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Stinson Beach Nature-Based Adaptation Feasibility Study

Study Memorandum 2

date	May 21, 2020
to	Marin County CDA
from	ESA Project Team
subject	Climate Scenarios and Evaluation Criteria for Adaptation Alternatives Task 2 Deliverable for Stinson Beach Nature-Based Adaptation Feasibility Study (ESA Project D17009.00)

This study memorandum presents climate scenarios and discusses adaptation criteria and thresholds that are used in the development and evaluation of nature-based adaptation alternatives at Stinson Beach. Climate scenarios represent near to mid-term sea level rise with and without potential coastal storm impacts. Adaptation thresholds provide the foundation for developing location specific design parameters and action thresholds for natural infrastructure at Stinson Beach. This memorandum is the deliverable for Task 2 of ESA's scope of work for the Marin County Community Development Agency (CDA).

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1. Climate Scenarios

Climate scenarios are used to define the potential future conditions that a project may experience during its design life. For this study, climate scenarios are used to understand the progressive coastal flooding and erosion impacts that may occur along Stinson Beach due to sea-level rise. The climate scenarios selected for this study provide a basis for the design and maintenance criteria for adaptation alternatives. Along with site-specific analysis, climate scenarios allow us to determine how long adaptation alternatives will function and can indicate when future adaptation pathways must be taken to maintain the Stinson community's resilience.

The primary climate factors that pertain to this study include long-term sea-level rise and event-based coastal storm impacts. For this study, a climate scenario is defined as a sea-level rise amount and storm scenario (e.g. no storm, 20-year or 100-year storm). Together, the scenarios represent the range of future conditions that are considered when evaluating the functional life and performance of nature-based adaptation alternatives for

Stinson Beach. The feasibility of adaptation alternatives are evaluated based on performance within these scenarios.

This study's assessment of long-term sea-level rise is based on the State of California Sea Level Rise Guidance 2018 Update (published by the California Natural Resources Agency and Ocean Protection Council). This latest state guidance was released after Marin CDA completed the C-SMART Vulnerability Assessment (2016) and Adaptation Plan (2018). Table 1 summarizes the scenarios selected for C-SMART. These scenarios are referenced to the hazard mapping *Our Coast Our Future* (Point Blue Conservation Science) developed using Coastal Storm Modeling Software (CoSMoS) modeling by the US Geological Survey, which includes sea-level rise from 0 to 2 meters in 0.25-meter (~10 inch) increments with options of four storm scenarios: average conditions (no storm), annual storm, 20-year storm and 100-year storm. Marin CDA is currently planning to update the C-SMART Vulnerability Assessment to include at least two scenarios for average conditions, which show long-term inundation from sea level rise without flooding from storm impacts. ESA is coordinating with CDA as this update progresses so that this study will include the updated scenarios.

TABLE 1
SEA-LEVEL RISE SCENARIOS USED IN C-SMART*

Sea-level Rise Scenario		Term
1	0.8 feet + annual storm	Near
2	0.8 feet + 20-year storm	Near
3	1.6 feet + 20-year storm	Medium
4	3.3 feet + 100-year storm	Long
5	6.6 feet + 100-year storm	Long

** C-SMART reports are accessible at https://www.marincounty.org/depts/cd/divisions/planning/csmart-sea-level-rise/csmart-publications-csmart-infospot*

The 2018 state guidance on sea-level rise now provides future sea-level rise projections for varying levels of risk aversion from the updated 2018 State guidance (see Table 2 below). Risk aversion can be considered the inverse of risk tolerance.

Given the extensive coastal housing development present along Stinson Beach, this study utilizes the sea-level rise projections for **medium-high risk aversion**. This risk aversion projection (corresponding to a 1-in-200 chance of sea-level rise exceedance) is appropriate since the underestimation of sea-level rise hazards could have high consequences for the Stinson community (State guidance recommends medium-high risk aversion projections for community-scale sea-level rise planning and analysis). For comparison, decisions made for an unpaved coastal trail could have a low risk aversion while decisions regarding a coastal power plant or wastewater facility would exercise extreme risk aversion. Further descriptions of sea-level rise scenarios and discussion of risk aversion can be found in the State guidance.

TABLE 2
SEA-LEVEL RISE PROJECTIONS FOR SAN FRANCISCO IN FEET (CALNRA & OPC 2018)

Year	Low Risk Aversion (16% probability of exceedance)	Medium-High Risk Aversion (0.5% probability of exceedance)	Extreme Risk Aversion (no probability calculated)
2030	0.5	**0.8**	1
2040	0.8	**1.3**	1.8
2050	1.1	**1.9**	2.7
2060	1.5	**2.6**	3.9
2070	1.9	**3.5**	5.2
2080	2.4	**4.5**	6.6
2090	2.9	**5.6**	8.3
2100	3.4	**6.9**	10.2

Probabilistic Projections (based on Kopp et al. 2014) are associated with high emissions scenario.

Note that the underlined Medium-High Risk Aversion values from the updated 2018 state guidance in Table 2 are similar to the C-SMART values for 2030 (0.8 feet), 2050 (1.9 feet = ~1.6 feet), 2070 (3.5 feet = ~3.3 feet) and 2100 (6.9 feet = ~ 6.6 feet). The similarity of the most recent California sea-level rise projections in Table 2 and C-SMART Vulnerability Assessment scenarios in Table 1 allow this project to be compatible with both. The proposed scenarios for this study are listed in Table 3.

Note that State guidance does not include the episodic increases in water levels associated with El Niños, King Tides or other storm surges and waves. State guidance does recommend consideration of extreme events. Extreme storm events, although infrequent are very important for Stinson; the community may appear safe and stable to a visitor today given its wide beaches but the risks that extreme storm events pose to the community are significant. Therefore, climate scenarios were chosen so that adaptation alternatives can be evaluated over time considering the long term progression of tides and shoreline erosion as well as extreme storm events. Table 3 lists the proposed climate scenarios for this study including the approximate timing of sea-level rise associated with the low and med-high risk aversion projections as defined by the Ocean Protection Council (OPC). The scenarios represent the average conditions (no storm) and 20-year storm conditions at existing and two future sea levels (1.6 and 3.3 feet sea-level rise).

TABLE 3
CLIMATE SCENARIOS PROPOSED FOR STINSON BEACH NATURE-BASED ADAPTATION FEASIBILITY STUDY

Scenario	Storm	Sea-level rise	Timing (by Risk Aversion)[1]
1	no storm[2]	0.8 feet (25 cm)	2040 low / 2030 med-high
2	20- year storm		
3	no storm	1.6 feet (50 cm)	2064 low / 2045 med-high
4	20- year storm		
5	no storm	3.3 feet (100 cm)	2098 low / 2068 med-high
6	20- year storm		

[1] *Timing interpreted from low and medium-high risk aversion sea-level rise projections in CalNRA & OPC 2018.*

[2] *Average conditions without storm impacts (regular tidal inundation and long term erosion)*

We note that many planning studies identify the 100-year storm as the "benchmark" event for evaluation. C-SMART included the 100-year for longer term planning (that is, with higher sea-levels), as shown in Table 1. For this study, we propose to focus on the near- to mid-term for design criteria and consider a 20-year coastal storm in addition to average conditions. Potential impacts from a 100-year coastal storm event are described in subsequent analysis task, but this study's evaluation and the ultimate feasibility of each nature-based adaptation alternative will focus on the 20-year storm. Such a storm is more likely to occur within the expected functional timeframe for nature-based adaptation and we anticipate that a 100-year storm would overwhelm the alternatives examined in this study (pending further analysis). Longer term vulnerabilities to sea-level rise and storms are addressed in terms of future potential adaptation pathways that may stem from the preferred alternative(s) analyzed in this study. Existing 100-year exposure is indicated by the FEMA flood hazards maps. The 1983 El Nino conditions provide another indication of a severe event and is often used as surrogate for events on the order of 100-year recurrence, although Ecker and Whelan (1984) estimated the 1982-83 El Nino to be a 10- to 12-year recurrence event at Stinson. Griggs and others (2005) report that severe damages occurred to homes and infrastructure in 1977-78, 1982-83 and 1997-98 El Nino winters. The USGS CoSMoS modeling also selected "storm" conditions for hazard mapping, which was considered in C-SMART. ESA will select a severe storm condition for analysis after consultation with the County and a review of these candidate sources.

2. Adaptation Evaluation Criteria and Thresholds

This section describes the various criteria that are used to evaluate adaptation alternatives, establishes a basis for adaptation thresholds relevant to nature-based adaptation at Stinson Beach based on existing guidance and reference sites, and proposes site-specific adaptation thresholds for each Stinson study reach. The adaptation thresholds are further refined during modeling of the adaptation alternatives in the next project task.

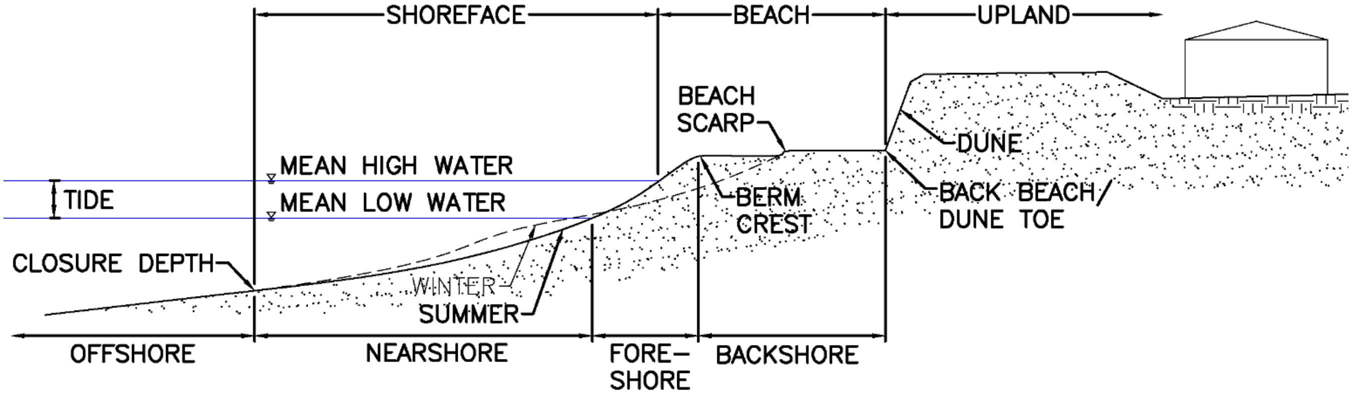
Section 2.1 develops a framework for establishing evaluation criteria and adaptation thresholds for Stinson Beach, using background on beach morphology and relevant adaptation guidance recently published by California, and prior work from the C-SMART program. Section 2.2 summarizes the information derived from other coastal locations with natural features, called reference sites. Section 2.3 summarizes existing shore geometry and geomorphic parameters pertinent to natural infrastructure. In Section 2.4, evaluation criteria are described along with preliminary reach-specific adaptation thresholds to be used in this Feasibility Study.

2.1 Framework

Adaptation by definition is a process of change. In the context of coastal hazards and sea-level rise, the thresholds that trigger adaptation actions are based on the progression of coastal flooding, inundation and erosion hazards in relation to shoreline assets (e.g. development). Evaluation criteria are the specific parameters (e.g. beach width, wave run-up elevation) used to analyze the adaptation alternatives in this project. The evaluation criteria were selected to articulate the specific shore morphology at Stinson Beach and enable a thorough analysis of the potential impacts from sea-level rise and storms. Thresholds were established for certain criteria to time the maintenance needs for each alternative and evaluate its overall feasibility. A range of adaptation measures and other concepts such as thresholds are discussed in the C-SMART Adaptation Report and Appendix B (ESA 2016).

2.1.1 Beach Morphology

A typical beach profile is shown in Figure 1, labeled with features that define a beach and determine its morphologic responses (i.e. erosion, migration) to physical forces (e.g. high ocean levels, sand supply, storms, sea-level rise). The profile is labeled for the typical summer/fall condition when the beach is widest, showing a beach scarp from a typical prior winter shoreline configuration (dashed line). The profile is similar to existing conditions in the Patios Reach where there are foredunes between the development and beach. As described in the Existing Conditions memo, the backshore along Stinson Beach study area is a mix of foredunes, shore armor and back beach/upland development. The pre-development shore was sparsely vegetated low dunes except at the western end (now Seadrift) which was likely an over-washed and dynamic sand spit. The concept of beach morphology illustrated in Figure 1 was applied to determine existing and future beach widths and the potential locations of dunes and cobble berms considered in this project.



SOURCE: ESA

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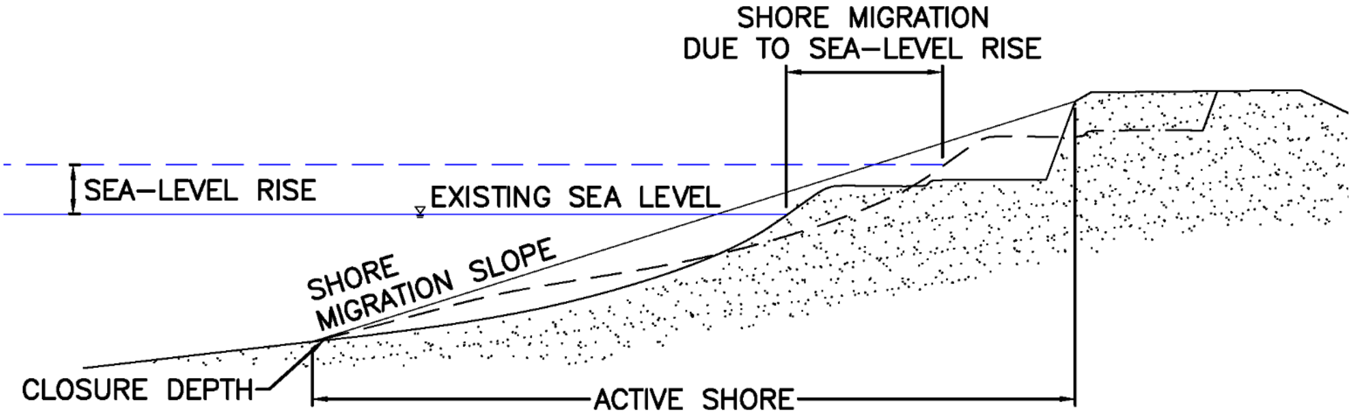
Figure 1
Typical Beach Profiles and Morphologic Features

Reach-specific evaluation criteria used to evaluate adaptation alternatives in this study are based on physical shore parameters shown in Figure 1 (e.g. beach and dune width, foreshore and overall profile slope) as well as physical forcing from the ocean (sea-level rise, storm surge and wave run-up). Sea-level rise and will have a long-term effect on the shore profile, determined for this study by the slope of the active shore. As shown in Figure 2 below, the active shore extends from the closure depth to the backshore-upland transition. In the case of Figure 2 (similar to Patios and NPS reaches), this includes the existing foredunes that can supply sand to the migrating beach. For existing conditions at Seadrift and Calles reaches, the active shore ends at the back of the beach where rock revetment (Seadrift) and beach-top development (Calles) are non-erodible. In these locations, the shore migration slope is flatter in comparison to the reaches with erodible dunes. The flatter migration slope as well as non-erodible armoring will lead to faster beach loss with sea-level rise. By implementing natural infrastructure such as foredunes the effective shore migration slope can be steepened, thereby reducing the lateral movement of the shore due to sea-level rise. Coastal storm impacts will also be evaluated based on the profile slopes as described in Section 2.4.



SOURCE: ESA

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Figure 2
Erodible Dune-Beach Profile Migration with Sea-Level Rise

The criteria used to evaluate adaptation alternatives are described in the context of existing conditions at Stinson Beach. Adaptation thresholds are established for some of these criteria to determine the timing of maintenance actions and potential future adaptation pathways.

2.1.2 Relevant Studies

The adaptation criteria and thresholds established for Stinson Beach build on local planning and regional guidance documents. This section summarizes relevant information from the Marin County Sea-level Rise Adaptation Report and State guidance on natural infrastructure. Selected adaptation criteria and proposed thresholds for Stinson Beach are discussed in Section 2.4.

C-SMART Sea-Level Rise Vulnerability and Adaptation Studies

This section summarizes key findings and recommendations from the C-SMART Sea-level Rise Vulnerability Assessment and Adaptation Plan as they pertain to Stinson Beach. The overall vulnerability of the Stinson community to sea-level rise is important to this feasibility study because the timing of other adaptation measures (e.g. to address flooding from Bolinas Lagoon and Easkoot Creek) may influence feasibility of natural infrastructure on the beach. ESA reviewed the coastal hazard maps developed for C-SMART Sea-level Rise Vulnerability Assessment (2016) with respect to each study reach so that nature-based adaptation along the Pacific shoreline can understood in the context of overall community vulnerabilities to climate change and sea-level rise. This will enable a more informed feasibility assessment and identification of potential adaptation pathways for the Stinson community.

The amount of sea-level rise that leads to exposure in each study reach is summarized in for three types coastal hazards: coastal storm event flooding, long term erosion and long term tidal inundation. The sea-level rise exposures correspond to a baseline condition where no intervention is taken and do not consider existing coastal armoring in order to fully understand the potential vulnerabilities. Similarly, FEMA flood hazard maps for this area conservatively assume a failed condition of the revetment at Seadrift. The sea-level thresholds correspond to when action must be taken to mitigate hazard impacts. Note that nature-based infrastructure along the Pacific coastline does not address tidal inundation and storm flooding impacts from Bolinas Lagoon and Easkoot Creek, these flood sources are described in the context of future adaptation pathways but not explicitly analyzed in this study.

TABLE 4 COASTAL HAZARD EXPOSURES WITH SEA-LEVEL RISE FOR STUDY REACHES

Reach	Coastal Storm Flooding, source	Long-Term Coastal Erosion	Tidal Inundation
Seadrift	0 to 1.6 ft (0 to 50 cm), wave run-up/lagoon	1.6 to 6.6 ft (50 to 200 cm)	4.1 ft (125 cm)
Patios	10 in (25 cm), lagoon	3.3 to 6.6 ft (100 to 200 cm)	1.6 ft (50 cm)
Calles	0 in, wave run-up	3.3 ft (100 cm)	1.6 ft (50 cm)
NPS	10 in (25 cm), wave run-up/overtopping	6.6 ft (200 cm)	> 6.6 ft (>200 cm)

Sea-level rise exposure determined from C-SMART coastal hazard zones for inundation and flooding (USGS/OCOF) and erosion (ESA)

Due to the low-lying nature of the sand spit that comprises the study area, at some point nature-based adaptation along the beach will not be enough to fully protect the Stinson community against the rising sea-level. In addition to impacts from wave-driven flooding and erosion on the Pacific coastline, the community is also at risk to tidal inundation and storm surge from Bolinas Lagoon as well as storm flooding from Easkoot Creek. Higher sea-levels may overwhelm the protection afforded by constructed natural infrastructure on the Pacific shoreline. Therefore, additional adaptation actions for areas outside of the backshore can be expected with as little as 2 feet of sea-level rise. The adaptation alternatives analysis will describe potential future adaptation pathways that may apply to these areas but does not explicitly analyze their feasibility.

Building on the Vulnerability Assessment, the Marin Open Coast Sea-Level Rise Adaptation Report (C-SMART 2018) establishes an adaptation framework for coastal adaptation in Marin County and describes various adaptation strategies that could be implemented at Stinson Beach. Given the beach's natural and recreational values to local residents and visitors, a preferable adaptation approach for Stinson Beach includes measures to preserve the beach. This feasibility study takes the County and Stinson community one step closer to smart sea-level rise adaptation by analyzing nature based adaptation. Specific adaptation thresholds were developed for beaches in the Stinson community in general. Relevant thresholds are summarized in Section 2.4 along with proposed thresholds for this study that account for the various shore conditions in each reach. The following beach width adaptation thresholds were identified in C-SMART (ESA 2016) and provide a general basis for this study:

- **Maintenance threshold, plan for action**: Fall season beach width of 80 feet or less; and,
- **Adaptation threshold, take action**: Fall season width less than 25 feet.

The fall season was selected because this is when the beaches are typically their widest with less variation year-to-year than in the winter months when conditions can change markedly within a day. While most people use the beach during the summer, a fall beach width is the appropriate reference condition for the purpose of implementing natural infrastructure. Natural infrastructure features would likely be constructed in the fall, outside of summer peak recreation season but at a time of year when beaches are widest for constructability (pending any environmental restrictions). Conceptually, a fall beach width of 80 feet is manageable relative to the average seasonal change of 40 to 120 feet at Stinson computed for this study, and may therefore be adequate for a winter season and storm induced erosion for moderate winters. However, a fall beach width of 25 feet will likely result in a near "zero" beach width by Spring and potential upland erosion and damages to development, hence spurring adaptation actions such as dune construction. Actual seasonal and event-induced beach width changes are quite variable and respond to multiple forcing parameters.

A planning level geomorphic analysis for C-SMART developed the following risk-based beach width thresholds based on a coastal storm erosion event that could occur every two to five years (see Table 5). If a beach width narrows to the point where coastal storm erosion exceeds the beach width, backshore development may be damaged. The beach width thresholds in Table 5 do not explicitly consider ecological function or recreation, which are important considerations in this feasibility study.

TABLE 5. RISK LEVELS FOR VARYING BEACH WIDTH.

Excess Beach Width W (feet)	Risk Level
W > 50	Low
50 > W > 33	Medium
33 > W	High

Stinson Beach width adaptation thresholds based on C-SMART can be interpreted here as:

- Target beach width minimum is 130 feet, measured in the Fall season;
- Maintenance triggered when fall beach width less 80 feet; and,
- Immediate action needed when beach width is less than 50 feet.

Along with natural infrastructure guidelines developed for the state and reference site geometry, these adaptation thresholds form a basis for site-specific thresholds described in Section 2.4.

Note that this feasibility study does not propose beach nourishment (widening) via placement of sand below the MHW line because the existing beaches are fairly wide along most of the study area, allowing adaptation measures to be taken along the backshore and upland. For this project, dune erosion will provide sand supply to reduce the extent of shore recession, and subsequent sand placement could be on the dry beach to rebuild the eroded dune, thereby avoiding sand placement in the Marine Sanctuary. Also, a cobble berm could be used to limit erosion while facilitating subsequent beach recovery. Additionally, sand placement to widen the beach beyond its existing width may increase the transport of sand to the Bolinas Lagoon inlet, may potentially have adverse effects and generally may be less effective than backshore adaptation. Finally, placement of sand in the ocean (generally below high tide) requires additional regulatory approvals and in particular is generally prohibited in the Marine Sanctuary offshore. However, alternatives could include beach nourishment that places sand on the back shore (above and landward of the beach face) to limit impacts to the nearshore. This study will address beach widening (sand placement, beach nourishment) as a longer-term adaptation action, consistent with future projections of very narrow beaches in response to sea-level rise.

Natural Infrastructure Guidance for California

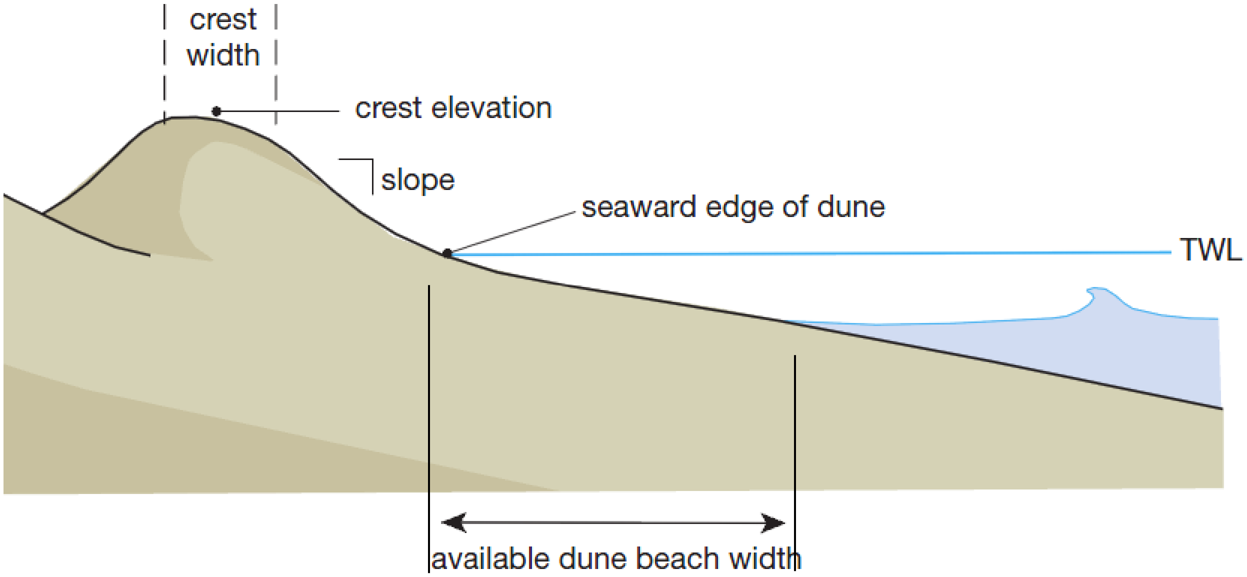
The State of California recently funded development of guidelines for use of natural infrastructure, including cobble berms and dunes, to mitigate coastal erosion and flood hazards (TNC and others 2018; ESA and others 2018). The resulting documents provide good starting points for developing adaptation thresholds. Adaptation thresholds can also be related to dimensions measured at reference sites with desired morphology. Dimensions can be tested using analysis of erosion and wave run-up hazards to assess the ability of the feature(s) to protect upland assets against sea-level rise and storms.

The following schematics developed by ESA for managing shoreline change in California show the characteristic dimensions for two natural shoreline infrastructure types that are assessed for this study: vegetated sand dunes and cobble berms. Natural vegetated sand dunes are located landward of the typical wave run-up zone, where the plants have time to establish and grow (Figure 3, Figure 4). Cobble berms (Figure 5) are typically farther seaward and in the zone of wave run-up during periods of elevated waves and water levels (i.e. storms). Note that the cobble berm in Figure 5 is shown covered by a sandy beach and shore, which is representative of a mild wave climate consistent with the summer-fall seasons. On sandy shores, natural cobble berms are typically covered by sand in the summer and fall when waves are smaller and may be exposed in the winter when larger waves move the sand offshore to form sand bars (as illustrated in Figure 1). During extreme conditions, wave run-up may overtop the crest and reach uplands and/or development. Engineered versions of dunes and cobble berms may locate these features farther seaward to limit erosion and preserve the landward beach and dune space. An example is the use of sand to bury rock armor at Seadrift; a similar approach with a cobble berm buried with sand could be employed with the understanding that extreme conditions will erode the dunes. Hence, when using natural shore infrastructure, it is helpful to understand the natural geometry and processes (aka geomorphology) and the degree to which development constrains the geomorphology and thus degrades the performance of natural infrastructure (reduced functional life, increased maintenance requirements, increased disturbance and reduced ecology and access benefits). The Natural Infrastructure Guidance report documents standard minimum design criteria for effective natural infrastructure implementation on open and sheltered coasts. Open coast dunes and cobble berm minimum design dimensions are shown in Figure 4 and Figure 5 and described in Section 2.4 along with specific recommended adaptation thresholds for each study reach.

The desired minimum beach width fronting dunes is on the order of 100 feet according to the concept-level parameters outlined in the Natural Infrastructure Guidelines (TNC and others 2018). This width was selected for dune sustainability, in terms of limiting wave-induced erosion while maintaining a dry beach for wind-blown sand supply (dunes naturally grow with help of onshore winds that blow sand off the dry beach which settles within vegetated areas). While this current study’s Existing Conditions assessment (ESA 2020) has found that natural dune accretion is limited at Stinson Beach, the utility of maintaining wide dunes to reduce storm erosion and wave run-up reduction remains important.

The Natural Infrastructure Guidelines indicate the following geometries for dunes and cobble berms, and associated beach widths that may be sustainable at Stinson Beach:

- Sand dune footprint width of at least 50 feet;
- Dune-fronting beach widths of at least 100 feet recommended; and,
- Cobble berms of at least 50 feet (top width).



SOURCE: TNC & ESA

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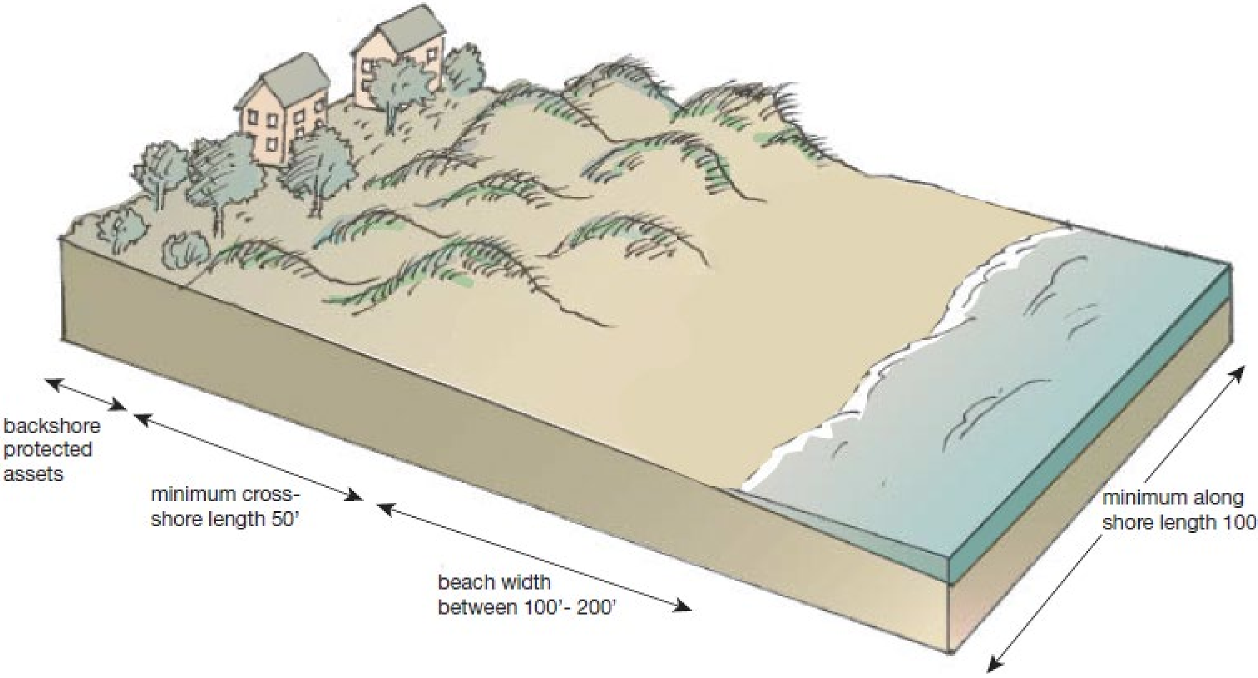
Figure 3
Conceptual dune cross section.
TWL refers to total water level which is the elevation of wave run-up that is seaward of stable dunes under typical conditions



SOURCE: TNC & ESA

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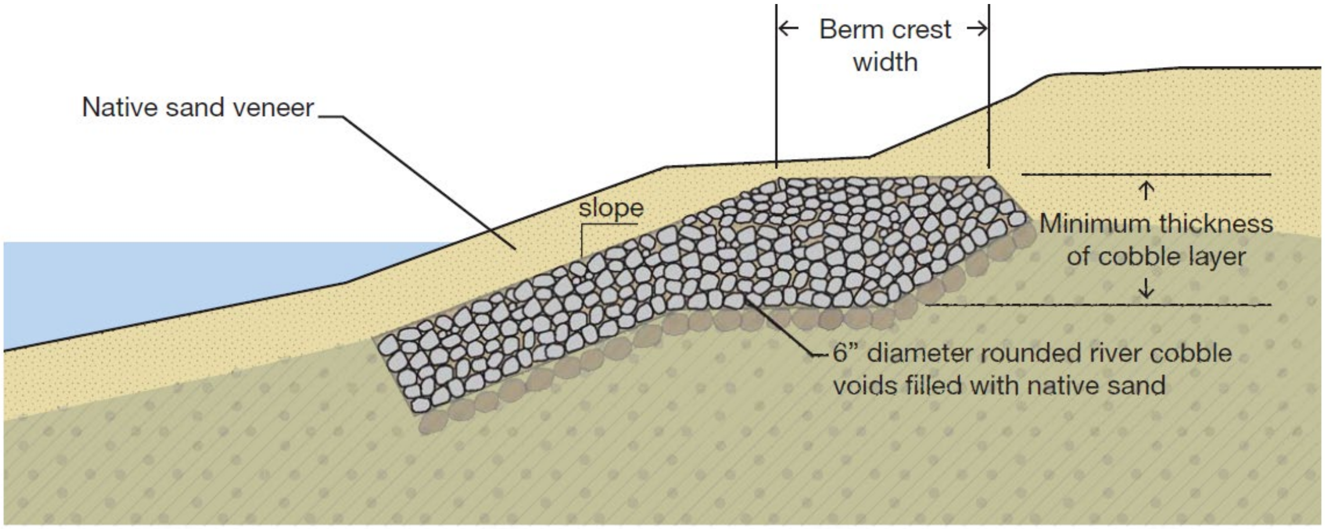
Figure 4
Oblique conceptual dune schematic showing the preferred location of development landward of beach-dune natural infrastructure that allows adequate space to support natural geomorphology that provides access and ecology benefits



SOURCE: TNC & ESA

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Figure 5
Conceptual cross section of a cobble berm located relative to ocean water levels and shore during typical conditions

2.2 Characteristic Dimensions of Natural Features at Reference Sites

As described in this study's Existing Conditions assessment (ESA 2020), reference sites provide important context for adaptation criteria and thresholds. Table 6 below lists typical shore dimensions at the four closest reference sites to the study area. Dunes at the Stinson NPS parking area, Limantour Beach and Doran Beach each indicate a stable dune form of approximately 100 feet wide and 10 to 15 feet above the fronting beach. Steep Ravine, located southeast of the Stinson Boulders, is a small cove with a cobble beach berm that is covered intermittently by a sandy beach. This local example indicates that wave action naturally builds up the cobble in this location to approximately 15 feet NAVD, based on available LiDAR data. This example cobble berm represents an upper limit of the design criteria for this study since this location is more exposed to wave action than the rest of Stinson Beach.

TABLE 6
REFERENCE SITE CHARACTERISTIC DIMENSIONS

Reference Site	Backshore Feature	Fronting Beach Elevation (feet NAVD)	Fronting Beach Width (feet)	Feature Width (feet)	Feature Elevation (feet NAVD)
Stinson NPS	Dune	10 to 12	250 to 260	80 to 100	20 to 25
Limantour	Dune	10 to 13	180 to 200	100 to 150	22 to 27
Doran	Dune	8 to 10	170 to 190	100 to 200	18 to 19
Steep Ravine	Cobble Berm	n/a	n/a	40	15 to 16 (crest)

Characteristic dimensions were determined from 1997, 1998, 2015, 2016 and 2018 LiDAR data.

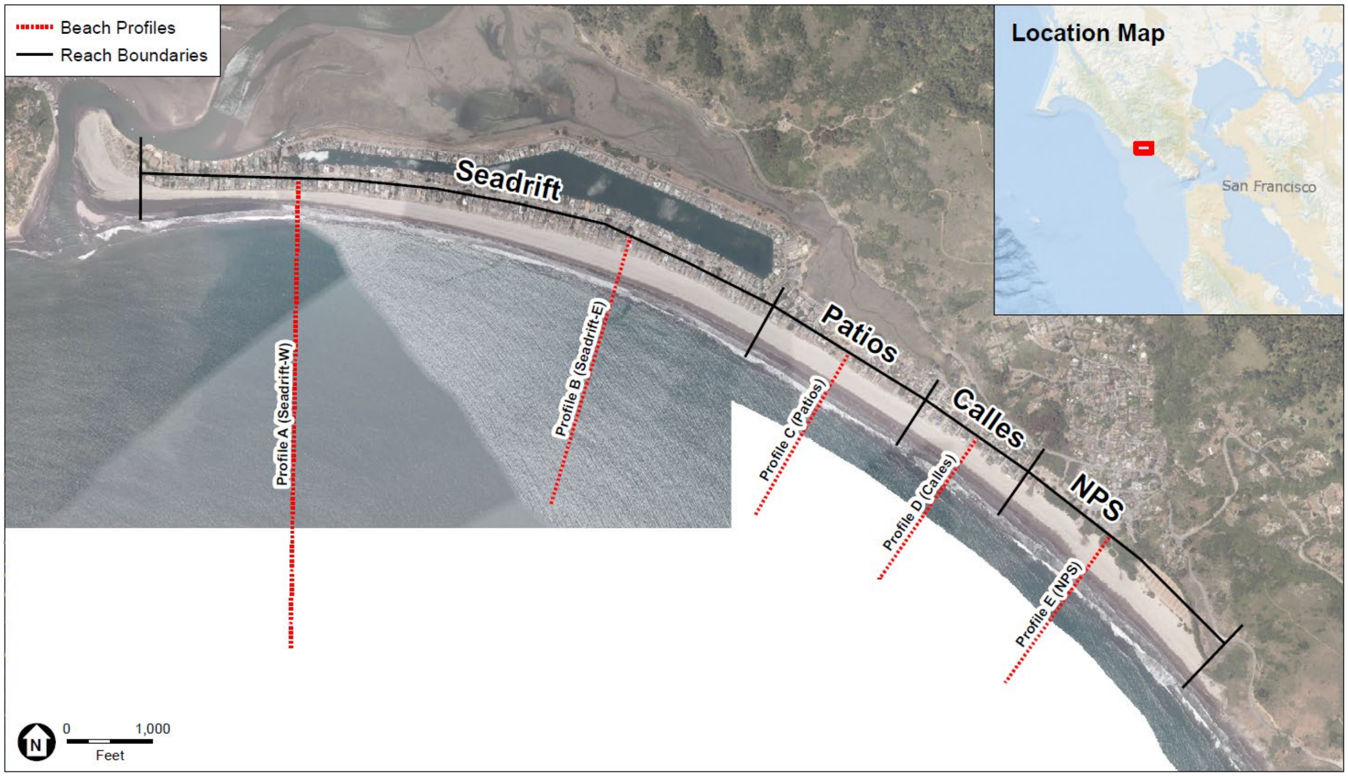
In summary, reference sites indicate potential geometries for dunes and cobble berms, and associated sandy beach widths:

- Sand dune footprints of 80 to 120 feet with crest elevations of 18 to 27 feet;
- Beach widths fronting the dunes between 170 and 260 feet; and,
- Cobble berm top widths of about 40 feet.

2.3 Existing Beach Characteristics at Stinson Beach

Existing conditions and historic trends at Stinson Beach establish the baseline from which adaptation alternatives can be modeled and evaluated for feasibility (see Study Memorandum 1, ESA 2020). Beach dimensions indicate the amount of space that is available today to construct natural infrastructure. Observed shoreline changes, beach elevations and slopes can be used to estimate future beach widths and space available for natural infrastructure.

Table 7 summarizes beach characteristics from a beach profile selected to represent each of the five study reaches at Stinson Beach. The Reach characteristics were developed from historical data, field measurements taken in the October 2019 (presented in the Study Memorandum 1: Existing Conditions, ESA 2020), and a calculation of the beach migration due to sea-level rise based on the shoreface geometry (explained below). These characteristics help us to define the adaptation thresholds as described in Section 2.4. Figure 6 below shows the study reaches and analysis profile locations for reference.



SOURCE: ESA, Marin County 2018 Imagery, ESRI

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Figure 6
Stinson Beach Study Reaches and Analysis Profiles

TABLE 7
BEACH CHARACTERISTICS AT ANALYSIS PROFILE LOCATIONS

Profile Location	Distance from Beach to Development (feet)	October 2019 Beach Width (feet)	Average seasonal shoreline change envelope (feet)	Extreme winter shoreline change envelope (feet)	Winter beach width, minimum to average (feet)	Shore Face Slope (from depth of closure to backshore / dune crest)	Shoreline Recession Potential (feet recession per foot sea-level rise)	Beach sea-level rise capacity (winter beach width – shore recession potential) (feet sea-level rise)
Seadrift W	0 (60) [1]	103	76	85	18 to 27	0.016 to 0.3 [2]	32 to 64 [2]	0 to 1
Seadrift E	0 (100) [1]	214	118	140	74 to 96	0.029	35	2 to 3
Patios	90	250	71	151	99 to 179	0.035	29	3 to 6
Calles	0	235	51	158	77 to 184	0.032	31	2.5 to 6
NPS	250 [3]	264	43	136	128 to 221	0.036	27	4.5 to 8

[1] Distance to homes reported in parentheses; distance from beach to rock revetment is zero feet at both Seadrift profiles.
[2] Seadrift west shore profile intercepts the Bolinas lagoon ebb shoal.
[3] Distance to parking lot; distances from back of beach to NPS buildings are 50 to 80 feet

Distance from Beach to Development – The typical distance from the 2019 surveyed back of beach to landward development (shore armoring, homes/buildings, parking lot, or road). Distances reported in Table 6 are at the specific profile location; distances vary within each reach. This distance in combination with beach width provides the available space for natural infrastructure.

October 2019 Beach Width – The beach was surveyed in the fall when beaches are expected to be their widest at Stinson Beach. The October 2019 beach width was wider than typically observed based on a review of aerial photographs and shoreline data, and hence indicates an optimistic assessment of available space. Constructing natural infrastructure such as dunes and cobble berms requires space, and this requirement must be balanced by the need to maintain adequate beach widths to support recreation and ecology, as well as allowing sufficient beach width to dissipate waves and wave run-up. These existing beach widths inform our study by establishing the baseline from which to project and analyze the adaptation alternatives.

Trends in shore position change – Trends in shore change are typically computed as the average change in position over many years. Because the shore line position changes continuously in response to a range of variable drivers (tides, waves, sand supply), the average shore position change is an approximate calculation dependent on the time period over which the average is computed. As summarized in Table 7, the average changes computed were less than a foot per year since the 1920s while beach accretion (seaward movement of the shore) was computed since 1990. The overall shore change trend in the project area is considered to be small (between -0.1 to +0.2 feet per year) relative to natural variability and calculation uncertainty, and for practical purposes a zero long-term change rate is selected as a baseline for evaluation.

Average seasonal shoreline change envelope – Aside from long term trends in erosion or accretion, shoreline location fluctuates between its seaward-most position in the late summer/fall to its landward-most position in the late winter/spring. The average seasonal shoreline change envelope was computed from available shorelines collected for this study, for each reach at Stinson.

Extreme winter shoreline change envelope – Stinson Beach has experienced its share of extreme winters in the last few decades. The available shoreline data provide examples of the extreme shoreline change that occurred over the 1998-1999 and 2015-2016 El Nino winters. These shoreline erosion distances provide an indication of the potential cumulative effects of an extreme winter on the shoreline positions along Stinson Beach. Similar to the values in Table 6, extreme winter shoreline erosion of most of the dry beach occurred in the 1977-78 and 1982-83 El Nino winters, followed by construction of rock revetment shore protection along Seadrift (Ecker and Whelan 1984; Griggs and others 2005).

Winter Beach Width – The range of beach widths for existing conditions was calculated by subtracting the extreme and average beach widths from the October 2019 beach width. As noted above, the October 2019 beach is considered abnormally wide and hence the computed winter beach width is also considered abnormally wide. The result is a range of beach widths that can be expected in the winter-spring seasons, by Reach, each likely a maximum width. This beach width is an indication of exposure to backshore flooding and erosion damages: A wider winter beach provides greater protection to the back shore from waves, while a narrower beach is an indication of damage risk. This winter beach width is used to compute the sea-level rise capacity, discussed below.

Shore Face Slope – The Shore Face is defined schematically in Figures 1 and 2, and the overall slope of this zone of active wave-driven sand transport is used to estimate the shore response to sea-level rise. This slope characterizes the active shore profile that experiences the forces of the ocean. The shore face extends from the backshore/upland transition (edge of dune or development) out to the (depth beyond which the shore profile does not change appreciably year-to-year (closure depth)). The shore face slope is used in coastal engineering to estimate the landward shoreline recession potential due to sea-level rise (Bruun 1964), discussed below. Field data collected for this project and existing bathymetric (seafloor elevation) data were used in estimating the shoreface slope (see Study Memorandum 1: Existing Conditions, ESA 2020). Note that Seadrift West shore is adjacent to the ebb tidal shoal (sand bar formed by falling tides) of the Bolinas Lagoon mouth, resulting in a flatter profile slope relative to the other shore profiles. For the purposes of this study, a shore face slope of 30:1 (horizontal:vertical) is selected, indicating that the shore can be expected to migrate about 30 feet landward for each foot of sea-level rise, and rise vertically with sea-level rise. This shore migration calculation is approximate, is predicated upon assumed adequate sand supply and sufficient wave energy to keep up with sea-level rise, assumes that wave exposure and sand transport are steady, and neglects seawalls.

Shoreline Recession Potential (with sea-level rise) – An important factor in the feasibility of nature-based adaptation at Stinson Beach is the amount of sea level rise that the design infrastructure can cope with. Nature-based solutions require space to be effective, and sea level rise can have a significant impact on the shoreline location and beach width. As indicated in Table 7, as little as 2 feet of sea level rise could all but eliminate beaches at Seadrift West while beaches at other reaches may persist longer.

Beach Sea-level Rise Capacity – The approximate amount of sea-level rise that can be accommodated while still having a beach at Seadrift and Stinson is provided in the last column in Table 7. The amount of sea-level rise that will result in complete loss of the winter beach is computed by dividing the winter beach width by the shoreline recession potential. The Seadrift reach is the least sustainable with a capacity of between 0 and 3 feet of sea-level rise. The Patios and Calles reaches have a capacity of 2.5 to 6 feet, and the NPS reach has a capacity of 4.5 to 8 feet. Note that backshore damages by waves can occur well before the beaches completely disappear, and the capacity to accommodate sea-level rise is used here in the context of available space for natural. The existing dunes at the Patios and NPS reaches are neglected even though the additional sand supply would be expected to reduce the shore migration.

Prior C-SMART analysis indicated the Seadrift beach widths would be lost with about 3.3 feet of sea-level rise (1 meter) and the remainder of the Stinson beaches would be lost with about 6.6 feet of sea-level rise (2 meters), based on the OCOF scenarios (ESA 2015). The results presented in Table 7 are more detailed and rigorous but generally consistent with the prior beach vulnerability assessment.

2.4 Stinson Beach Nature-Based Adaptation Evaluation Criteria and Adaptation Thresholds

The nature-based adaptation alternatives are developed using criteria linked to beach morphology and the proximity of the developed backshore, for each study reach. Evaluation criteria for beach width, dune width, cobble berm width and wave run-up intensity are described below. When conditions violate the criteria, e.g. the beach width is less than the criterion value, the feasibility of the natural infrastructure type becomes uncertain. When future conditions result in a violation of criteria, a threshold for adaptive action is reached. Here, we develop criteria by reach for existing and future conditions in order to support formulation of alternatives, and to serve as a foundation for feasibility analysis of alternatives.

Criteria and thresholds proposed in this section are based on relevant guidance, reference sites, and the shore dynamics at Stinson Beach, as well as the sea-level rise scenarios presented above.

At this stage of the project, these criteria are focused on the sustainability of the natural infrastructure types under consideration, in order to formulate alternatives for subsequent analysis. The criteria presented here may be refined and additional design criteria and adaptive thresholds may be developed based on analysis of the alternatives and public engagement.

2.4.1 Sea-level Rise

For the purpose of the adaptation alternatives evaluation in this study, sea-level rise amount is the independent variable with which the evaluation criteria described here are analyzed in addition to storm impacts (see Section 1). The results of this feasibility study will include updated, site-specific sea-level rise thresholds for future adaptation at Stinson Beach based on the evaluation of criteria described below. It is important to note that nature-based adaptation along the Pacific shore can only addresses a portion of overall adaptation needs of the Stinson-Seadrift community: Other adaptation measures are needed to address flood impacts from Easkoot Creek and Bolinas Lagoon with sea-level rise (see community-wide sea-level rise thresholds summarized in Section 2.1).

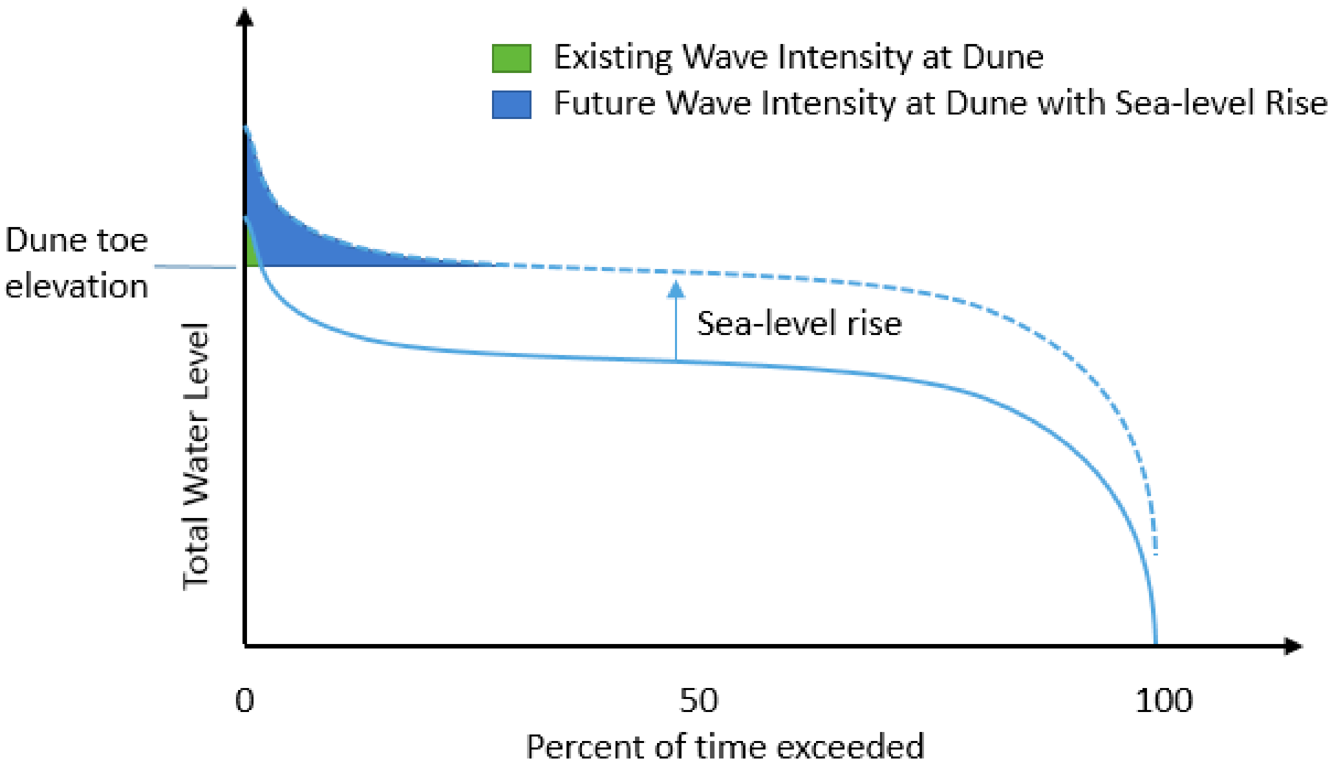
2.4.2 Wave Run-up Intensity

Wave run-up intensity are used to evaluate the performance of dune and cobble adaptation measures at Stinson Beach and establish thresholds for maintenance and further adaptation actions. While wave run-up and associated onshore sand transport are constructive processes that formed the Stinson shore, extreme wave run-up is the driver of flooding and erosion risk to backshore development that will increase with sea-level rise.

The action of wave run-up and overtopping has influenced the formation and evolution of the Stinson sand spit over time. A geomorphic interpretation is that the Stinson–Seadrift landform is a littoral spit that was likely reinforced by sand delivered by wave run-up and overtopping. Prior studies have also identified that the landform is likely to settle following strong seismic events, and requires sand from the ocean to rebuild (PWA 2006, Alt & Hyndman 1975, Alt & Hyndman 2000). Nature-based types perform best when sited to accommodate and survive, at least partially, extreme coastal storm events while providing protective services to the backshore. For the adaptation alternatives evaluation, wave run-up elevation and extent that is exceeded several times per year are used as an indicator of the seaward limit of the feature, and wave run-up intensity for the 20-year storm are used to assess dune erosion potential and protection of the backshore. Potential wave run-up intensity for the 100-year storm is analyzed but it will not inform the maintenance scheduling of nature-based adaptation alternatives in this study.

One way to evaluate the intensity of wave run-up is to identify the extent and frequency of wave run-up reaching a particular location such as a dune or development. The intensity of wave run-up can then be quantified as the extent that it crosses a point defined relative to the sea in horizontal distance and elevation. This concept was developed for the California Coastal Resilience projects as conceptually depicted in Figure 7 to predict erosion of dunes, bluffs and beyond coastal structures, as well as to predict run-up overtopping of natural and man-made barriers and associated inland flooding. The cumulative distribution of total water level (TWL = ocean level plus wave run-up) at a particular shore location is computed, showing the percent time that the TWL exceeds an elevation on the shore (e.g. dune toe elevation). The area of the cumulative TWL curve above the elevation is defined as the intensity of wave run-up at the selected location. This intensity can be converted to volume of water overtopping the barrier, momentum-force loadings on structures, as well as an indicator of backshore dune erosion.

Based on published guidelines (TNC and others 2018), the future location and elevation of the back beach (at the toe of the dunes) can be preliminarily projected based on total water levels that are exceeded only about 10 to 20 days per year, or exceeded about 4% of the time (conceptual diagram shown in Figure 7). Cobble berm crests are overtopped more frequently while also lowering wave run-up due to greater dissipation, and their crest elevations for active cobble-gravel berms (storm berms are higher) can be preliminary projected at an elevation of about 80% of that for a dune toe (TNC and others 2018). In order to check these general guidelines, we computed wave run-up at Stinson Beach and compared the run-up elevations to the existing dune toe elevations at the NPS Reach. Computed wave run-up at Stinson (see Study Memorandum 1: Existing Conditions, ESA 2020) for estimated winter conditions indicates the 4% exceedance is a reasonable approximation, yielding elevations ranging from 11.4 feet NAVD at NPS to 13.9 feet NAVD at Seadrift West and comparing favorably to the existing dune toe elevations at the NPS Reach (~11 feet NAVD in winter 2018, 12.4 feet NAVD in fall 2019). A preliminary estimate for cobble berm crest elevation corresponding to 80% TWL exceedance is around 6-8 feet NAVD along the study area. Pending selection of alternatives by reach and more detailed analysis of the alternatives, the Implementation Criteria and Adaptive Thresholds for dune and cobble-gravel berms are summarized in Table 8.



SOURCE: ESA

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Figure 7
Concept of wave run-up intensity at a dune as cumulative distribution of total water level

TABLE 8
PROPOSED DUNE TOE, DUNE CREST AND COBBLE-GRAVEL BERM CREST ELEVATIONS / THRESHOLDS FOR STINSON BEACH NATURE-BASED ADAPTATION

	Selected for Implementation (feet)			**Threshold for Adaptive Action (feet)**		
Study Reach	**Dune Toe Elev.**	**Dune Crest Elev.** [1]	**Cobble-Gravel Berm Crest** [2]	**Dune Toe Elev.**	**Dune Crest Elev.** [3]	**Cobble-Gravel Berm Crest** [2]
Seadrift E	10	15 to 20	8 to 10	13	n/a	7
Patios	10	15 to 20	8 to 10	12	n/a	7
Calles	10	15 to 20	8 to 10	12	n/a	6
NPS	10	15 to 20	8 to 10	11	n/a	6

1. Dune crest elevation range for fore dunes (lower elevations) and barrier dunes (higher elevation)
2. Cobble-gravel berm crest elevation can range between these approximate values.
3. Dune crest elevation threshold to be determined

2.4.3 Beach Thresholds

For this study, beach width is defined as the beach above mean high water (MHW) that extends landward to where the beach meets the edge of development, dune toe or armoring structure. Wave run-up dissipates with distance traveled over a beach, hence wider beaches result in lower wave run-up and less erosion on upland features and development. Conversely, a narrow (or absent) fronting dry beach offers little protection to uplands. Without the buffering effects of a wide beach, more wave energy reaches the uplands which results in greater run-up, erosion of dunes and bluffs, and hydrodynamic loading on coastal armoring structures. Wider beaches also provide increased recreational and ecological values. More generally, beaches are an important component of the coastal morphology at Stinson Beach.

Conceptually, a resilient beach at Stinson could accommodate seasonal changes as well as a typical coastal storm erosion event and while retaining a nominal beach width at its narrowest (spring). An important consideration when thinking about beach width is that repairs or expansions of dunes or other natural features in the future will require space on the beach to work and build the feature(s). Thus, it is prudent to maintain a minimal beach width so that after (or during) extreme winters, the ability to build/maintain natural infrastructure is maximized while limiting impacts to the intertidal beach and nearshore (a National Marine Sanctuary). As indicated in Table 7 above, average beach width at Stinson Beach has remained relatively stable in recent history but extreme coastal storms have caused significant shoreline erosion and damages to coastal development. Sea level rise could cause shoreline recession that reduces the beaches over time, further exposing development to greater storm impacts.

Existing reports and observations provide a basis for design dimensions for beaches at Stinson:

- C-SMART risk analysis described in Section 2.1 indicates a **target minimum fall beach width of 130 feet,** computed by adding the maintenance threshold width (80 feet) *plus* an excess beach width to result in low risk from severe events (50 feet).
- The California natural infrastructure guidelines suggest a minimum fronting beach width of 100 feet for nature-based adaptation measures such as dunes and cobble berms.
- Reference Sites at Stinson (NPS Reach), Limantour and Doran beaches have beaches ranging from 170 to 260 feet wide.
- Observations from the 1998 and 2016 El Ninos indicate potential shoreline storm erosion up to 220 feet.

Criteria for beach widths in each study reach are provided in Table 9 below and based on typical seasonal and extreme El Nino winter shoreline changes. The beach width considers two distances: the average seasonal shoreline change envelope plus 50 feet OR the observed extreme El Nino winter shoreline change. Beach width is modeled according to the climate scenarios described in Section 1 to determine maintenance needs and feasibility of each adaptation alternative. The proposed criteria in are used to formulate alternatives and may be refined during subsequent evaluation of alternatives.

TABLE 9
BEACH WIDTH CRITERIA / THRESHOLDS FOR STINSON BEACH NATURE-BASED ADAPTATION ANALYSIS

Study Reach	Minimum Beach Width for Implementation (feet)	Beach Width Threshold for Action, (feet)
Seadrift E	130	170
Patios	130	160
Calles	130	150
NPS	130	140

2.4.4 Dune Thresholds

Dunes provide a natural buffer to flooding and erosion landward of beaches. Dunes naturally erode during coastal storm events and over the long term as the shoreline moves landward due to natural erosion trends and/or sea-level rise. Dunes constructed for nature-based adaptation ideally would be sized to accommodate the potential erosion, wave run-up and overtopping from an extreme coastal storm event. Depending on the available space in a given area, a constructed dune would ideally be built wider than the design storm erosion distance in order to accommodate long term erosion and delay the need for reconstruction. In any case, the dune width would be tracked over time to determine when reconstruction is needed to maintain the level of protection of the dune or when a change in the adaptation pathway is warranted. To maximize protection of backshore development against coastal erosion and wave run-up, maintenance or reconstruction is needed once the dune erodes past the design storm erosion distance. Additional protection could be provided by increasing the height of the dunes or implementing other adaptation measures such as a cobble berm core or other traditional armoring at the landward side of the dunes.

Prior studies and observed conditions at reference sites provide examples of design dimensions for dune features:

- C-SMART adaptation analysis considered a linear dune 13 feet tall (above the beach) and 50 feet wide.
- The California Natural Infrastructure Guidelines suggests a minimum footprint width for dunes to be on the order of 50 feet.
- Reference Sites at Stinson (NPS Reach), Limantour and Doran beaches have dunes ranging from 80 to 150 feet wide.
- Observations from the 1977-78 winter indicate up to 90 feet of dune erosion occurred along Seadrift (Griggs et al. 2005)

Adaptation threshold distances for dunes in each study reach are provided in Table 10 below. The thresholds are based on the potential erosion distance associated with the 20-year storm. Constructed dune dimensions are determined for each Stinson Beach reach based on available space, type of dune, and wave run-up intensity and extents. These minimum thresholds are used to determine timing of additional maintenance of constructed dunes and may be refined during the alternatives evaluation analysis.

TABLE 10
DUNE WIDTH THRESHOLDS FOR STINSON BEACH NATURE-BASED ADAPTATION ANALYSIS

Study Reach	Dune Width Minimum Desired for Implementation (feet)	Dune Width Threshold for Action (feet)
Seadrift E	100	50
Patios	100	55
Calles	100	60
NPS	100	65

2.4.5 Cobble Berm Thresholds

A cobble berm can act as a soft revetment whether buried under dunes or constructed by itself. During a coastal storm event, a constructed gravel/cobble berm can buffer the backshore from flooding but not without eroding and flattening from the wave power. Thus there is a minimum amount of elevated cobble berm width that should be maintained to provide adequate protection. This threshold berm width may correspond to the potential erosion of a design storm event (e.g. 100-year wave event). For adaptation alternatives in which a cobble berm is buried and or behind vegetated dunes, this threshold would only be met once the fronting beach and dunes erode. The following berm widths are summarized from existing studies and data from a reference site adjacent to Stinson:

- C-SMART analysis selected a cobble berm with a width of 50 feet seaward of dunes.
- The California Natural Infrastructure Guidelines suggests a minimum top width of 50 feet with a crest elevation based on wave run-up that is close to but lower than that for sandy beaches without cobble, and a base width of at least 80 feet.
- An assessment of Steep Ravine indicates a dynamic cobble berm top width of about 40 feet has persisted in this cove adjacent to Stinson Beach.

These dimensions are used to assess whether there is adequate space for cobble based on existing conditions, and minimums are used for maintenance triggers or potential failure, and are hence thresholds for adaptive action. The design cobble berm geometry is determined based on available space and wave run-up exposure.

Preliminary adaptation threshold distances for dunes in each study reach are provided in Table 11 below. Constructed cobble berm dimensions are determined for each Stinson Beach reach based on available space, type of dune, and wave run-up extents, with these minimum thresholds used as triggers for adaptation on such constructed dunes.

TABLE 11
COBBLE BERM WIDTH THRESHOLDS FOR STINSON BEACH NATURE-BASED ADAPTATION ANALYSIS

Study Reach	Cobble Berm Width Minimum Desired for Implementation (feet)	Cobble Berm Width Threshold for Action (feet)
All Reaches	50 top, 80 base	30

3. Summary

Climate Scenarios used in this study (Table 3) are selected based on the prior C-SMART study and the most recent sea-level rise guidance from the State of California.

The existing shore geometry at Stinson Beach is compatible with natural shore infrastructure approaches that employ cobble berms and vegetated sand dunes, and is expected to remain compatible through at least mid-century, with the exception of the Seadrift reaches which have limited to marginal beach space available.

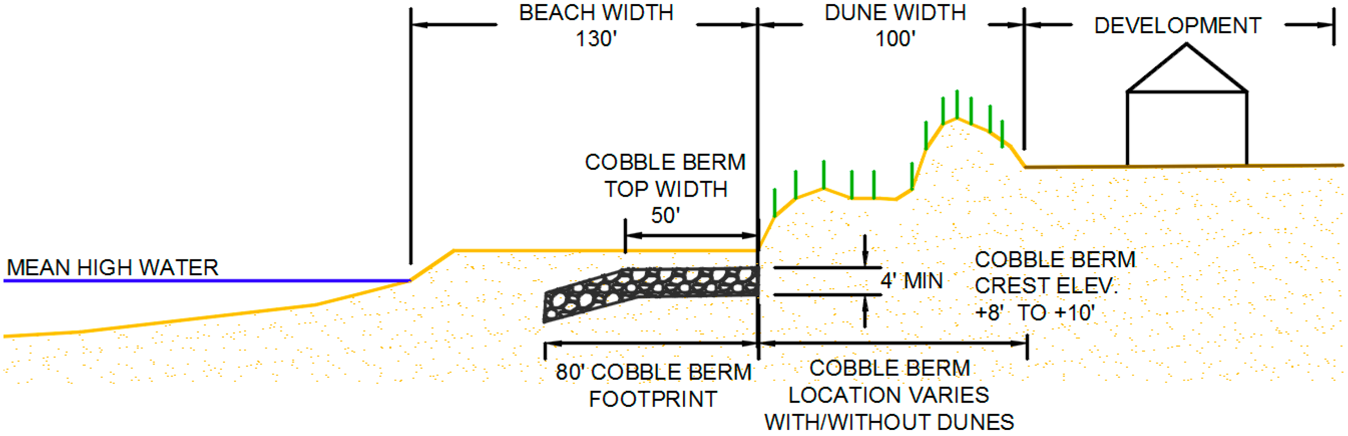
The October 2019 beach widths vary from about 100 feet to 260 feet, with development located between 0 and 250 feet landward of the back of the beach. In general, Seadrift West has the least beach width and distance to development, the Calles reach is next in terms of development setback distance, followed by the Patios reach. The NPS reach has the greatest development setback distance.

Beach widths in Seadrift are expected to narrow to essentially zero with less than 3 feet of sea level rise, with Seadrift West particularly vulnerable owing to the existing narrow beach. The Patios and Calles beaches are wide enough to persist longer, and accommodate 3 to 6 feet of sea-level rise. The NPS reach is the widest and is expected have some beach remaining with sea-levels 4.5 to 8 feet higher than now. These values are updated using recently-collected data but are similar to values reported in C-SMART (Section 2.1). In order to maintain beaches and natural infrastructure for the purpose of recreation, ecological function and hazard reduction, thresholds are established in Table 12 below.

TABLE 12
SUMMARY OF PROPOSED THRESHOLDS FOR STINSON BEACH NATURE-BASED ADAPTATION

Study Reach	Beach Width Threshold for Adaptation Action (including other natural infrastructure feet)	Dune Width Threshold for Action (feet)	Cobble Berm Width Threshold for Action (feet)
Seadrift E	170	50	30
Patios	160	55	30
Calles	150	60	30
NPS	140	65	30

The minimum desired dimensions for implementation of natural infrastructure types are provided schematically in Figure 8. These dimensions are used to select alternatives by reach.



SOURCE: ESA 2020

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Figure 8
Conceptual Desired Dimensions for Natural Infrastructure Elements at Stinson Beach

Study Memorandum 3 details the design and maintenance scheduling of natural infrastructure alternatives for each Stinson Beach study reach. The alternatives are informed by consideration of desired space (based on guidelines, reference sites and informed by Stinson shore dynamics summarized above) and the available distance between development and the shore. The alternatives are evaluated with respect to potential erosion and wave run-up for existing and future conditions with sea-level rise. Wave run-up and total water level (TWL) are computed with future sea-level rise and used to assess the function of natural infrastructure alternatives. Ultimately, benefits and relative costs of each nature-based alternative are evaluated relative to a traditional armoring approach.

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