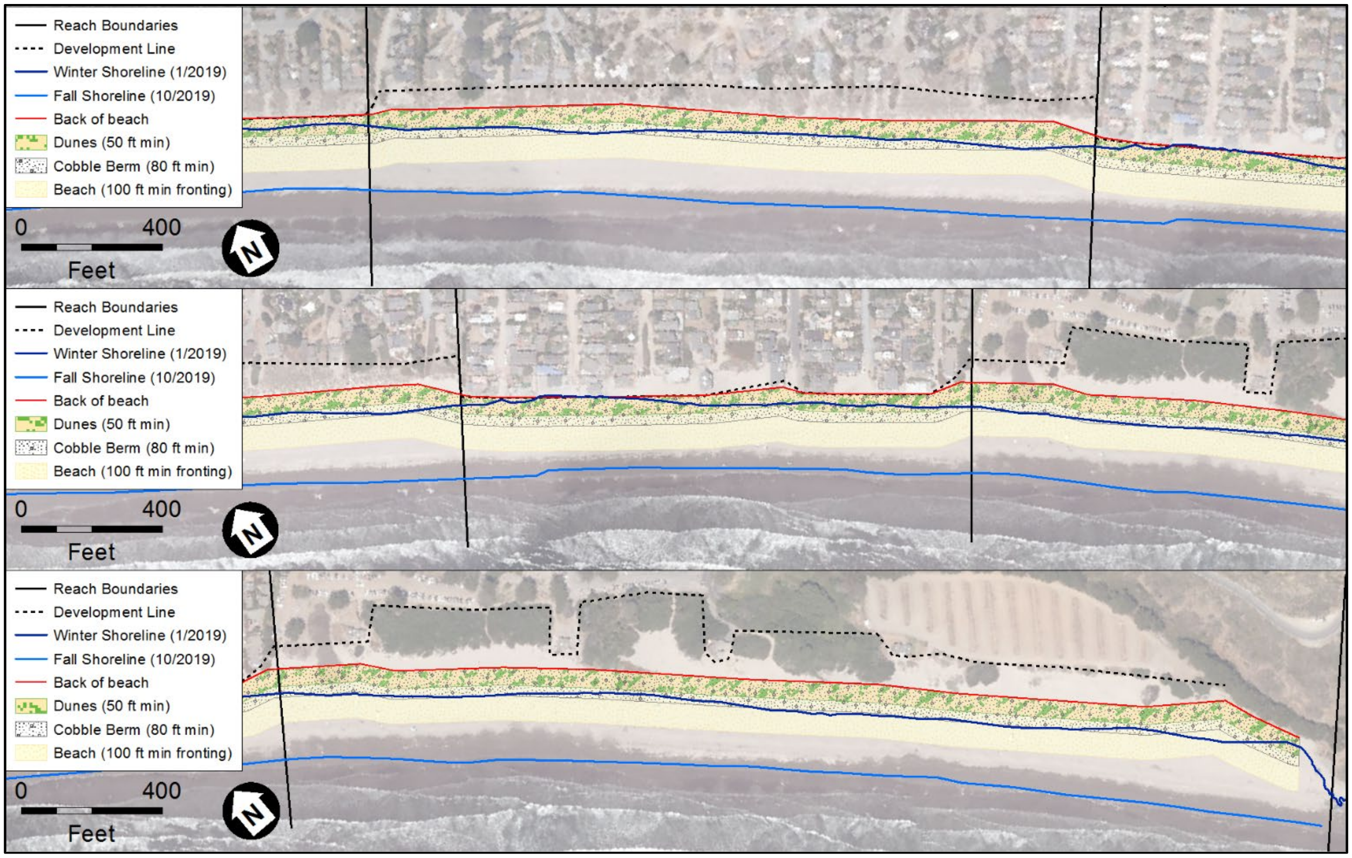
- The Patios reach (Figure 15 top) has 50 to 100 feet of unarmored dunes fronting the development, which can be considered as available dune space when evaluating alternatives.
- The Calles reach (Figure 15 middle) has small dunes intermixed with development along the shoreward edge. A straight line connecting the most seaward development is used as the back of beach in order to determine available space. Small pockets exist between the most seaward homes that provide additional space for natural infrastructure. By removing the seaward-most homes, wider continuous natural infrastructure could be built.
- The NPS reach (Figure 15 bottom) has larger dunes present and the back of beach here is located at the dune toe (the dune face is bare and looks like beach sand in the aerial imagery).



SOURCE: ESA, Marin County 2018 Imagery

Stinson Beach Nature-Based Adaptation Feasibility Study . 171009.00

Figure 14
Available Space for Natural Infrastructure along Seadrift Reach: West (top), Center (middle) and East (bottom)



SOURCE: ESA, Marin County 2018 Imagery

Stinson Beach Nature-Based Adaptation Feasibility Study . 171009.00

Figure 15
Available Space for Natural Infrastructure along Patios (top), Calles (middle) and NPS (bottom) Reaches

3.3. Suitability of Nature-Based Infrastructure by Reach

Table 1 provides a comparison of minimum desired infrastructure width and actual beach width available based on the existing beach widths surveyed in October 2019. The fall beach condition is used to determine suitability because the natural infrastructure would be ideally constructed in late summer/fall. Note that the beach widths measured in October 2019 are wider than typical beach widths, and therefore natural infrastructure types that require smaller footprints were emphasized. Several nature-based infrastructure types are selected as potentially suitable for each reach, as marked by “Y” in Table 1, effectively screening the types and identifying those suitable for each reach.

TABLE 1. SUITABILITY OF NATURAL INFRASTRUCTURE TYPE BY REACH, SCREENED BY AVAILABLE BEACH WIDTH

	Beach width (feet)[1]	Foredunes	Foredunes with Cobble-Gravel Berm	Dune Embankment	Dune Embankment with Cobble-Gravel Berm	Cobble-Gravel Berm	Notes
Desired Natural Infrastructure Width (feet)		230	130	100	100	80	
Seadrift West	103			Marginal	Marginal	Y	See text regarding potential use of a dune embankment, with or without Cobble-Gravel berm
Seadrift East	214		Y	Y	Y	Y	
Patios	250	Y	Y	Y	Y	Y	
Calles	235	Y	Y	Y	Y	Y	
NPS	264	Y	Y	Y	Y	Y	See text regarding Cobble-Gravel lag geometry option

[1] Measured Oct 2019, wider than typical beach width.
Y= feasible alternative based on space considerations.

For the Seadrift West Reach, it seems possible based on the average October 2019 beach width of about 100 feet that a dune embankment with or without a cobble-gravel berm could be employed along some of this reach. However, this area is known to have narrow beaches with wave run-up reaching the rock revetment on the back of the beach during winters (see Study Memorandum 1). For the more typical narrow beach conditions, dunes would be subject to frequent wave action resulting in a vertical scarp that is generally not desirable from an access perspective (see Figure 16). Similarly, a cobble-gravel berm located seaward of the dunes would be exposed much of the time, resulting in a rocky instead of sandy shore. Therefore, it is our judgment that dunes with or without cobble are not likely to perform well at Seadrift West reach.

At the NPS Reach, an option for a cobble-gravel lag instead of the cobble-gravel berm is noted. This option is provided in recognition of gravel stream sediments that exist in the area due to the proximity of Easkoot Creek. Historically, during flood flows, Easkoot overtops its banks and flows across the NPS reach to the ocean. Placement of a cobble-gravel mass in the form of a low apron, or lag, could facilitate these flood flows across the dunes with less erosion, however dune repairs would be expected after significant Easkoot overflows.

e

SOURCE: Bob Battalio, early 2000s

Stinson Beach Nature-Based Adaptation Feasibility Study . 171009.00

Figure 16
Scarp at eroded dune embankment, Ocean Beach, San Francisco

4. Adaptation Alternatives Development

The nature-based adaptation alternatives proposed for Stinson Beach build upon the adaptation strategies presented in the C-SMART Adaptation Report (Marin County 2018) and suitably natural infrastructure types described above. A range of near-term adaptation alternatives were selected for this study (Section 4.1) that combine one or more natural infrastructure types. The potential natural infrastructure combinations were then prioritized using qualitative selection criteria. Two adaptation alternatives were developed for the study area by combining the appropriate natural infrastructure types for each reach (Section 4.2). The nature-based alternatives were evaluated along with an armoring baseline (Chapters 6, 7). Long-term adaptation pathways consistent with the near-term alternatives analyzed in this study are also discussed to facilitate integrated adaptation planning for the greater Stinson-Seadrift community (see Chapter 8).

4.1. Priority Rating of Nature-Based Infrastructure Combinations

Adaptation Alternatives for Stinson Beach were selected from applicable nature-based infrastructure combinations using a priority rating scheme. Priority ratings of high, medium or low were developed by qualitatively applying several criteria. The overall rating was assigned based on the average of the ratings of the selection criteria, as shown in Table 2. The selection criteria used to form the overall ranking (Table 2) of adaptation alternatives are described below. Alternative evaluation criteria described in Chapter 6 are derived from these selection criteria.

- **Natural Context:** A nature-based infrastructure type is more desirable if it is consistent with the natural setting. A review of reference sites indicates that foredunes are the most natural shore typologies under consideration (Baye 2019). Linear dune embankments and cobble-gravel berms are not native to the Stinson Beach area, with the exception of cobble-gravel deposits associated with Easkoot Creek, which occasionally overflows across the NPS reach to the ocean. Native dune vegetation is likely to be more compatible with backshore beach habitat quality suitable for western snowy plovers, compared with European beachgrass. Native beach wildrye and associated broadleaf perennial dune plants tends to form gentler, wider foredune slopes and more open, sparse vegetation cover at the seaward edge of the foredune.

- **Ecology Benefits:** The more natural foredunes support native plants and associated fauna and therefore provide the highest ecology outputs. In addition, because foredunes promote the natural cycling of sediment and accommodate rather than reflect wave energy, they tend to increase beach width which is beneficial for shorebirds. In central and California shorebird abundance is greater on beaches with wider, flatter swash zones and wider upper beach areas (Neuman et al. 2004, Neuman et al. 2008). Wide upper beaches are especially important for plover species that forage and roost at or above the high tide drift line and are strongly associated with beach cast wrack deposits (Dugan et el. 2003, Nielsen et al. 2013), including the federally protected western snowy plover occurs in the area. Dune embankments, depending on their persistence and types of plants can provide ecology benefits as well by increasing beach width relative to beaches backed by hard armor, but may not be the correct shape to retain the beach cast wrack that is beneficial to shorebirds. Cobble-gravel berms are believed to have some ecological value similar to but less than a sandy beach and increased shoreline habitat diversity may increase the diversity of shorebird species using the area (Point Blue unpubl. data). The cobble helps limit beach erosion and promotes wider beaches which is beneficial for shorebirds. However, if the cobbles become mobile in the swash zone, they may crush invertebrates and negatively impact beach ecology when exposed for long periods.

- **Effectiveness of Protective Services:** The goal of this application of natural shore infrastructure is to provide protection to development from coastal erosion and flooding hazards with sea-level rise. Where there is adequate space, the foredunes provide this benefit most efficiently. Dune embankments may appear to be more effective owing to their higher relief, but they also tend to erode and scarp more than foredunes. Cobble-gravel berms and lag can restrict erosion but are naturally overtopped by wave run-up during extreme events: Hence cobble-gravel berms function best in combination with dunes that dissipate overtopping wave run-up. The effectiveness of protective services for alternatives are quantified in Chapter 6, which include estimation of maintenance requirements (and thus costs) with future sea-level rise. Native foredune vegetation, including widely creeping perennials, is more likely to facilitate rapid post-storm recovery of storm wave-eroded foredunes. Native foredune vegetation is also less likely to form foredune morphology with high, steep, narrow seaward slopes that form reflective wall-like erosional scarp profiles after major winter storms, compared with foredunes built by European beachgrass.

- **Access and Aesthetics:** Foredunes provide the least barrier to shore access and views, and are generally considered aesthetically pleasant because they naturally form as gradual transitions from the beach to uplands. The high relief (steep) geometry of dune embankments could impede coastal recreation access and views of the ocean to a greater extent. The dune embankment height or face steepness can make it difficult to traverse without access improvements such as stairs. On the other hand, dune embankments may also be favored, especially for the visual sense of protection resulting from the higher dune crest elevations. Cobble-gravel berms are accessible but not as comfortable to walk on when exposed, especially on the sloping face, and have a different appearance than the native beach strand. However, cobble-gravel berms are more natural and traversable compared to other engineered armoring structures.

- **Relative Cost:** nature-based infrastructure types with a lower cost of construction and lower maintenance requirements are given a higher ranking. Foredunes are the lowest initial cost type if adequate space is available, and low maintenance once the desired vegetation is established. Dune embankments require greater amounts of sand and grading, and may require irrigation for planting and access structures to traverse grade changes, resulting in greater costs. Additionally, dune embankments are more subject to wave run-up erosion impacts due to their exposed steep face. Cobble-gravel berms require import of the sediments and hence have the highest initial cost. However, the maintenance requirements of Cobble-gravel berms can be low. All features will need increased maintenance (and costs) with higher sea levels (see Chapter 6).

TABLE 2. NATURAL INFRASTRUCTURE SELECTION CRITERIA RANKING

Selection Criteria	Foredunes	Foredunes with Cobble-Gravel Berm	Dune Embankment	Dune Embankment with Cobble-Gravel Berm	Cobble-Gravel Berm
Natural Context[1]	High	Medium	Medium	Low	Lowest
Ecological Benefits	High	Medium	Medium	Medium	Low
Effectiveness for Protective Services (provided space available)	High	Highest	Medium	Medium-high	Medium
Access / Aesthetics	High	Medium	Medium-low	Medium-low	Low
Relatively lower Cost / Maintenance Needs[2]	High	Medium	Low	Med-low	Medium
OVERALL RATING / PRIORITY	**HIGH**	**MEDIUM**	**MEDIUM-LOW**	**MEDIUM-LOW**	**LOW**

[1] For reaches except NPS, which ranks relatively higher for Cobble-Gravel berm because it has a natural source of cobble and gravel from Easkoot Creek.

[2] High ranking assigned to low cost.

4.2. Alternatives Selected by Reach

Alternatives were selected for each reach from the various nature-based infrastructure alternatives in Table 2. Additional considerations that informed the selection of alternatives include existing development location/type and beach conditions in each reach. The selection process is described below by reach with details pertinent to alternative suitability. Additional information can be found in Study Memorandum 1 (ESA 2020a).

Seadrift: Seadrift West already has a shore armor device and has limited space available for dunes (Table 1). Given the existing rock and limited space, a cobble-gravel berm was selected as potentially beneficial to limit the extents of erosion and wave run-up and facilitating beach recovery. The beach is progressively wider with distance eastward, and Seadrift East has sufficient space for a dune embankment.

Patios: development in the Patios Reach is set back farther, and the more desirable foredunes are potentially feasible with or without a cobble berm. A dune embankment with or without a cobble-gravel berm, or a cobble-gravel berm alone could be suitable, but are considered less ecologically beneficial options.

Calles: The development in the Calles Reach includes a range of setbacks from the ocean, and both dunes and cobble-gravel berm were selected. Either foredunes or a dune embankment alternatives are selected.

NPS: The NPS reach has the greatest available space: it has a wide beach today and relatively high accommodation space for beach and dune migration with sea-level rise. The reach has dunes of varied height along the back beach today. Foredunes alone and with a cobble-gravel berm are selected for this reach. The cobble gravel berm would include a lag deposit at the west end of the reach to facilitate Easkoot Creek discharge during high flood flows (Figure 17), and consistent with coarse creek sediments (Figure 18). The lag deposit would be lower in elevation, and slope toward the shore forming an apron for the creek discharge. This treatment would likely be localized where the creek flows are directed based on park renovation or NPS guidance. In summary, foredunes and dune embankments (with or without cobble berm) are suitable for all but Seadrift West reaches while the cobble-gravel berm is suitable for all reaches. The selected nature-based adaptation alternatives for feasibility analysis are listed in Table 3.

The nature-based adaptation alternatives are depicted in cross section and plan view schematics in Chapter 5. Following review with the project TAC and County in June 2020, these selected alternatives were evaluated for effectiveness in mitigating sea-level rise and storm impacts based on coastal engineering assessment (Chapter 6). The evaluation includes a baseline condition to compare and quantify the relative benefits of nature-based features. The armoring baseline (referred to as Alternative 0 in this evaluation) assumes that development is armored using a traditional rock revetment. The evaluation also identifies if and when additional adaptation actions may be required such as armoring or structural modifications to development.

TABLE 3. SELECTED NATURE-BASED ADAPTATION ALTERNATIVES BY STUDY REACH

Reach	Adaptation Alternative	Notes
Seadrift West	1. Cobble-Gravel Berm	Marginal space, existing shore armor
Seadrift East	1. Dune Embankment 2. Cobble-Gravel Berm	Limited but increasing space, existing shore armor
Patios	1. Foredunes 2. Foredunes + Cobble-Gravel Berm	Development set back, some existing foredune infrastructure
Calles	1. Foredunes + Cobble-Gravel Berm 2. Dune Embankment + Cobble-Gravel Berm	Irregular development line creates pockets of additional space for natural infrastructure
NPS	1. Foredunes 2. Foredunes + Cobble-Gravel Berm	Cobble-Gravel berm with cobble-gravel lag geometry added as third option

SOURCE: NPS May 2018

Stinson Beach Nature-Based Adaptation Feasibility Study . 171009.00

Figure 17

Easkoot Creek scour at NPS reach. Blue line shows channelized Easkoot Creek. Dashed red line shows flood flow avulsion through parking lots and dunes to beach

SOURCE: : Louis White 2019

Stinson Beach Nature-Based Adaptation Feasibility Study . 171009.00

Figure 18
Easkoot Creek sediment basin (left) and scour repair using creek sediments, covered by beach sand (right), NPS reach

4.3. Integration of Reach-based Alternatives

The reach analysis using typical profiles has resulted in the selection of two alternative natural shore infrastructure types for each reach. While it is possible that a project for one or more reaches proceeds separately, it is also reasonable to consider a multi-reach project. Hence, it makes sense to consider similar natural shore infrastructure alternatives for all reaches: this could be considered a potential project that would be constructed at one time, for example. Following this concept integrating all reaches, it may make sense to consider alternatives as a function of time: That is, as sea levels rises and the shore narrows, the entire shore treatment may be modified within the context of a project adaptation. For example, the initial project may consist of dunes where there is adequate space and cobble-gravel berms where there is not. Given a future sea-level above a threshold, cobble-gravel berms could be added to the remaining reaches. Conversely, it is possible that reaches may act separately, similar to the way the Seadrift community has armored its shore, and the Park Service is unlikely to construct shore protection owing to their national guidelines to limit interference with natural coastal processes.

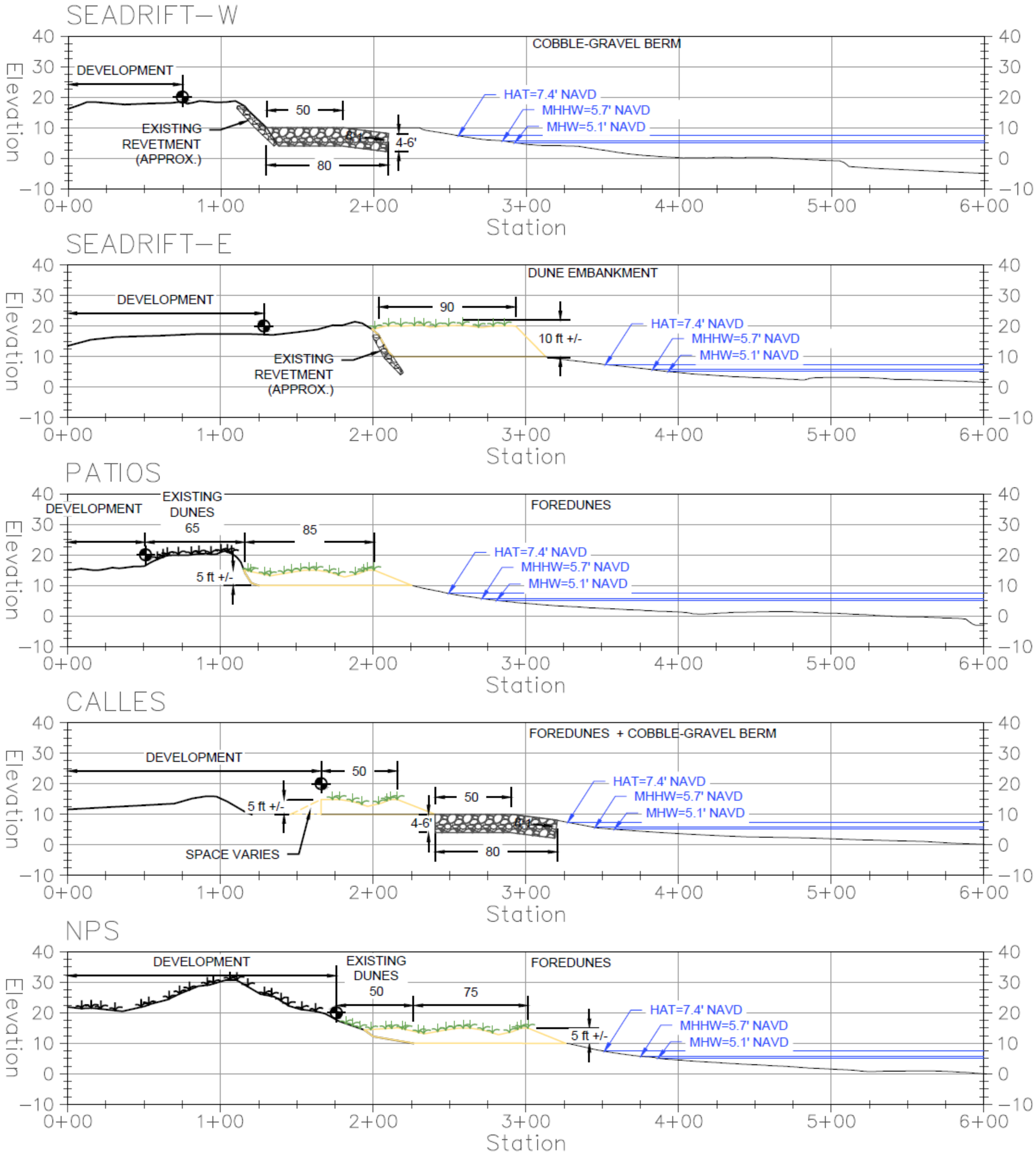
5. Adaptation Alternatives Cross Section and Plan View Detail

The nature-based infrastructure adaptation alternatives evaluated for feasibility are depicted in cross section (Figure 19 and Figure 20) and plan view (Figure 22 and Figure 23). Alternative 1 presents the “more natural” of nature-based infrastructure types, consisting of foredunes where there is sufficient space and dune embankments where space is limited. Alternative 2 presents more structural versions of nature-based infrastructure, including cobble-gravel berms with dunes where there is sufficient space, and only a cobble-gravel berm in the Seadrift West and East reaches where there is limited space. See Section 6.1 for details on typical cross section development for the alternatives.

Figure 21 shows a cross section for the west end of NPS reach to illustrate the cobble lag deposit that could be implemented as part of a cobble berm alternative to facilitate drainage of Easkoot Creek overflows and prevent impacts to adjacent property. This lag feature is important to consider for natural infrastructure at NPS given recent flooding impacts, but the lag deposit was not evaluated for performance in this study.

Typical water levels are shown in the cross section figures for reference to illustrate that alternatives are constructed at the back of the dry beach and above the tide range. Note that development in NPS reach is limited to a few buildings amidst dunes. The representative location of development is annotated on each cross section with a marker placed arbitrarily at elevation 20 feet for illustrative purposes. The baseline adaptation alternative (Alternative 0, not shown in figures) assumes rock revetment is constructed to protect development and maintained with sea-level rise. The armoring would be located along homes in Patios reach (beneath/behind existing dunes), along homes in Calles reach, and in front of the three buildings in the NPS reach (not the entire reach length).

Note that cobble berms are shown near the surface in the following figures; the cobble berms would be buried just below beach elevations when constructed.

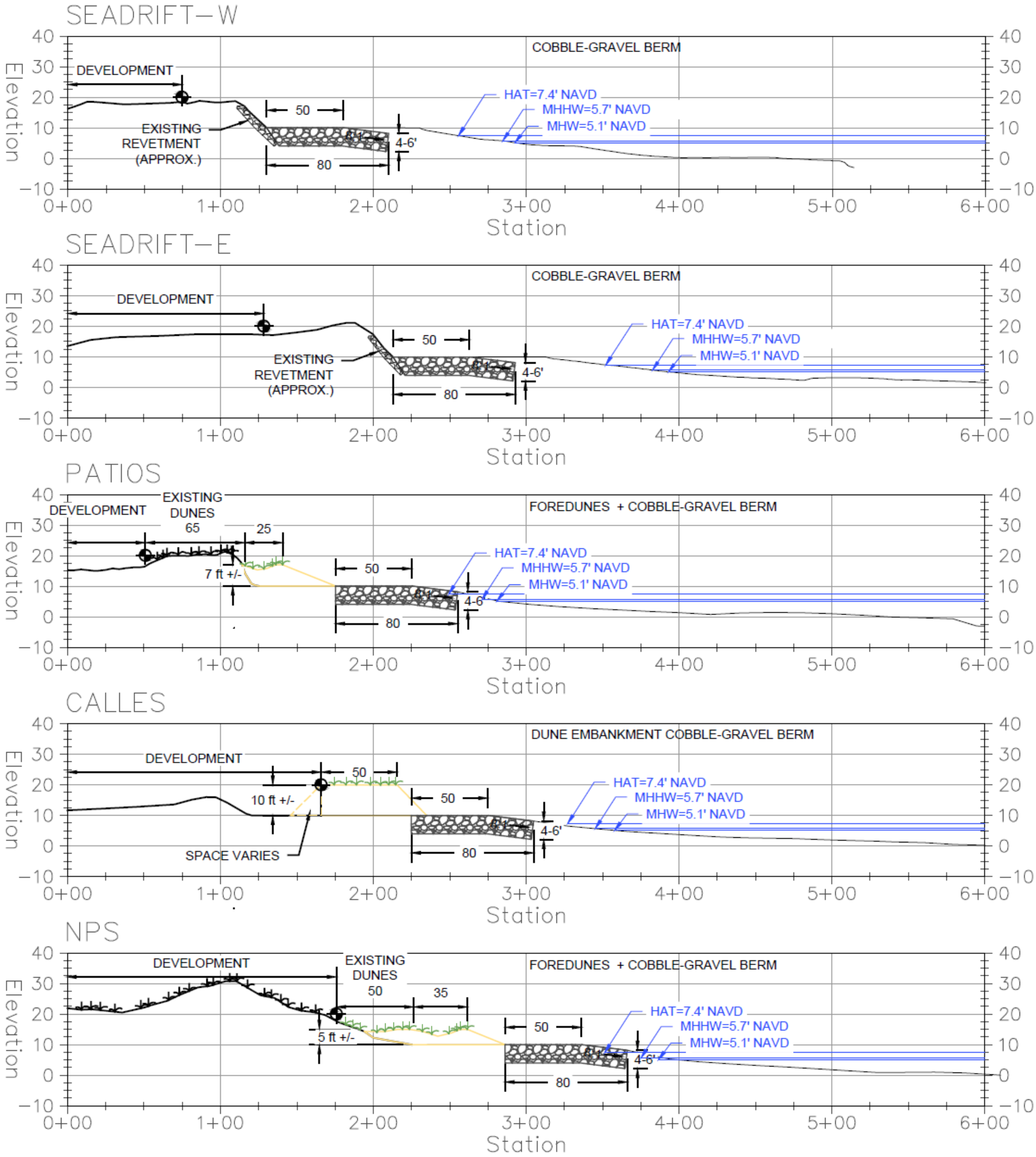


SOURCE: ESA

Stinson Beach Nature-Based Adaptation Feasibility Study . 171009.00

NOTE: 2X Vertical Exaggeration, axes in feet

Figure 19
Alternative 1 Cross Sections

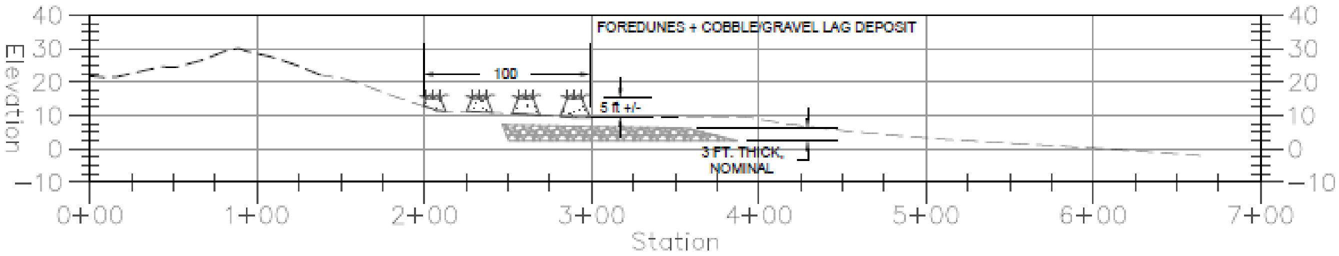


SOURCE: ESA

Stinson Beach Nature-Based Adaptation Feasibility Study . 171009.00

NOTE: 2X Vertical Exaggeration, axes in feet

Figure 20
Alternative 2 Cross Sections

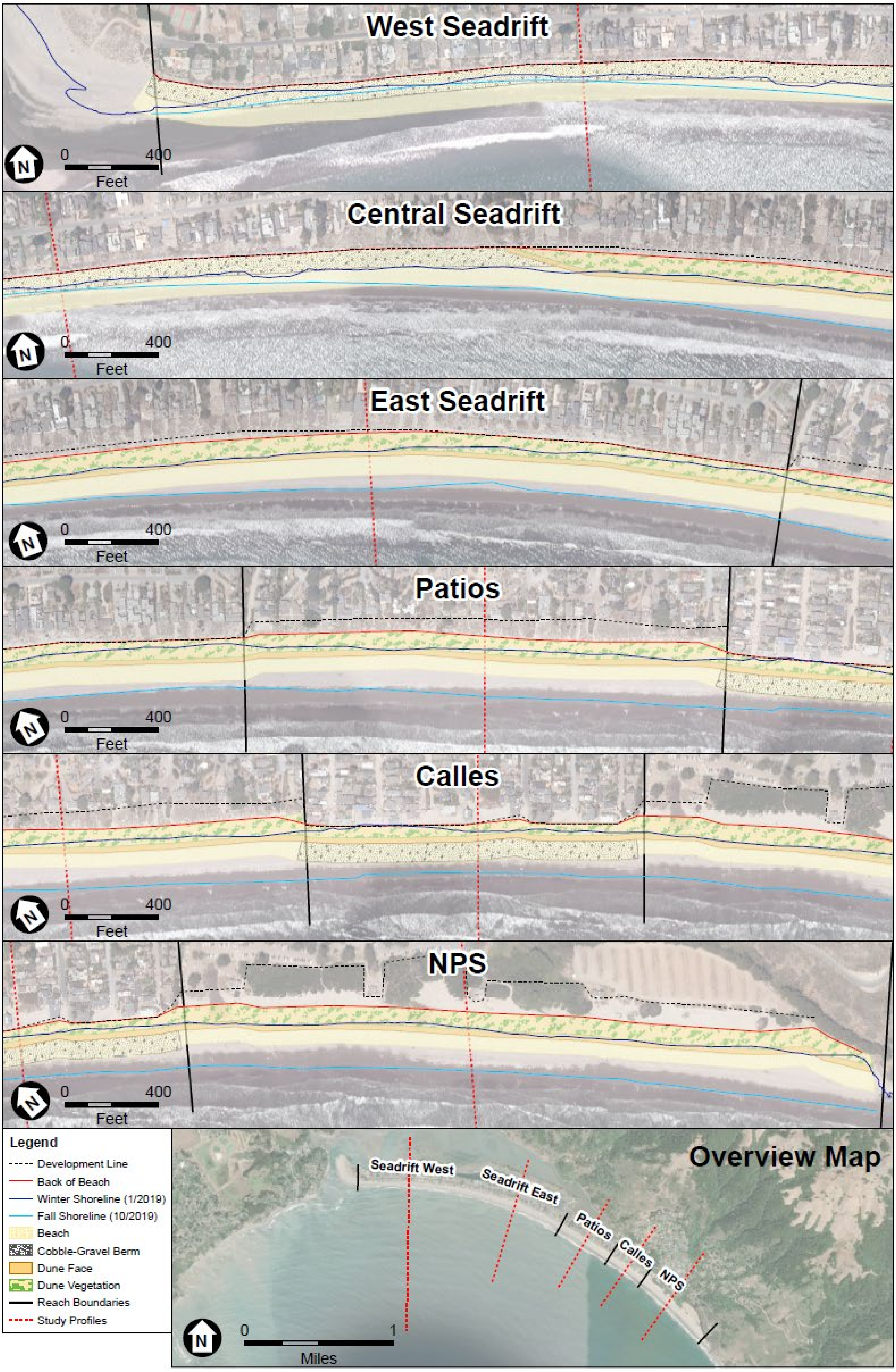


SOURCE: ESA

Stinson Beach Nature-Based Adaptation Feasibility Study . 171009.00

NOTE: 2X Vertical Exaggeration, axes in feet

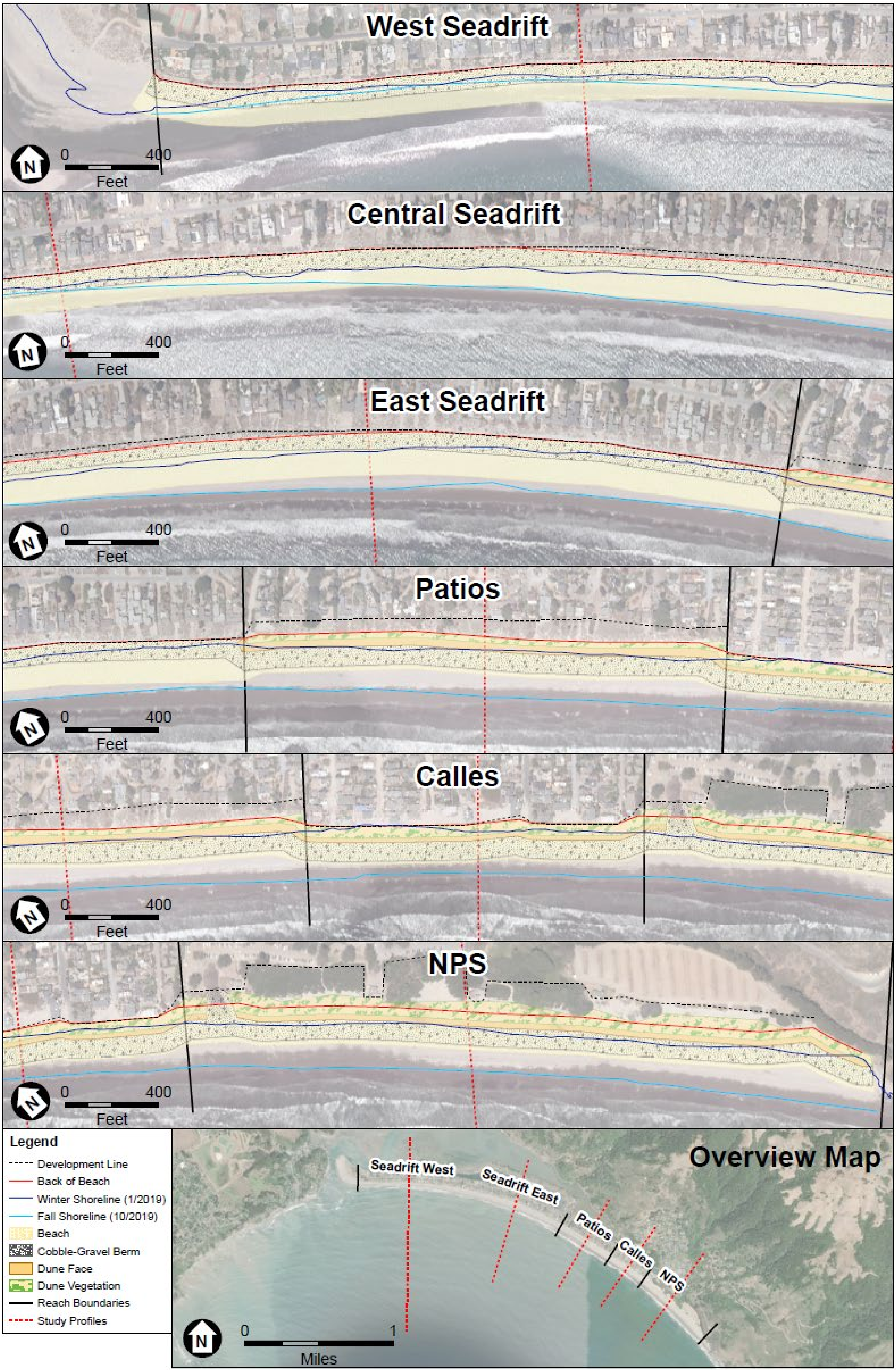
Figure 21
NPS Cross Section illustrating cobble lag deposit at west end (not evaluated)



SOURCE: ESA, Marin County 2018 Imagery

Stinson Beach Nature-Based Adaptation Feasibility Study . 171009.00

Figure 22
Alternative 1 Plan View



SOURCE: ESA, Marin County 2018 Imagery

Stinson Beach Nature-Based Adaptation Feasibility Study . 171009.00

Figure 23
Alternative 2 Plan View

6. Adaptation Alternatives Evaluation

The nature-based adaptation alternatives evaluated for this study are intended to provide sea-level rise protection for vulnerable development along the Pacific shore and maintain the ecological and recreational values of the beach and dunes at Stinson Beach. The adaptation alternatives are based on the community values identified through the C-SMART process, stakeholder engagement for this study as well as a detailed understanding of existing conditions and coastal processes along the study area. Adaptation alternative performance was determined with two technical analyses: modeling shoreline evolution with sea-level rise and modeling of wave run-up for initial and future conditions with sea-level rise. The nature-based alternatives are evaluated along with a traditional shoreline armoring baseline to illustrate the relative persistence of beach (and dune) widths and associated benefits with and without the use of natural infrastructure. This Chapter describes the evaluation process and results.

The outputs of the shoreline evolution modeling directly inform the design life analysis and storm protection benefits. The cross-shore widths of the beaches and dunes over time are used as indicators of both ecological and recreation values (coastal resources benefits), as well as storm and sea-level rise hazard reduction benefits to backshore development (protective services benefits).

Section 6.1 describes the starting conditions for shore profiles used to size and locate natural infrastructure along the shoreline as well as model their evolution with sea-level rise. The following sections describe the methods and results of the evaluation criteria listed below.

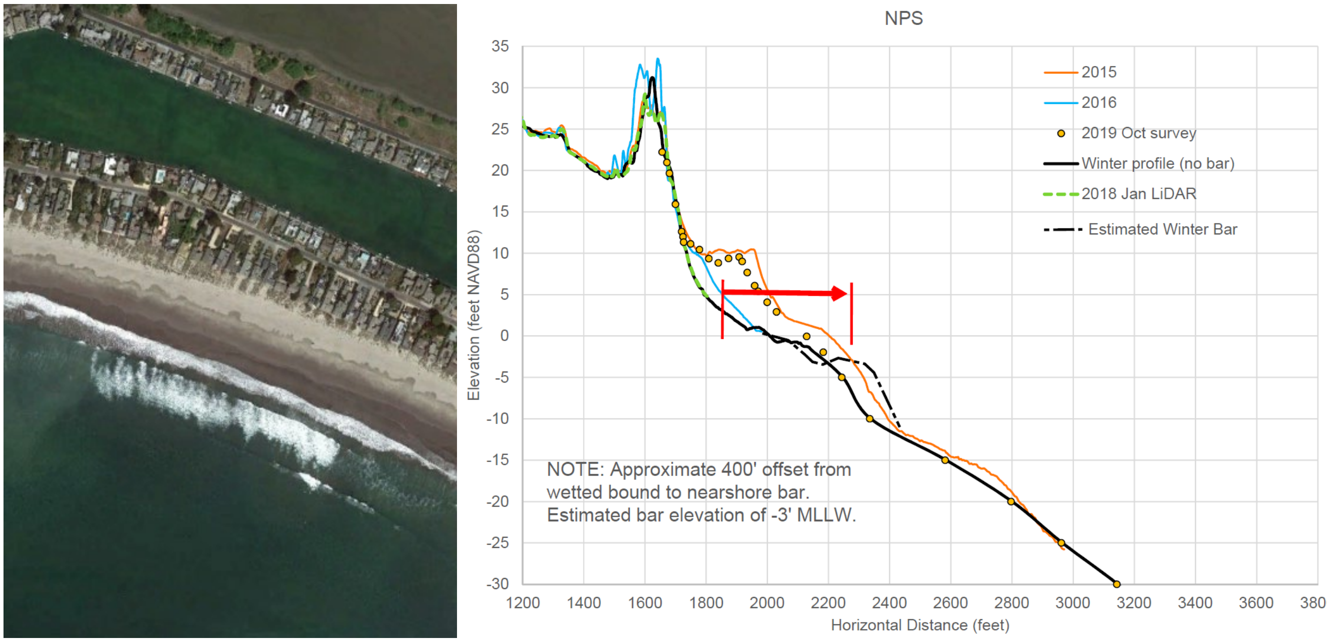
- Design Life Analysis (Section 6.2)
- Storm Protection Benefits (Section 6.3)
- Geomorphic and Habitat Benefits (Section 6.4)
- Constructability (Section 6.5)
- Environmental Impacts and Regulatory Considerations (Section 6.6)
- Public Access (Section 6.7)

An adaptation alternatives evaluation summary matrix that includes relative scoring for each of these categories is presented in Chapter 7.

6.1. Initial Conditions Shore Profiles for Alternatives Evaluation

Initial conditions shore profiles were developed for each reach to evaluate the adaptation alternatives. This section describes the considerations that went into the initial conditions for the armoring baseline and nature-based alternatives. The armoring baseline alternative assumes backshore armoring is constructed and/or maintained when needed to protect backshore development. Winter conditions, when coastal storms occur and beach widths are narrow, were used to evaluate alternatives' functional design life and performance reducing wave run up. Summer conditions, when beaches are wide, were used to consider seasonally influenced factors such as recreational access and beach ecology.

Initial conditions shore profiles were developed starting with 2019 winter LiDAR elevations onshore (above water only) and 2019 fall bathymetry survey data for offshore elevations. The limited bathymetric survey data are not representative of winter conditions in the surf zone, requiring the creation of representative profiles for our analysis. Typical coastal practice entails estimating a winter profile (sometimes called “the Most Likely Winter Profile – MLWP; FEMA 2005). A shore-parallel sand bar was added to the profiles to better represent typical winter conditions that affect wave run-up: Aerial photographs with breaking waves were used to locate the nearshore bar crest and estimate its depth. Figure 24 shows a plan and cross section view of the estimated nearshore sand bar feature. While this is an estimate, it is our experience that winter sand bars typically occur and limit wave run-up on the beach by forcing waves to break farther offshore: Hence, omitting a nearshore bar in the calculations will likely result in an over-estimate of wave runup.



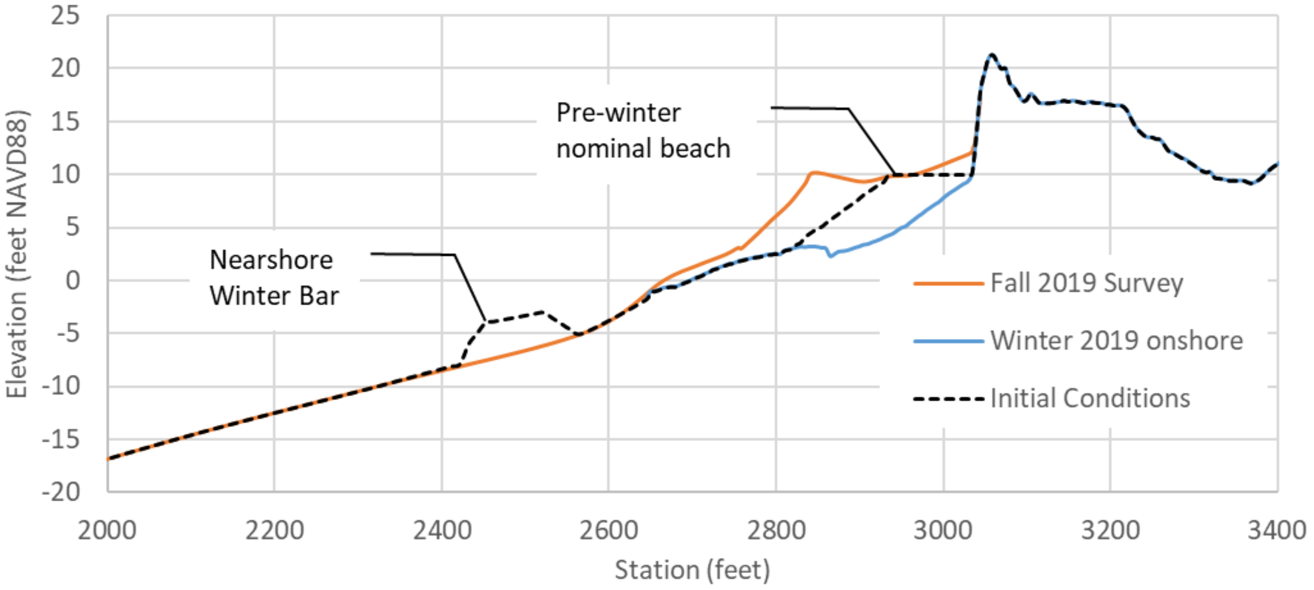
NOTE: Approximate 400' offset from wetted bound to nearshore bar. Estimated bar elevation of -3' MLLW.

SOURCE: ESA, USGS, USACE, Google, Marin County

Stinson Beach Nature-Based Adaptation Feasibility Study . 171009.00

Figure 24
Nearshore bar estimation

Since we expect the natural infrastructure to be constructed prior to winter, the profiles extracted from mid-winter LiDAR data were modified to represent a wider beach berm; a 100-foot nominal beach berm at elevation 10 feet NAVD was added to each profile except for the Seadrift West profile where a 50 foot top width was added to represent narrow beach conditions. For each profile, the resulting widened beach berm was connected to the lower profile using representative beach slopes. An example of the resulting initial conditions profile for Seadrift East is plotted in Figure 25, showing mid-winter 2019 conditions onshore, fall 2019 beach and nearshore conditions, and the added nearshore bar and nominal pre-winter beach width. Adaptation alternative components (cobble berm, foredunes / embankment) were sized accordingly to fit onto the initial conditions profiles to provide protection against a stormy winter (e.g. a 2015-2016 El Nino winter).



SOURCE: ESA

Stinson Beach Nature-Based Adaptation Feasibility Study . 171009.00

Figure 25
Initial conditions profile development with nearshore bar and nominal beach berm that can accommodate natural infrastructure

6.2. Design Life Analysis

The functional life of constructed natural infrastructure depends on seasonal shoreline fluctuations, long term shore evolution with sea-level rise and event-based coastal storm erosion. These shoreline morphology concepts are applied to evaluate the nature based adaptation alternatives over time. This section describes the geomorphic methods and results of the design life analysis including relative engineering costs to construct and maintain alternatives with up to 1 meter (3.3 feet) of sea-level rise. The beach, dune and cobble width outputs from the design life analysis are then used to evaluate the storm protection, recreational, and ecological benefits provided over a traditional shore armoring baseline (Sections 6.3 to 6.5). Beach width is defined as the distance from the backshore (dune or armoring toe) to the MHW shoreline. Dune width is defined from the toe of the dune to the first line of development. Existing dunes are included in the evaluation of Patios and NPS reaches.

6.2.1. Modeling long term shoreline evolution with sea-level rise

The effective life of each adaptation alternative depends in part on long term sea-level rise. Beach, dune and cobble shore evolution were estimated using geomorphic models of the response of the shore to long term sea-level rise. The models evaluate the longevity of both constructed and existing natural infrastructure along the study area and indicate the need for reconstruction or other adaptation actions once erosion surpasses a minimum natural infrastructure width. Dune and cobble erosion methodologies are described in the subsections below followed by the results for the baseline and alternatives. Coastal storm event impacts are discussed below in relation to long term shoreline evolution.

Beach and dune erosion with sea-level rise is modeled for the baseline and nature-based adaptation alternatives for each reach. Erosion of the shoreline, dunes and cobble berms is calculated based on beach width (BW). In general, erosion of dunes and cobble increases from wide beach (no backshore erosion) to narrow beach (greatest erosion), as described in the following subsections.

Dune Erosion

A wide beach provides a buffer against wave run-up at the backshore and can limit dune erosion and damages to development under normal (non-storm) conditions over time. As the beach narrows, waves begin to impact the backshore and erode dunes (if present) at an increasing rate. Once the beach width shrinks to the stable minimum width, the shoreline and dune erode at the same rate, this minimum beach width is maintained by the sand eroded from the dunes, once the dunes erode completely, the beach width diminishes and may disappear especially during stormy winters.

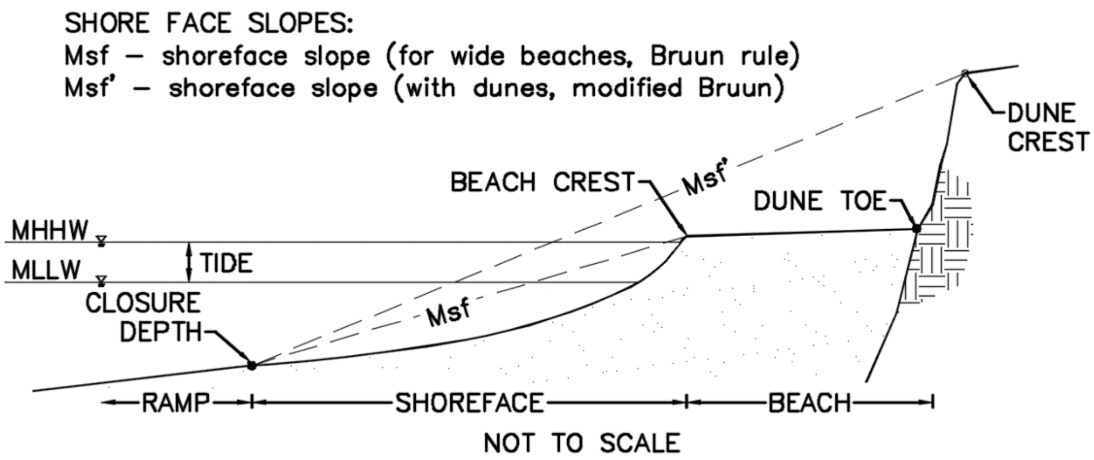
Dune erosion (without cobble berm) is based on the Bruun rule (1962) which assumes the equilibrium shore face slope of wide beaches is maintained with sea-level rise. The shore face is the active portion of a beach profile that is affected by waves, the shore face extends from the beach crest to the closure depth (offshore location on a shore profile beyond which the profile does not change over time). Dune (and shoreline) erosion was modeled in three stages depending on beach width, described below.

(1) **<u>Beach Width</u> > Average Winter Width** – A wide beach provides a buffer limiting dune erosion. The shoreline shifts landward on the equilibrium shore face slope extending from the beach berm crest out to the depth of closure (i.e. standard Bruun slope for wide beaches, shown as Msf in Figure 26).

(2) **Average Winter Width > <u>Beach Width</u> > Minimum Stable Width** – In this transitional condition, the dune begins to gradually erode as the beach approaches the minimum stable width. The shoreline shifts landward on a shore face slope that transitions linearly between the standard Bruun slope and a modified Bruun slope that accounts for the height of dunes behind the beach that contribute sand to the beach during erosion events (shown as Msf' in Figure 26).

(3) **<u>Beach Width</u> < Minimum Stable Width** – The shoreline and backshore erode on modified Bruun profile slope (from backshore toe/crest to depth of closure).

Figure 26 shows the standard Bruun slope (**Msf**) and the modified Bruun slope (**Msf'**) that accounts for sand in the dunes that is mobilized to the lower profile during erosion events. The minimum stable beach width is observed to be approximately 60 feet on average along Stinson Beach. The average winter beach width ranges from 90 feet at Seadrift West to 140 feet at NPS based on observed winter shorelines obtained for this study.



SOURCE: ESA

Stinson Beach Nature-Based Adaptation Feasibility Study . 171009.00

Figure 26
Schematic shore profile with shore face slopes used for geometric erosion model

Cobble Berm Erosion

The cobble berm is included in some adaptation alternatives to provide a greater level of protection against wave run-up and erosion. The cobble berm is placed in front of existing backshore or constructed dunes, just beneath the beach elevation (10 feet NAVD88 for the purpose of this study). With sea-level rise, any beach fronting the cobble berm is assumed to erode according to the standard Bruun slope until the cobble is exposed. The cobble berm then gradually becomes part of the shifting beach profile as the shoreline meets the cobble berm. The shore face slope steepens as more cobble is exposed, slowing the rate of shoreline erosion until the cobble berm is overwhelmed. When the cobble berm fails, the backshore begins to erode at the same rate as the shoreline.

(1) **<u>Beach Width</u> > Cobble Berm Width** – a wide beach acts as a buffer that limits backshore erosion; the shoreline erodes on standard Bruun profile slope (from the beach berm to depth of closure).

(2) **Cobble Berm Width > <u>Beach Width</u> > Minimum Stable Cobble Width** – The transitional condition in which the cobble berm begins to erode. The shoreline and cobble berm erode on a slope that gradually steepens due to the increasing fraction of cobble berm exposed (height) relative to the overall sand shore face height (from depth of closure to cobble berm crest elevation). The transgression slope ranges from the standard Bruun (when the shoreline meets cobble) to a cobble recession slope of 6H:1V. The initial constructed cobble berm width is 80 feet, while the cobble berm failure threshold width is 30 feet (i.e. **Minimum Stable Cobble Width**). At 30 feet width, the cobble berm needs to be reconstructed. The cobble is mobilized by rising sea-levels as follows:

  - Wave run-up builds the berm landward and upward at a distance equal to SLR
  - Scour of sand in front of the berm drops the seaward end of the berm downward at a distance equal to SLR
  - Increased breaking waves flatten the cobble slope
  - The cobble berm width is monitored until it is reduced to 30 feet

(3) **<u>Beach Width</u> < Minimum Stable Cobble Width** – cobble berm fails and dune erosion begins, shoreline and backshore erode on modified Bruun profile slope (from backshore dune crest to depth of closure).

A cobble-gravel berm can act as a barrier to the sand stored in the upper profile (dry beach and dunes), preventing its transport to the lower profile (foreshore, intertidal zone) by waves over time. While a cobble barrier reduces overall cross-shore sediment transport, the longshore sediment transport rates along Bolinas Bay are assumed to be sufficient to supply sands to the surfzone seaward of the cobble berm face. This assumption is considered to be less valid for larger amounts of sea-level rise, conceptually over ~3 feet, which will result in a demand for sand that exceeds the supply by longshore transport.

Seasonal Erosion

Seasonal changes in ocean conditions result in narrowing of the beaches in the winter through spring and widening of the beaches through the summer, typically reaching maximum widths in the fall. When the winter shore approaches the natural infrastructure features (dunes and c-g berms), we expect some degradation of the features before the following summer recovery of the beach. Dune and cobble-gravel berm erosion were computed based on the extent the features encroached into the winter beach. Reach-average seasonal shoreline fluctuations were taken from Study Memorandum 1.

The “seasonal erosion” can be tracked along with erosion due to sea-level rise, and the cumulative erosion used to determine when reconstruction thresholds are reached. Alternatively, maintenance can be applied to mitigate seasonal impacts. In practice, renovation for natural and traditional infrastructure is typically addressed after the cumulative effects of seasonal and extreme event(s) reach a threshold of reduced performance considered a “trigger” for maintenance.

Erosion Thresholds for Action

Erosion thresholds for dune and cobble berm width are documented in Study Memorandum 2. The cobble berm failure threshold width is 30 feet as described above. Dune threshold widths were determined based on observed erosion that occurred during the 2015-2016 El Nino; dunes eroded by 45 to 65 feet in some locations. These thresholds were applied to determine the maintenance needed to sustain natural infrastructure features with 3.3 feet sea-level rise. Corresponding volumes and associated costs of sand and cobble needed to maintain protective natural infrastructure features are described in Section 6.4.

6.2.2. Model Outputs of Natural Infrastructure Widths

Natural infrastructure widths are computed from the erosion at each sea-level rise increment. Beach width is defined as the distance from the backshore (dune or armoring toe) to the MHW shoreline. Dune width is defined from the toe of the dune to the first line of development, including existing dunes located at the patios and NPS reaches.

The location, type and density of development vary along the study area. The NPS development is of low density and is primarily parking lot and visitor serving amenities For other reaches, development spans the entire reach and is situated at the back of beach (see development line in Figure 22 and Figure 23). The Seadrift reach has a rock revetment that is treated as the non-erodible backshore for calculating infrastructure widths. Built residences along Seadrift are set back at varying distances from the revetment. The Calles reach has homes situated at the back of beach with the seaward-most developments location used as the reference for infrastructure widths.

The shore response modeling described in Section 6.2.1 are applied for both sea-level rise and seasonal fluctuations.   Fall beach widths were used to an indicator of ecology and recreation benefits, with greater benefits associated with wider fall beaches. Existing shore (dune and beach) widths are reported in Table 4 along with future widths for the eroded shore resulting from 3.3 feet (1 meter) of sea-level rise. The desired additional space after 3.3 feet of sea-level rise is included in the right-most column of Table 4, and computed as the difference between the initial constructed natural infrastructure width and the future remaining summer shore width available for constructing natural infrastructure. The results in Table 4 are discussed below.

TABLE 4. WINTER AND SUMMER SHORE WIDTH RESULTS FROM ADAPTATION ALTERNATIVES EVALUATION

Reach	**Alternative**	**Initial (Post-construction) Conditions Widths with no SLR (feet)**						**Future Conditions Widths with 3.3 feet SLR (feet)**						*Additional shore width needed for NI with 3.3 feet SLR*[2]
		Winter Beach Width	Winter Dune Width	**Winter Shore Width**	Summer Beach Width	Summer Dune Width	**Summer Shore Width**	Winter Beach Width	Winter Dune Width	**Winter Shore Width**	Summer Beach Width	Summer Dune Width	**Summer Shore Width**	
Seadrift West	0. Armored at Development	92	n/a	**92**	172	n/a	**172**	0	n/a	**0**	76	n/a	**76**	*54*
	1. Cobble-Gravel Berm	92	n/a	**92**	172	n/a	**172**	59	n/a	**59**	80	n/a	**80**	*50*
Seadrift East	0. Armored at Development	102	n/a	**102**	182	n/a	**182**	6	n/a	**6**	86	n/a	**86**	*94*
	1. Dune Embankment	30	73	**103**	98	100	**198**	20	0	**20**	100	0	**100**	*80*
	2. Cobble-Gravel Berm	102	n/a	**102**	182	n/a	**182**	65	n/a	**65**	80	n/a	**80**	*100*
Patios	0. Armored at Development	127	70	**197**	207	70	**277**	54	44	**98**	134	44	**178**	*52*
	1. Foredunes	30	159	**189**	109	175	**284**	30	73	**103**	110	73	**183**	*47*
	2. Foredunes + Cobble-Gravel Berm	73	125	**198**	158	125	**283**	47	125	**172**	80	125	**205**	*25*
Calles	0. Armored at Development	134	n/a	**134**	214	n/a	**214**	41	n/a	**41**	121	n/a	**121**	*69*
	1. Foredunes + Cobble-Gravel Berm	61	75	**136**	156	75	**231**	49	75	**124**	80	75	**155**	*35*
	2. Dune Embankment + Cobble-Gravel Berm	69	70	**139**	157	70	**227**	50	70	**120**	80	70	**150**	*40*
NPS[1]	0. Armored at Development	138	55	**193**	218	55	**273**	76	25	**101**	156	25	**181**	*34*
	1. Foredunes	42	146	**189**	122	155	**277**	42	86	**128**	122	86	**208**	*7*
	2. Foredunes + Cobble-Gravel Berm	83	110	**193**	163	110	**273**	49	110	**159**	80	110	**190**	*25*

[1] NPS results represent conditions for the few areas with development; most of the reach has existing dunes with the capacity to retreat landward over time and maintain beach width.

[2] Desired additional width needed to maintain functional natural infrastructure (beach, cobble, dunes) along study shore.

Shore width results interpretation

The following paragraphs interpret the shore width results presented in Table 4. The interpretation focuses on width of the shore (beach and dunes) at winter minimum dimensions with some discussion of the results pertaining to protective services (erosion and wave run-up reduction). The subsequent report sections build on these shore width results in terms of Storm Protection Benefits (Section 6.3), Geomorphic and Ecological Benefits (Section 6.4), Environmental Impacts (Section 6.6) and Public Access (Section 6.7). In general, wider shore widths provide greater benefits to storm protection, ecology and public access.

Seadrift reach is divided in two for the purposes of this study, as beaches along the western half are considerably more eroded than the eastern half. Implementing a cobble gravel berm can sustain shore width with sea-level rise (winter shore width of 60-65 feet and summer width of 80 feet with 3.3 feet SLR), providing protective services, access and ecological functions beyond that of the armoring baseline (winter beach width disappears with 3.3 feet SLR). Beach width may be able to recover along the eastern reach with 3.3 feet SLR, but the more exposed western reach will experience limited summer beach recovery. Implementing a dune embankment along the eastern half of the reach can help to maintain a small winter beach width (20 feet) with 3.3 feet SLR.

Note that the winter beach widths in front of the existing rock revetments are forecast to decrease substantially with 3.3 feet of sea-level rise: from about 90-100 feet now to 6 feet or less. The narrow forecast beach width means that waves will directly impact the rock revetments during the winters, increasing the risk of backshore damages. While natural infrastructure alternatives are forecast to provide a wider winter beach, the incremental increase may not be realized during strong events that may destabilize the cobble mass modeled at Seadrift East. Hence, the Seadrift area appears to require additional adaptation measures, such as flood proofing and raising the homes on piles, etc. Further discussion on wave run-up is in Section 6.3.

Patios reach has more sea-level rise capacity owing to the existing dunes present and more landward development. Implementing foredunes provides additional protective services in the near term but only a marginal increase in beach widths with sea-level rise. A dune embankment may be worth considering in this location in order to maximize sand volume and mitigate wave run-up, especially within the context of adaptation at the adjacent reaches. Adding a cobble berm is predicted to increase protective services substantially for future conditions with SLR of 3.3 feet, due to a much wider winter shore (74 feet wider compared to baseline).

Calles reach does not have notable existing dunes and thus a cobble gravel berm is included with each natural infrastructure alternative. The natural alternatives perform similarly over the armoring baseline: beach width is reduced initially by constructing the natural infrastructure but results in an overall greater shore width with sea-level rise (approximately 30 feet wider in the summer and 80 feet wider in the winter than baseline with 3.3 feet SLR).

NPS reach contains a few developed areas near the back of beach, whereas the rest of the reach has limited backshore development and thus can accommodate dune and beach transgression from sea-level rise. For areas with development, implementing natural infrastructure can lead to a sustained fronting winter shore width that is 30 to 60 feet greater than the armoring baseline with 3.3 feet SLR, providing greater protective services. The fore dunes in alternative 2 are forecast to result in a slightly wider shore with more dunes and less beach. Adding cobble (alternative 3) doesn't provide much benefit except for a wider winter shore width.

Other considerations

Note that results for the baseline alternative (armoring) indicate that the winter beach for much of the shore would be mostly lost with 3.3 feet of sea-level rise without natural infrastructure. This finding is consistent with the C-SMART Vulnerability Assessment (Marin County 2016) that led to this study.

For alternatives with a cobble-gravel berm, the beach width results in Table 4 include portions of the cobble berm that are exposed above high tide. As the beaches reach their minimum width in winter, cobble and gravel will become exposed along the intertidal and upper beach face depending on the severity of winter storms and amount of sea-level rise that occurs. Thus cobble and gravel will make up portions of the winter beach width and these exposed portions of the cobble gravel berm will slowly become buried in sand over the summer.

Over time with sea-level rise, the shore will migrate toward developed areas. The landward extent of coastal flooding and erosion hazards will also migrate landward and the risk of damages to development will increase. The reduction of space between the development and migrating shore will also degrade coastal resources and reduce the space available for natural infrastructure to function. Here we review the modeling of shore change in terms of space needed for natural infrastructure function. This space needed is simply the space desired for natural infrastructure function minus the space available. This concept of "space needed" is useful toward developing design criteria for additional adaptive actions such as:

- Beach nourishment – widening the beach seaward by sand placement,
- Retreat or realignment – widening the beach and/or dunes landward by realigning development, and
- Hybrids – combining beach widening (beach nourishment and retreat) with other measures to reduce required space, such as engineered structures and raising homes on piles)

Beach width calculations for the armoring baseline assume that armor is placed to protect backshore development (homes, buildings) and the existing rock armor along Seadrift is maintained. The footprint of this new armor is not accounted for in the beach width results for Alternative 0. In reality, armoring will result in a reduced beach width due to the footprint of the armoring structure. For example, rock sloped revetments require a footprint roughly 10 to 30 feet wide or more depending on the type of structure.

6.2.3. Sensitivity of natural infrastructure widths to seasonal changes and storms

The nature-based adaptation alternatives are expected to provide benefits over the armoring baseline in terms of sustained shore width with sea-level rise. However, California natural foredune dynamics are generally dominated by unpredictable infrequent, significant, extreme storm erosion events (single or consecutive storm events), and longer (multi-year) post-storm recovery phases during which beach growth, vegetation succession, and foredune accretion occur. This is an important consideration at Stinson Beach as foredune accretion potential is low (Study Memorandum 1) so recovery of eroded dunes depends on maintenance actions by humans.

Sensitivity analyses were performed to highlight the effects of seasonal shoreline changes and coastal storms on natural infrastructure widths. Two primary factors influence the performance of adaptation alternatives for sea-level rise protection. The first factor is that a nominal beach width was added to represent fall conditions when the alternatives would be constructed on dry beach before winter. Results in Table 4 were thus adjusted for seasonal fluctuations to illustrate the potential minimum and maximum beach widths for alternatives. Secondly, starting with the first winter after construction, seasonal shoreline fluctuations would impact the natural infrastructure to some degree. Over time, erosion of the dunes will trigger maintenance. Adjustment for these two factors reduced the performance of the baseline (Alt 0) more than the natural infrastructure alternatives (Alts 1 and 2).

Coastal storm impacts

While natural infrastructure widths in Table 4 indicate natural infrastructure could persist with up to 3.3 feet of sea-level rise under average conditions, coastal storms will continue to impact the Stinson shore as they have in recent decades (see Study Memorandum 1). Recent storm impacts to Stinson from the 2015-2016 El Nino winter include 45 to 65 feet of dune erosion in hot spots along the study area on the order of a couple hundred feet along shore. This 2015-2016 winter was considered a proxy for the 20-year event in this study.

Table 5 presents the probability of a given 20-year (5% annual chance) or 100-year (1% annual chance) coastal storm event occurring over the design life of natural infrastructure. The years for each SLR amount correspond to the Medium-High risk projection that OPC (2018) recommends for community planning. The probabilities of storm occurrence summarized in Table 5 indicate that portions of the constructed natural infrastructure (dunes and or cobble berms) will likely need to be rebuilt over time due to storm impacts before sea-level rise requires larger-scale maintenance actions for dunes and cobble berms. This study considers impacts of the 20-year event. This is a simplification; impacts for more extreme events, while less likely, can be more widespread and will need to be considered in further study.

TABLE 5. STORM EVENT PROBABILITY OF OCCURRENCE OVER TIME

SLR (m)	SLR (ft)	***Year****	Probability of event occurring between 2020 and ***Year***		Probable number of events occurring between 2020 and ***Year***	
			20-year event	100-year event	20-year event	100-year event
0.25	0.8	***2030***	40%	10%	0.5	0.1
0.5	1.6	***2046***	74%	23%	1.3	.3
1	3.3	***2067***	91%	38%	2.4	0.5

* timing from OPC 2018 Med-High projection

6.2.4. Engineering Costs of Adaptation Alternatives

Typical engineering unit costs were compiled from applicable sources to quantify the construction and maintenance costs of natural infrastructure features for long term sea-level rise impacts and storm event impacts. Table 6 lists engineering unit costs from comparable traditional and nature-based adaptation projects.

TABLE 6. COMPILATION OF ENGINEERING UNIT COSTS FOR SHORELINE ADAPTATION

Material	Unit[1]	Cost	Source
Beach-quality sand	CY	$45	Climate Ready Monterey Bay (ESA 2013) (inland/offshore sources)
Beach-quality sand	CY	$25	Pacifica LCP Adaptation Plan (2018) escalated from 2018. Offshore sources and 700,000 cubic yards.
Beach-quality sand	CY	$60	Pacifica BBIRP draft (GHD, 2021). 1,000,000 cubic yards.
Sand Embankment	CY	$15	Ocean Beach Sand Backpass Project. Free sand sourced within 5 miles. Unrestricted trucking of sand on roadway. Dumping and minor grading.
Cobble/Gravel Berm with sand cover	LF	$1,600	Ocean Beach Master Plan (SPUR 2012), which considered Surfers Point Phase 1 (constructed 2010)
Dune Vegetation Establishment	Ac	$9,000	Estimated for this study (see Appendix A)
Dune Vegetation Revegetation	Ac	$8,600	Humboldt Dunes removal of non-natives and invasives, planting and maintenance of desired native vegetation. Escalated from 2015.
Foredune Construction	Ac	$130,000 to $275,000	Surfers Point Phase 1 dune construction and planting with fencing. Range based on actual costs using volunteers and estimated cost with traditional construction contracting, escalated from 2012.
Dune Restoration	Ac	$116,000	Humboldt Dunes, including vegetation establishment, escalated from 2015.
Rock Revetment[2]	LF	$8,000	Pacifica Sea Level Rise Adaptation Plan (ESA 2018)
Rock Revetment	LF	$17,800	Pacifica BBIRP draft (GHD, 2021). 2,700 feet of shore.
Reinforced Concrete Seawall[2]	LF	$18,000	Pacifica Sea Level Rise Adaptation Plan (ESA 2018)

[1] CY=cubic yard; LF=linear foot; Ac=acre.

[2] Armoring baseline assumes Rock Revetment is used, Reinforced Concrete Seawall is provided for comparison

ESA estimates the following unit costs for the Stinson Beach adaptation alternatives shown in Table 7. These are preliminary estimates for alternative comparison, based on other projects with an expected uncertainty of +50% to -30%. These estimates do not include ancillary items of work that can increase actual project costs by up to 100%. Engineering, environmental review, permitting, construction administration and monitoring “soft costs” are not included.

TABLE 7. ENGINEERING UNIT COSTS SELECTED FOR STINSON ADAPTATION ALTERNATIVES EVALUATION

Material	Unit[1]	Cost
Beach-quality sand	CY	$45
Cobble/Gravel Berm with sand cover	LF	$1,600
Dune Vegetation Establishment	Ac	$9,000
Rock Revetment	LF	$8,000

[1] CY=cubic yard; LF=linear foot; Ac=acre.

Volumes to construct and maintain the alternatives for storms and 3.3 feet of sea-level rise were calculated from the constructed dimensions, shore evolution modeling described above and potential storm impacts that could occur during the timeframe for 3.3 feet sea-level rise. Table 8 presents the volumes of sand and cobble needed to build and maintain natural infrastructure at Stinson Beach for 3.3 feet of sea-level rise. These volumes may be lower or higher depending on storm impacts that occur during the project timeframe.

TABLE 8. ESTIMATED QUANTITIES TO IMPLEMENT NATURE-BASED ADAPTATION ALTERNATIVES

Materials	*Alternative 1*	*Alternative 2*
Construction		
Sand	**157,000 cubic yards**	**63,000 cubic yards**
Cobble	**95,000 cubic yards**	**255,000 cubic yards**
Dune Vegetation	**16.8 acres**	**6.3 acres**
Maintenance for storms and 3.3 feet SLR		
Sand	**326,700 cubic yards**	**118,000 cubic yards**
Cobble	**190,000 cubic yards**	**510,000 cubic yards**
Dune Vegetation	**4.1 acres**	**4.1 acres**

The probable construction and sea-level rise maintenance costs for the baseline and alternatives are summarized in Table 9. These costs only include the raw materials (sand, cobble/gravel, plantings) summarized in Table 8. Engineering design, permitting, and construction administration costs are not included but could be estimated as 30% of the engineering costs in Table 9. The adaptation baseline assumes a rock revetment is constructed along the development (e.g. existing Seadrift revetment) and is reconstructed after major storm events along 15% of the total structure (per maintenance records for the Seadrift revetment described by Noble et al 2007). The total engineering costs for a baseline that uses a reinforced concrete seawall can be 2-4 times the Baseline cost shown in Table 9. See Chapters 4 and 5 for detailed descriptions and figures of the nature-based adaptation alternatives.

TABLE 9. ENGINEERING COST ESTIMATES FOR STINSON ADAPTATION ALTERNATIVES

	Engineering costs for construction and maintenance with 3.3 feet SLR and coastal storm recovery for two events		
Reach	**Baseline**	**Alternative 1**	**Alternative 2**
Seadrift West	$39,900,000	$12,300,000	$12,300,000
Seadrift East	$39,500,000	$13,600,000	$12,200,000
Patios	$38,300,000	$4,800,000	$8,800,000
Calles	$26,900,000	$7,400,000	$7,000,000
NPS	$10,000,000	$7,500,000	$14,000,000
TOTAL	**$154,600,000**	**$45,600,000**	**$54,300,000**

Total engineering costs for the baseline assume existing armoring along Seadrift is intact, new armoring is constructed along the entire Patios and Calles reaches and only existing buildings are protected in NPS reach (other areas in NPS are allowed to erode). The cost for the baseline assumes reconstruction of all armoring at 3.3 feet sea-level rise. Costs for the alternatives include sand and cobble volumes needed to construct and sustain minimum feature widths with 3.3 feet of sea-level rise as well as sand volumes needed for coastal storm recovery maintenance. Minimum feature widths are set by storm erosion thresholds defined for each reach. Storm recovery assumes erosion impacts from a 20-year storm that occurs twice over the course of 3.3 feet of sea-level rise (i.e. year 2067, see Table 5 for storm occurrence probability versus sea-level rise).

Dune transgression with sea-level rise was calculated starting with constructed conditions shore profiles at existing sea-level. Given a lack of dune building observed (see Existing Conditions, ESA 2020a), dunes are not assumed to accrete with SLR. Additional sand volume and revegetation efforts are included in the SLR maintenance for dunes to maintain their overall height above the beach to maintain storm erosion and flooding protection. Storm erosion impacts were estimated assuming 30% of each reach is eroded during the design storm (based on Patios and NPS erosion extents measured from the pre and post 2015-2016 El Nino LiDAR data). Costs for recovery include sand volume and revegetation of eroded dune width. Dune erosion behind cobble berms was limited to 50% of erosion without cobble, owing to the dissipation of wave breaking and run-up provided by the cobble berm. Since lower-relief foredunes are naturally resilient to wave run-up and overtopping compared to artificial dune embankments (Figure 27), they may require less revegetation efforts after storms than estimated for this study.

SOURCE: ESA

Stinson Beach Nature-Based Adaptation Feasibility Study . 171009.00

Figure 27

Wave run-up impacts on two dune types: Ocean Beach San Francisco dune embankment scarp is eroded (left) while Surfers Beach Ventura foredunes are overtopped yet resilient (right)

6.3. Storm Protection Benefits

Storm protection benefits of the alternatives were evaluated by comparing wave run-up with and without nature-based adaptation for initial constructed conditions and future conditions with sea-level rise. The extent of wave run-up was computed for two wave events representing the 20-year (March 2016) and 100-year (January 1983) coastal storms. The landward extent of the run-up was used, and a distance from the seaward edge of development was computed for comparison. Conceptually, the farther into the development the wave run-up extends, the lower the storm protection benefits. The wave run-up results for the two alternatives assume that dune and cobble features are maintained above the minimum threshold dimensions for storm erosion protection (see Section 6.2).

6.3.1. Design storm event protection

The 20-year coastal storm is used to evaluate the alternative protective services since it is the benchmark event used to size and maintain the alternatives in the Design Life Analysis (Section 6.2). Table 10 presents the 20-year coastal storm wave run-up extents relative to the location of backshore development within each reach. The results show that the presence of dunes and cobble berms can reduce wave run-up through physical obstruction as well as the increased roughness provided by dune vegetation and cobble/gravel when compared to flat bare sand fronting an armoring structure. The Seadrift revetment is overtopped by the 20-year event. Patios and NPS reaches are buffered by existing dunes but seaward-most properties in the Calles reach are exposed at existing sea level. Maintained natural infrastructure alternatives can reduce the landward extent of wave run-up and are therefore considered to provide a protective service (benefit). However, the calculations indicate that natural infrastructure alternatives may provide complete protection in some locations when adequately maintained.

TABLE 10. WAVE RUN-UP REDUCTION OF 20-YEAR STORM EVENT BY NATURE-BASED ADAPTATION ALTERNATIVES

	Inland Wave Run-up Extent, feet relative to backshore development Positive (+) is seaward, Negative (-) is landward					
	Constructed conditions at existing sea level			Future conditions with 3.3 feet sea-level rise		
Reach	**No Alt**	**Alt 1**	**Alt 2**	**No Alt**	**Alt 1**	**Alt 2**
Seadrift W	-71	-39	-39	-130	-52	-52
Seadrift E	-92	11	-80	-112	-69	-88
Patios	26	79	83	-22	22	35
Calles	-102	29	24	-150	-35	-3
NPS	0	79	79	-43	-3	2

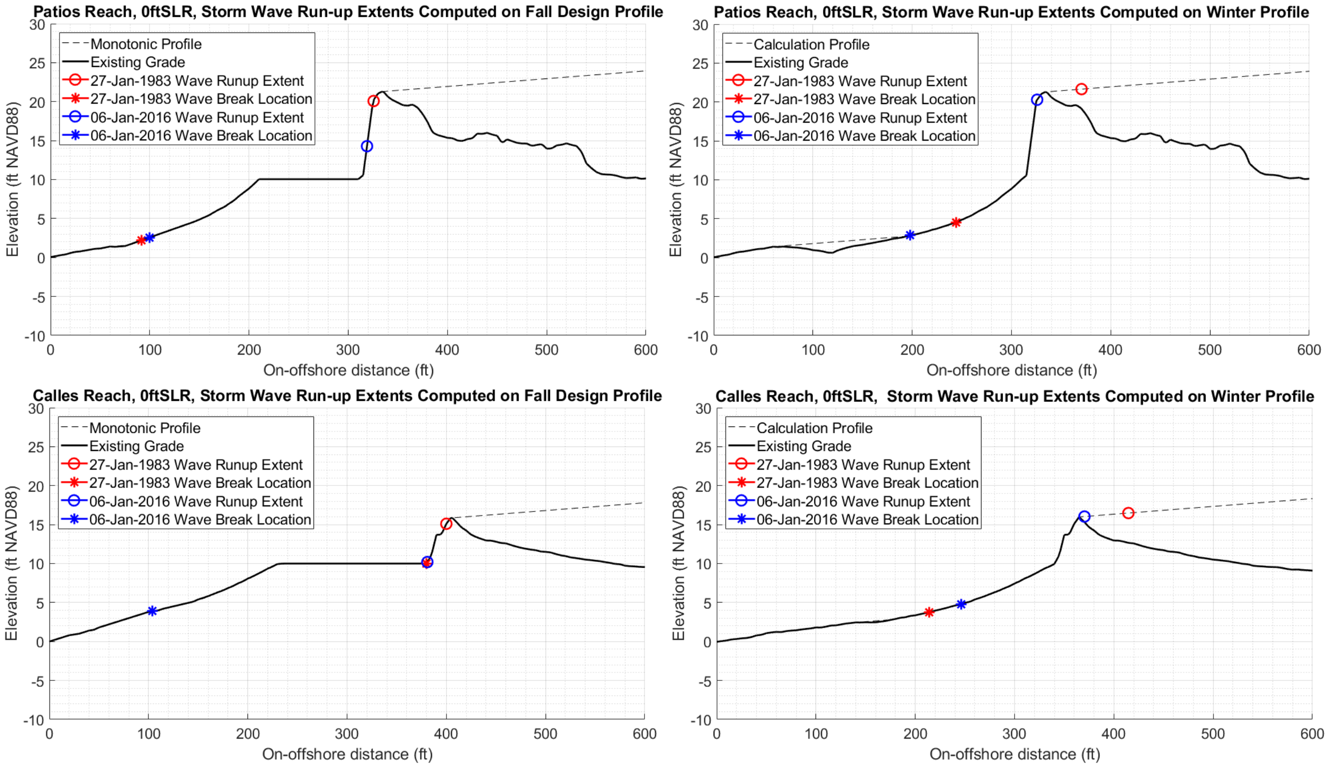
6.3.2. Sensitivity of wave run-up to seasonal changes and storms

The wave run-up results in Table 10 account for average seasonal beach width fluctuations in each reach that would occur after the alternatives are constructed on a fall beach profile. Wave run-up impacts may be different than reported in Table 10 depending on timing of wave run-up event(s), the actual reductions of natural infrastructure widths from seasonal changes, and erosion during stormy winters (El Ninos) or singular extreme events. This section discusses the sensitivity of wave run-up computed for the alternatives evaluation to these factors. Natural infrastructure constructed along Stinson Beach will be stressed by seasonal shoreline changes that can reduce the effectiveness of natural infrastructure at reducing wave run-up during storms. Wave run-up during a storm that occurs in late fall (when the beach is still wide) will not extend as far landward as a similar storm that occurs during late winter (when the beach is narrowest from cumulative effects of stormier conditions. To highlight the effect of a wide beach on run-up extents, wave run-up computed using the January 2019 winter profile are compared to the run-up extents given a 100-foot wide beach berm. The differences in run-up extents between the late fall (100-foot beach berm added to the 2019 winter profiles) and late winter profile conditions are shown in Table 11.

TABLE 11. COMPARISON OF 20-YEAR STORM WAVE RUN-UP EXTENTS FOR LATE-FALL AND LATE-WINTER BEACH CONDITIONS FOR THE ARMORING BASELINE

Inland Wave Run-up Extent, feet relative to backshore development Positive (+) is seaward of development, Negative (-) is landward			
Reach	**Late Fall**	**Late Winter**	*Difference*
Seadrift W	-7	-33	*-26*
Seadrift E	-4	-14	*-9*
Patios	66	59	*-7*
Calles	-46	-75	*-30*
NPS	39	22	*-17*

Without the nominal beach berm added, wave run-up extends 10 to 30 feet further landward assuming the same conditions landward of the beach. Calles reach shows the greatest difference in run-up extents because it has no backshore dunes and is thus lower in elevation, whereas the Patios reach shows the smallest difference in run-up given its existing dunes with a steep dune face. The 20-year results in Table 11 correspond to the 2016 wave event plotted in Figure 28. The plots depict the wave breaking location (star) and run-up extent (circle) corresponding to maximum events from 1983 (red) and 2016 (blue). Run-up was computed on the existing shore profile (black line) with calculation profile shown (dashed line). Wave run-up results in Table 10 account for average seasonal adjustments that were observed in each reach and documented in Study Memorandum 1.



SOURCE: ESA

Stinson Beach Nature-Based Adaptation Feasibility Study . 171009.00

Figure 28
Comparison of wave run-up extents for Patios (left) and Calles (right) profiles with (top) and without (bottom) 100-foot beach berm

Wave run-up extends further landward when the beach is narrow in winter (right plots) for each wave event compared to the design fall profile (left plots) that includes a 100-foot wide beach berm. Top plots show the Patios profile with taller dunes that buffer wave run-up with and without the beach berm. Bottom plots show the Calles profile, where the lack of taller dunes leads to a greater difference in wave run-up without the beach berm. These results indicate that gravity (a barrier with higher elevation forces wave run-up upward against gravity) is the dominant factor in reducing wave run-up compared to roughness over a distance (e.g. vegetation and minor topography changes). While this may indicate a taller dune embankment is preferable, lower foredunes may prove to be more resilient during wave events (Figure 28) and provide other benefits, most notably native ecology.

Extreme storm wave run-up reduction

While the natural infrastructure alternatives are not designed to withstand wave run-up and erosion from more extreme events (e.g. 100-year storm), they can reduce the overall impacts to coastal development. This potential reduction of storm impacts is quantified in terms of inland wave run-up extents for a representative extreme coastal event modeled on the winter shore profile. Table 12presents the inland wave run-up extents computed for the January 1983 El Nino event used as the characteristic 100-year storm. Protection benefits provided by well-maintained natural infrastructure is limited with 3.3 feet of sea-level rise, but the results show that these features do reduce the overall inland wave run-up extent compared to the armoring baseline.

See Section 6.3.3 for discussion on results sensitivity to seasonal changes and storms. The results account for seasonal adjustments that would occur over the winter after construction of alternatives during late fall. Overall, the relative benefit of Alt 1 and 2 depends on the beach conditions at the time of the 100-year event. Note that the run-up results presented below do not include the beach and dune erosion that would occur during the 100-year storm and hence likely underestimate inland wave run-up extent.

TABLE 12. WAVE RUN-UP REDUCTION OF 100-YEAR STORM EVENT BY NATURE-BASED ADAPTATION ALTERNATIVES

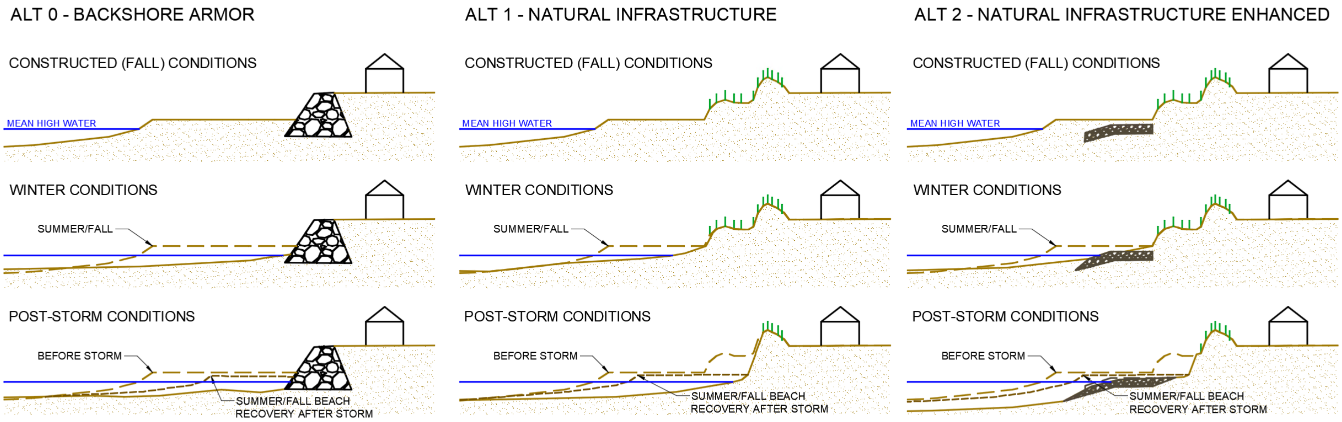
	Inland Wave Run-up Extent, feet relative to backshore development Positive (+) is seaward, Negative (-) is landward					
	Constructed conditions at existing sea level			Future conditions with 3.3 feet sea-level rise		
Reach	**Alt 0**	**Alt 1**	**Alt 2**	**Alt 0**	**Alt 1**	**Alt 2**
Seadrift W	-107	-49	-49	-213	-152	-152
Seadrift E	-118	-30	-83	-160	-100	-99
Patios	-19	38	37	-111	-18	1
Calles	-176	-35	10	-266	-186	-63
NPS	-30	1	0	-69	-34	-26

6.4. Geomorphic Changes and Ecologic Benefits

Nature-based adaptation alternatives increase the resiliency of a dune and beach system compared to traditional shoreline armoring approaches. The following sections discuss the geomorphic changes expected after the implementation of the adaptation alternatives (Section 6.4.1) and resulting benefits to shore ecology (6.4.2).

6.4.1. Geomorphic Changes from Natural Infrastructure Implementation

Nature-based approaches can change shore geomorphology in a way that provides benefits to beach ecology by harnessing the dissipative effects of natural infrastructure, as well as their ability to recover seasonally and after storms. In contrast, traditional shore protection structures tend to exacerbate beach erosion and suppress recovery, thereby degrading ecology as the shore evolves over time. Conceptual cross sections of the baseline and adaptation alternatives are shown in Figure 29 to illustrate the typical geomorphic response of each alternative to seasonal changes and coastal storm impacts. The typical conditions associated with each alternative are described below for constructed (fall) conditions when a wide beach is present, in late winter when the beach is narrowest and after an extreme coastal storm event.



SOURCE: ESA

Stinson Beach Nature-Based Adaptation Feasibility Study. 171009.00

Figure 29
Conceptual schematics of seasonal shore morphology for adaptation alternatives

Constructed (Fall) Conditions: The top schematic for each alternative depicts typical conditions after construction in the fall when a wider beach is present. A rock revetment is shown for the armoring baseline (Alternative 0), compared to dunes (Alternative 1) and dunes with cobble berm (Alternative 2).

Winter Conditions: The middle schematics show potential conditions after winter, when the beach is narrowest. Without natural infrastructure the beach may shrink to a narrow band of wet sand or disappear in front of armoring even during an average winter. Seadrift West, which has only a narrow beach in summer months and limited wet intertidal slope in winter, provides an example of potential winter conditions that could develop in other reaches if an armoring approach is taken in other reaches. For natural infrastructure alternatives, winter erosion of the beach may impact existing or constructed dunes at the back of beach depending on how stormy a winter is and whether a cobble berm is included. Cobble berms that are buried within the beach footprint may become exposed during the winter.

Post-storm Conditions: The bottom schematics show typical conditions after an extreme coastal storm event during which the beach is eroded. The armoring alternative may lose much if not all dry beach during the storm and experience scour at the toe of the armoring structure, leaving less sand available for beach recovery. The alternatives with dunes can reduce the overall beach erosion and aid in quicker beach recovery. The dunes provide new sand volumes to release during erosion events, and enlarge the volume of sand available where dunes are present. This volume is however finite and can be overcome by consecutive storms. The dunes erode to a lesser extent when a cobble berm is placed in front of the dunes. The cobble berm will deform and migrate inland during the storm or series of storms, as described in Section 6.2.1,.

The benefits of natural infrastructure to shore ecology functions are further described below.

6.4.2. Ecological Benefits of Natural Infrastructure

Natural infrastructure alternatives proposed at Stinson Beach would provide direct benefits to ecology by increasing the longevity of a sandy beach and dunes. Pacific Coast sandy beaches are shaped by their morphodynamic state and by significant biological inputs of macroalgal wrack and associated nutrients from the adjacent nearshore marine ecosystem. Sandy beaches of the California coast are inhabited by a wide array of shorebird species that use beaches for both roosting and foraging. Most shorebird species that occur at Stinson Beach are present in winter and during spring and fall migration periods with the exception of the federally listed western snowy plover, which occasionally nests on the outer spit and uses Stinson Beach for foraging and roosting throughout the year. In the Stinson Beach region, shorebird abundance on sandy beaches is correlated with macroinvertebrate abundance, species richness, and biomass (Nielsen et al. 2013), underscoring the importance of invertebrate foraging resources for shorebirds. Sandy beaches also play an important role as alternate habitat for estuarine and intertidal-associated shorebirds, many of which are experiencing declines in global population size (Rosenberg et al. 2019). The proximity of Bolinas Lagoon to Stinson Beach likely influences both species diversity and overall abundance of shorebirds using Stinson Beach. See Study Memorandum 1 (ESA 2020a) for more information on shorebirds at Stinson Beach.

Dunes: Dunes provide protection to development while maintaining beach width longer than traditional armoring approaches. Sand eroded from the dunes dissipates wave energy, reduces beach erosion, and nourishes beaches with sand, thereby making the sandy beach relatively higher, wider and more persistent than without dunes. The sand provided by dunes maintains beach ecology functions as well. Dunes are especially beneficial during winter when the beach is narrowest. For example, during field visits in December 2019, the beach in front of Seadrift was absent, lacking the beach berm with wrack that supports invertebrates that shorebirds feed on. Compare this condition to the Patios reach which has dunes, a beach was present, even at high tide, providing space for foraging shorebirds. While both types of dunes can increase resiliency of beaches, lower foredunes are a more natural form in areas of narrow shores and support native flora and fauna. Vegetation native to California can thrive in and reinforce development of foredunes, thereby creating a basis for increased ecology benefits. In comparison, taller embankment dunes with steeper slopes will lead to more frequent erosion scarps on the dunes that are less favorable for maintenance of high native plant diversity.

Cobble: While cobble berms reduce erosion and flooding behind them, they become exposed during winter and effectively reduce the available sandy beach area during mid- to late-winter. However, a lens of sand may persist on the top of the cobble berm for wintering shorebird habitat, depending on the elevation of the berm in relation to sea level and how stormy each winter is. See examples from Surfer's Beach in Ventura County and Pacifica State Beach below. Similar to sand and gravel beaches, native invertebrates and insects can survive in cobble shores, providing food for other fauna and an overall ecological benefit that is not found with engineered boulder revetments. The cobble berm also facilitates sand beach recovery and protects sand dunes behind it from waves, thereby increasing ecology benefits relative to seawalls and boulder revetments. These functions are further advanced by the capture of organic materials (seaweed, kelp, large wood) on the cobble berm crest. There are however some tradeoffs for ecological and geomorphic benefits with cobble berms. Seasonal or chronic exposure of cobble berm at or near the sand surface would likely restrict the colonization and establishment of native foredune and backshore vegetation, and select for species with plant functional traits that are less efficient at trapping sand and naturally rebuilding foredunes. Deep long-term burial of cobble berms by thick sand deposits (beach or dune) would reduce the potential inhibitory impact of cobble berms on regeneration of foredune vegetation (i.e. burying a cobble berm within a dune would limit the berms effects on native vegetation establishment until the dune is eroded and cobble berm is exposed.

Sand lens atop constructed cobble berms at Surfer's Beach in Ventura County (left) and Pacifica State Beach (right). Source: Bob Battalio

In summary, the utilization of natural infrastructure features for shoreline adaptation at Stinson can help sustain an overall wider shore area that includes sandy beach, vegetated dunes, and/or cobble gravel berm compared to traditional armoring. Table 13 quantifies the relative ecologic benefits provided by the natural infrastructure alternatives, calculated as the difference in winter and summer shore width between the baseline (Alternative 0) and nature-based alternatives (Alternative 1 or 2). The overall shore width includes beach and dune width (winter beach width includes some cobble), as adjusted for winter and subsequent summer widths shown in Table 4. The results show that the surplus shore width is greatest in winter when storms impact the shoreline, which indicates the greater protective services of the nature-based alternatives (see Section 6.3) as well as increased benefits to ecology (migrating shorebirds during winter season). Both nature-based alternatives provide a wider shore for nearly all reaches in summer and winter, indicating benefits to shore ecology in the form of sustained high intertidal habitat, wrack deposition and resulting macroinvertebrate populations and shorebird roosting/foraging habitat. Alternative 1 in Patios reach has less shore width surplus over the baseline owing to the existing dunes in this reach.

Table 13. Benefits of Nature-based Adaptation Alternatives compared to Armoring Baseline

	Winter Shore Width Surplus		Summer Shore Width Surplus	
Reach	**Alt 1**	**Alt 2**	**Alt 1**	**Alt 2**
Seadrift W	59	59	36	36
Seadrift E	14	59	14	0
Patios	5	74	5	47
Calles	83	79	36	36
NPS	27	59	27	40

Ecological benefits (or impacts) of these natural infrastructure landforms to native foredune vegetation depends in part on the duration of their intermediate erosional states, and the disturbance intervals associated with maintenance or reconstruction. The foredune designs are more likely to provide net ecological benefits to native plant populations if relatively prolonged intervals of low-energy winter storm conditions (multiple consecutive years of low erosion and disturbance) follow construction and vegetation establishment, and ample winter rainfall. This sequence would enable vegetation to establish and accumulate before storm erosion occurs. However, low storm intensity may be associated with winter drought conditions that are unfavorable for initial foredune vegetation post-transplant survival and establishment. Wet, stormy winters following construction and revegetation of artificial foredunes are likely to cause erosion before bud banks and seed banks accumulate to sizes that effectively recolonize eroded beach and foredune zones. If erosion intervals recur frequently, with short post-storm recovery (beach accretion) intervals, foredune vegetation recovery periods may be insufficient to restore or enhance resilient biological diversity. Over a decade or more, if the constructed foredune system exists in prolonged post-erosion partial recovery states, it may likely require supplemental repair or maintenance actions (sediment replacement and replanting).

Since sea-level rise rates and the frequency of major coastal storm erosion events are likely to increase within the next few decades, the likelihood of substantial net ecological benefits of constructed foredunes will depend on external climate variables and related intensification of maintenance and repair actions. A “best-case” scenario for vegetation would entail weak storm conditions for 1-3 years after initial construction and revegetation, coinciding with average to wet well-distributed winter and spring rainfall. A “worst-case” scenario would entail either extreme heat or drought events (especially winter drought) coinciding with the first growing season after vegetation, or major storm erosion within the first 1-2 years. These circumstances are not readily predictable. Adaptive management based on contingencies for substantial supplemental revegetation or sediment replacement may be needed to offset ecological uncertainties.

If optimal or substantially successful vegetation outcomes are reached, the Stinson Beach foredune system may provide the longest foredune dominated by native vegetation on the North-Central Coast, and the largest population of North Coast pink sand-verbena, for a decade or more. Longer-term sustainability of the foredune under higher sea levels, however, would likely depend on landward transgression of the foredune zone, which is precluded by development except in the NPS reach. The NPS reach, therefore, is the most likely segment to sustain long-term ecological benefits for foredune vegetation. Additional background information on beach and foredune vegetation zones and dynamics, including conceptual planting plan and costs for Stinson Beach, are provided in Appendix A.

6.5. Constructability

The nature-based alternatives formulated for this study are intended to be constructed at the back of the beach, whether in front of existing dunes, existing armoring structures or unarmored development. Construction would ideally occur in the late fall when beach recreation has slowed but beaches are still wide. Natural infrastructure would be constructed on the landward side of the dry beach to avoid impacts to the intertidal beach and nearshore. Specific constructability considerations are summarized below.

Construction of beaches, dunes and cobble berms is relatively straight-forward because it is primarily “rough grading” of imported materials with conventional construction equipment. The primary constraints are:

1. Acquiring desired sand and cobble (sizes and other characteristics)
2. Delivering the sand and cobble to the site
3. Establishing native vegetation which requires management of foot traffic.

The traditional engineering armor baseline alternative is more complicated to construct than a cobble berm or dune, whether a rock revetment or reinforced concrete seawall (or other) structure is used. For dunes and cobble berms, sourcing and delivering desired quality sand and cobble will be the greatest obstacles. Further study of sediment sources and characteristics is needed to properly assess the constructability of these alternatives (ESA 2020a). Otherwise, dune features require vegetation planting and public access management techniques to reduce impacts to vegetation. Foot-traffic management approaches add elements to the construction of either natural or engineered alternatives, but are not overly-complicated. For low foredunes, simple roped paths could be used to manage foot traffic through the dunes, while taller dune embankments require more substantial elements such as wooden stair cases down the face. These public access features are discussed further in Section 6.7.

6.6. Environmental Impacts and Regulatory Considerations

Environmental impacts associated with the baseline and natural infrastructure alternatives are discussed in terms of beach (onshore) and benthic (nearshore) ecology. For this study, environmental impacts are discussed with regards to ecosystem functions that affect shorebirds, invertebrates and natural beach flora. Impacts from each alternative include construction activities, effects on long term cross-shore and longshore sediment transport, and maintenance activities. Regulatory considerations are also summarized for the various agencies with jurisdiction near the study area. Table 14 presents a qualitative ranking of adverse ecological impacts that may occur as a result of the baseline armoring and natural infrastructure adaptation alternatives.

TABLE 14. ECOLOGICAL IMPACT OF ADAPTATION ALTERNATIVES

Qualitative Ranking of Adverse Impacts (High to Low)			
Reach	**Alt 0**	**Alt 1**	**Alt 2**
Seadrift West	High	Medium	Medium
Seadrift East	High	Medium	Medium
Patios	Medium	Medium	Medium
Calles	Medium	Low	Medium
NPS	High	Low	Medium

The natural infrastructure modeling results from Table 4 were used to rank the ecological impacts in each reach. We assume that a greater beach and dune width results in more positive ecological benefits so any reduction in width from existing conditions is considered a negative impact. We also assume that all three alternatives will have impacts from either construction, maintenance or both. However, we assumed that the ecological impacts of construction and maintenance of Alternative 2 would be greater than Alternative 1 because of the introduction of non-native cobble to the system that could crush or otherwise harm invertebrates when exposed to wave action. We assume the ecological impacts from the armoring alternative are the greatest because in addition to impacts from maintenance that would be similar to the other alternatives, we assume that scour from existing and new armor could increase erosion when exposed and degrade ecological functions. We find that in general, the ecological impacts of Alternatives 1 and 2 are less than the armoring alternative. Additionally, we find that the impacts of Alternatives 1 and 2 are similar in the Seadrift East and Patios reaches. However, in the Calles and NPS reaches, we find that sufficient beach and dune width is protected in Alternative 1 so the additional ecological impacts of Alternative 2 outweigh protective ecological benefits within these reaches. Specific environmental impacts are discussed in the following subsections.

All of the alternatives, including the baseline, have adverse impacts at construction and during maintenance. In addition, the team anticipates a net degradation in ecology over time due to erosion of the beaches and foredunes with sea-level rise and the effects of existing armoring. The relevant point of comparison isn't how the alternatives compare to existing conditions, but rather how the natural infrastructure alternatives compare to the traditional armoring adaptation approach. Relative impacts were computed to illustrate the comparative performance of Alternatives 1 and 2 to the baseline. Relative scores were calculated by subtracting the Alt 0 scores from Alt 1 and Alt 2 in Table 14 above. Negative scores mean less impact than the baseline. Table 15 illustrates that nature-based alternatives can have less environmental impacts overall than traditional armoring approach to shoreline protection. See Section 6.4 for descriptions of the geomorphic and habitat benefits that natural infrastructure provides over armoring.

TABLE 15. RELATIVE ECOLOGICAL IMPACT OF NATURE-BASED ADAPTATION ALTERNATIVES COMPARED TO TRADITIONAL ARMORING

Relative Impact Score (compared to armoring baseline Alt 0)*		
Reach	**Alt 1**	**Alt 2**
Seadrift West	lower	lower
Seadrift East	lower	lower
Patios	similar	similar
Calles	lower	similar
NPS	much lower	lower

6.6.1. Potential Impacts to Beach and Benthic Ecology

Shore ecology is discussed in terms of beach (onshore, dry) and benthic (offshore, subtidal). Figure 30 shows a typical shore cross section (top) with the backshore berm (i.e. dry beach), swash, surf, and breaker zones at the top panel. Ecological features are shown on the lower panel.

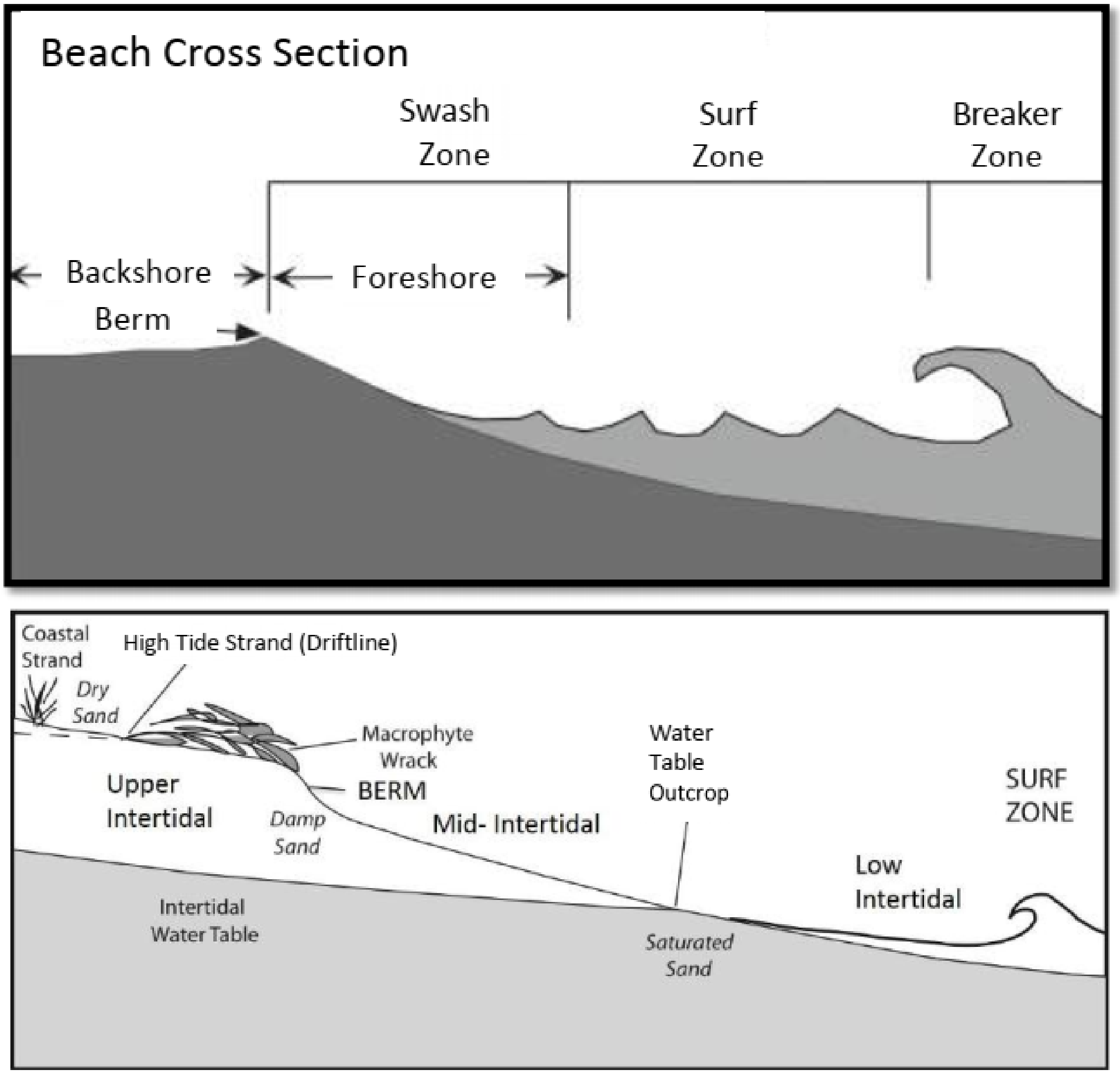


Figure 3. Profile of an exposed sandy beach. Upper panel shows zones and lower panel shows relative locations of driftline, water table outcrop, invertebrate types and coastal strand vegetation. Figure modified from Dugan & Hubbard 2010 (lower) and http://www.tulane.edu/~sanelson/Natural_Disasters/coastalzones.htm (accessed 26 Feb 2017) (upper).

SOURCE: Neilsen et al 2017

Stinson Beach Nature-Based Adaptation Feasibility Study. 171009.00

Figure 30
Beach geomorphic and ecology zones

Potential changes to beach and benthic ecology for the armoring baseline are illustrated in Figure 31 below from Dugan 2017. The graphic provided shows that armoring an eroding shoreline leads to loss of high intertidal zone and corresponding reduced species abundance and diversity, fewer trophic levels on the shore, decrease water exchange, decreased productivity and changes in wrack deposition. In contrast, natural infrastructure implementation will have temporary impacts to the shore via construction and maintenance but over time increases beach longevity and its ecological functions with sea-level rise. The potential impacts are discussed in the following sections.

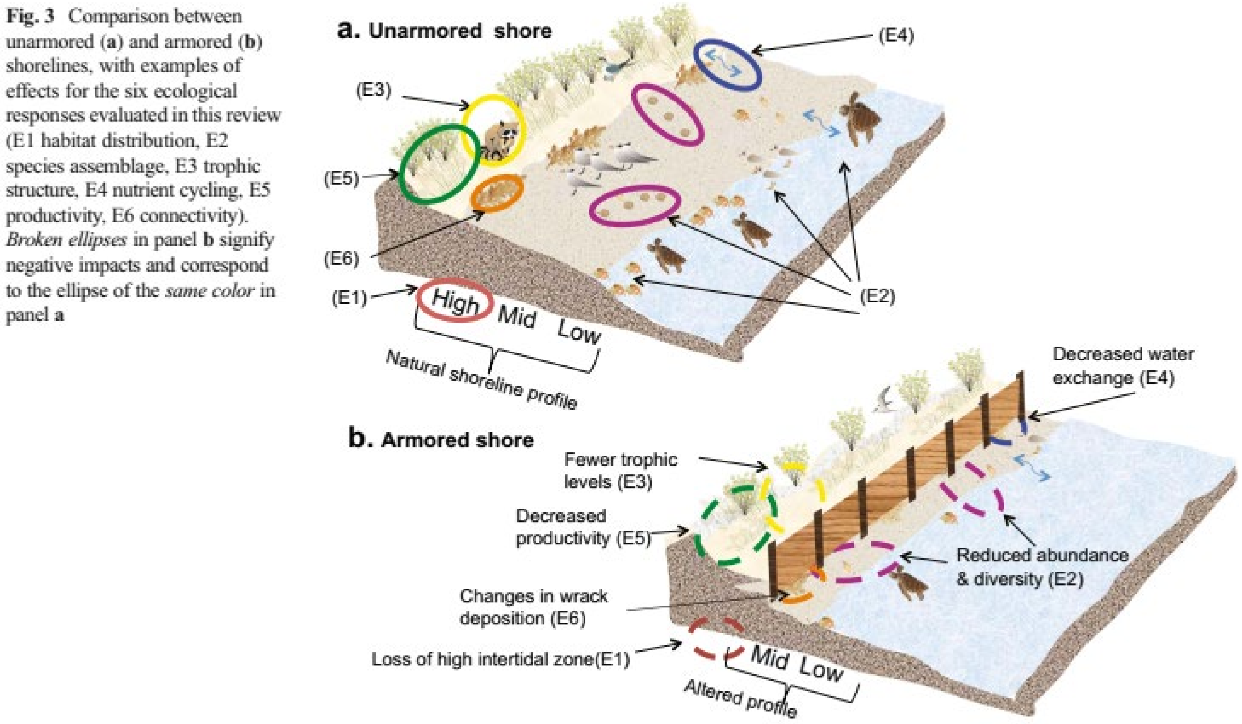


Fig. 3 Comparison between unarmored (**a**) and armored (**b**) shorelines, with examples of effects for the six ecological responses evaluated in this review (E1 habitat distribution, E2 species assemblage, E3 trophic structure, E4 nutrient cycling, E5 productivity, E6 connectivity). *Broken ellipses* in panel **b** signify negative impacts and correspond to the ellipse of the *same color* in panel **a**

SOURCE: Dugan 2017

Stinson Beach Nature-Based Adaptation Feasibility Study. 171009.00

Figure 31
Comparison of unarmored and armored shoreline and ecological responses, adapted from Dugan 2017

Onshore Beach Ecological Impacts

Construction of the proposed natural infrastructure typologies (cobble, foredunes, dune embankments) in Alternatives 1 and 2 likely will result in three types of ecological impacts to sandy beach shorebirds: 1) impacts related to initial construction/installation; 2) impacts resulting from repeated maintenance; and 3) conversion of existing habitats into other habitat types. Sediment placement directly on intertidal zones of sandy beaches causes mortality of invertebrates resulting from direct burial by sediments and from crushing and mechanical disturbance from heavy machinery (Schlacher et al. 2014). Construction equipment can cause significant mortality of surface-dwelling wrack-associated invertebrates (e.g., Talitrid amphipods) and soft-bodied benthic invertebrates associated with the wet and semi-wet beach areas. Burial of kelp wrack during construction also may inhibit the re-population of affected reaches by wrack-associated invertebrates, which are dependent on the presence of wrack for dispersal and are only capable of dispersing small distances (Grantham et al. 2003). The probability of these impacts depends on how the construction is performed and the overall space (beach width) available at the time of construction. If there is any heavy machinery on the wet/semi wet beach, there could be indirect mortality from crushing. The nature-based alternatives were designed to be constructed at the landward side of the dry beach in part to minimize these impacts. Any implemented natural infrastructure should optimize construction timing and limit the work area to the most landward and highest beach areas to minimize these ecological impacts. Maintenance or reconstruction of natural infrastructure (i.e., application of additional sediment or cobble, shaping of topographic features) that results from expected erosion will result in similar, repeated impacts to sandy beach invertebrate populations. Because invertebrate populations may be relatively slow to recover after significant disturbances (Schlacher et al. 2014), the time between planned maintenance events will have a large influence on the relative level of overall impact.

Installation of the natural infrastructure typologies also may result, in some cases, in a conversion of flat, sparsely vegetated beach habitat to more continuously vegetated foredune habitat, and narrowing of the existing beach. Conversion of the area above MHW to dunes, dune embankments, or cobble will result in a reduced amount of gently sloping beach above MHW and the slope of the converted area above MHW likely will increase. More steeply sloped beaches are less suitable for shorebirds that forage in the swash zone (Neuman et al. 2008) and also may negatively impact species, such as the western snowy plover, that typically occupy the gently-sloped, semi-wet to dry shoreline above MHW. Available swash zone habitat also will decrease which may limit foraging opportunities for shorebirds in the affected areas. Because surface-dwelling and sub-surface dwelling invertebrate taxa are the primary prey of shorebirds on sandy beaches, construction and maintenance of the natural infrastructure typologies may have negative impacts on shorebird use of the affected reaches, with less overall use of the altered habitats above MHW and potentially less use of the swash zone. The backshore beach is also habitat for seedling establishment ("nursery" habitat) for some rare strand plant species, like North Coast pink sand-verbena. Habitat trade-off between unvegetated or sparsely vegetated flat sand beach (invertebrate and shorebird habitat), to more terrestrial vegetated foredune (vascular plant and terrestrial insect habitat) is a direct consequence of constructing vegetated foredune features in the backshore.

Under the baseline armoring alternative (Alt 0), ecological impacts will be caused by failure to mitigate the climate effects of sea-level rise and erosion which will result in much lower quality habitat over time. Existing hard armored shoreline areas will be exposed at a much earlier date, exacerbating the negative ecological impacts caused by hard armoring. New armoring constructed to protect development would broaden the extent of negative ecological impacts. These impacts include loss of the high intertidal zone, lower trophic diversity, and changes in wrack deposition (Dugan et al. 2017). In contrast, implementing the nature-based adaptation alternatives will help maintain high intertidal zones along the shore, reducing the long term negative ecological impacts of sea-level rise at Stinson Beach.

Nearshore Benthic Ecological Impacts

The nearshore zone along the entire length of Stinson Beach is comprised of sand bottom habitat while rocky reefs are found extending off Duxbury Point (Duxbury Reef) to the northwest and Rocky Point to the south of the study area (Merkel & Associates 2019). Details on benthic habitats and features are detailed in Study Memorandum 1 (ESA 2020a). Adaptation alternatives proposed on and above the dry beach will have limited to no impacts to nearshore ecology.

The ecology of the subtidal environment within the project area is expected to reflect the dynamic nature of a wave exposed sand bottom habitat. Organisms in this environment are adapted to transitory sand movement and either adapt by vertical movement in the sediment (e.g., polychaetes and bivalves), or lateral movement up and down the beach (e.g., most arthropods, fish). In addition, sand beaches have a significant component of effectively short-lived annual species that are decimated in abundance during storm periods when the sand substrate disturbance is greatest and then recruit heavily during the spring months. This active beach community is well adapted to shifting sand conditions driven by natural seasonal cycles, and it is resilient to differences in the intensity of disturbance that occur with infrequent major storms.

The adaptation alternatives evaluated in this study are restricted to actions proposed on the high beach environment and none of the alternatives are expected to have a substantial impact on the characteristics of the subtidal beach environment below the swash zone. While an argument may be made that some of the alternatives may favor expanded or reduced beach erosion and thus transport of sediment long-shore or offshore, the character of the subtidal environment would not change from baseline under any of the alternatives considered. As a result, the nearshore environment would remain a sandy soft bottom habitat with seasonal and localized dynamism due to wave climate conditions.

6.6.2. Regulatory Considerations

The alternatives evaluated in this Feasibility Study, including the armoring included in the baseline, will require permits from a range of environmental regulatory agencies. Due to the nature of the proposed activities, geographic location of the site, environmental sensitivity of beach and dune habitat, and multiplicity of jurisdictions and regulations involved, the permitting process for either Alternative 1 or 2 would require an extensive effort to obtain agency approval. However, the more traditional approach of using hard armoring to protect the back shore (Alternative 0) would present a much larger permitting challenge and would likely not be approved due to environmental impacts and the fact that less ecologically damaging alternatives exist.

Alternatives 1 and 2 would require close collaboration with a number of permitting and resource agencies during the project planning and regulatory compliance process. Study Memorandum 4: Regulatory and Policy Considerations, includes a detailed overview of the required permits and approvals, involved agencies, and necessary actions required for the permitting process. Beyond the procurement of permits, the overall regulatory compliance process consists of environmental review (pursuant to CEQA), followed by permitting and/or agency approvals, and concludes with compliance review and documentation. Permits and/or approval would be required from: U.S. Army Corps of Engineers (USACE); U.S. Environmental Protection Agency (EPA); U.S. Fish and Wildlife Service (USFWS); Greater Farallones National Marine Sanctuary (GFNMS); National Marine Fisheries Service (NMFS); California Coastal Commission (CCC); California Department of Fish and Wildlife (CDFW); Regional Water Quality Control Board (RWQCB); California State Lands Commission (CSLC), and; County of Marin.

Additional information on regulatory issues are discussed in Study Memorandum 4. Regulatory and Policy Considerations.

6.7. Public Access

Public access across and along the shoreline is important to maintain; the beach is visited by millions of people annually including local residents. The natural adaptation alternatives provide long term benefits to public access while having some temporary impacts. Traditional armoring structures can lead to a loss of fronting beach and hindered public access as seen along the western portion of Seadrift during winter months. With sea-level rise, beaches in front of armoring structures along the rest of the study area may be lost during winter. The following sections summarize the benefits and impacts of natural adaptation to public access.

6.7.1. Benefits to public access

Overall, natural infrastructure alternatives provide benefits to access by maintaining dunes and beaches over time compared to a traditional armoring baseline. As detailed in Table 4, while it’s not possible to maintain existing beach widths with sea-level rise, the natural infrastructure alternatives result in wider beach widths compared to the Alternative 0 baseline.

6.7.2. Impacts to public access

Public access impacts are discussed in terms of potential impacts during construction, potential impacts during coastal storms and considerations for long term shore evolution with sea-level rise.

Construction period access

Construction of natural infrastructure for adaptation would ideally occur during late fall when beaches are wide and recreation is lower. Nonetheless, cross-shore access would be limited during construction of natural infrastructure or traditional armoring alternatives. Depending on the beach widths when alternatives are constructed, alongshore beach access could be maintained seaward of the active construction area as features are be built along the back of the beach.

Access during coastal storm flooding and erosion events

Access along the shoreline and beach is dangerous during coastal storm events. Traversing along the top of a traditional armoring structure where the beach is absent can be treacherous during storms because waves are likely to run-up along the structure. Natural infrastructure alternatives can provide benefits to coastal access during and after storm events. In comparison to the traditional armored shoreline described above, the top of a dune or cobble berm may provide a relatively safer place for lateral access during a coastal storm event but beachgoers must exercise caution at the beach at all times especially during extreme events. Compared to hard armoring that reflects wave energy and magnifies beach erosion during storms, natural infrastructure can respond to wave impacts during a storm, erode, and provide room for the beach to respond such that beach widths are not depleted completely during the storm and facilitate post-storm access along the shoreline even at high tides.

Example of reduced lateral access along Seadrift rock revetment in winter illustrates potential long term beach conditions with sea-level rise and/or post-storm conditions for the traditional armoring baseline (Peter Baye 2019)

6.8. Adaptation Alternatives Evaluation Summary

The evaluation of baseline and nature-based adaptation alternatives is summarized in Table 16 below. Scores ranging from 1 (worst) to 5 (best) were developed for the various evaluation categories. The scores are based on qualitative analysis performed to estimate construction effort and costs, shore width modeling, wave run-up calculations, and interpretations of shore widths for the purpose of ecology and recreation/public access and expert elicitations regarding ecologic impacts and regulatory considerations.

The sum of scores are, out of a maximum of 35:

- Alternative 0 – Baseline Armoring = 11
- Alternative 1 – Natural Infrastructure (dunes, some cobble berms) = 23
- Alternative 2 – Natural Infrastructure Enhanced (dunes with cobble berms) = 21

The baseline armoring scores relatively poorly because of lower scores for all criteria. Alternative 1 which focuses on sand dunes with limited cobble armor scores the highest, and adding cobble berms (Alternative 2 scores slightly lower. Different weighting of the numerical scores can represent different perspectives and judgments, and there are uncertainties associated with the scores. For example, cobble berms may be considered armoring similar to rock revetments and hence rank lower in regulatory considerations. Sand sources and cobble-gravel sources have not been identified, and there may be reduced reliability with natural features verses structures, both of which could increase the cost of the natural infrastructure and hence lower their "cost" ranking. However, the rankings for natural infrastructure (Alternatives 1 and 2) are substantially higher than armoring (Alternative 0) and therefore likely to remain so even with refined different scores and weights.

TABLE 16. ADAPTATION ALTERNATIVES EVALUATION MATRIX

Category	Design Life Analysis	Storm Protection Levels	Coastal Habitat Benefits	Environmental Impacts	Regulatory Considerations	Public Access Benefits	Constructability	Total Score (Sum)
Metric[1]	Cost	Run-up and Erosion Reduction Potential	Beach and Dune Resilience	Expert Elicitation	Expert Elicitation	Beach Width	Methods and Materials	
Alternative 0 Backshore armoring baseline for comparison	**Score: 2** **$155M to construct and maintain with 3.3 ft SLR** Armoring structures will require costly upgrades and repairs as sea-level rises and beaches erode, leading to more frequent wave overtopping potential..	**Score: 2** **Two reaches overtopped today, three reaches with 3.3 ft SLR.** Armoring structures can withstand erosion from waves but are overtopped during storm events, especially when fronting beach width and elevation is low (from sea-level rise effects and/or due to the reflective nature of armoring that increases beach erosion).	**Score: 1** **Average shore width with 3.3 feet SLR: 49 feet winter to 121 feet summer** Armoring structures create a barrier to sediment exchange between the beach and any dunes behind them, this leads to beach loss on eroding shores (Seadrift is an example). NPS reach could retain more dunes with SLR given the reduced extent of armoring needed to protect development in this reach. Otherwise beaches along the shore may disappear in front of continuous armoring structures with as little as 1 to 3 feet SLR.	**Score: 1** **Medium-High Impacts** Armoring structure construction and maintenance impacts beach ecology. Over time and during storms, scour at armoring structures increases beach erosion and degrades habitat functions including loss of high intertidal zone and corresponding reduced species abundance and diversity, fewer trophic levels on the shore, decrease water exchange, decreased productivity and changes in wrack deposition.	**Score: 1** Alternative 0 may be difficult to approve for this location due to environmental impacts and the fact that less ecologically damaging alternatives exist.	**Score: 2** **Average beach width 30 feet winter to 109 feet summer with 3.3 feet SLR** Hard armoring reflects wave energy during storms and can increase beach erosion, leading to loss of lateral beach access. Armoring structures are more difficult to traverse when exposed and require additional cross-shore access such as stairs.	**Score: 1-2** Armoring structures require more rigorous construction preparations and methods but are straightforward. Rock revetments require base prep and additional equipment and care during rock placement; reinforced concrete seawalls require base prep, rebar and forming and concrete pouring.	**Score Total: 11**
Alternative 1 Natural infrastructure (dunes, some cobble berms)	**Score: 3** **$46M to construct and maintain with 3.3 ft SLR** The sandy shore naturally responds to SLR with less intervention over time resulting in a more resilient beach. Stormy winters and extreme events may increase maintenance requirements.	**Score: 3** **One reach overtopped today, two reaches overtopped with 3.3 ft SLR.** Properly maintained natural infrastructure can reduce wave run-up and impacts to development. Dunes respond dynamically to wave run-up during storms and maintain beach width and elevation compared to armoring. However, maintenance will be needed after extreme events and stormy winters.	**Score: 3** **Average shore width with 3.3 feet SLR: 77 feet winter, 144 feet summer** Constructing and widening dunes increases the adaptive capacity of beaches for sea-level rise. Sand eroded from the dunes during winter or a given storm dissipates wave energy and nourishes beaches, thereby making the sandy beach relatively higher, wider and more persistent than without dunes. Foredunes also provide foraging opportunities and other habitat features for beach organisms.	**Score: 3** **Medium-Low Impacts** Construction and maintenance will impact beach ecology via construction activities and habitat conversion from beach to dune. However, beach erosion is reduced over time by presence of dunes, prolonging ecological functions over armoring Alternative 0.	**Score: 4** Alternative 1 would require construction activities including placement of fill. Due to the nature of the proposed activities, geographic location of the site, environmental sensitivity of beach and dune habitat, and multiplicity of jurisdictions and regulations involved, the permitting process for either Alternative 1 or 2 would require an extensive effort to obtain agency and stakeholder approval.	**Score: 3** **Average beach width 40 feet winter to 108 feet summer with 3.3 feet SLR** Dunes provide sand to maintain beaches over time with SLR and after storms, preserving beach recreation area and lateral shore access. Placement of natural infrastructure reduces recreation area on beaches initially but results in a more resilient and accessible beach-dune shore form. Cross-shore access through foredunes provided by roped or fenced paths. Dune embankment requires more significant access features such as stairways	**Score: 3-4** Nature-based alternatives are highly constructible, however the availability of sand and cobble is unknown. Sand-only dunes are easiest to construct without the need for over-excavation to place cobble berm.	**Score Total: 23**
Alternative 2 Natural infrastructure enhanced (dunes with cobble berms)	**Score: 3** **$54M to construct and maintain with 3.3 ft SLR** Cobble berms increase the resilience of the shore width by reducing wave run-up on dunes and the erosion caused over time and during storms. Stormy winters and extreme events may increase maintenance requirements.	**Score: 3** **One reach overtopped today, two reaches overtopped with 3.3 ft SLR.** Introducing cobble berms adds protective benefits in the form of increased roughness that reduces wave run-up and erosion of dunes behind them that further buffer wave run-up.	**Score: 4** **Average shore width with 3.3 feet SLR: 105 feet winter, 149 feet summer** Cobble berms lengthen the functional life of dunes behind them, but can be exposed during storm events/winters. However, native invertebrates and insects can live in cobble shores, providing food for other fauna and an overall ecological benefit compared to armoring. Cobble berms also facilitate sand beach recovery and reduce wave impacts to sand dunes behind them.	**Score: 2** **Medium Impacts** Similar construction impacts as Alternative 1, with slightly more beach and dune area preserved with sea level rise. Addition of cobble-gravel berm introduces potential for invertebrate crushing or other impacts when exposed to wave action.	**Score: 3** Alternative 2 requires a more extensive construction process and placement of more cobble berm than Alternative 1. Due the potential environmental impacts of the project construction and the placement of material in these highly protected and ecologically sensitive locations, this alternative would require additional scrutiny and review by permitting agencies, presenting a relatively more challenging permitting scenario than Alternative 1.	**Score: 3** **Average beach width 56 feet winter to 100 feet summer with 3.3 feet SLR** Compared to Alt 1, Alt 2 may maintain upper beach and dunes longer with use of cobble berm, better preserving lateral shore access. Results indicate similar Cross-shore access through foredunes provided by roped or fenced paths. Dune embankment requires more significant access improvements	**Score: 2-3** Nature-based alternatives are highly constructible, however the availability of sand and cobble is unknown. Cobble berms require additional effort to over-excavate sand, place and bury the cobble berm.	**Score Total: 21**

[1] Score ranges from worst (1) to best (5).

Page is intentionally left blank

7. Long-term Adaptation Pathways for Stinson Beach

The distinction between near-term and long-term shore adaptation alternatives is based on projected sea-level rise. With sea-level rise, the Pacific shoreline will migrate landward. The beach will become narrower as the shore approaches the existing development. The reduction in available space between the shore and development will make nature-based infrastructure less sustainable – indeed, the beach is part of the natural shore infrastructure at Stinson Beach. The beach and other natural shore infrastructure types can be maintained by reconstruction but the frequency of damage and reconstruction will increase with rising sea levels, likely reaching practical limits. Therefore, additional adaptation measures for the study reaches are likely to be needed later in the century when sea levels rise over 3 feet.

A range of future sea-level rise adaptation measures are described in the C-SMART Adaptation Report (Marin County 2018). A supporting technical memorandum to the C-SMART Adaptation Report provides additional information on adaptation strategies, including case studies of Seadrift and Stinson Beach (ESA 2017). These adaptation case studies are compatible with the proposed nature-based adaptation alternatives and informed this study.

Reach-based example adaptation pathways are summarized below as one set of adaptation pathways for Stinson-Seadrift to guide community planning efforts by the County, local residents and other stakeholders. The adaptation pathways illustrate how future adaptation measures may follow the near-term alternatives developed for this study. For Seadrift, the existing rock revetment is presumed to be maintained and renovated for more extreme conditions forecast with sea-level rise. When wave overtopping cannot be adequately mitigated by the beach and shore armor, raising the homes above the flood levels was identified as an additional adaptation measure. An example adaptation pathway for Seadrift reach is provided in Table 17.

TABLE 17. EXAMPLE ADAPTATION PATHWAY FOR SEADRIFT REACH

Year	Adaptation Action
2020	Existing revetment is adequately maintained/upgraded
2030	Construct cobble berm along toe of revetment, rebuild/upgrade cobble berm and repair revetment after storm impacts
2040	Rebuild/upgrade cobble berm and repair revetment after storm impacts
2050	Upgrade revetment for higher sea-levels, rebuild cobble berm, elevate and/or retreat the most vulnerable homes
2070	Elevate and/or retreat homes in FEMA V-zone
anytime	*Emergency cobble/revetment repairs if extreme storm erosion occurs*

For the remainder of Stinson Beach, a wider range of adaptation strategies were considered potentially feasible. In addition to the adaptation strategies identified for Seadrift (shore armor, beach nourishment and raising buildings), natural shore infrastructure comprised of dunes with and without cobble-gravel berms were identified. Modification of Easkoot Creek was also identified as a flood risk reduction strategy. Allowing flood discharge across Stinson Beach was identified because this additional flow path, which occurred at the NPS reach in 2014 and 2016, lowers the flood levels downstream in the more developed area. Another adaptation strategy identified for the NPS reach was retreat, likely consisting of relocation of parking and facilities farther inland to accommodate shore migration without shore armoring. While the adaptation alternatives in this feasibility study focused on natural infrastructure, a hybrid approach may be taken at one or more reaches that includes a buried wall or other armoring structure at the landward side of dunes or cobble berm that could act as a backstop for higher sea-levels and or extreme winter dune erosion events. Some homes in the Calles reach are located seaward of the overall neighborhood, creating pockets where wider natural infrastructure features may be constructed. These homes could be relocated at some point to provide room for a wider natural infrastructure project for the entire reach. Example adaptation pathways for the eastern reaches are provided in the tables below.

TABLE 18. EXAMPLE ADAPTATION PATHWAY FOR PATIOS REACH

Year	Adaptation Action
2020	Construct foredunes with cobble berm at toe of foredunes
2030	Maintain dune width for storm protection as needed
2040	Maintain cobble berm and dune width for storm protection as needed
2050	Maintain cobble berm and dune width for storm protection as needed
2060	Rebuild cobble berm for higher sea levels, raise dune elevations to match sea-level rise
2080	Elevate and/or retreat homes and restore dunes
anytime	*Emergency dune repairs if extreme storm erosion occurs*

TABLE 19. EXAMPLE ADAPTATION PATHWAY FOR CALLES REACH

Year	Adaptation Action
2020	Construct dune embankment with cobble berm at toe of foredunes
2030	Maintain dune width for storm protection as needed
2040	Maintain cobble berm and dune width for storm protection as needed
2050	Maintain dune width for storm protection as needed
2060	Rebuild cobble berm for higher sea levels, raise dune elevations to match sea-level rise, elevate or retreat of seaward most homes.
2080	Elevate and/or retreat homes and restore dunes
anytime	*Emergency dune repairs if extreme storm erosion occurs*

TABLE 20. EXAMPLE ADAPTATION PATHWAY FOR NPS REACH

Year	Adaptation Action
2020	Construct cobble berm or foredunes along select buildings/development, implement cobble lag at west end of reach for Easkoot overflow drainage.
2030	Maintain dune widths for storm protection as needed in front of buildings
2040	Maintain cobble berm and dune widths for storm protection as needed
2050	Maintain dune width for storm protection as needed, begin landward retreat of seaward most buildings.
2060	Rebuild cobble berms for higher sea levels, raise dune elevations to match sea-level rise. Continue retreat planning for buildings and other development.
2080	Retreat remaining structures, restore dunes
anytime	*Emergency dune repairs if extreme storm erosion occurs*

8. Conclusions and Next Steps

This chapter presents salient conclusions of the study (Section 8.1) and recommended next steps for nature-based adaptation at Stinson Beach (Section 8.2).

8.1. Conclusions

We evaluated two nature-based adaptation alternatives along with a traditional armoring baseline (Alternative 0). The two natural infrastructure alternatives consist of a more natural Alternative 1 that prioritizes foredunes and an enhanced Alternative 2 that incorporates cobble berms and taller dune embankments to increase protective services.

Natural infrastructure implementation at Stinson Beach is a feasible alternative to traditional shoreline armoring approaches for near term sea-level rise (up to ~3.3 feet). The exception is in the Seadrift reaches where the existing beach is narrow, providing limited space for dunes seaward of the existing rock revetments: In this location, sand placement would need to be more frequent and may not provide the ecologic benefits of a natural system.

The sand dune elements (foredunes and barrier dune embankment) are more consistent with the setting than the cobble-gravel berms, resulting in concerns about the cobble-gravel degrading access and ecology. However, the cobble-gravel berms provide greater “protective services” in terms of dissipating wave run-up and mitigating landward shoreline movements during elevated wave conditions. Hence, the cobble-gravel berms can be thought of as a natural or dynamic revetment with some attributes of a traditional shore armoring, but with better access and recreation. The cobble-gravel features can be implemented initially or as a future adaptive action.

Natural infrastructure provides ecology and recreation benefits beyond the armoring baseline and does not preclude future implementation of other adaptation measures such as shore armor, beach nourishment, raising homes in place (e.g., on pilings), and relocating homes to higher ground (realignment). While the construction of natural infrastructure converts existing beach area to new habitats (vegetated dunes; cobble berms during winters), the overall shore width of dunes and beaches is maintained longer than with traditional armoring structures. Dunes erode during storms and provide sand to the beach, reducing beach loss and facilitating quicker beach recovery after storms compared to traditional armoring. Cobble berms increase the resilience of the beach and dunes to erosion while being more traversable than traditional armoring structures. By increasing beach and dune resilience with natural infrastructure, public access and recreation are improved over a traditional armoring baseline. Overall beach space is reduced after the initial construction of natural infrastructure but the dunes and cobble berms can provide better cross and alongshore access over time with sea-level rise.

Natural infrastructure could be constructed and maintained with 3.3 feet sea-level rise for approximately one third the cost of a traditional rock revetment as modeled for this study. This estimate assumes two 20-year storms equivalent to the 2015-2016 El Nino occur over the ~50-year timeframe during which this amount of sea-level rise is anticipated to occur in the scenario modeled. Maintenance would be required following each event. Maintenance requirements for all alternatives evaluated may be higher or lower depending on the severity of winters and occurrence of significant coastal storm events and the amount of sea-level rise that occurs.

Natural infrastructure alternatives can provide storm protection levels greater than traditional armoring structures if maintained at adequate widths. This is because a wider beach and dune system dissipates wave run-up and limits the landward extents of flood and erosion risks. Cobble-gravel berms provide even greater wave run-up dissipation, and are more resilient to elevated wave conditions than sand dunes alone. Together, a cobble berm and sand dune system provides an enhanced buffer to elevated wave conditions. An important aspect of successful natural infrastructure project will be a commitment to maintenance after stormy winters or singular events. This study considered the impacts of the characteristic 20-year storm given the timeframe of implementation but greater storms have and may occur at Stinson Beach.

The design life of natural infrastructure depends on the timing of construction and revegetation establishment relative to unpredictable coastal storm events. California foredune dynamics (and elsewhere) are generally dominated by unpredictable infrequent, significant, extreme storm erosion events (single or consecutive storm events), and longer (multi-year) post-storm recovery phases during which beach recovery, vegetation succession, and foredune accretion occur. The ultimate stewards of natural infrastructure built at Stinson Beach for adaptation need to commit to ongoing maintenance program and ready to respond to coastal storm impacts. The management implications are that natural infrastructure investments like this provide a different trade-off between shoreline stabilization and all other ecologic/public benefits of Stinson Beach: instead of more predictable hard armored engineering designs that severely conflict with ecological, esthetic, and recreational benefits that make Stinson Beach valuable, the softer, dynamic nature-based alternatives provide significant but less predictable stabilization benefits while conserving ecological, aesthetic, and recreational benefits of the shoreline for longer periods – a human generation, an important time-scale - until sea level rise overcomes their capacity to function effectively at the current shoreline position. With sea-levels greater than 3.3 feet above existing conditions, additional adaptation actions will be needed to ensure protection of the Stinson Beach community.

The alternatives evaluated in this Feasibility Study, including the armoring included in the baseline, will require permits from a range of environmental regulatory agencies. Due to the nature of the proposed activities, geographic location of the site, environmental sensitivity of beach and dune habitat, and multiplicity of jurisdictions and regulations involved, the permitting process for either Alternative 1 or 2 would require an extensive effort to obtain agency approval. However, the more traditional approach of using hard armoring to protect the back shore (Alternative 0) would present a much larger permitting challenge and would likely not be approved due to environmental impacts and the fact that less ecologically damaging alternatives exist. The use of cobble and gravel along Stinson Beach may raise concerns with regulatory agencies akin to traditional shore armor. A possible exception is at the NPS reach where Easkoot Creek flood flows would naturally transport coarse sediment to and across the beach to the extent it avulses from its sediment-choked channel, and hence placement of these sediments in this location would be consistent with the setting.

Current regulatory restrictions on beach nourishment to the shore face (nearshore, intertidal to subtidal profile nourishment) limit the alternatives examined for this study to include only backshore actions above the tidal influence. Future potential changes in regulatory restrictions on beach nourishment may open up additional opportunities for shoreface or profile nourishment including intertidal to subtidal. Beach nourishment in the supratidal-intertidal-subtidal gradient is essentially a regulatory consideration, not a physical or ecological feasibility barrier to feasibility other than the potential impacts to Bolinas lagoon mouth by longshore sediment transport (see Study Memorandum 1). Long-term shoreline resilience at Stinson Beach, following the design life of the examined nature-based adaptation alternatives, which excludes intertidal sand placement or drift retention structures (groin field), should be revisited when regulatory policies restricting profile nourishment are reviewed. Long-term adaptive strategies for significantly higher sea-level rise are likely to depend on a sequence of natural infrastructure implementation followed by sediment nourishment and/or managed retreat.

8.2. Next Steps

Next steps for implementation of natural infrastructure at Stinson Beach include:

- Develop a preliminary design of an integrated project for the study area. The preliminary design process can facilitate refinements based on analysis as well as community and stakeholder preferences for the types and extents of natural infrastructure, and informed by regulatory and resource agency feedback. The preliminary design can then be subjected to further environmental review and associated refinements.
- The preliminary design scope of work should address the following:
    - Evaluation of sediment sources with consideration of sediment characteristics, availability, requisite studies, and costs of acquiring, transporting and placing. Beneficial reuse of sediments that may become available due to other activities should be considered, consistent with "opportunistic sources" concepts developed by the Coastal Sediment Management Workgroup[1].
    - Coordination with the National Park Service regarding implementation as well as integration with future renovation of the Stinson Beach facility.
    - Public access elements such as boardwalks and fencing through the dunes.
    - Refine analysis of sediment movements away from the placement area, and the response of cobble-gravel berms to elevated wave and water level events.
    - Refine analysis of shore erosion and backshore flooding and damages.
    - Engineer's estimates of likely construction quantities and costs
    - Preliminary construction drawings
    - Renderings (graphic depictions) of the post construction conditions.
    - Implementation funding, potentially including small test projects (Pilot projects)
    - Repeated beach topographical and ecological surveys to better understand seasonal and storm changes (coordinate with ongoing surveys reach by GGNRA staff)

---

[1] https://dbw.parks.ca.gov/?page_id=29239 and https://dbw.parks.ca.gov/?page_id=29355 last visited May 2021.

9. References

Baye 2019. Existing ecological conditions assessment, Stinson Beach backshore and foredune zone, with reference to indicators of feasibility for "living shoreline" adaptive management methods, Prepared by Peter R Baye Ph.D.. Prepared for ESA. December 26, 2019.

Dugan, J.E., D.M. Hubbard, M.D. McCrary and M.O. Pierson. 2003. The response of macrofauna communities and shorebirds to macrophyte wrack subsidies on exposed sandy beaches of southern California. Estuarine Coastal and Shelf Science 133-148.

Dugan, J.E., K.A. Emery, M. Alber, C.R. Alexander, J.E. Byers, A.M. Gehman, N. McLenaghan, and S.E. Sojka. 2017. Generalizing ecological effects of shoreline armoring across soft sediment environments. Estuaries and Coasts DOI 10.1007/s12237-017-0254-x.

ESA 2016. Marin County Coastal Hazards and SLR Adaptation Strategies, Prepared by Environmental Science Associates, Prepared for Marin County, Appendix B to Marin Ocean Coast Sea Level Rise Adaptation Report, 2016.

ESA 2017. Surfers Point Monitoring Report. Prepared by ESA and the City of Ventura for the California Coastal Commission.

ESA 2017. Marin County Coastal Hazards and Sea-level Rise Adaptation Strategies, Prepared for Marin County, April 28 2016.

ESA 2018. Pacifica Sea-level Rise Adaptation Plan. Prepared for the City of Pacifica. July 2018.

ESA 2020a. Stinson Beach Nature-Based Adaptation Feasibility Study Memorandum 1: Existing Conditions - Task 1 Deliverable for Stinson Beach Nature-Based Adaptation Feasibility Study (ESA Project D17009.00). May 21, 2020.

ESA 2020b. Stinson Beach Nature-Based Adaptation Feasibility Study Memorandum 2: Climate Scenarios and Evaluation Criteria for Adaptation Alternatives - Task 2 Deliverable for Stinson Beach Nature-Based Adaptation Feasibility Study (ESA Project D17009.00). May 21, 2020.

ESA 2020c. Ormond Beach Restoration and Public Access Project Final Plan. Prepared for the California State Coastal Conservancy, The Nature Conservancy and City of Oxnard. August 2020.

Everts, C. H., Eldon, C. D., and Moore, J., 2002. Performance of Cobble Berms in Southern California. Shore & Beach, 70(4), pp. 5-14.

Grantham, B. A., Eckert, G. L., & Shanks, A. L. (2003). Dispersal potential of marine invertebrates in diverse habitats. Ecological Applications 13:108–116.

Judge and others, 2017. Judge, J., Newkirk, S., Leo, K., Heady, W., Hayden, M., Veloz, S., Cheng, T., Battalio, B., Ursell, T., and Small, M. 2017. Case Studies of Natural Shoreline Infrastructure in Coastal California: A Component of Identification of Natural Infrastructure Options for Adapting to Sea Level Rise (California's Fourth Climate Change Assessment). The Nature Conservancy, Arlington, VA. 38 pp

Lorang, M.S., 2002. Predicting the Crest Height of a Gravel Beach. Geomorphology. Number 48: p. 87 – 101.

Marin County 2016. Marin Ocean Coast Sea-Level Rise Vulnerability Assessment. Accessible at https://www.marincounty.org/depts/cd/divisions/planning/csmart-sea-level-rise/csmart-publications-csmart-infospot

Marin County 2018. C-SMART Adaptation Report. Accessible at https://www.marincounty.org/depts/cd/divisions/planning/csmart-sea-level-rise/csmart-publications-csmart-infospot

Neuman, K, G Page and S Connors. 2004. Factors affecting abundance and distribution of shorebirds on sandy beaches in Monterey Bay California. Unpubl. Report to Oiled Wildlife Care Network.

Neuman, K.K., L.A. Henkel, and G.W. Page. 2008. Shorebird use of sandy beaches in central California. Waterbirds 31: 115-121.

Newkirk and others 2018. Newkirk, Sarah, Sam Veloz, Maya Hayden, Walter Heady, Kelly Leo, Jenna Judge, Robert Battalio, Tiffany Cheng, Tara Ursell, Mary Small. (The Nature Conservancy and Point Blue Conservation Science). 2018. Toward Natural Infrastructure to Manage Shoreline Change in California. California's Fourth Climate Change Assessment, California Natural Resources Agency. Publication number: CCCA4-CNRA-2018-011.

Nielsen, K.J., S.G. Morgan, and J.E. Dugan. 2013. Baseline Characterization of Sandy Beach Ecosystems in California's North-Central Coast Region. Final Report. California Marine Life Protection Act Initiative. 118 pp.

Nielsen, K.J., J. E.Dugan, T. Mulligan, D.M. Hubbard, S.F. Craig, R. Laucci, M.E. Wood, D.R. Barrett, H.L. Mulligan, N.Schooler, M. L. Succow. 2017. Baseline Characterization of Sandy Beach Ecosystems along the North Coast of California Final Report. May 31 2017.

Noble, R.M., C.D. Fassardi and R.M. Kamieniecki. 2007. Maintenance and Case History of the Seadrift Revetment, Stinson Beach, California, USA. Coastal Structures 2007: Proceedings of the 5th International Conference.

Rosenberg, KV, AM Dokter, PJ Blancher, JR Sauer, AC Smith, PA Smith, JC Stanton, A Panjabi, L Helft, M Parr, PP Marra. 2019. Decline of the North American avifauna, Science 366: 120–124.

Schlacher, TA, AR Jones, JE Dugan, MA Weston, L Harris, DS Schoeman, DM Hubbard, F Scapini, R Nel, M Lastra, A McLachlan and CH Peterson. 2014. Open coast sandy beaches and coastal dunes. Chapter 3 In Coastal Conservation. B Maslo and JL Lockwood Eds. Cambridge University Press.

SPUR 2012. Ocean Beach Master Plan. Accessible via https://www.spur.org/featured-project/ocean-beach-master-plan