Appendix A: Plant Palette

	Common Name	Recommended Setting
Abronia latifolia	Yellow Sand Verbena	Foredune Foreslope, Foredune, Transitional Foredune-Backdune
Ambrosia chamissonis	Beach Bur	Foredune Foreslope, Foredune, Transitional Foredune-Backdune
Amsinckia spectabilis	Seaside amsinckia	Roadside Dune Scrub Buffer
Artemisia pychocephala	Coastal Sagewort	Transitional Foredune-Backdune
Chorizanthe cuspidata	San Francisco Spineflower	Roadside Dune Scrub Buffer
Ericameria ericoides	Mock Heather	Roadside Dune Scrub Buffer
Erigeron glaucus	Seaside glaucus	Transitional Foredune-Backdune
Erigonium latifolium	Seaside Buckwheat	Transitional Foredune-Backdune
Extriplex californica	Beach Saltbush	Embryo Foredunes, Foredune
Fragaria chiloensis	Beach Strawberry	Transitional Foredune-Backdune
Lathyrus littoralis	Silvery Beach Pea	Foredune, Foredune Crest, Perched Dunes
Leymus mollis	Beach Wildrye	Foredune Crest, Foredune, Perched Dunes
Leymus pacificus x triticoides	Unknown	Transitional Foredune-Backdune
Lupinus arboreus	Yellow Bush Lupine	Roadside Dune Scrub Buffer
Lupinus chamissonis	Dune Bush Lupine	Transitional Foredune-backdune, Roadside Dune Scrub Buffer
Phacelia distans	Distant Phacelia	Roadside Dune Scrub Buffer
Poa douglasii	Douglas Bluegrass	Transitional Foredune-Backdune

Appendix B: Active Shore Zone Constraint to Dune Enhancement (ESA)

Final

SUNSET NATURAL AREAS PROJECT

Active Shore Zone Constraint to Dune Enhancement

Prepared for
San Francisco Estuary Institute (SFEI)

December 2023

In collaboration with Peter Baye. PhD and SFEI

In support of Coastal Zone Planning and the staff of
City and County of San Francisco and National
Park Service, Golden Gate Natural Recreation Area

ESA

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575 Market Street
Suite 3700
San Francisco, CA 94105
415.896.5900
esassoc.com

ESA

Atlanta	Palm Beach County	San Diego
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Oakland	Rancho Cucamonga	Tampa
Orlando	Sacramento	Thousand Oaks

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EXECUTIVE SUMMARY

This document addresses the space available for vegetated dune enhancement at Ocean Beach, San Francisco in support of the Sunset Natural Areas Project (Sunset Project) to assist the City and County of San Francisco (CCSF) and National Park Service, Golden Gate Natural Recreation Area (NPS) develop nature-based and multi-objective management actions. The project is funded by the California State Coastal Conservancy and supported by CCSF and NPS. Environmental Science Associated (ESA) is a subcontractor to the Sunset Project lead, the San Francisco Estuary Institute (SFEI) and has collaborated with Peter Bay, PhD (Baye, also a subcontractor). ESA focused on physical processes (coastal hydrodynamics, applied geomorphology and engineering) while Baye focused on bio-physical processes (botany and applied geomorphology). This report is organized into sections, which are summarized below

Introduction

The purpose of the dune component of the Sunset Project is to address enhancement of vegetated dunes at Ocean Beach, San Francisco for multiple benefits including increasing ecology as well as supporting other objectives of the land managers, CCSF and NPS. While vegetated dunes exist on the site, most of the dunes are degraded owing to several stressors requiring increasing maintenance and raising concerns regarding the trajectory of Ocean Beach. This report quantifies the space available for dune enhancement by characterizing the constraint caused by erosion induced by ocean waves.

Historical Context

The existing conditions at Ocean Beach have been affected by prior interventions dating back to the mid 1800s. These interventions have induced a strong erosion potential primarily due to the construction of the Great Highway which entailed building the shore seaward several hundred feet into a very active surf zone. Subsequent dredging of the Main Ship Channel (MSC) across the offshore San Francisco Bar (from the 1920s to present) is associated with a change in sand supply and evolution of Ocean Beach, leading to accretion in the northern portion since the 1970s and increasing erosion in the southern portion. Construction of sewer conveyance facilities along Ocean Beach in the 1980s-1990s included construction of a vegetated dune embankment along the Great Highway: While these dunes were expected to erode and require reconstruction, substantial action to restore their geometry and function is not apparent. Sea level rise is expected to reduce beach width, increase dune erosion and increase the exposure of the backshore to wave-related hazards as noted in the Ocean Beach Master Plan (SPUR and others 2012).

Wind-driven sand transport results in road closures and related problems such as impeded storm water drainage. The CCSF and NPS use mechanical means (earth-moving construction equipment) to move the wind-blown sand from pavement and away from seawalls and place it primarily back on the beach closer to the water. The perception is that increasing maintenance is required while results are progressively worse. The ‘stabilization’ of sand with vegetated dunes is being considered as an alternative to increasing maintenance and is attractive owing to the potential for ecology and recreation co-benefits.

Wave Driven Active Shore Zone

The Wave Driven Active Shore Zone at Ocean Beach is assessed in terms of selected morphometrics indicative of the seaward constraint on vegetated dunes:

- *Recent Historical Shorelines*: Fluctuations and Trends are quantified in terms of seasonal and event-related fluctuations and net change in shore location over time. Winter and Spring swells and seas cause the beaches to narrow and wave runup to extend to the dunes in many places while summer and fall conditions typically result in ‘recovery’ of sand and wider beaches. These seasonal fluctuations vary and have been more extreme during el nino climate conditions and extreme wave and water level events. Trends are computed as the net change in shore position averaged over the 30-year period of 1992 to 2022, resulting in a rate in terms of average distance of shoreline movement per year, with erosion being ‘negative’ and accretion ‘positive’.
- *Rip Embayment Constraint on Seaward Dune Extent:* Large rip current cells induce a landward progression of the shore over the winter and spring months. The shore and beach width changes associated with the larger rip cells are quantified.

These metrics are not uniform across Ocean Beach, largely because the wave exposure is not uniform, with offshore depths focusing wave power primarily in the middle to south portions of the study area. Also, backshore conditions vary and include seawalls, vegetated dunes and compacted embankments. Consequently, four reaches (A, B, C and D) were delineated based on these coastal conditions, as indicated by Figure ES-1. The shore change metrics were computed for each Reach.

- Reach A extends 4,400 feet from Point Lobos (north end) to Lincoln Way (south end). A wide, flat beach has accreted since the 1970s and is backed by the O’Shaughnessy Seawall constructed when the beach was narrowed in the early 1900s. Wind driven sand travels over the seawall and deposits on the parking and roadway hardscape. Maintenance consists of bulldozing sand away from the seawall toward the beach to slow the wind driven transport. Figure ES-2.
- Reach B extends 4,200 feet from Lincoln Way to Noriega Street. A moderately wide beach fronts vegetated sand dunes that extend to elevations around 40 feet. Foot traffic has degraded vegetation and sand dunes are migrating onto the Great Highway. Maintenance consists of removing sand from the Great Highway and placing the sand back on the beach, primarily in South Ocean Beach (south of Sloat Blvd.) but also in Reach C. Figure ES-3.
- Reach C extends 3,400 feet from Noriega Street to Santiago Street. A narrow beach is backed by a seawall constructed in the 1980s. Maintenance consists of bulldozing sand seaward from the base of the seawall in an attempt to limit wind-blown sand transport onto the seawall and Great Highway. Sand is also excavated from the seawall promenade and placed on the beach.

Vegetated foredunes have formed but are limited and not persistent due to wave action and mechanical beach grading. Figure ES-4 and Figure ES-5.

- Reach D extends 2,800 feet from Santiago Street to Sloat Blvd. A very narrow beach is backed by eroded dunes with frequent exposure of compacted earth embankment and rubble. The wet-weather sewer overflow outfall extends across most of the dry beach. Figure ES-6.

Overview of Analysis: Shore line positions were mapped between a baseline (1992) and existing conditions (2022) using published data (previously mapped shorelines) and augmented with more recent available aerial photographs and lidar. Two morphometric shorelines were mapped:

- High Tide shoreline, and
- Dune Toe (where the dune meets the beach).

Beach widths were calculated as the distance between the High Tide and Dune Toe lines. Representative cross-shore profiles were drawn for the Reaches (Profiles A, B1, B2, C and D; see Figure ES-1). These Profiles were developed in collaboration with, and used by, Baye and SFEI.

Interpretation: The results are interpreted and parameterized using representative values for each of the four shore Reaches. The metrics are presented in Table 1. We note that the historical extent of the dune toe and associated vegetation is not necessarily the maximum seaward extent possible. Further, the dunes were found to be building seaward in Reaches A and B, ephemeral in Reach C and eroding in Reach D. Existing management actions (i.e. mechanical movements of sand, plant trampling, plant types) are apparently a strong driver of existing conditions. Figures ES-7 through ES-11 summarize metrics interpreted from the 1992 through 2022 data set for each of the Reaches: Reach D is segregated into north and south 'subreaches'. Overall, the northern portion of Ocean Beach (Reaches A and B) are relatively wide and accreting, the middle portion of Ocean Beach (Reach C) is narrow with relatively large fluctuations and eroding, and the southern portion (Reach D) is eroding and narrow.

Wave Runup Constraint on Vegetated Dunes:

Wave runup over the beach was investigated as an indicator of the potential seaward constraint on the vegetated dune toe. This analysis augments the shoreline mapping (previous section) by isolating the natural constraint from management constraints, thereby informing the potential extent of dunes if management activities are modified.

Background and *Conceptual Model of Wave Runup Constraint on Dune Toe Location* develops this concept (that wave action can indicate the seaward extent of dunes) based on published technical literature. Wave runup and Total Water Level (the elevation of wave runup) are described as part of the conceptual model.

Total Water Levels and Dune Toe Elevations at Ocean Beach: Wave runup was computed for a 23-year period (2000 to 2023) using coastal engineering methods. The statistical representation of wave runup was compared to the mapped dune 'shorelines' (aka dune toe) for each Reach.

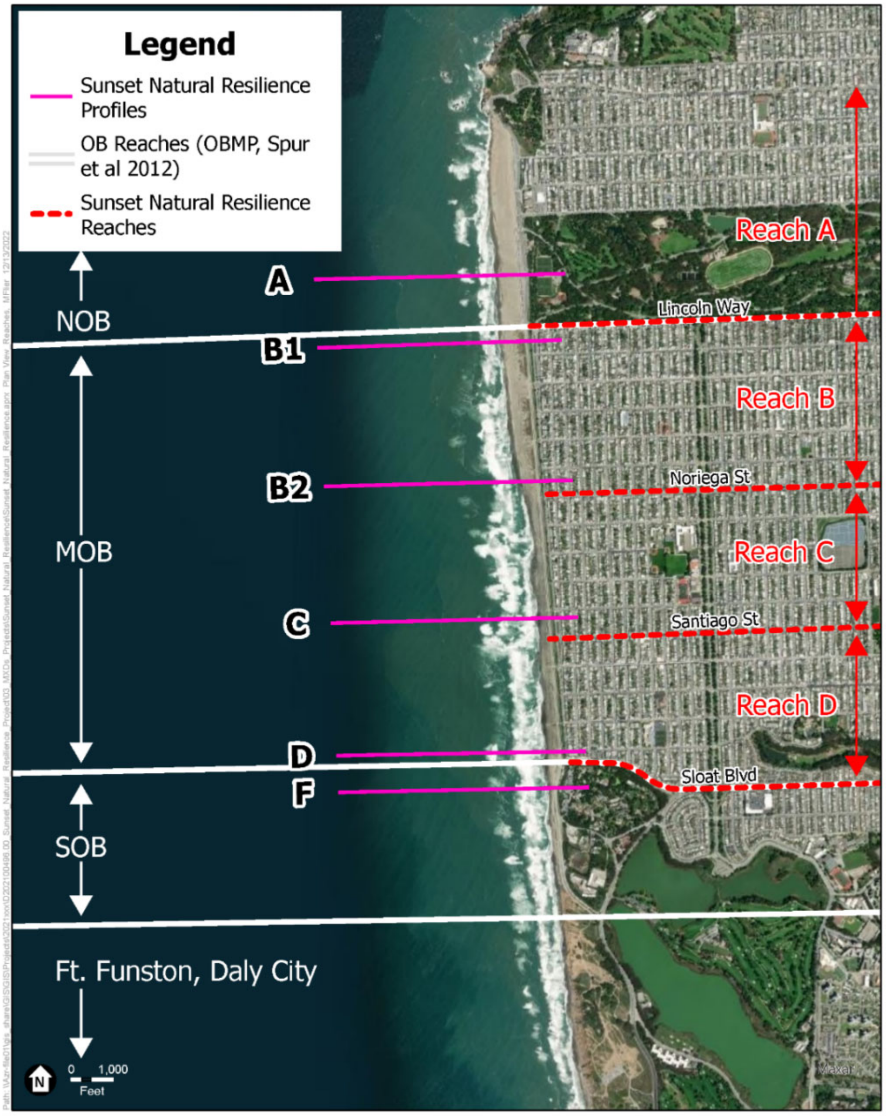
Potential Seaward Extents of Dunes at Ocean Beach: The wave runup calculations were compared to the mapped dune toe elevation (from the typical profiles) and published data to estimate the seaward-most extent of vegetated dune persistence at each of the Reaches. The runup data were used to further extend the conceptual model to distinguish between the seaward extent of 'perennial' dunes (persistent vegetated dunes) and 'ephemeral' dunes (dunes that are expected to require maintenance following large wave events). The results are summarized in Figure ES-12.

Conceptual Design Vegetated Dune Natural Infrastructure

A Conceptual Design of vegetated dunes across the study area was developed in collaboration with Baye (2023) and SFEI (2023). ESA's interpretation of the potential for dune enhancements is depicted schematically in Figure ES-13 on shore profiles for each of the study reaches.

The Conceptual Design entails application of three Dune Zones:

- Low relief and ephemeral vegetated foredunes in Reaches C and D. This zone is compatible with wrack and can be augmented with large wood to provide structure for resilience and ecology.
- High to Low Relief, perennial vegetated dunes in Reaches A and B. Starting at least 100 feet landward of the winter-spring shoreline, vegetated foredunes are expected to persist with the ability to recover from erosion scarps formed by wave runup; and,
- High Relief, sacrificial vegetated dunes in Zone D. These dunes will be similar to those constructed in the 1980s and 1990s, and hence will be less 'natural' and will erode during high wave events, thereby releasing sand to maintain a beach while protecting the backshore.



SOURCE: ESA, 2022

Sunset Natural Resilience Project

Figure 1
Plan View of Ocean Beach Profiles

ESA

Figure ES-1

Study Reaches and Typical Shore Profiles. Location of Study Reaches (A, B, C and D) and Shore Profiles A through D used in this study. Study reaches and shore profiles used in the Ocean Beach Master Plan (OBMP, SPUR and others 2012) also shown for reference.

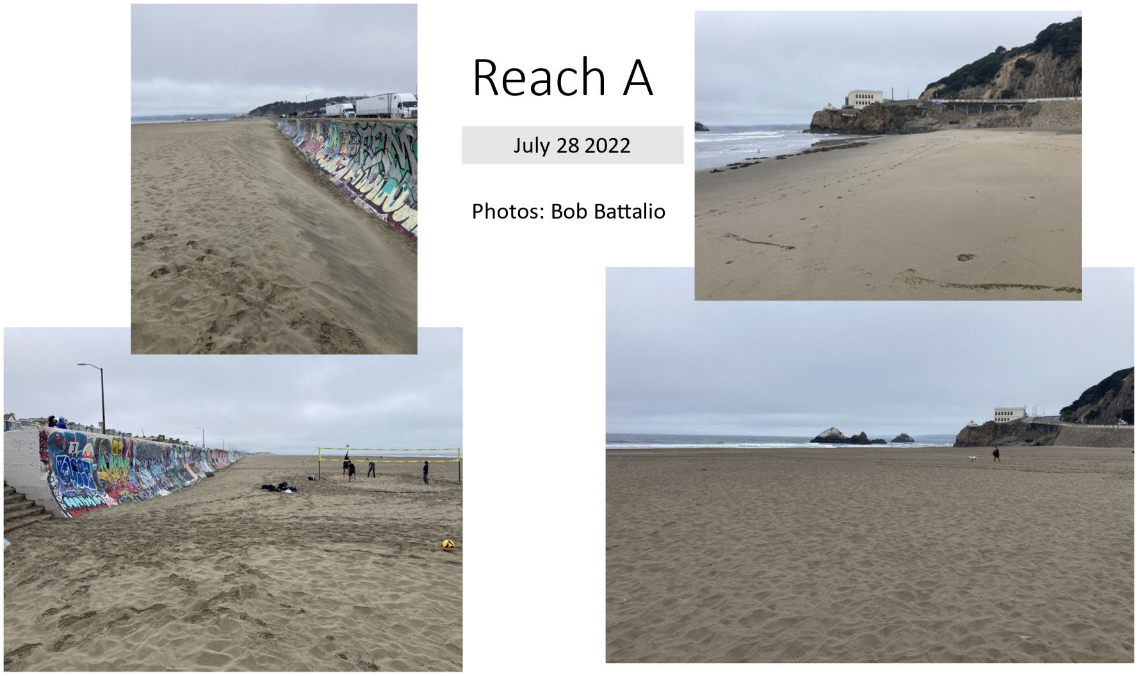


Figure ES-2
Reach A photographs.

Figure ES-3
Reach B photographs.

Figure ES-4
Reach C photographs.

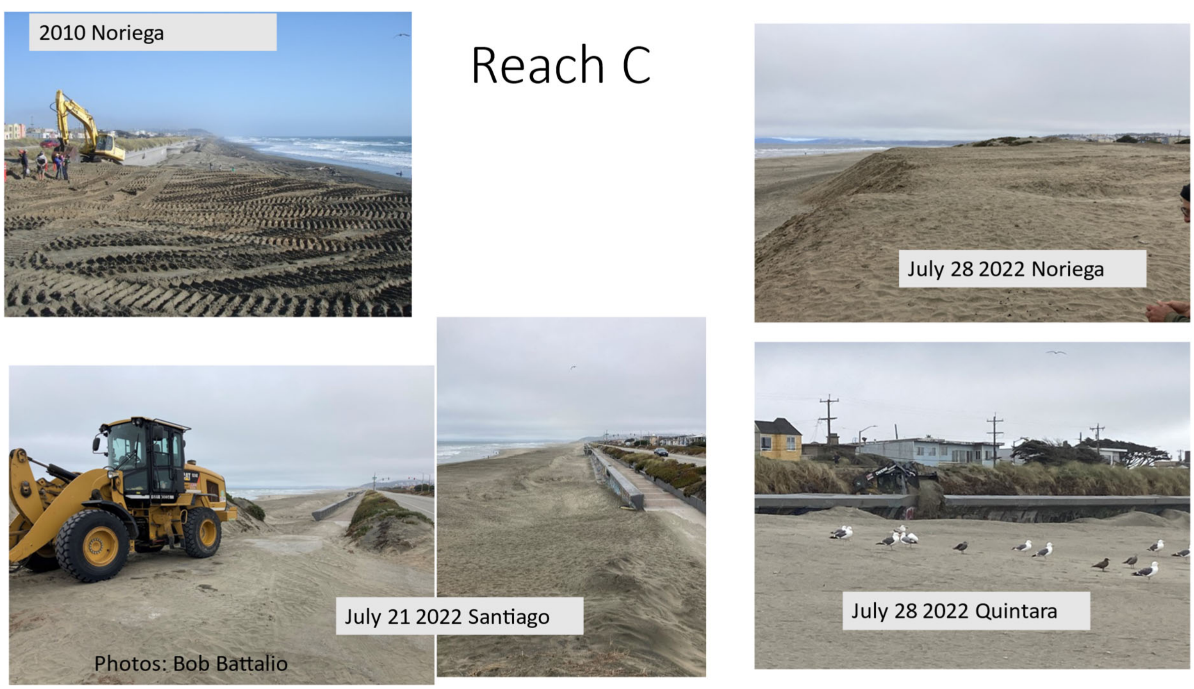


Figure ES-5
Reach C photographs of management activities.

Figure ES-6
Reach D photographs.

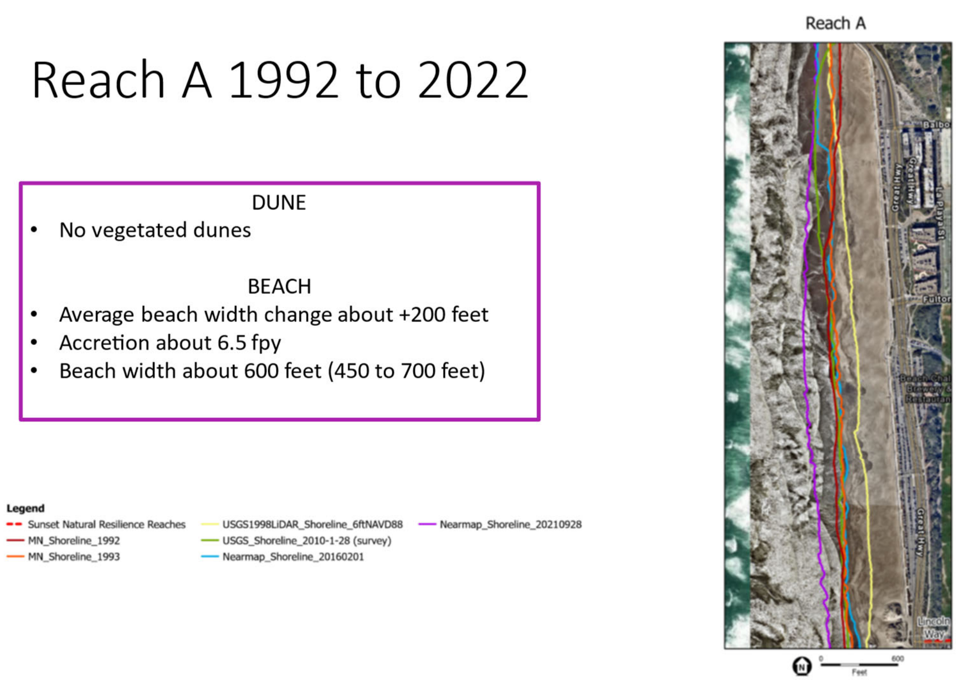


Figure ES-7
Reach A metrics interpreted from historical data.

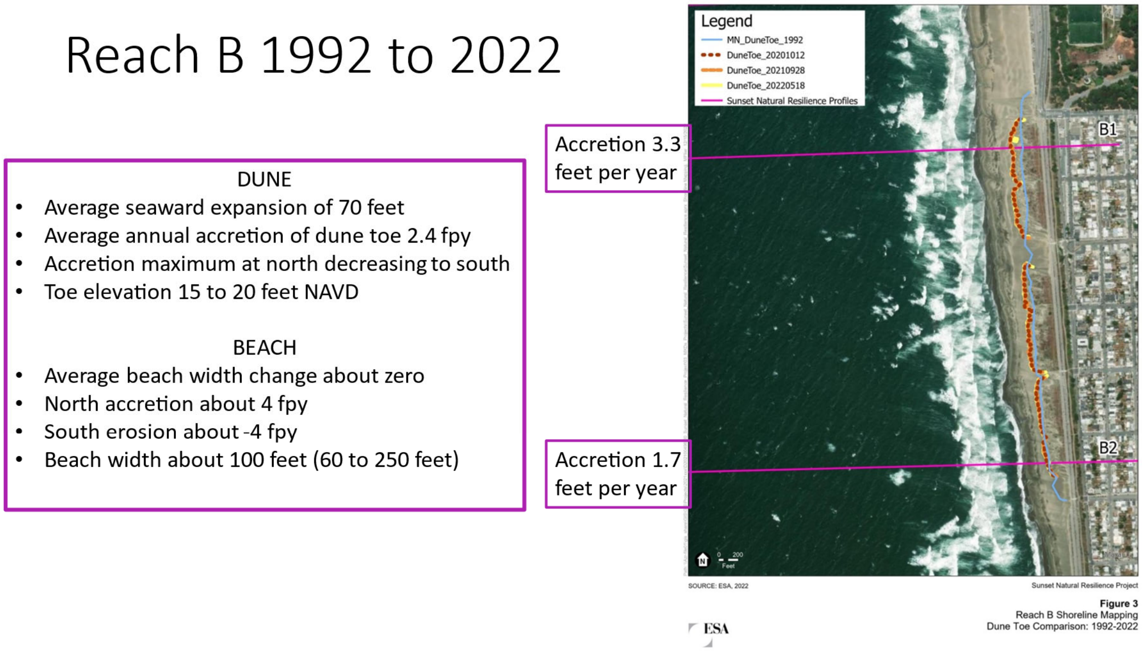


Figure ES-8
Reach B metrics interpreted from historical data.

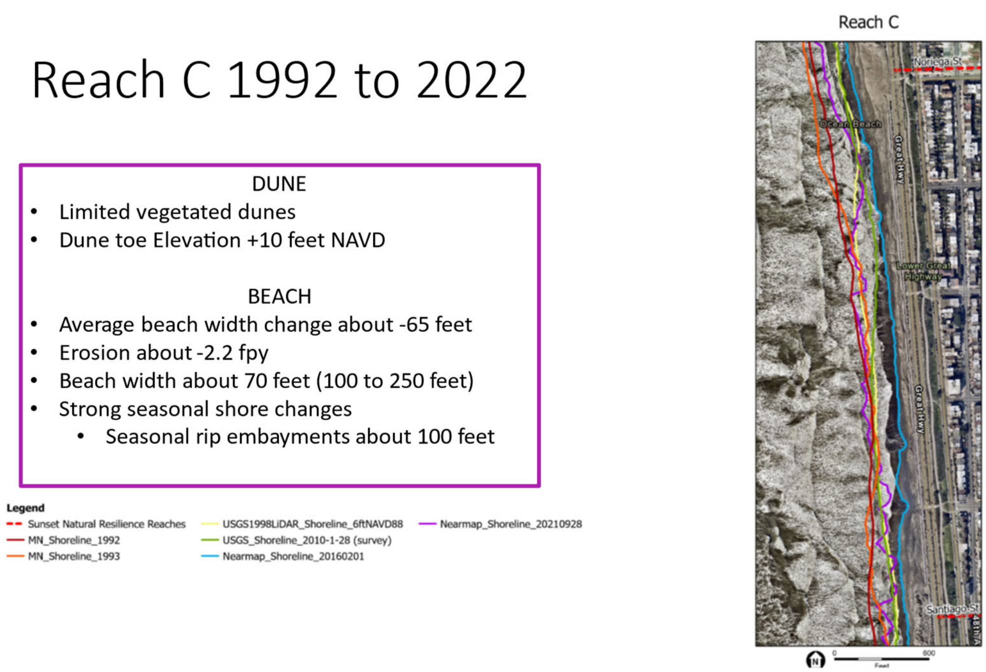


Figure ES-9
Reach C metrics interpreted from historical data.

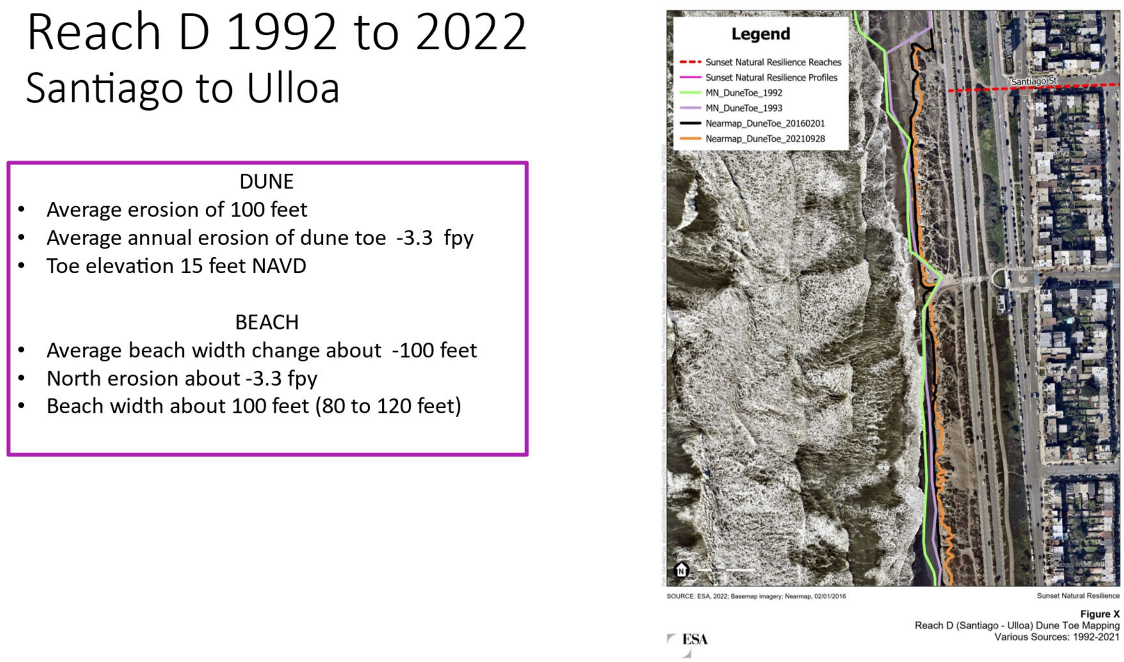


Figure ES-10
Reach D north metrics interpreted from historical data.

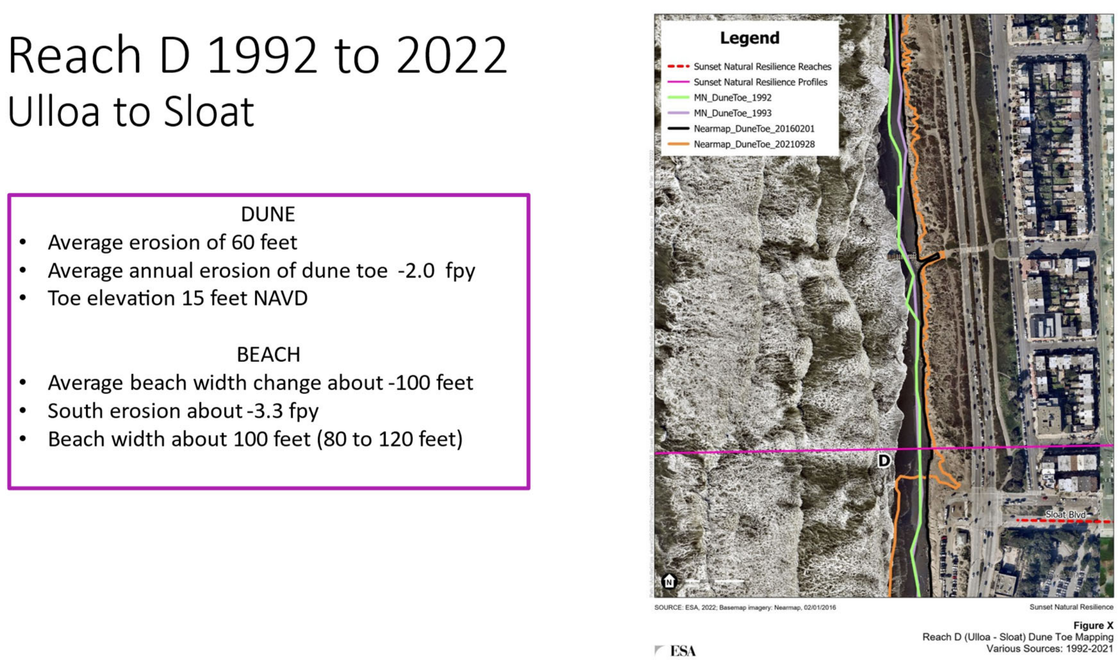


Figure ES-11
Reach D south metrics interpreted from historical data.

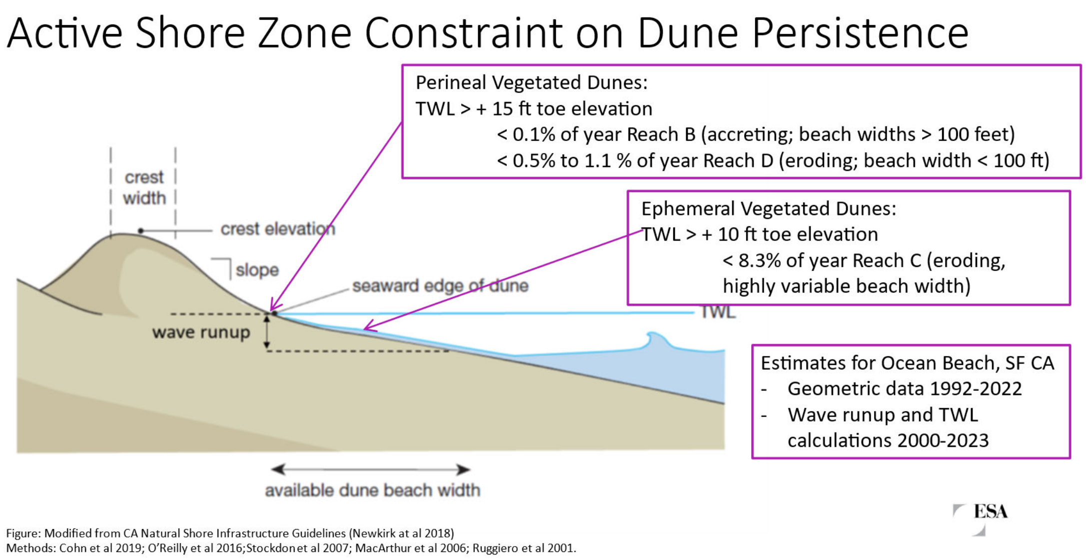


Figure ES-12
Depiction of the potential seaward extents of vegetated dunes, both perineal and ephemeral, for Reaches A, B, C and D.

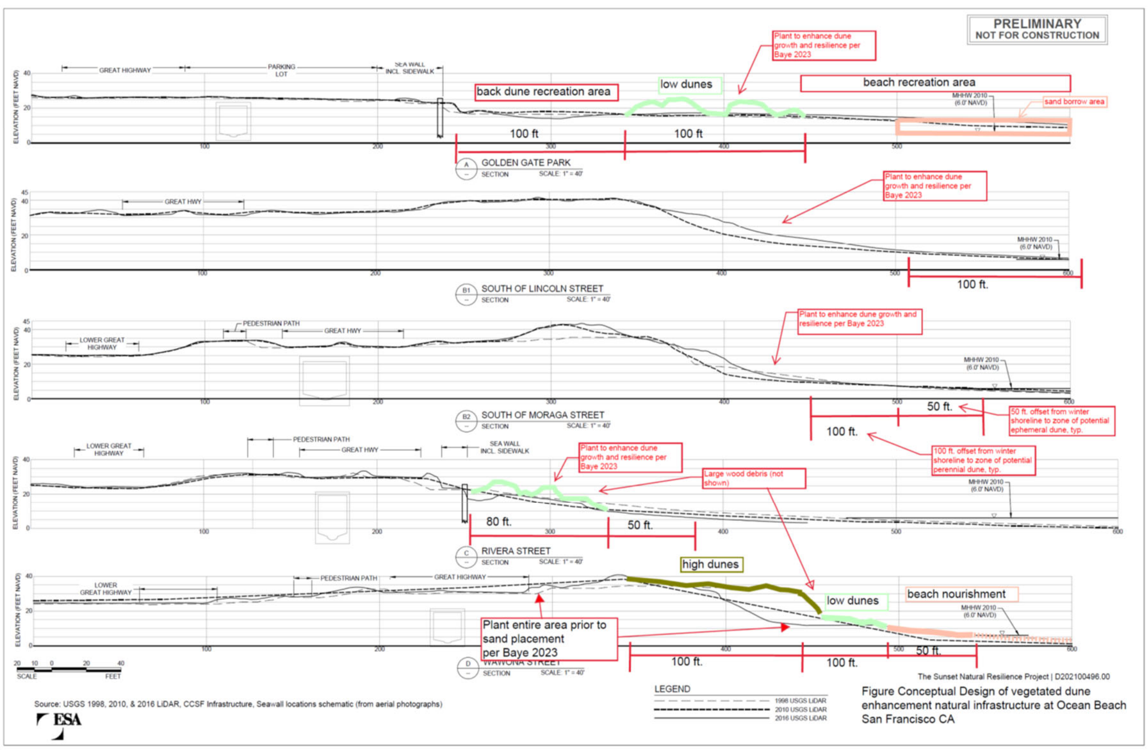


Figure ES-13
Conceptual design diagram for vegetated dunes in Reaches A, B, C and D, depicted on typical shore profiles A, B, C and D, respectively.

SUNSET NATURAL AREAS PROJECT

Active Shore Zone Constraint to Dune Enhancement

Background and Purpose

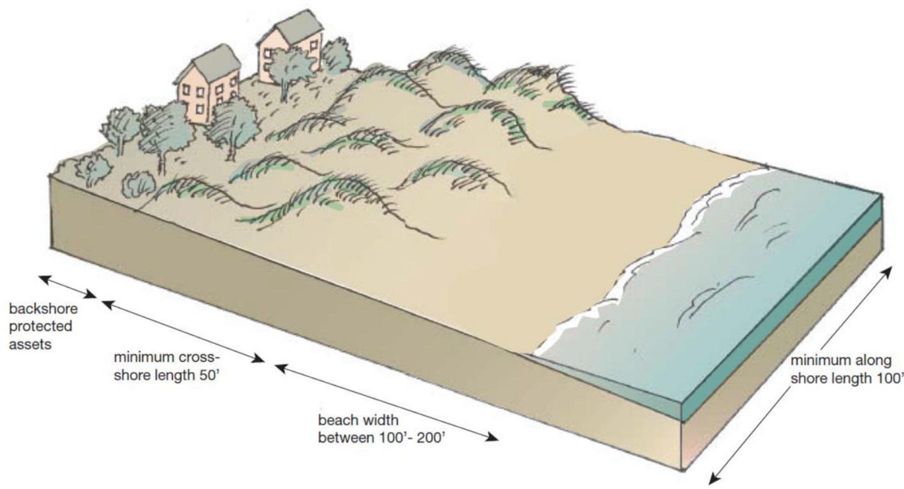
The Sunset Natural Areas Project (Project) is assessing the feasibility of vegetated dune enhancement at Ocean Beach, San Francisco. San Francisco Estuary Institute (SFEI), Peter Baye PhD and ESA are collaborating, along with City County San Francisco (CCSF) and National Park Service (NPS) toward conceptual dune enhancement plans as part of the Project.

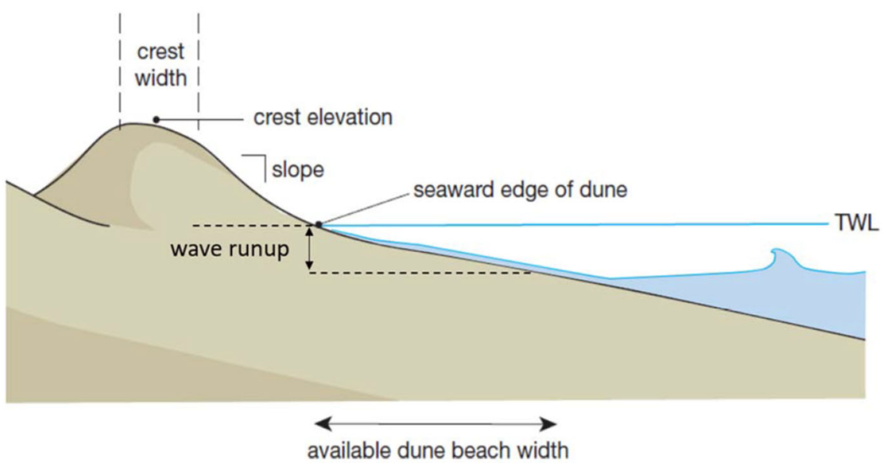
Dune enhancement can provide multiple benefits; reduction of wind-blown sand transport onto roads and dissipation of erosive wave runup, which reduce public works costs, as well as enhancing ecology and increasing resilience to sea level rise, while providing pleasant experiences consistent with public uses.

California's Fourth Climate Assessment included guidance for natural shore infrastructure[1] to manage coastal change (Newkirk et al 2018; Cheng et al 2018). Providing adequate space to sustain geomorphic and bio-geomorphic processes was emphasized in the guidance, as depicted schematically below. The dimensions represent the approximate minimum for self-sustaining vegetated dunes in California. With less space initially, or over time as the shore migrates landward, progressively increasing maintenance can be expected and eventually the dunes may not be sustainable without accommodation space for landward migration. The seaward edge of the dune is defined by the location where: (1) total water level (top of ocean water level + wave runup) reaches infrequently (10 days per year or less); and (2) dry sand area during the summer is sufficient to supply wind-blown sand to rebuild dunes.

[1] See Abbreviations and Definitions at end of this document.

Ocean Beach is also exposed to very large waves and has an active surfzone and beach system with wave runup that reaches the existing sand dunes annually. Conceptually, the space available for vegetated dunes is between the Great Highway and zone of ‘excessive’ disturbance by wave runup. While the threshold of ‘excessive disturbance’ is not quantified, we perceive it to be related to the intensity and frequency of erosion that impedes re-establishment of dune vegetation, essentially destabilizing dune bio-morphology. This report approximately quantifies the space available for foredune persistence using as a surrogate historical shore fluctuation, available beach width and computed wave runup.





Historical Context

Ocean Beach is substantially modified from its natural state, leaving a relatively narrow, shore-parallel zone available for dunes between the Great Highway and the ocean. The recent history of Ocean Beach is pertinent to dune establishment in terms of existing conditions and activities, opportunities, and constraints.

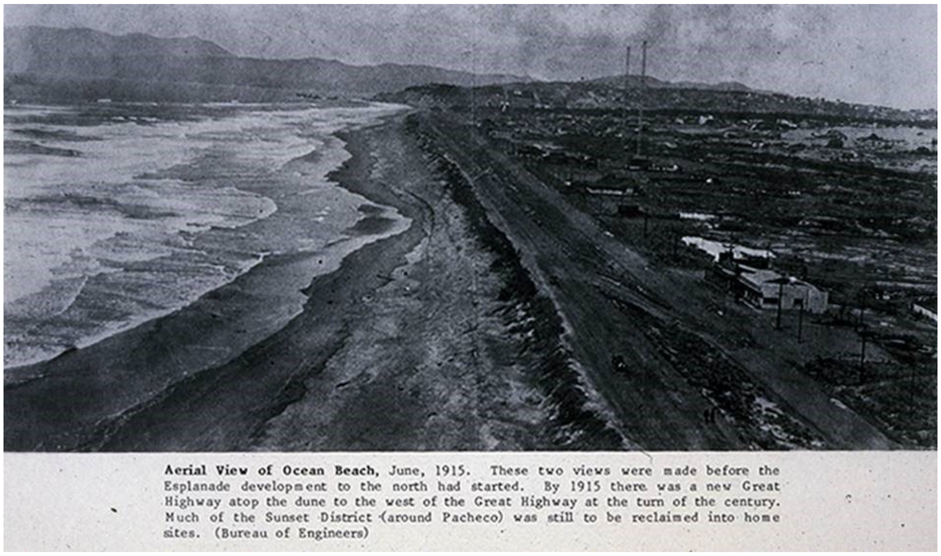
A very simplified summary is as follows:

- Pre-1900s: Ocean Beach was part of a large sand shed that spread eastward (inland) several miles (**Figure 1**);
- Mid-1800s to mid 1900s: The shore was filled seaward several hundred feet and the Great Highway was constructed on a sand-earth-rubble embankment (**Figures 2 and 3**). Several seawalls were constructed to prevent the shore from migrating back to its natural position (somewhere near the contemporary location of the Lower Great Highway) landward of the Great Highway;
- 1970s: The maintenance dredging of the San Francisco Shipping Channel through the San Francisco Bar (horseshoe-shaped ebb tidal shoal extending to 5 miles off the Golden Gate) was modified to both deepen the shipping channel and to discharge the dredged sand on the Bar, presuming this would keep the sand within the littoral cell, for the benefit of beaches. The result (theorized Battalio & Trivedi 1996; Battalio 2014) was increased sand transport landward to Ocean Beach and widening of the northern beaches by several hundred feet (**Figure 4**), with limited apparent increase in beach width elsewhere (**Figure 5**). Since then, the beach north of Lincoln Way (Reach A) has remained wide. The wide relatively flat beach actually includes low-relief linear mounds (transverse dunes) shaped by winds. Mechanical grading inhibits dune growth and vegetation.
- 1980s and 1990s: As part of the Clean Water Program, San Francisco's combined storm and waste sewer system was upgraded, including massive sewer conduits, treatment and discharge facilities along the Great Highway corridor. The work also included realignment of the Great Highway resulting in a 50-foot setback of the ocean side and construction of vegetated dunes (actually, a linear sand embankment with non-native vegetation) intended to maintain a sandy beach by releasing sand during coastal erosion events. It was anticipated that the dunes would erode and that maintenance in terms of sand placement and vegetation would be required. Also, as a part of the Clean Water Program, rubble was consolidated and buried at the base of the embankment supporting the Great Highway. Owing to a natural landward embayment of the winter shore, a seawall was constructed between Noriega and Santiago cross-streets (called the 'New Seawall' in this report).
    - The shore conditions were documented in the mid-1990s and provide a baseline for subsequent shore evolution.
    - Pertinent to dune formation but only tangentially pertinent to the active shore zone is the change to pedestrian access resulting from the Clean Water Program. Pedestrian tunnels under the Great Highway (at Judah, Taraval and Wawona streets) were closed (partially demolished) to construct the Westside Transport Box carrying wastewater under the Great Highway. At grade crossings with traffic lights were installed to provide pedestrian access. Parking along the Great Highway was prohibited.

North Ocean Beach, 1865 (Source: SF Public Library Historical Photo Collection)

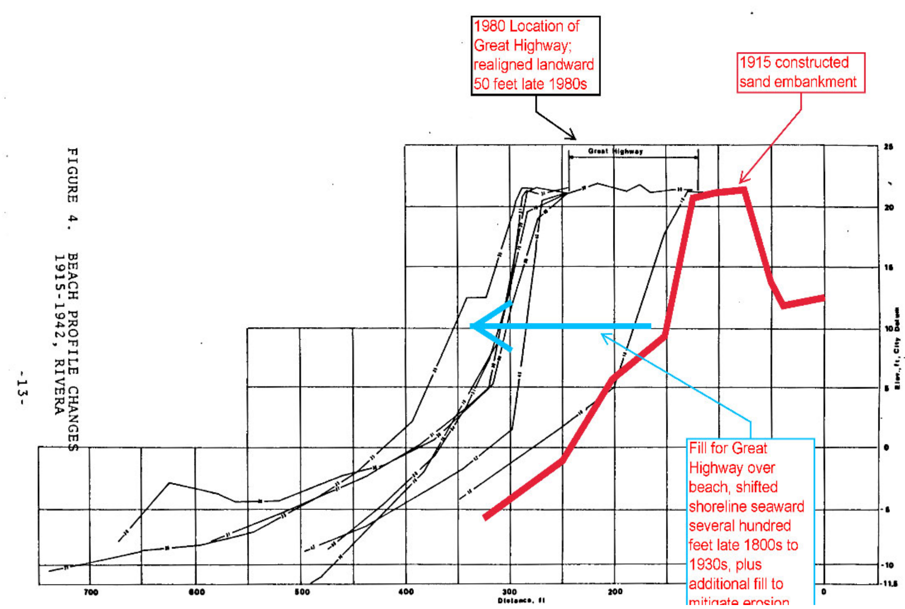
Looking southeast from Pt Lobos bluff (near Cliff House) toward North Ocean Beach (Area A) and what was called Kelly's Cove where the shore was naturally hundreds of feet landward of the rocky headland. In the background is Seal Rock House and natural dunes circa. 1865 Sources: Top: Olmstead & Olmstead 1979, Bancroft Library; Bottom: SF Public Library Historical Photo Collection.

Figure 1
North Ocean Beach in the mid 1800s.



Vicinity of Rivera street looking north beyond Pacheco street (Reach C, with Reaches B and A in background). The fill embankment for the Great Highway is shown as of 1915. Note the shore embayment characteristic of this location, where a seawall was constructed in the 1990s. Source: Olmsted and Olmsted, 1979.

Figure 2
Middle Ocean Beach Early 1900s.



The 1915 is the landward-most profile (landward to the right and highlighted in red), showing a constructed barrier dune close to the shoreline. Additional profiles indicate fill by CCSF onto the beach, pushing the shore seaward by several hundred feet. The location of the Great Highway in the 1980s prior to the Clean Water Program is sketched at the top of the embankment. The Great Highway was narrowed about 50 feet landward as part of the Clean Water Program. Vertical axis is City Datum which is about 11.3 feet above NAVD and MLLW, and close to the natural beach elevation. Horizontal axis is in feet, indicating a seaward shoreline shift of 200 to 300 feet. Source: Modified from Ecker 1980; shore profiles provided by City County of San Francisco, 1915 to 1942.

Figure 3
Effect of Great Highway Construction on Shore.

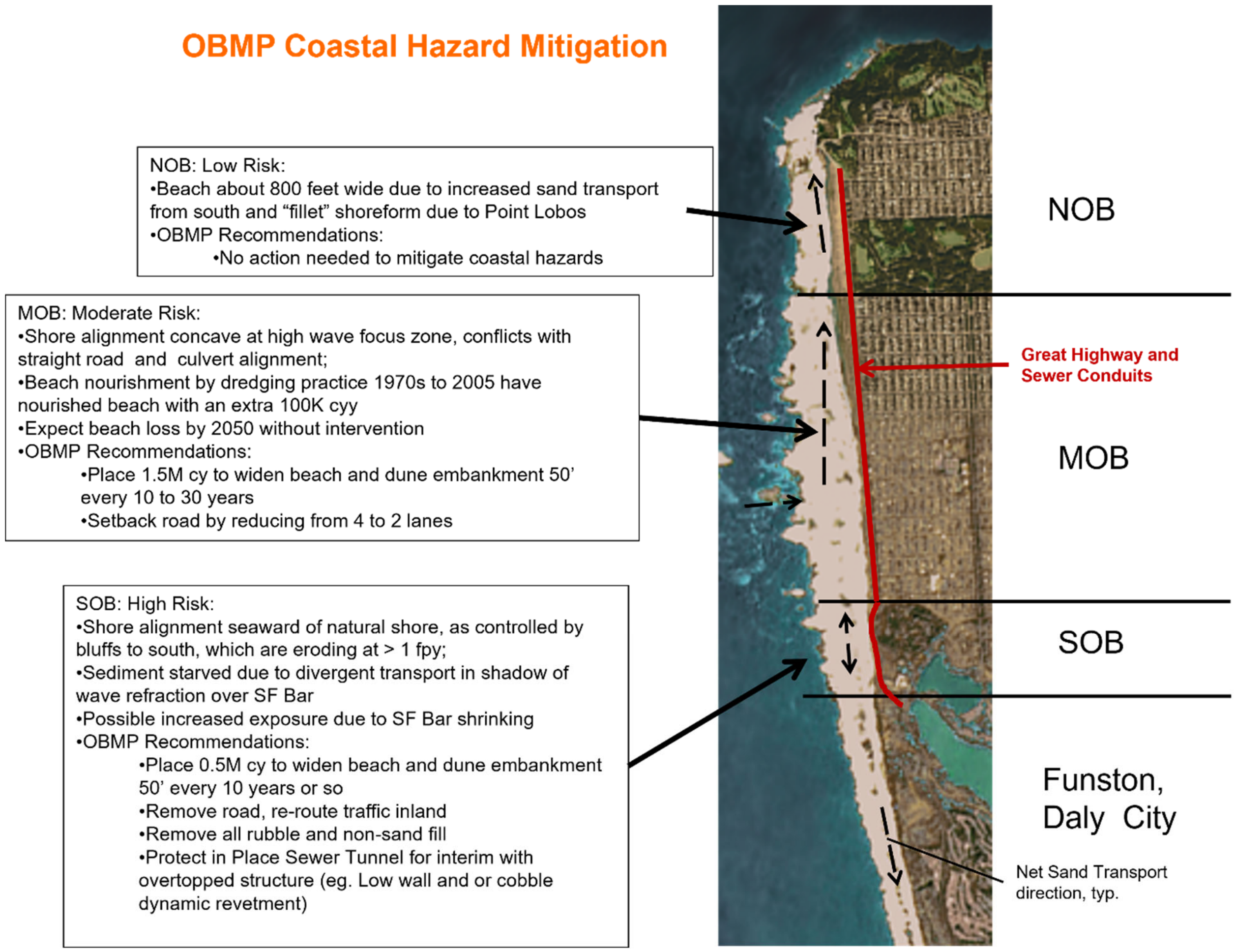
Photographs circa 1972 (top) and 2009 (bottom). This is the same location shown in Figure A, also known historically as Kelly's Cove. In 1972 and prior years the base of O'Shaughnessy Seawall was exposed, and the beach was narrow. The beach widened in the 1980s, and has remained wide since. Source: Battalio 2010. Source of Photos: California Coastal Records Project Copyright © 2004-2005 Kenneth & Gabrielle Adelman - Adelman@Adelman.COM

Figure 4
North Ocean Beach Accretion.

Counter clockwise from top left: O'Shaughnessy Seawall constructed 1915-1927 in North Ocean Beach (Reach A – see also Figures A and D), now partially buried by sand.Reach C. In background is the "New Seawall" constructed as part of the Clean Water Program (1987-1993). The seawall design is similar to the O'Shaughnessy seawall. See also Figure F. Reach D: Taraval seawall constructed in the 1940s. This is the location of the Taraval pedestrian tunnel demolished during the Clean Water Program. Source: Battalio 2010.

Figure 5
Seawalls at Ocean Beach circa 1990s.

- 2000s to present: A long-term adaptation plan called the *Ocean Beach Master Plan* (OBMP) was completed in 2012. The plan recommended increased sand supply to maintain beaches as well as other interventions. Implementation of the OBMP has focused on South Ocean Beach (SOB) owing strong erosion and degraded. Also, sand management activities are developed and implemented by CCSF and NPS primarily consisting of mechanical movement of sand.
    - *Ocean Beach Master Plan* (SPUR and others 2012). In response erosion and shore armoring at South Ocean Beach, the CCSF, NPS and California State Coastal Conservancy developed a long-term plan to adapt to erosion and flood hazards with sea level rise through the year 2100. The Plan explored several alternatives within an active public process, resulting in a suite of actions organized over time and by North, Middle and Southern Ocean Beach (**Figure 6**). The OBMP was integrated into the Local Coastal Program update approved by the Coastal Commission. Dune enhancement was considered for North and Middle Ocean Beach at a conceptual level and appeared worthwhile. The first plan implementation actions were focused on South Ocean Beach owing to rapidly degrading and hazardous conditions (ESA and others 2015). Actions include the sand backpass, large sand placement in 2021, and design for landward realignment of the shore, which includes closure of the Great Highway south of Sloat Boulevard.



Subsequently it was clarified that realignment of the Great Highway in MOB was not expected to be considered until after 2050. Also, the desired beach nourishment requirement for South Ocean Beach has been increased, which may affect the sand placement rate for Middle Ocean Beach as well as sand supply for the entire study area. Source: Battalio 2013b, derived from SPUR and others 2012.

Figure 6
Summary of the Ocean Beach Master Plan.

- *Shore management* has consisted primarily of two disconnected activities, and one change to pedestrian access:

  (1) Mitigation of wind blown sand deposition on vehicular and pedestrian hardscape consists of grading sand away from the seawalls (**Figure 7**) and hardscapes (parking, walkways). Sand removed from the hardscape was dumped on the shore south of Sloat Boulevard to mitigate erosion at south Ocean Beach, as well as on the beach in Reach C.

looking south from vicinity of Noriega Street toward Reach C. Sand grading to limit wind blown sand transport onto the new seawall and Great Highway. Photo Battalio circa early 2000s.

Figure 7
Area C Sand Management.

(2) Increasing sand supply to beaches, which may effect beach width and potential dune formation, although it is too early to discern from the data:

- The CCSF and NPS have collaborated to move sand from north OB (where there is excess sand) to south OB (where beaches are limited by back shore encroachment): This operation is called a ‘backpass’ because the sand placed at SOB is considered to be placed *back* to the south and expected to migrate *back* north.
- The US Army Corps of Engineers (USACE) have further modified their dredge disposal practices to place sand offshore of southern OB including a pilot project that entailed ~ 300,000 cubic yards of sand placed in a ‘sacrificial’ sand embankment in 2021.
- The sand at Ocean Beach apparently contains a greater proportion of finer sand than historically existed (Battalio 2014).
    - The increase in finer sand deposits is hypothesized to result from mobilization of finer sands by maintenance dredging of the offshore channel. The median grain size is about 0.15mm vs the 0.3 to 0.5mm historical median grain size at Ocean Beach. The sand depositing in the channel consists of finer sands transported by ebb tides out of San Francisco Bay, and these sands are disposed nearshore or on the SF Bar where waves can transport the sand landward. Historically, when the channel was significantly deepened (see 1970s, above), coarser sands

native to the SF Bar were dredged, and subsequently coarse sands sloughed into the channel and were dredged, while now primarily the finer sands are dredged (Battalio 2014).

    - The sand backpass from NOB to SOB is now likely moving finer sand blown by wind into the back shore borrow area.
    - Wind-blown sand removed from inland and placed on the may have a role in the apparent increase of fine sands, despite these sands recirculating landward by wind.

- Starting during the COVID virus pandemic in 2020, the Great Highway was closed to vehicles, and remains closed during the weekends. Pedestrian access to the beach across the Great Highway dunes is not constrained to the signalized crosswalks and other paths when the road is closed to vehicles. It appears that foot traffic has spread, impacting vegetation and increasing wind-blown sand transport.

Wave Driven Active Shore Zone

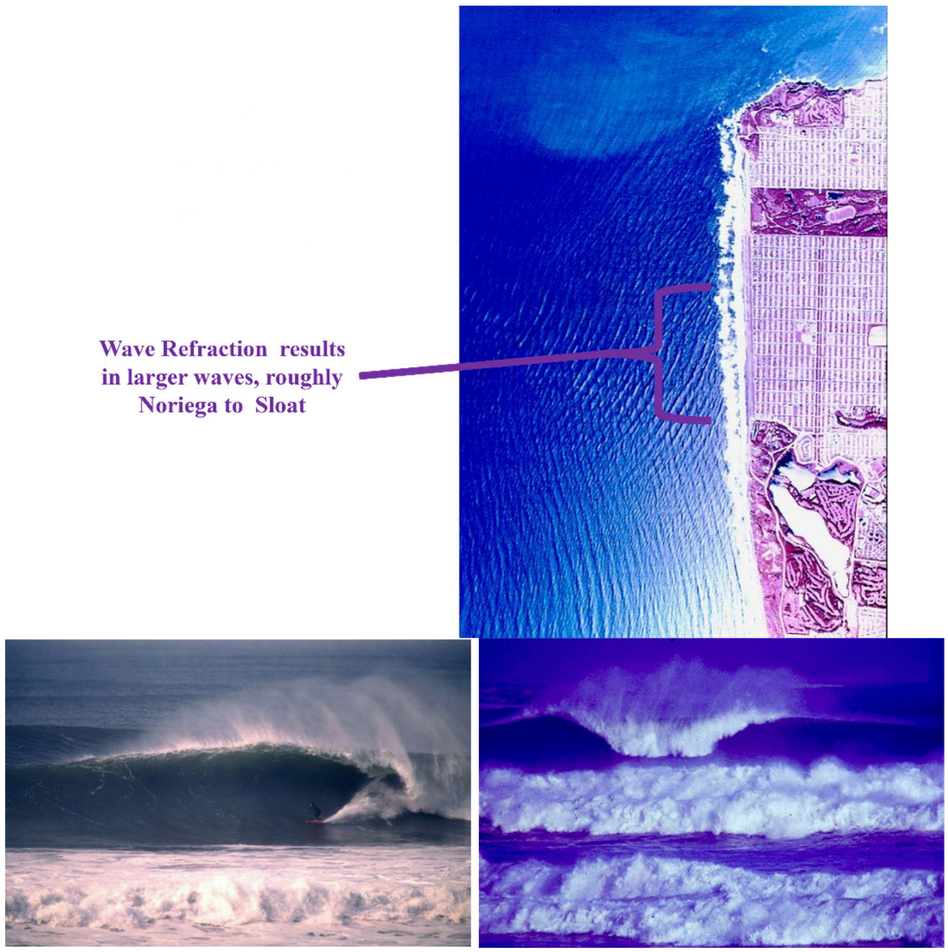
Ocean Beach is a very dynamic area, seasonally exposed to large, powerful waves (**Figure 8**) and strong winds. Wave refraction starting about 25 miles offshore around the Farallon Islands and Cordell Bank can also focus swells at Ocean Beach. Refraction causes a single swell to cross itself, locally amplifying the wave height. The greatest focusing is in Reaches C and D (Middle Ocean Beach). The resulting water transport landward causes a setup of the water level at shore, resulting in strong rip currents directed seaward, and longshore currents directed to the north and south toward smaller wave areas.

Prior reports that addressed shore positions were reviewed. Some of these reports evaluated shorelines prior to the 1990s (Olmsted & Olmsted 1979; MNE 1993; 1995; Battalio & Trivedi 1996) while others included more recent shore information (USGS 2006: 2007; Barnard et al 2009; Hansen and Barnard (2009); Vandebroek and Battalio 2013; Barnard et al 2013a; 2013b; ESA PWA 2012a; 2012b; Battalio 2014; ESA 2015).

Hansen and Barnard (2009) found correlation between shoreline change averaged over 500 meter reaches (1,600 ft) and incident wave conditions averaged for the prior five days. Consequently, it is difficult to ascertain a trend in shore change with precision using only a few shoreline positions: Shore change rates computed for a range of time frames for the ocean-side of the San Francisco Littoral Cell (San Francisco south to Pacifica) also demonstrates this variability **(Figure 9;** ESA and CSMW, 2012). At Ocean Beach, historical shore changes (1850 to 2010) vary by substantially by location (**Figure 10**; Battalio 2014) with:

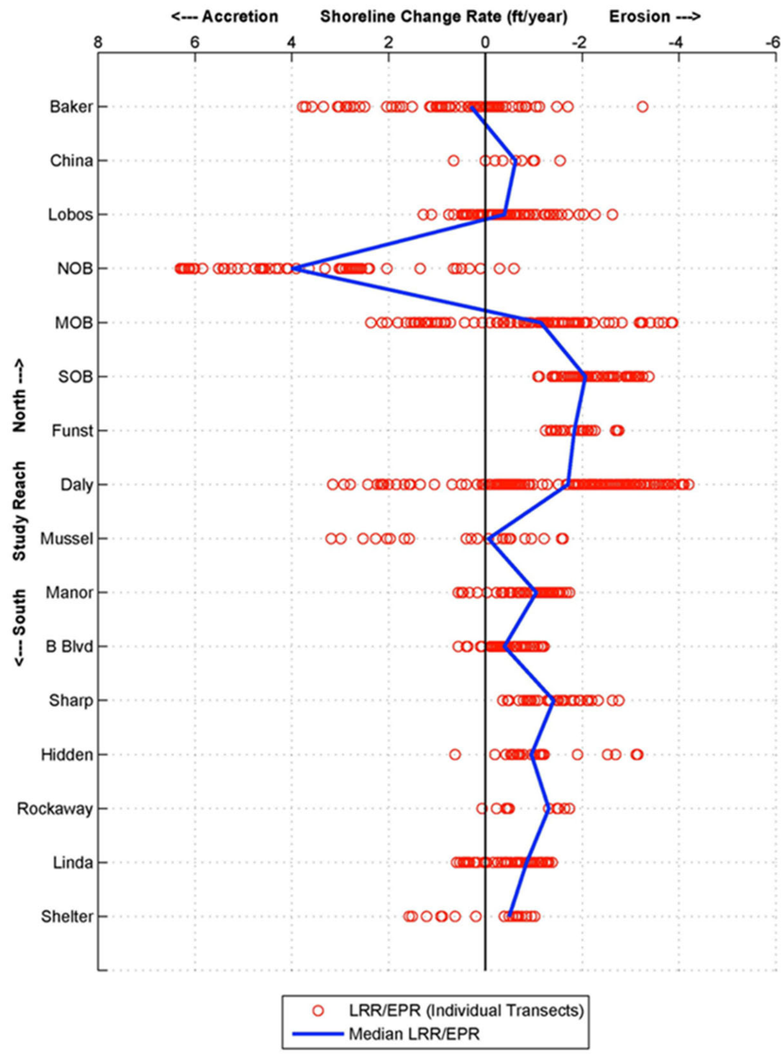
- accretion in North Ocean Beach (Reach A);
- fluctuations in Middle Ocean Beach (Reaches B, C and D), and
- erosion in South Ocean Beach (see Figure 1 for location of South Ocean Beach, aka ‘SOB’).

For the Ocean Beach Master Plan (SPUR and others, 2012), long-term average historical shore change rates selected for planning were +1fpy (NOB), -1fpy (MOB) and -1fpy (SOB); with the SOB erosion rates increased to -2 fpy based on accelerated erosion (ESA and others 2015). Short term rates (one to 30 years) can be on the order of 100 to 5 times these rates, respectively.



Clockwise from top: (a) Waves are focused on Ocean Beach due to wave refraction over the offshore seabed as indicated by the crossing wave crests due to refraction over the San Francisco Bar (sand ebb shoal associated with the Golden Gate extending about 5 miles offshore). Photograph courtesy of the US Army Corps of Engineers. (b) The wave crossing patter creates a 'peaked' breaking pattern with the breaking zone migrating laterally as the wave propagates landward. Photograph courtesy of Tim Britton. (c) The result is a challenging but exceptional surfing opportunity. Ocean Beach is considered one of the best surfing beaches in the world. Photograph courtesy of Martha Jenkins. Sources: Battalio 2010, 2014.

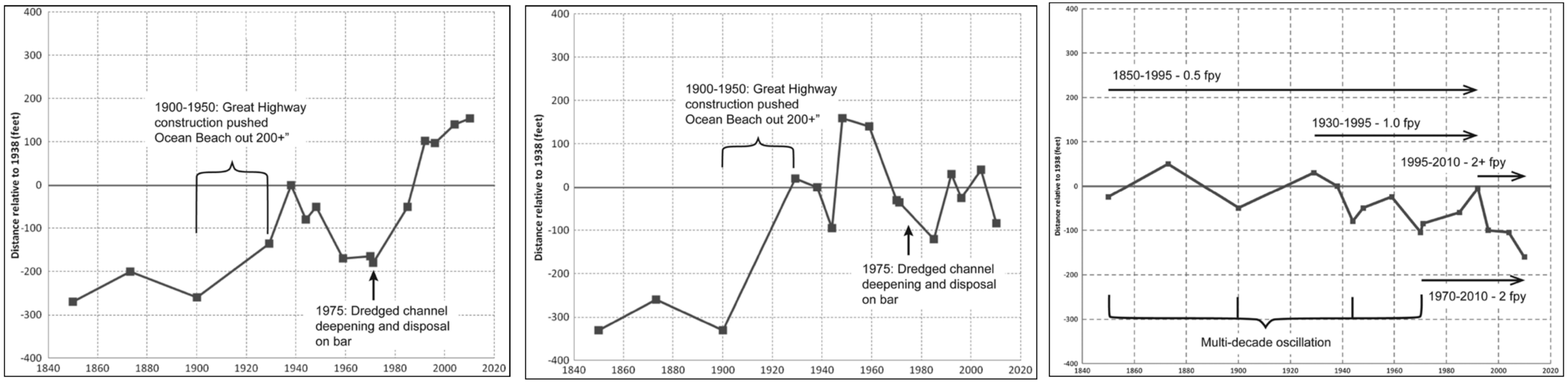
Figure 8
Wave Focusing at Ocean Beach.



Each red circle is an individual location within the reach, and the blue line an average for the reach. Linear regression rates (LRR) was used unless there were only two shorelines and an end point rate (EPR) was used. The graphic provides a visual representation of the data range, as well as an indication of the longer term trend in terms of accretion or erosion. This Sunset Project study area is represented by NOB and MOB. (Source: ESA PWA and CSMW 2012.)

Figure 9

Shore change rates for each reach of the San Francisco Littoral Cell.



Graphs of shore position change for North (left), Middle (center) and South Ocean Beach (right0 between 1850 and 2010 based on aerial photographs and US Coast and Geodetic Survey maps. For each graph, the zero on the vertical axis locates the 1936 shoreline from aerial photographs. North Ocean Beach (left) was shifted seaward by filling and subsequently eroded. The shore accreted after the 1970s, likely related to a change in dredging, specifically deposition of sand in a location where waves moved the sand onshore and increased sand supply. Middle Ocean Beach (center) is characterized by large (200 to 300 feet) fluctuations about a somewhat uniform location since the 1970s. South Ocean Beach (right) has an accelerating erosion trend and a more coherent (apparent) multi-decade oscillation. Source: Battalio 2014.

Figure 10
Historical Shore Change at Ocean Beach

Recent Historical Shorelines: Fluctuations and Trends

The wave driven active shore zone is derived for the Sunset Natural Areas Project from analysis of historical shore and dune line locations from the 1992-3 baseline conditions to 2022.

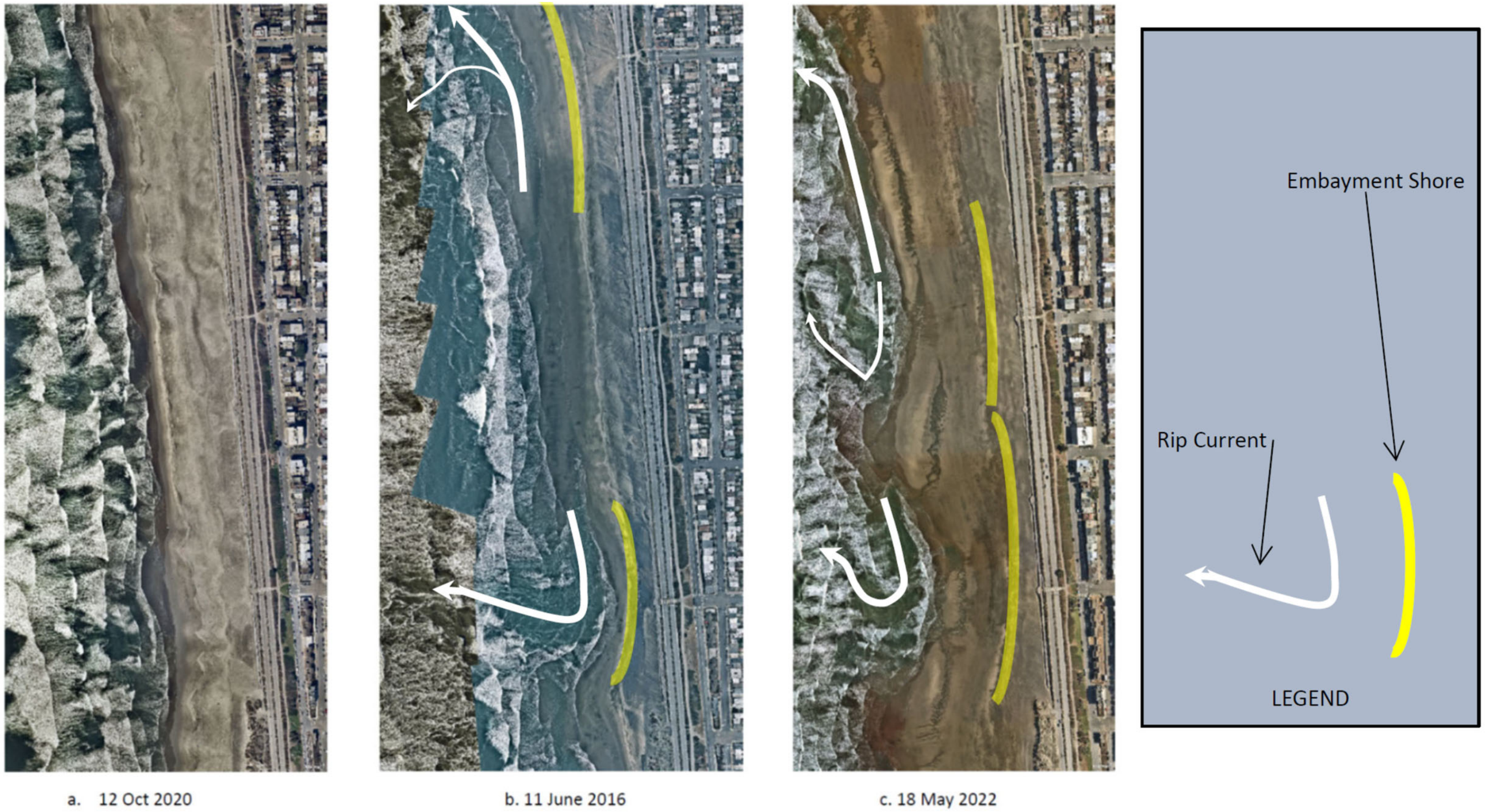
The shore zone analysis focuses on conditions following the last major intervention in the 1980s-1990s, which was the construction of sewer infrastructure and associated dune and seawall construction. Beach management has been fairly consistent to date, with the exception of sand placement to enhance beaches in southern Ocean Beach mostly after 2010 and the increase in wind-blown sand problems (see ***Historical Context***). Shoreline and dune toe lines in the early 1990s were documented via surveys and aerial photograph interpretation (MNE 1993), providing a useful starting point for shore change analyses. More recent shoreline positions were located from aerial photography, lidar and ground survey. Historical ground photographs were used to inform interpretation of the shoreline data, and better characterize shore conditions.

More recent aerial lidar and photographs were reviewed and used to map shorelines with georeferencing accomplished in a GIS format. Shorelines were primarily associated with high tide lines, often using the wet-dry line (aka ‘wetted bound’) as a surrogate although the oldest are wrack lines from USCGS “T-sheets” and are associated with wave runup and hence likely biased landward. Dune toe lines are defined as the break in slope between the relatively flat beach and the upward sloping sand dune face although the limit of vegetation is used as an indicator and generally the dune toe location can be difficult to define. Hence, neither the ‘wet’ high tide lines nor the dune toe lines were precisely mapped and georeferenced. A description of accuracy can be found in MNE 1993 and USGS 2006; 2007.

Rip Embayment Constraint on Seaward Dune Extent

Rip currents are seaward flowing currents forced by elevated water levels at the shore caused by breaking waves driving water shoreward. The rip currents affect sand transport and can scour channels through the surf zone, with both the rip current and the change in depths affecting wave patterns. Under certain conditions, a synergy develops and the rip-wave pattern results in an small embayment where the shoreline erodes landward at the rip location. The resulting narrower beach allows wave runup to extend farther landward and erode dunes. Additional information can be obtained from Thornton et al 2007, who found strong correlation with dune erosion and rip embayments and rip currents in southern Monterey Bay.

Rip currents occur throughout Ocean Beach and vary in intensity and morphologic response with the seasons as largely driven by the intensity of incident waves. Offshore depths focus waves toward the middle of Ocean Beach, resulting in recurring strong rip currents and a landward shift in the winter shoreline between Noriega and Santiago cross-streets (Reach C, **Figure 11**). The rip embayments result in an amplified shore response to waves, and a more landward extent of the active shore zone constraining dune persistence.



Three photographs of middle Ocean Beach between cross streets Noriega (top) and Santiago (bottom, just beyond extents shown).(a) Fall conditions with seasonally wider beach and suppressed rip embayment. (b) Late Spring conditions at low tide showing defined rip embayment at Rivera Street with a smaller version of Noriega Street. (c) Late Spring conditions at low tide showing defined rip embayments at Rivera Street and Pacheco-Noriega Street.

Photograph source: NeapMap.

Figure 11
Rip Current Embayments.

Overview of Analysis

After a review of the shorelines, a subset were selected to characterize the 'envelop' of plan-view shore and dune toe locations. The envelop is approximated using:

- Extreme landward shorelines: winter-spring 1998, 2010 and or 2016, and
- Extreme seaward shoreline: fall 1992 or fall 2021.

The long-term average trends in dune and shore line changes were computed using the endpoints defined by changes between Fall 1992 to Fall 2021. Also, seasonal and large rip embayment fluctuations were approximately quantified, along with minimum beach widths and offsets to hardscape defined by the Great Highway and adjacent seawalls.

Figure 12 shows the sections of shore, called "Reaches" used in this analysis, along with the location of cross-shore elevation Profiles selected to be representative of the Reaches:

- Reach A: North of Lincoln Way, along the O'Shaughnessy Seawall;
  - North Ocean Beach in OBMP (SPUR et al 2012)
  - Profile A located across from Golden Gate Park (same location as OBMP Profile D).
- Reach B: Between Lincoln Way and Noriega Street
  - North portion of Middle OB in OBMP
  - Profile B1 located just north of Kirkham Street
  - Profile B2 located just south of Moraga Street (same location as OBMP Profile C).
- Reach C: Between Noriega and Santiago Streets
  - Middle portion of MOB in OBMP
  - Profile C located just south of Rivera Street (same location as OBMP Profile B)
- Reach D: Between Santiago Street and Sloat Boulevard
  - Southern portion of MOB in OBMP
  - Profile D located near Wawona street.

Figure 13 is a plot of the five shore elevation profiles (A, B1, B2, C and D) representative of the four reaches (A, B, C and D). Two profiles are provided for Reach B to better characterize the inflection from accretion (B1) and erosion (B2).

Figure 14 shows the mapped dune toe shorelines for the four reaches.

Figure 15 shows the mapped high tide shorelines for the four reaches.

Figures 16 and 17 provide color coded elevation maps based on lidar for Area B and D, respectively.

Table 1 is a summary of metrics derived from the shoreline analysis.

Figure 12
Plan View of Ocean Beach Profiles

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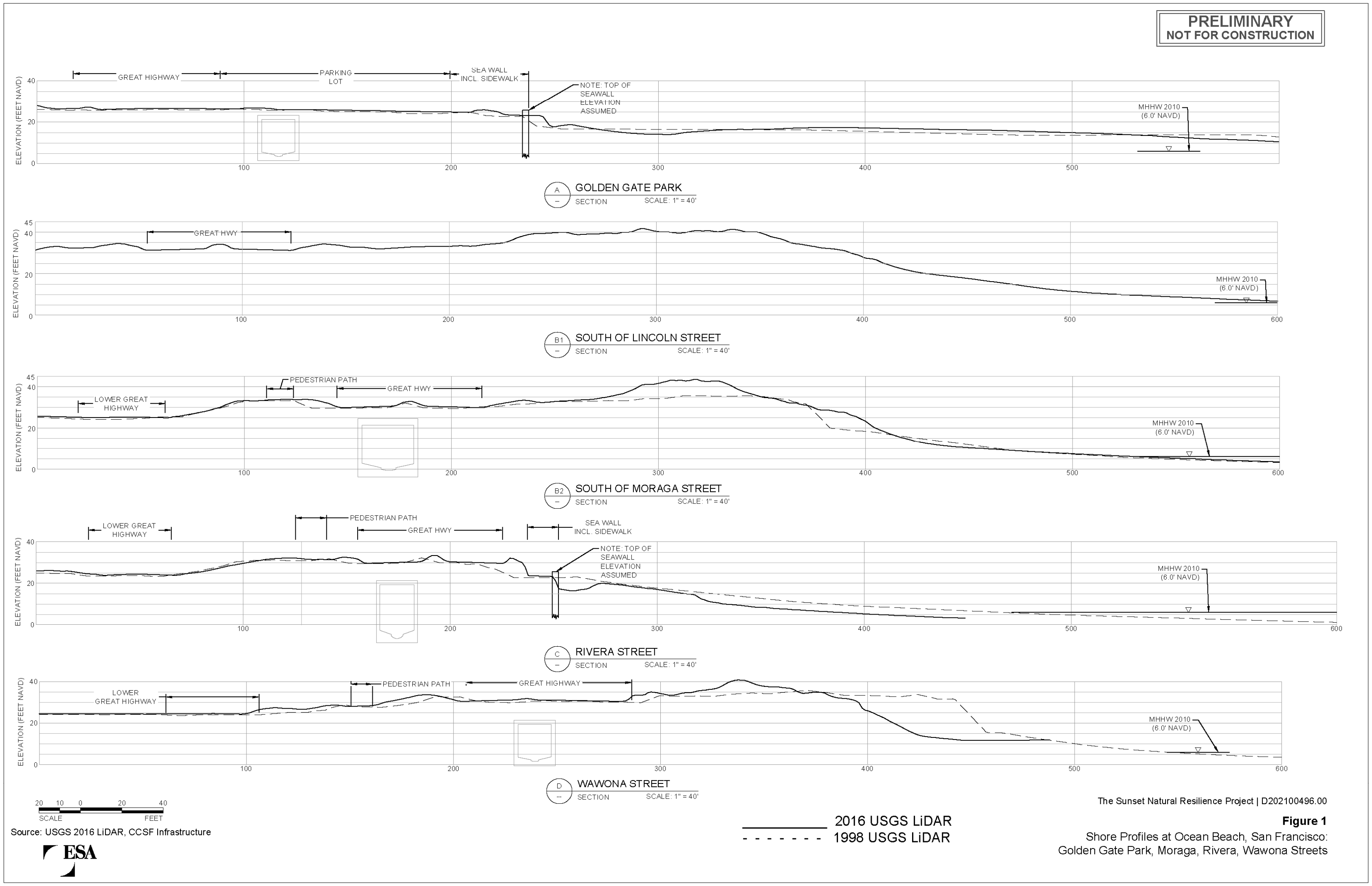


Figure 13

Elevation profiles representative of Reaches A, B, C and D. Source: adapted from ESA 2012 for this project.

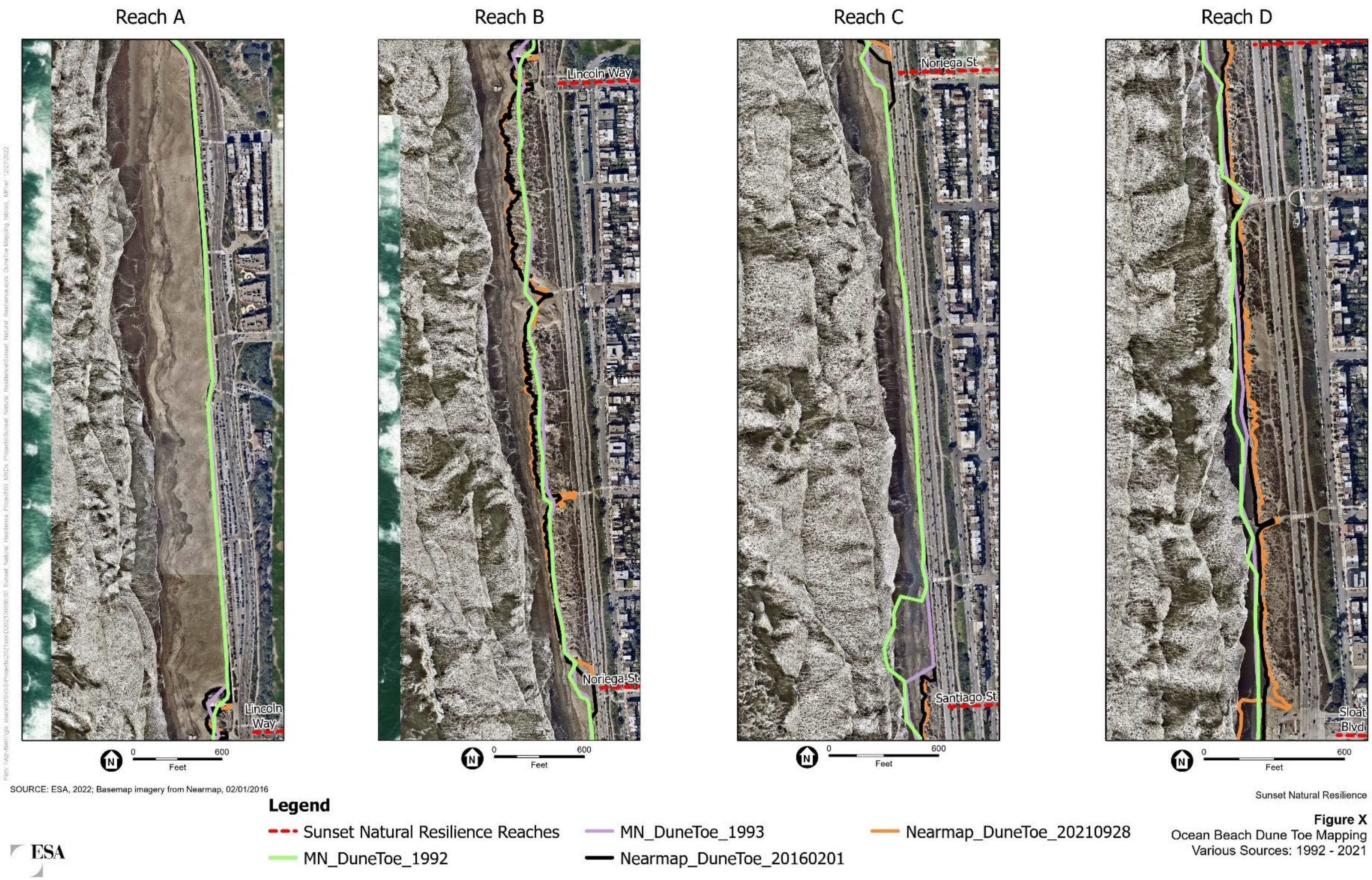
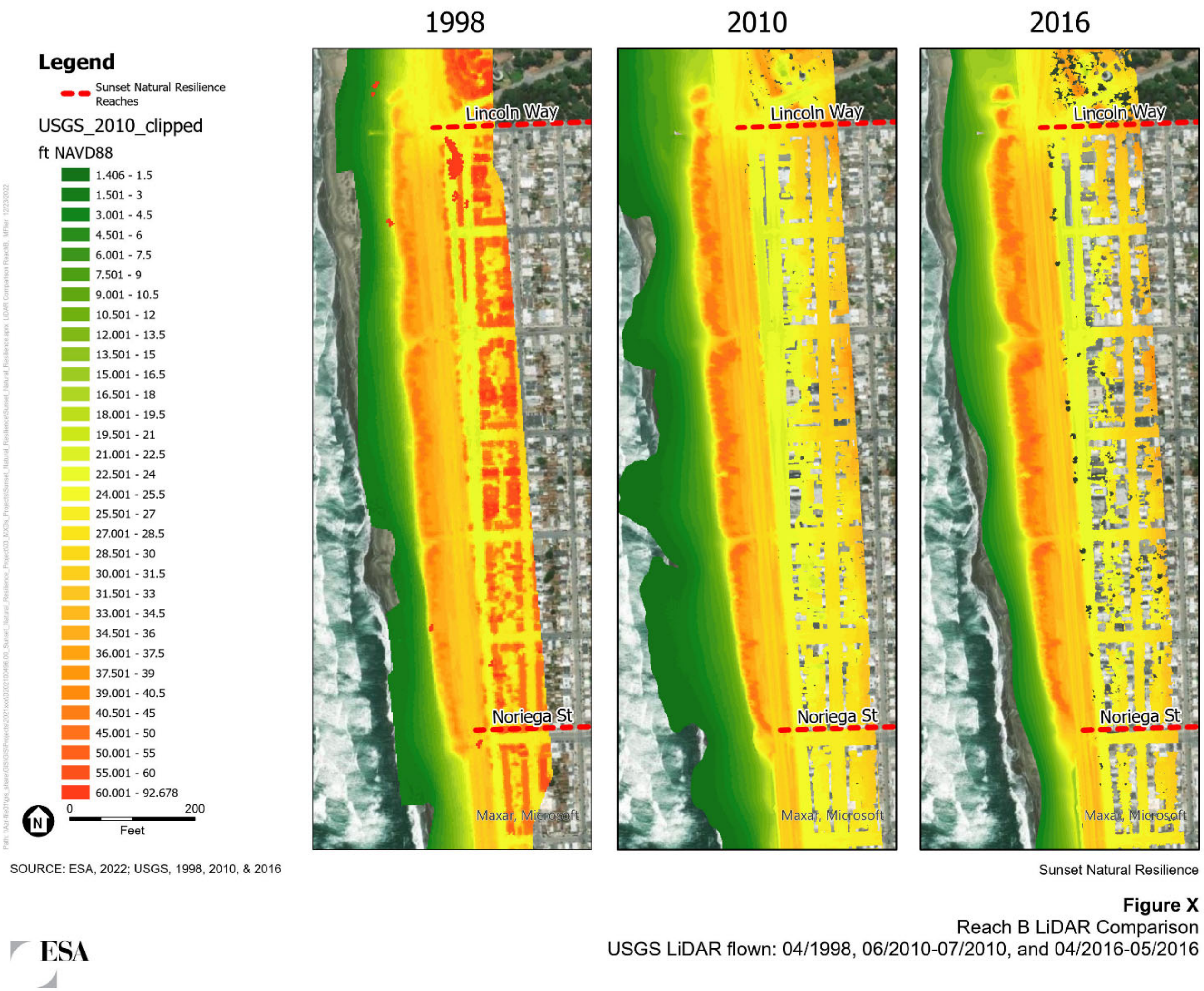


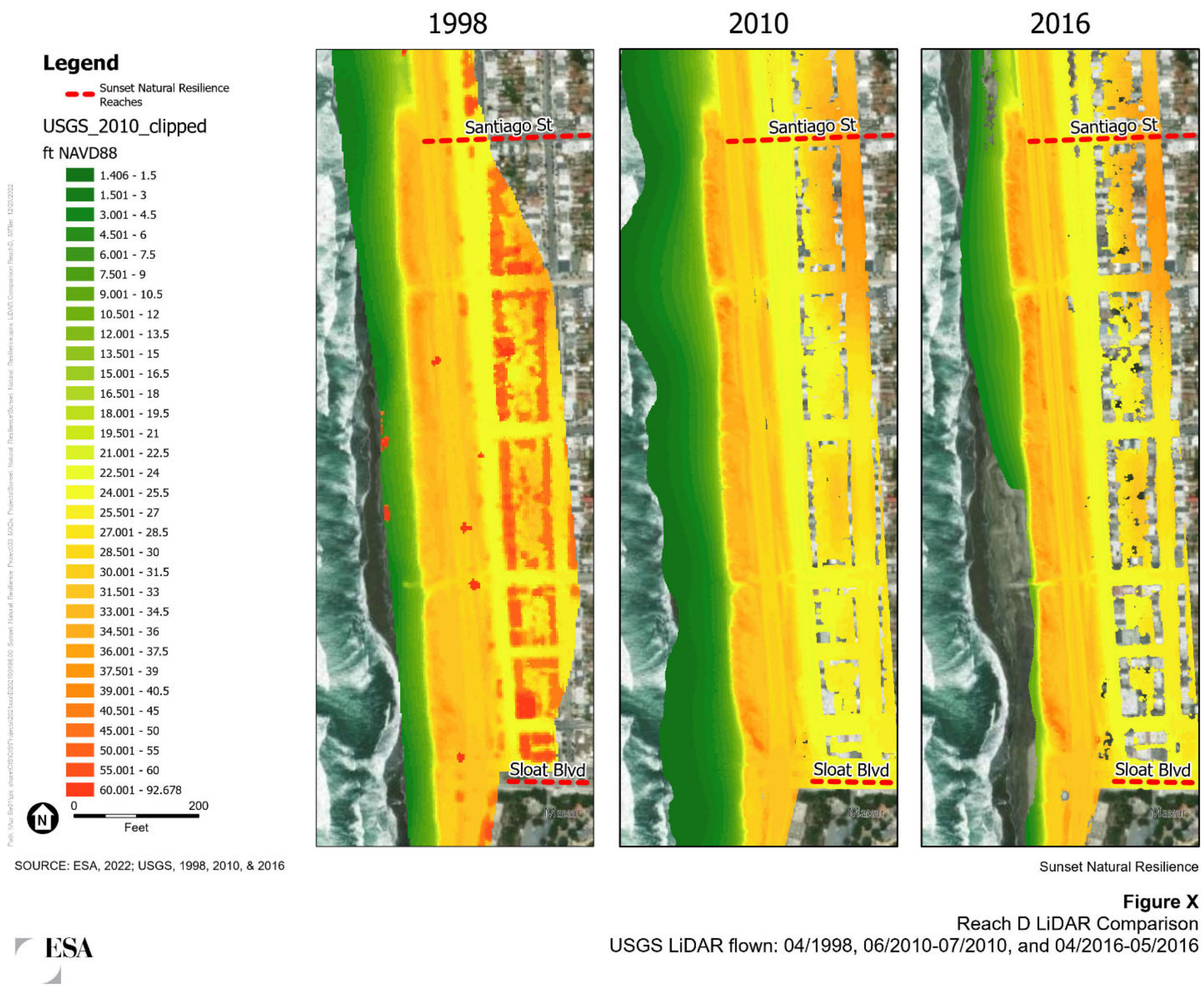
Figure 14
Selected dune toe shorelines.

Figure 15
Selected high tide shorelines.



Constructed using lidar collected in 1998, 2010 and 2016 for Reach B. Dune accretion is apparent except for the vicinity of Noriega Street and pedestrian paths where erosion is apparent.

Figure 16
Reach B Elevation maps.



Elevation maps from lidar collected in 1998, 2010 and 2016 for Reach D. Dune erosion is apparent.

Figure 17
Reach D Elevation maps.

TABLE 1
DUNE AND HIGH TIDE SHORELINE METRICS BY REACH. NOTE THAT REACH A HAS LOW HEIGHT LINEAR DUNES THAT ARE UNVEGETATED (BAYE 2023): THESE DUNES ARE INCLUDED IN THE BEACH WIDTH.

		DUNE			BEACH							
REACH	Length (ft)	Width = Offset, hardscape to dune toe (ft)	Dune Width Change fall 1992 to fall 2021	Dune Width Change Rate 1992 to 2021 (ft/year)	Beach width 9-28-2021 (ft)	Min beach width (ft)	Min beach date	Seasonal Change fall 1992-spring 1993 (ft)	Extreme seasonal change (ft)	Beach width change fall 1992 to fall 2021 (ft)	Beach width change rate 1992 to 2021 (ft/yr)	comments
A	4400	0			700	450	2-2016	60	240	200	6.5	Seawall; Note because of accretion, neglected 1998 eroded condition;
B	4200	300			250	60	4-1998	70 (0 - 140)	190			Gradient alongshore;
north			100	3.3						140	4	Lincoln
mid			70	2.3						0	0	Kirkham-Lawton
south			50	1.7						-140	-4	Noriega
Ave			73	2.4						0	0	
C	3400	0			250	100	2-2016	70	150	0	0	Gradient alongshore; New Seawall; highly variable shore position with large rip embayments
north					300	150			50' +100 rip embayment	-100	-3	Ortega -Pacheco
mid					230	80			150' 2-2016	0	0	Pacheco- Quintara
south					250	100			50'+100 rip embayment	-100	-3	Quintara-Rivera
ave										-67	-2.2	
D	2800	150			150		2 - 2016	50	100	-100	-3	Along shore gradient
north			-100	-3.3		50						Rivera -Santiago
mid			-40	-1.3		0						Santiago-Taraval – Ulloa (seawall)
south			-60	-2.0		50						Ulloa – Sloat
Average			-66	-2.2		33				-100	-3	
Average			16	0.5						27	0.9	Weighted by shore length

Interpretation

Our interpretation of the shore data is provided as an (a) Overview and (b) by Reach.

Overview:

Ocean Beach is very dynamic in response to waves, winds and water levels, and is also affected by management activities. Winter conditions result in narrower shores with wave runup reaching the backshore dunes and seawalls with the exception of Area A (wide beach and limited dunes).

The distance between the hardscape (Great Highway, parking) and the high tide shoreline during fall is about 700 feet in Area A, and decreases to 500 feet in Area B, to 300 feet in Area C and to 150 feet in Area D. During the winter the distance decreases by 50 to 70 feet, with extreme fluctuations of 240 feet in Area A and decreasing to 150 feet in Area D.

Beach widths, defined as the distance between the high tide and dune toe shorelines, have typical (minimum) values ranging from 700 feet (450 feet) in Area A to 250 feet (60 feet) in Area B, to 250 feet (100 feet) in Area C and 150 feet (50 feet) in Area D.

The northern shore is accreting and the southern shore is eroding, with the transition between accretion and erosion in Area B (for high tide shoreline) and Area C (for dunes). The linear dunes in Area B are accreting while those in Area D have eroding back to the historical earth and rubble embankment of the Great Highway.

Reach A:

Reach A consists of an artificially (graded) wide dry beach backed by a seawall and promenade. The shore accreted 200 feet from 1992 to 2021 (an apparent rate of 6.5 feet per year). Our geomorphic interpretation is that the shore accretion is near a maximum due to anticipated sea level rise (OBMP 2012) and transport toward the north past Point Lobos (Battalio 2014). There is adequate space (about 400 feet) between the active shore and seawall for dunes to persist. Of note, borrow for sand back pass is close to the seawall and it would be better located closer to the shore where coarser sand is replenished by wave action and to provide space for dune establishment.

Reach B:

Reach B consists of a relatively wide vegetated dune embankment approximately 300 feet wide which widened an average of 2.4 feet per year between 1992 and 2021, ranging from 3.3fpy at the north (near Profile B1) to 1.7fpy at the south near Noriega Street. The high tide shore and beach width accreted about 140 feet (about 4.4fpy) at the north near Profile B1 but eroded about 140 feet (-4.4fpy) at the south near Noriega Street. We interpret that the dunes have already adjusted to the maximum space available and, despite the recent accretion, will likely not practically sustain much additional dune growth seaward due to sea level rise. Pedestrian trampling of vegetation is apparent and has likely contributed to sand migration onto the Great Highway, primarily south of Kirkham.

Reach C:

Reach C consists of a narrow beach fronting a seawall. The high tide shoreline in this area has a concave planform owing to wave focusing, with amplified erosion and rip embayment formation during high wave events: Runup has reached the seawall, including on January 5 2023 (**Figure 18**).

Wave runup reached the seawall in Reach C on January 5 2023. Video footage from the same day show water overtopping the wall and water flowing along the promenade, but not reaching the Great Highway. Photograph by Michael Friedman, ESA.

Figure 18
Wave runup at New Seawall in Reach C.

Minimum beach widths are about 70 feet although typical winter beach widths are greater, approaching 100 feet. The Reach-average trend in shore change is neutral, showing neither accretion or erosion, between 1992 and 2021, except for the northern and southern ends which indicate erosion of about 100 feet.

Our interpretation is that there is space for foredunes with a footprint of less than 100 feet. We expect that the vegetation will be impacted by severe wave events on the order of once every 10 to 30 years, becoming more frequent with sea level rise. However, the dunes would likely mitigate wind transport of sand toward the seawall and Great Highway, and incrementally dissipate wave runup.

Reach D:

Reach D is narrow and eroding. The high tide shoreline receded about 100 feet (3.3fpy) between 1992 and 2021 while the dune toe eroded an average of 66 feet (about 2.2fpy). The sand placed in the 1980s-1990s linear dune embankment was mostly eroded by 2016 exposing compacted earth and rubble (**Figure 19**). Recently, wind has caused sand to deposit and form a low incline (ramp) but this feature appears temporary. The Taraval Seawall allows a small veneer of sand to persist seaward of adjacent areas with less of a scarp and more vegetation (**Figure 20**).

Eroded dune embankment south of Taraval Street with rubble exposed. March 11 2016. Photograph Bob Battalio ESA.

Figure 19
Dune Toe Reach D.

Figure 20
Taraval Seawall Vegetated sand embankment 'dune' perched on the Taraval Seawall. March 11 2016. Photograph Bob Battalio ESA.

Our assessment is that reconstruction of the linear dunes in Area D is required to maintain a beach, consistent with the initial actions in 1980s-1990s and associated permit conditions and sand management plans. These dunes will be sacrificial in terms of eroding progressively during high wave events, with the eroded sand temporarily enhancing the elevation and width of beach, as has occurred over the last 30 years. It is interesting to note that prior study predicted that these dunes would be essentially denuded of sand by 2022 unless maintenance was applied, resulting in reduced beach widths and associated problems (Ecker 1990): **Figure 21** shows the recent eroded condition. Whether an ecological lift in terms of dune habitat can be realized is not clear, and to be determined by others.

Eroded shore Reach D just north of Sloat Blvd. February 10 2023. Note the large wood wrack deposited by the high wave runup in early 2023. Predicted tide about 4 feet MLLW. Photograph Bob Battalio ESA.

Figure 21
Reach D Shore in 2023.

Wave Runup Constraint on Vegetated Dunes

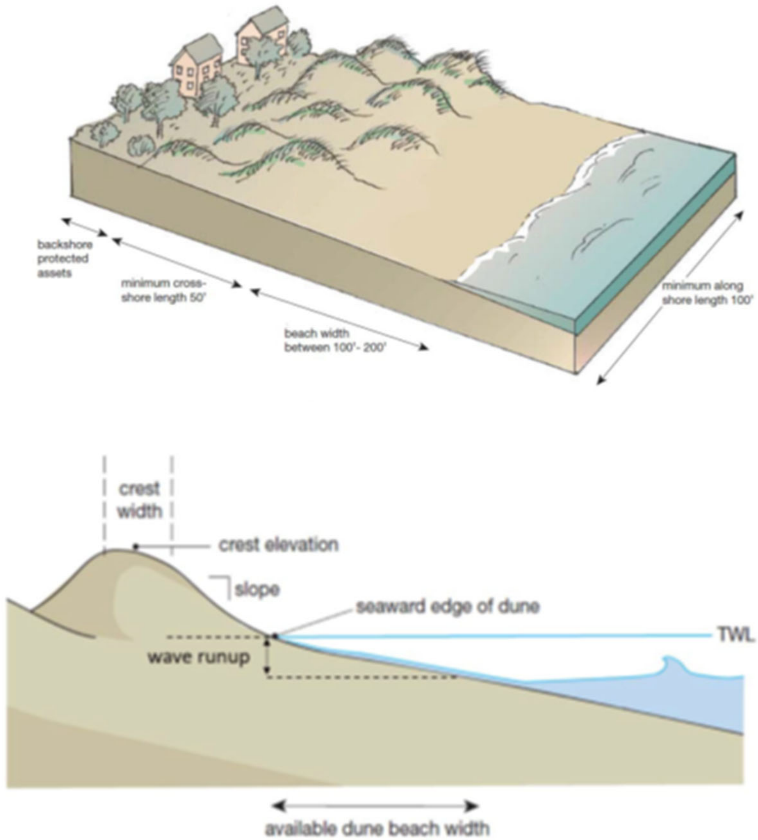
Vegetated coastal dune geometries and dynamics are the result of geomorphic processes (e.g. wind-blown sand transport) and bio-geomorphic processes (e.g. vegetation effects on sand transport) (Schwarz et al 2019), as well as littoral processes (e.g. ocean water levels and sand transport) (Ruggiero et al 2001). Vegetation and bio-geomorphic processes for Ocean Beach are addressed in Baye (2023), which is a companion report for the Sunset Project. This section addresses a Conceptual Model of Wave Runup as an indicator of the Seaward Constraint on Vegetated Dune Natural Infrastructure at Ocean Beach.

Background

California’s Fourth Climate Assessment included guidance for natural shore infrastructure to manage coastal change (Newkirk et al 2018; Cheng et al 2018). This guidance emphasized the space required to sustain geomorphic and bio-geomorphic processes, as depicted schematically below for vegetated dunes (**Figure 22**). The dimensions represent the approximate minimum for self-sustaining vegetated dunes in California. The seaward edge of the dune is defined by the location where: (1) total water level (top of ocean water level + wave runup) reaches infrequently (10 days per year or less); and (2) dry sand area during the summer is sufficient to supply wind-blown sand to rebuild dunes. Note that there is an offset between the shoreline and the seaward edge of the dune: This offset is the width of the sandy beach in the above schematics. With less space initially, or over time as the shore migrates landward, increased maintenance can be expected and at some point the dunes may not be sustainable without accommodation space for landward migration. Unfortunately, it is likely that intervention is being contemplated because space is limited owing to legacy landside encroachments and or landward shore migration. The Guidelines note that, where space is marginal, the required maintenance may not be substantial and natural shore infrastructure may be worth pursuing as an alternative. Where the available space is lacking, increasing the available space via landward realignment or beach widening are recommended. Note that these Guidelines are for screening and conceptual assessments of potential viability of vegetated dunes and other natural shore infrastructure, with more detailed site-specific assessments recommended prior to implementation.

Ocean Beach is also exposed to very large waves and has an active surfzone and beach system with wave runup that reaches the existing sand dunes annually in most locations. Conceptually, the space available for vegetated dunes is between the Great Highway and zone of ‘excessive’ disturbance by wave runup. While the threshold of ‘excessive disturbance’ is not quantified, we perceive it to be related to the intensity and frequency of erosion that impedes re-establishment of dune vegetation, essentially destabilizing dune bio-morphology. For historical reference, dune toe elevations reached about +22’ elevation in the 1990s and 1950s with wide beaches and was as low as +11’ elevation in the 1970s when beaches were narrow and low (Tables 4-10 MNE 1994).

In this section we approximately quantify the seaward dune limit in terms of elevation and beach width, driven by wave runup between the winter shoreline and dune toe.

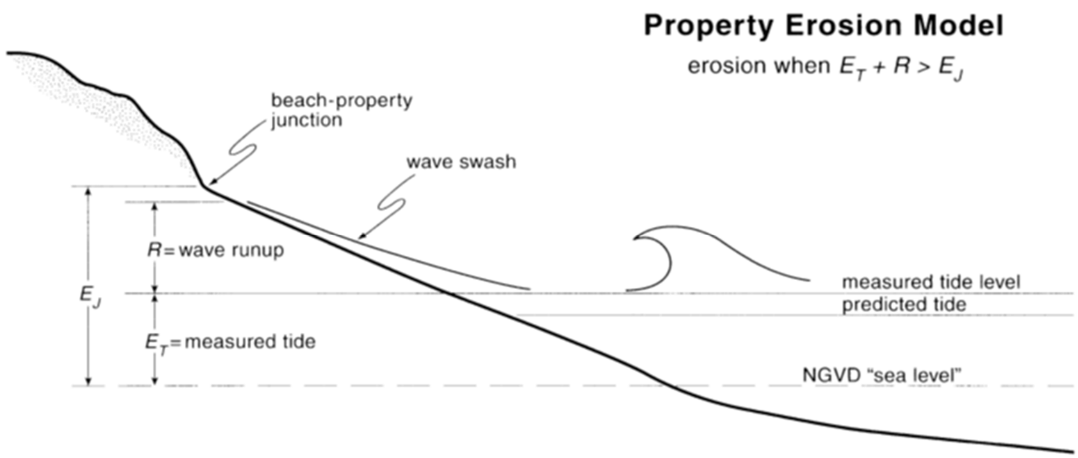


Schematic representation of spatial parameters associated with vegetated dune natural shore infrastructure for shore adaptation. Desired beach width seaward of dunes is 100 to 200 feet, and seaward-most dune toe location is far enough landward that wave runup extends to the dunes no more than 10 days per year. Source: Newkirk et al 2018.

Figure 22
Vegetated Dune Guidance

Conceptual Model of Wave Runup constraint on Dune Toe Location

The seaward limit of the dune toe is correlated with the landward extent of excessive disturbance by high ocean water levels, apparently related to erosion of substrate and or salinity, depending on vegetation and the also the frequency of damaging events and sand supply (Hesp 2013). The linkage between wave runup and seaward extent of dunes is characterized in terms of wave runup in **Figure 23** (Ruggiero and others 2001): The 'beach-property junction' in the figure is a generic term for a range of backshore conditions, which in our case is a sand dune toe or seawall. This location is labeled E_j which refers to an elevation which is compared to the elevation of wave runup. As the equation indicates, when the wave reaches the backshore, there is a potential for dune erosion. Note that the space between the shoreline defined by the ocean tide level (labeled E_t) and the dune toe (E_j) is the space occupied by wave runup, which in our case is equivalent to the beach width. The authors found that dune erosion occurs when the wave runup reached the dune toe on the order of 10 hours per year or more, and dunes were stable to accreting (growing seaward) if the runup reached the toe less than an hour per year. The authors point out that these elevations are location specific, affected by tides, wave exposure, and shore conditions. The dune erosion conceptual model proposed by Ruggerio et al (2001) is similar to others (e.g. Komar et al 2002; Kriebel and Dean (1993)) and additional discussion can be found in the Pacific Coast Guidelines for FEMA Flood Studies (FEMA 2005).

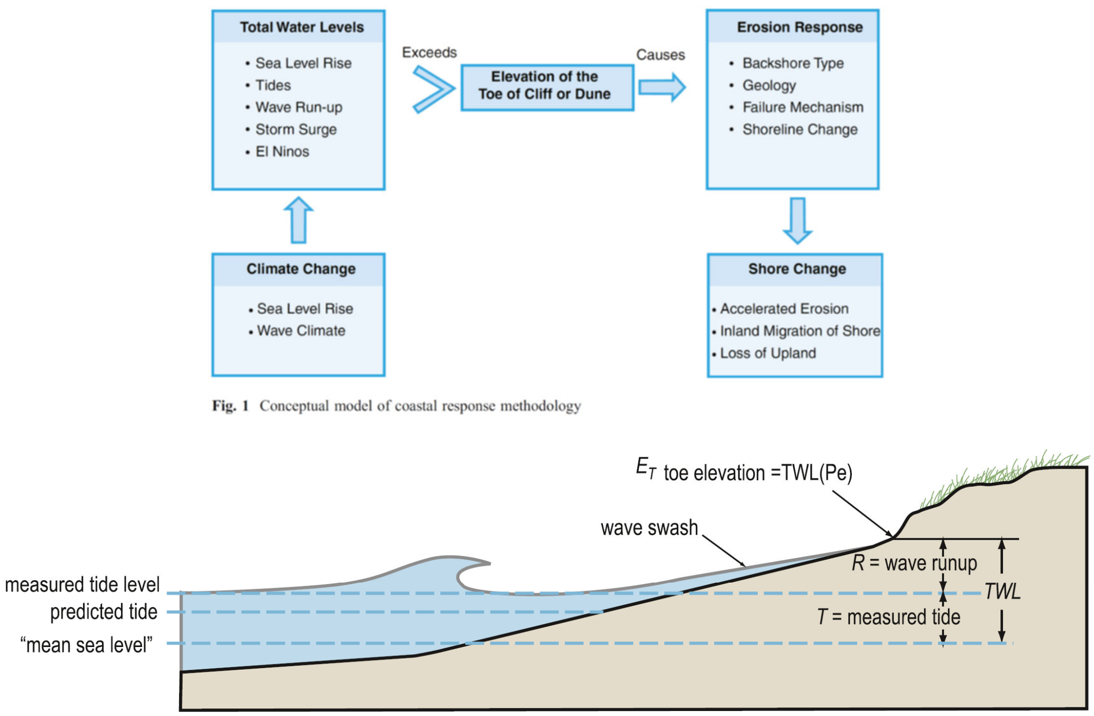


Schematic of dune erosion conceptual model relating the seaward extent of a vegetated dune relative to the landward extent of wave runup. Source: Ruggiero et al 2001.

Figure 23
Dune Erosion Schematic

This conceptual model has been adopted in coastal engineering practice to predict dune erosion during storm events (FEMA 2005) and extended to future conditions with sea-level rise (**Figure 24,** Revell and others 2011), and applied in California's Coastal Resilience exposure mapping (e.g. Los Angeles County AdaptLA, ESA 2016). Note that these references use the term *Total Water Level (TWL)* which is simply the elevation of the runup, and computed by adding the runup height to the ocean water level. Additional information is provided in the following section ***Wave Runup, Total Water Level, Dune Toe Elevation and Winter Beach Width at Ocean Beach***.

More recent research has shown that wave runup can result in sand deposition and accretion of the dune in some cases, apparently when the back beach slope is flat (i.e. flatter than 0.03[2]) and when the ocean water levels are not substantially elevated (Cohn et al 2019). A further complexity is that the dune toe elevation (Ej) and location vary along shore and on several time scales (Cohn et al 2019): For example, during shore erosion the beach elevation typically lowers and an erosion scarp can form at the dune toe, leading to the Ej lowering (Collins and Sitar, 2008). Also, wave runup is difficult to measure. Hence, application of the conceptual model benefits from use of reference sites, field data and calculations to increase confidence in estimates.



Top: Extension of the Ruggiero and others 2001 conceptual model used to map future coastal erosion and flooding with sea-level rise in California. Bottom: Total Water Level (TWL) is defined as the sum of ocean level and wave runup on the shore. Source: Revell and others 2011.

Figure 24
Conceptual Model of Dune Erosion with Sea Level Rise

[2] The slope is defined as the vertical change divided by the horizontal change. Hence 0.03 = 1/33 and can also be written as 33:1 (horizontal:vertical) meaning that the beach drops one foot for every 33 feet of horizontal distance.

TWL exceedance Field measurements and modeling by Cohn et al 2019 can be used to quantify TWL exceedance thresholds for application to Ocean Beach. We interpret **Figure 25** to indicate:

- Dune Erosion Threshold (panel g): Dune erosion is less likely when the TWL exceeds the dune toe less than 50 hours per year (~ 0.6% of the year).
- Dune Erosion Extent (panel g): When TWL exceeds the dune toe elevation by about 100 hours per year (~ 1.1 % of the year), dune erosion of about 2 m^3/m or shore can be expected to erode. This threshold was selected because 2 m^3/m (21.5 ft^3 per foot of shore) is consistent with a ~2 foot vertical scarp identified as a maximum scarp height for dune grass recovery (Baye 2023)[3].

[3] A triangle with height of 2 feet and length of 20 feet ~= area of 20 square feet and is consistent with a flat slope of about 10:1

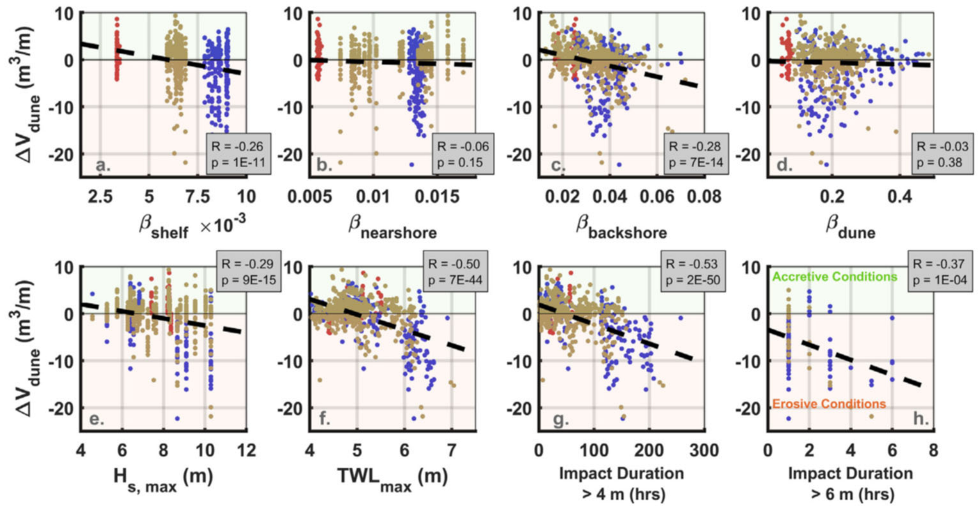


Fig. 8. Field observations of dune volume change compared with relevant morphometric property (a–d), maximum wave height calculated between topographic survey dates (e), maximum TWL calculated between topographic survey dates (f), duration of TWLs above 4 m (g), and duration of TWLs above 6 m (h) at the three field sites (SBSP tan; NLC, blue; OSYT, red). Least squares linear regression fits are also plotted between each morphometric property and ΔV_{dune} with corresponding correlation coefficients (R) and p-values. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

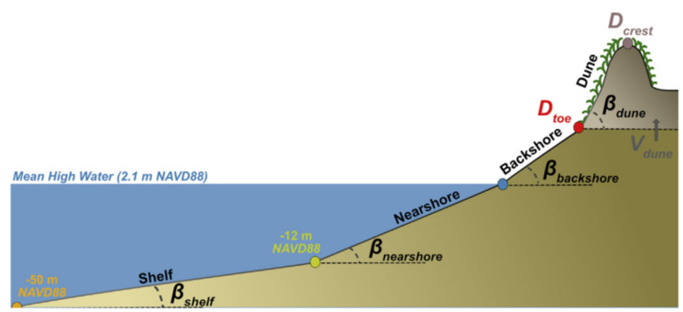


Fig. 3. Definition schematic of morphologic parameters, including shelf, nearshore, backshore, and dune slopes and dune crest/toe, extracted from field datasets and used to generate synthetic profiles for input to XBeach.

Measurements of dune geometry and wave runup in Oregon. Note panel C which indicates increased dune erosion potential with increased backshore slope. Also, note that the site represented by red circles has a relatively flat slopes (panels a – d) and has the lowest erosion potential. Panel g indicates that dune erosion is limited when TWL exceeds the dune toe (nominally elevation 4 meters at the study locations) about 50 hours per year, while erosion is likely at and above 100 hours per year: These values correspond to about 0.6% and 1.1% exceedance per year. The bottom figure defines the different slopes, and locates the dune toe (Dtoe). Source Cohn et al 2019.

Figure 25

Quantification of dune parameters and wave runup

- Beach Width from Shore Slopes (panel c): Dune erosion correlates with the slope of the back shore (between the dune and the shoreline, essentially the beach), with flatter sloped backshores less likely to have dune erosion. Note that a flatter slope indicates a wider beach fronting the dunes, given the same nominal dune toe and shoreline elevations. Based on the slopes in (c) and the nominal beach height of about 6.2 feet[4] in the study area, beach widths were mostly greater than 100 feet. Hence, the Dune Erosion and Extents are associated with beach widths of greater than 100 feet. Since wave runup is dissipated over its travel distance, the beach width fronting the dunes is as important as the dune toe elevation. Beach width is also easier to use than beach slope from a data collection and engineering perspective.

The above interpretations are applied in the next section using data from Ocean Beach.

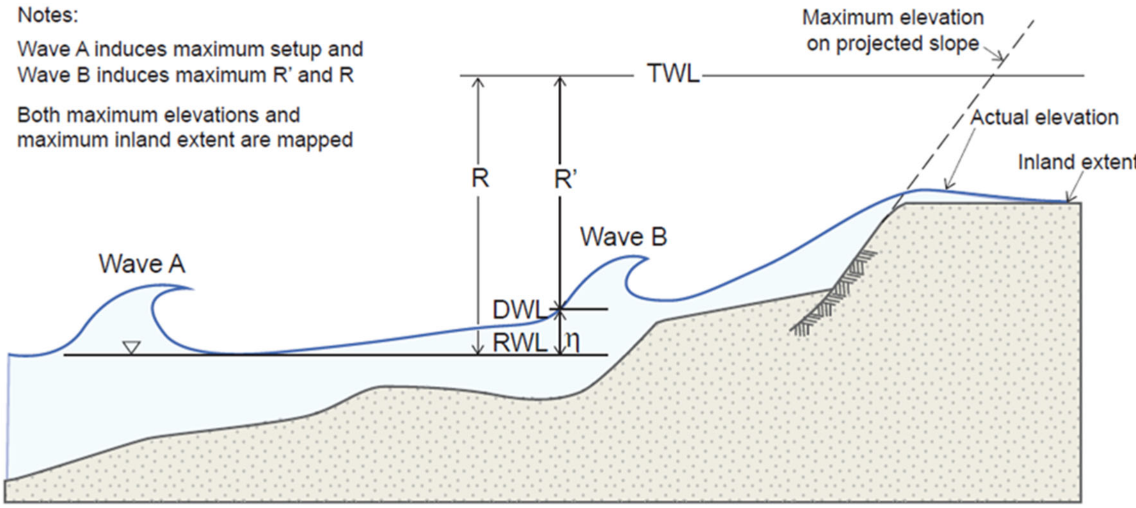
Total Water Levels and Dune Toe Elevations at Ocean Beach

Wave runup is the uprush of water over land driven by the momentum of waves breaking on the shore. There are several components that contribute to the wave runup (also called ‘wave uprush’), and these are typically called setup (wave setup fluctuates and is sometimes split into the average (aka ‘static setup’) and fluctuating (aka ‘dynamic setup’) components) and runup (also called swash) (MacArthur et al 2006). Total Water Level (TWL) is the elevation of wave runup and is computed as the wave runup magnitude added to the ocean water level, variously called ‘tide level’, Still Water Level (SWL) and or Reference Water Level (RWL) (Battalio et al 2016). **Figure 26** is a schematic of these components. Note the emphasis on wave setup caused by waves breaking offshore, which is important at Ocean Beach and other coasts exposed to large swell.

- Wave runup and total water level elevations were computed at the project profiles (A, B1, B2, C and D). TWLs were computed using the Stockdon Equation (Stockdon et al 2006) and an average of the 2010 and 2016 profile nearshore slopes. The TWL exceedance curves are shown along with the previously described dune erosion thresholds derived from Cohn et al (2019) in **Figure 27** using vertical lines.
- The elevations for Profile B2 are provided in the legend as a reference, because this curve provides the approximate median of all the TWL exceedance curves[5]:
- Dune Erosion Threshold, 0.5% TWL exceedance corresponds to approximately +13’ NAVD dune toe elevation;
- Dune Erosion Extent, 1.1% TWL exceedance corresponds to approximately +12’ NAVD dune toe elevation.

[4] The backshore slope was computed between the dune toe (4m) and MHW (2.1m) indicating a height of 1.9m = 6.2 feet. 6.2 ft divided by a slope of 0.06 = ~ 100 width. Panel (c) shows most slopes < 0.06, and hence beach widths > 100 feet.

[5] Also included in Figure TWL (a) and (c) are curves from a prior study using a different data set (OPC B2 from PWA 2009) and a contemporary recalculation (SF41) for comparison. The prior study used climate model outputs of synthetic water levels and waves for 2000 to 2100 produced by Scripps Institution of Ocean Oceanography (Bromirski et al 2012) and unpublished wave transformations provided by the Coastal Data Information Program (CDIP): The recalculation used contemporary transformed wave time series from CDIP and real measured water levels for the period 2000 to 2023. We note that the curves for OPC B2 and SF41 are similar and differences are likely due to the shorter data record which does not include larger TWL events. Curve B2 is similar to OPC B2 and SF41 curves, which provides confidence in the precision of these results.



TWL = Total water level = RWL + R

RWL = Reference water level ~ still water level

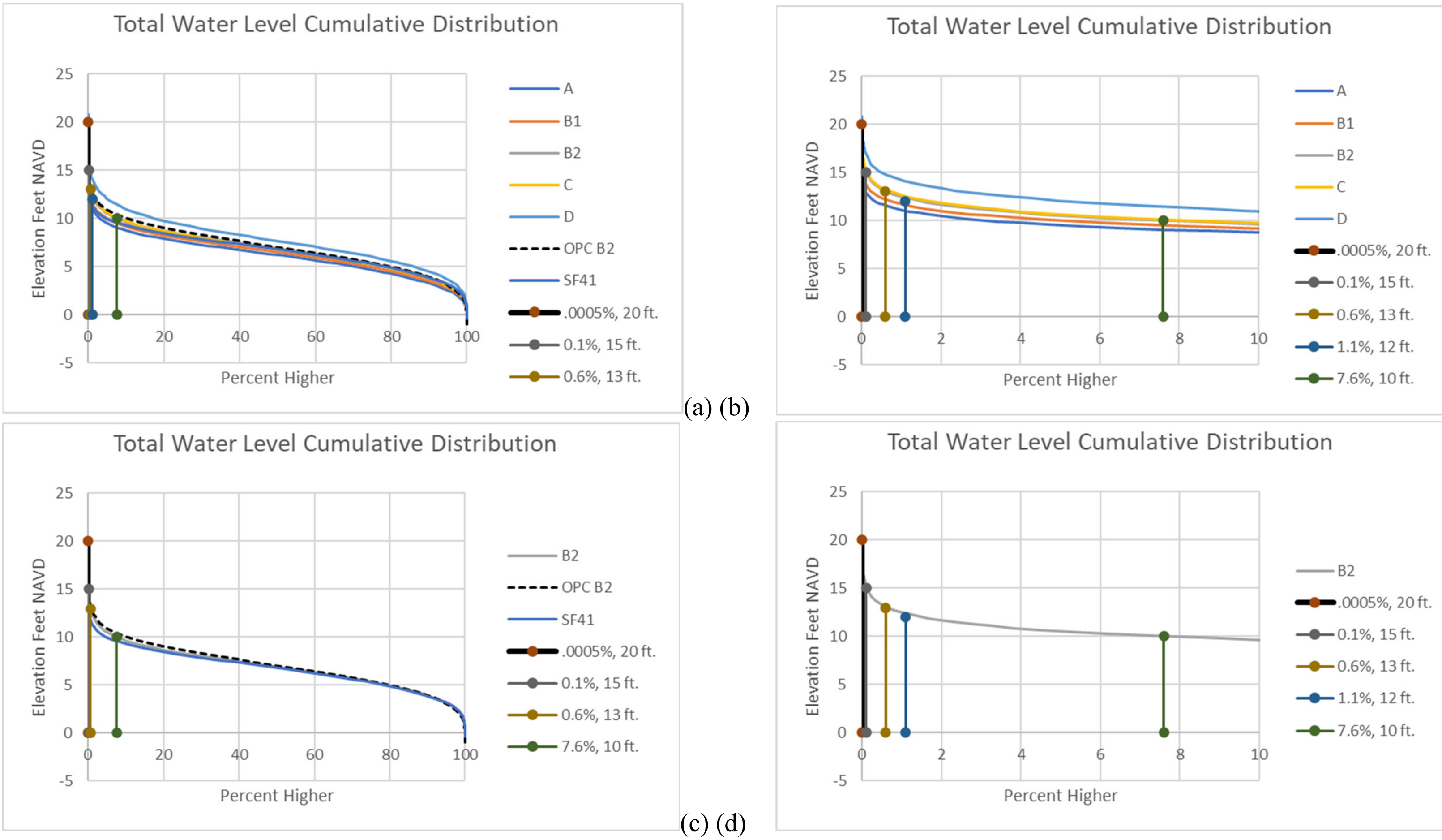
DWL = Dynamic water level, typicallly 2% exceedence ~ mean setup (aka “static”) + 2x standard deviation

η = 2% setup at RWL shoreline, wave A

R = runup, including setup, above RWL, wave B typically on projected slope above back shore

Total Water Level (TWL) = Ocean Water Level (RWL) + Runup (R). FEMA flood maps indicate the potential elevation based on extending the backshore slope, to inform potential development on this ‘edge’. In this study, we are using the elevation of the inland extent on a beach. Source Battalio et al 2016.

Figure 26
Total Water Level definitions



. Each figure plots the Total Water Level (TWL) elevation for the labeled location at Ocean Beach in terms of percent exceedance: Low percent exceedance is associated with a high TWL elevation, and vice versa. Also shown are vertical lines at TWL precent exceedances indicative of dune erosion thresholds based on published values ((0.6 and 1.1 percent) and dune toe elevations measured at Ocean Beach following erosive winters (20, 15 and 10 feet). (a) All curves; (b) All curves to 10%; (c) Median curve B2 compared to OPC B2 and SF41; (d) B2 up to 10%.

Figure 27
TWL statistics and reference elevations

Dune toe elevations were measured at four of the five Project Profiles (B1, B2, C, and D are tabulated in **Table 2**: Profile A was excluded because the existing dunes are subtle with low relief and unvegetated (*unvegetated transverse* dunes; see Baye 2023 for additional interpretation). The TWL cumulative curves (Figure 27) were used to identify the percent exceedance for the measured dune toe elevations. The TWL and TOE values vary by location along Ocean Beach but are generally of the same order. Toe elevations are estimated to range from 10 to 20 with a median of 15 (elevations in feet NAVD). Beach widths measured from the profiles and from shoreline-duneline mapping (Table 1) are also provided in Table 2. Note that the profiles are based on surveys following winter-spring seasons with strong erosion and hence represent seasonally eroded beach conditions. The minimum beach widths from shoreline mapping are also associated with eroded conditions including the effect of rip embayments. The February 2016 shoreline location (Figure 4) can be used as a reference from which to offset to the dune toes.

TABLE 2
COMPARISON OF MEASURED DUNE TOE ELEVATIONS AND COMPUTED TWL

Reach Profile	Dune Condition	Dune Toe Elev. (feet NAVD)	TWL Exceedance (%)	Beach Width to Toe from Profiles (feet)	Beach Width from Photos and Maps (min to max in feet)
A1	Unvegetated transverse	NA [a]	NA [a]	360 to 4001	450 to 7001
B1	Accreting	15 to 20	0	140	60 to 250
B2	Accreting	15 to 20	0.1 to 0.0	120	
C	Ephemeral, disturbed [b,c]	103	8.3	55 to 85	100 to 2502
D	eroding	15	0.5	80 to 120	33 to 150

NOTES:
a. Reach A dunes are spatially ambiguous and unvegetated and hence Not Applicable (NA), and beach widths are measured from seawall to shoreline.
b. Reach C beach widths from plan-view are from seawall to shoreline and include dunes.
c. Toe in Reach C may be unvegetated scarp. Sand is graded seaward away from seawall and therefore dune formation is suppressed.

The dune toe elevations in Table 2 (10, 15 and 10 feet) are located in Figure 27 along with the TWLs percent exceedances from Cohn et al (2019).

We find that:

- Reach A: Potential vegetated dune locations can be inferred from Reach B.
- Reach B beaches are the widest (120 to 140 feet) and have the highest dune toes (+15 to +20 feet). A large range is used because these dune toes are difficult to locate, likely due to the infrequent impact of wave runup. The toe elevations have computed TWL exceedances of < 0.1%, well below the stable dune threshold of 0.5% with elevations higher (15 to 20 feet) than the stable TWL threshold (13 feet). These data indicate the dunes are accreting.
- Reach C has the largest range of beach widths (55 to 250 feet) and the lowest dune toe elevation (+10 feet). We note that the selected dune toe was likely not a purely natural feature due to the frequent grading in the area. This dune toe elevation has a TWL exceedance of about 8% which is well into the ‘eroding’ range. We note that the beach and dune in this

reach have low relief (relatively flat) which likely decreases scarping in favor of overwash. We consider the dune condition to be ephemeral, disturbed owing to the amplified beach fluctuations and mechanical disturbance.

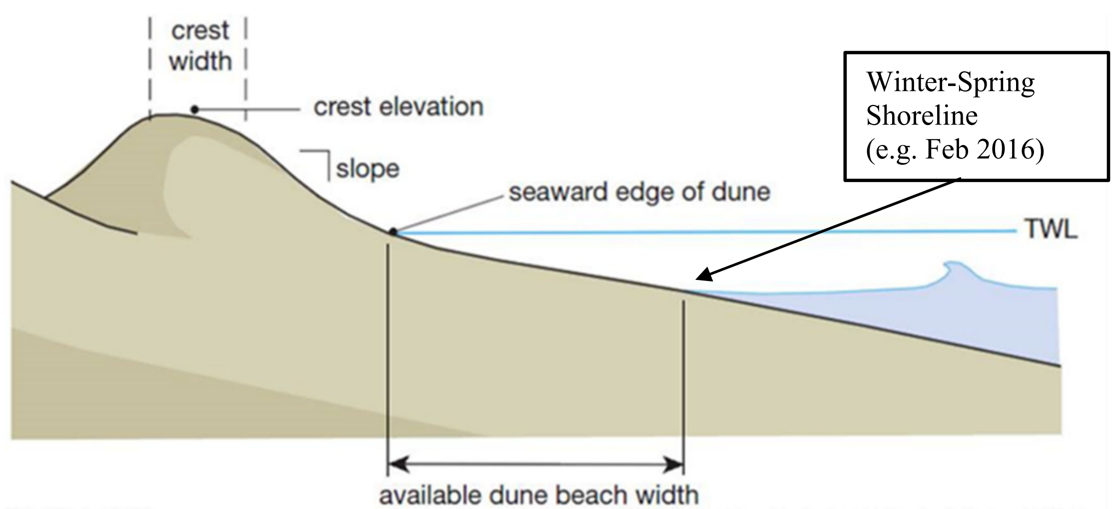
- Reach D has a median dune toe elevation (+15 feet) but the narrowest beaches based on aerial mapping and lidar-based elevation profiles (33 to 80 feet and less than 100 feet, respectively). The dune toe elevation (15 feet) has a TWL exceedance at the erosion threshold (0.5%) but the erosion threshold (1.1 %) is computed to be only one foot lower (14 feet). Our interpretation is that Reach D is eroding but the dune toe elevation is elevated due to sand supply from sand placement at adjacent South Ocean Beach and or local sloughing of sand from the eroding dunes.

In summary, while the dune toe elevations provide a geomorphic reference, the elevation fluctuates in response to TWL and varies depending on other factors (sediment supply, vegetation type, disturbances such as pedestrians and grading and backshore encroachments). Beach width emerges as an important parameter with wider beaches dissipating waves and hence reducing dune erosion. However, beach widths also vary according to the aforementioned factors affecting dune toe elevations.

Potential Seaward Extents of Dunes at Ocean Beach

The potential seaward extent of dunes at Ocean Beach is located based on a review of historical information of the Ocean Beach shore dunes and shore morphology, literature on the constraint formed by wave runup, and calculations of wave runup at Ocean Beach, as detailed in this report.

The seaward extent of dunes at Ocean Beach are located in terms of a lateral offset from aa seasonally narrow shoreline winter-spring following moderate to severe wave conditions (e.g. Feb 2016) and minimum likely elevation of dune vegetation as shown schematically in **Figure 28**.



The potential seaward edge of the dunes is located horizontally based on the minimum beach width from the reference shoreline, and vertically with the minimum elevation.

Figure 28
Beach Width Surrogate for Seaward Dune Location

There are two zones proposed, Perennial and Ephemeral. The minimum beach widths, toe elevations are summarized along with a description of their functions and limitations:

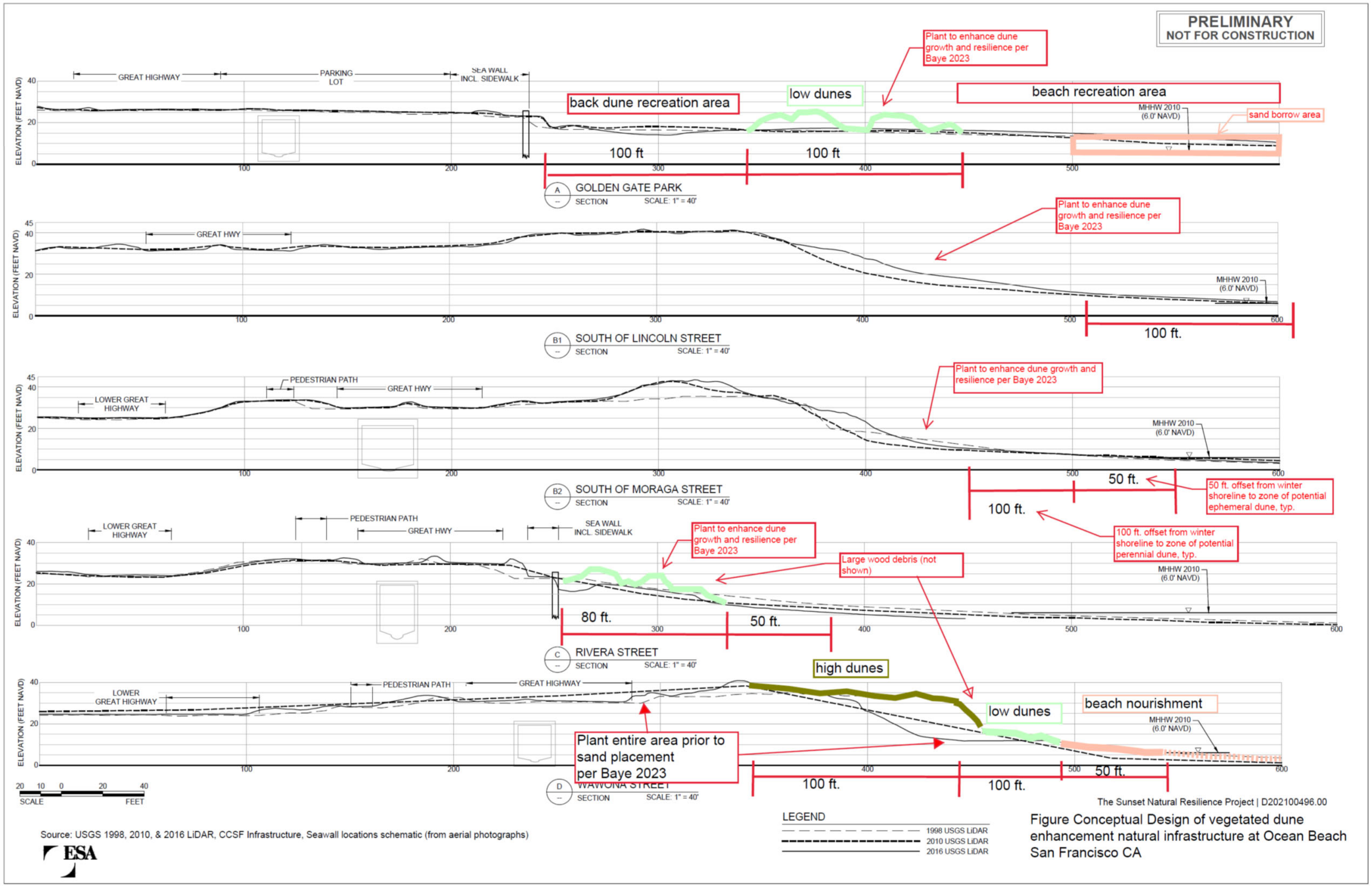
- Perennial Zone: Stable to accreting: Offset >100 feet from Feb 2016 shoreline with dune tow at or above +13':
  - Beach minimum width threshold nominally 100 feet;
  - Dune Erosion Threshold, 0.5% TWL exceedance corresponds to approximately +13' NAVD dune toe elevation;
  - Reaches A and B: High elevations, high relief dunes to trap wind-blown sand and prevent wave runup overtopping.
- Ephemeral Zone: Ephemeral, requires maintenance: Between 100 and 50 feet from Feb 2016 shoreline and dune toe above +10':
  - Beach minimum width 50 feet
  - Dune Erosion Extent, 1.1% TWL exceedance corresponds to approximately +12' NAVD dune toe elevation with erosion scarp down to +10 feet.
  - Consider use of large wood debris to provide structure and mitigate erosion.
  - Reach C: Low elevation, low relief dunes more likely to survive due to limited scarping and capture of limited wave driven sand supply. However, higher relief dunes adjacent to the seawall may reduce wind-blown sand transport more effectively.
  - Reach D: Sacrificial dune embankment to deliver sand to beach during erosive events with high elevations, high relief to also trap wind-blown sand and prevent wave runup overtopping.

Conceptual Design Vegetated Dune Natural Infrastructure

A conceptual design for vegetated dune natural infrastructure for Ocean Beach is shown on typical sections for Reaches A though D (**Figure 29**). The Conceptual design builds upon prior study at the site and technical papers regarding coastal vegetated dunes, historical data including in particular shoreline and dune toe position changes, and calculation of wave runup extents. A key driver of this conceptual design is provided by a companion report on dune vegetation and associated bio-geomorphology of coastal dunes (Baye 2023): This report provides additional basis and in particular plant types, establishment and pedestrian management needed to maintain.

Conceptual Dune Zones:

- Low relief, ephemeral: The seaward extent of the dune vegetation is at least 50 feet landward of the seasonally-eroded shore, represented by the winter-spring 2016 shore geometry. Between 50 and 100 feet, dunes are expected to eroded by waves every decade or so, and hence dunes in this zone are considered 'ephemeral' with low potential vertical relief.
  - This zone is compatible with wrack, and can be augmented with large wood to provide structure for resilience and ecology.



Natural Infrastructure at Ocean Beach San Francisco, CA

Figure 29
Conceptual Design of Vegetated Dune Enhancement

- High to Low Relief, perennial: Starting at least 100 feet landward of the winter-spring shoreline, vegetated foredunes area expected to persist with the ability to recover from erosion scarps formed by wave runup.
- High Relief, sacrificial: Zone D is eroding and has lost much of the protective dune constructed in the 1980s and 1990s. Dunes in these areas will be less 'natural' and will erode during high wave events, thereby releasing sand to maintain a beach while protecting the backshore. This is an area where sand placement is anticipated to be needed to 'restore' the landscaped dunes.
  - This zone is compatible with large wood placement (Figure 21)

The conceptual designs by Reach are briefly described:

Reach A, Typical Section A: The existing wide, flat beach and low-relief, unvegetated dune field is conceptualy divided into three zones, from the seawall, seaward:

(1) Backdune Recreation Area: Approximately 100 feet to remain open and unvegetated supporting existing uses (volley ball, fire pits) but enhanced via wind sheltering of proposed new dune field;

(2) Dune Enhancement Area: Approximately 100 feet of vegetated sand dunes with low relief (nominal heights on the order of 2 meters (6 to 7 feet)). Pedestrian access pathways through the dune field will be identified with visual guides to limit trampling of plants.

(3) Beach Recreation Area: Over 250 feet (winter - spring) to 500 feet (summer - fall) of open beach supporting existing uses.

    a. This zone will also serve as sand borrow area for future sand backpass operations in order to access the coarser sands that are rapidly replenished by wave action in this accreting area.

Reach B, Typical Sections B1 and B2: This accreting reach will be vegetated to limit wind blown sand transport, while enhancing ecology and enhancing controls on vertical and lateral access. Dune vegetation will be enhanced per Baye (2023), which will trap wind blown sand (reducing sand delivery to Great Highway), increase resilience to erosive wave events, and improve ecology. Grading will occur along the landward side around the Great Highway to create stabilized, vegetated dunes that reduce sand transport onto the Great Highway.

Reach C, Typical Section C: This reach in front of the seawall narrows substantially during the winter-spring months due to focused, elevated wave exposure that drives formation of rip current embayments. Dune vegetation will be enhanced per Baye (2023), which will trap wind blown sand (reducing sand delivery to the seawall and Great Highway), increase resilience to erosive wave events, and improve ecology. Visual fencing will be used to control vertical access through the dunes to the beach. Beach nourishment can be accommodated in this Reach seaward of the dunes. Large wood can be placed (or left in place) to add structure to the dunes.

Reach D, Typical Section D: This eroding shore has exposed rubble and earth fill during extreme winters because the previously constructed vegetated dune embankment has eroded back to the

Great Highway embankment. The design calls for reconstruction of the barrier dune with enhancements, in phases as follows:

(1) Plant desired dune grasses throughout area existing dunes in order to accumulate root rhizomes that can spread and recover vegetation following erosion events. The estimated time frame to develop adequate root stock is approximately three years (Baye 2023).

(2) Place large wood on back shore at dune toe to emulate beach wrack. The large wood will provide sand trapping and enhance vegetation establishment.

(3) Place sand on beach in order to lift and widen beach, and provide dry sand for wind-blown transport to back shore to facilitate dune growth. Coarser sands found in the vicinity of wave runup (near the shore) are recommended.

(4) Monitor and augment sand and vegetation, and install access controls to facilitate dune resilience.

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References

Battalio R.T., and D. Trivedi 1996. “Sediment transport processes at Ocean Beach, San Francisco, CA.” Proc. 25th Int. Conf. Coastal Engineering, Orlando, FL. ASCE, 2691-2704.

Barnard, P.L., L.H. Erikson, and J.E. Hansen 2009. “Monitoring and modeling shoreline response due to shoreface nourishment on a high-energy coast.” J. Coastal Res., Special issue 56, 29-33.

Battalio 2010. The Shaping of Ocean Beach. Presentation to the San Francisco Planning + Urban Research (SPUR), San Francisco, October 21, 2010 https://www.spur.org/sites/default/files/2013-09/10.21.10%20The%20Shaping%20of%20Ocean%20Beach%20-%20Bob%20Battalio.pdf .

Battalio 2013. Littoral Processes along the Pacific and Bay Shores of San Francisco, California, USA Headwaters to Oceans-H2O San Diego May, 2013 Bob Battalio, PE.

Battalio 2013b. OBMP Methods Presentation to the Technical Advisory Committee, Coastal Protection Measures & Management Strategy for South Ocean Beach, San Francisco, California USA October 31, 2013.

Battalio 2014. Littoral processes along the Pacific and bay shores of San Francisco, California, USA By Bob Battalio, P.E. *Shore & Beach* Vol. 82, No. 1, Winter 2014, American Shore and Beach Preservation Association.

Battalio et al 2016. Battalio, R. T., P. D. Bromirski, D. R. Cayan, L. A. White (2016). Relating Future Coastal Conditions to Existing FEMA Flood Hazard Maps: Technical Methods Manual, Prepared for California Department of Water Resources and California Ocean Science Trust, Prepared by Environmental Science Associates (ESA), pp. 114.

Baye 2023. Peter R. Baye, Ph.D. General and reach-specific conceptual models of beach-dune interactions at Ocean Beach, basis for recommendations on climate change adaptation and resilience. December 12, 2023.

Bromirski, P. D., D. R. Cayan, N. Graham, R. E. Flick, and M. Tyree (Scripps Institution of Oceanography). 2012. Coastal Flooding Potential Projections: 2000–2100. California Energy Commission. CEC-500-2012-011.

Cheng et al 2018. Tiffany Cheng, Environmental Science Associates; Bob Battalio, Environmental Science Associates; Sarah Newkirk, The Nature Conservancy; Kelly Leo, The Nature Conservancy; Walter Heady, The Nature Conservancy; Maya Hayden, Point Blue Conservation Science; Sam Veloz, Point Blue Conservation Science; Jenna Judge, National Oceanic and Atmospheric Administration's San Francisco Bay and Outer Coast Sentinel Site Cooperative; Tara Ursell, California State Parks; Mary Small, California State Coastal Conservancy 2018. Natural Shoreline Infrastructure: *Technical Guidance for the California Coast. Toward Natural Infrastructure to Manage Change in California*. California's Fourth Climate Change Assessment, California Natural Resources Agency.

Cohn et al 2019. Nicholas Cohn, Peter Ruggiero, Gabriel García-Medina, Dylan Anderson, Katherine A. Serafin, Reuben Biel,Environmental and morphologic controls on wave-induced dune response, Geomorphology, Volume 329, 2019, Pages 108-128, ISSN 0169-555X, https://doi.org/10.1016/j.geomorph.2018.12.023.)

Collins BD, Sitar N (2008) Processes of coastal bluff erosion in weakly lithified sands, Pacifica, California, CA. Geomorphology 97:483–501.

Ecker, R.M. and Towill, Inc. (1980) Ocean Beach Sand Replenishment Program, prepared for City and County of San Francisco.

ESA and CSMW 2012. Coastal Regional Sediment Management Plan for the San Francisco Littoral Cell. Prepared for the US Army Corps of Engineers, 2012.

ESA and others 2015. Coastal Protection Measures & Management Strategy for South Ocean Beach, Ocean Beach Master Plan: Coastal Management Framework Prepared for San Francisco Public Utilities Commission Under Contract to SPUR Prepared by SPUR ESA PWA Moffatt & Nichol McMillen Jacobs Associates AGS, Inc. April 24, 2015.

ESA 2016. Coastal Hazards Analysis to Assess Management Actions, Technical Methods Report, Appendix A of Climate Ready – Southern Monterey Bay [Leo et al 2017, Prepared for The Nature Conservancy. January 2016. https://maps.coastalresilience.org/california/methods/ENBA_Monterey.pdf

ESA 2016b. Los Angeles County Coastal Hazard Modeling and Vulnerability Assessment Technical Methods Report Prepared for City of Santa Monica and AdaptLA, September 30, 2016. https://maps.coastalresilience.org/california/methods/SLR_LosAngeles.pdf

Hesp 2013. Hesp, P.A., 2013. A 34 year record of foredune morphodynamics at Dark Point, NSW, Australia In: Conley, D.C., Masselink, G., Russell, P.E. and O'Hare, T.J. (eds.), Proceedings 12th International Coastal Symposium (Plymouth, England), Journal of Coastal Research, Special Issue No. 65, pp. 1295-1300, ISSN 0749-0208.

Heberger et al 2009. Heberger M, Cooley H, Herrera P, Gleick PH (2009) The impacts of sea level rise on the California Coast. California Climate Change Center . CEC-500-2009-024-F.

Komar, P.D., W.G., Marra, J.J. and Allan, C.J. 2002. Coastal Erosion Processes and Assessments of Setback Distances, in Proceedings of Solutions to Coastal Disasters '02, Feb 24-27, 2002, San Diego, California, pp 808-822.

Kriebel, D.L. and Dean R. G. 1993. Convolution method for time-dependent beach profile response, Journal of Waterway, Port, Coastal, and Ocean Engineering, ASCE, 119: 204-226.

Leo K, Battalio R, Heady WN, King P, McGregor A, Cohen B, Calil J, Vandebroek E, Jackson J, DePaolis F, Revell D, Vaughn R, Giliam J, Newkirk S. 2017. Economic Impacts of Climate Adaptation Strategies for Southern Monterey Bay. Technical Report prepared for the California State Coastal Conservancy by The Nature Conservancy. 2017/07. ClimateReadyGrant#13-107. https://maps.coastalresilience.org/california/methods/ENBA_Monterey.pdf

MNE 1994. Moffatt & Nichol Engineers 1994. Shoreline Mapping for Ocean Beach, San Francisco, CA. Prepared for: U.S. Army Corps of Engineers, San Francisco District.

MNE 1995. Moffatt & Nichol Engineers 1995. Sediment Transport Processes Study, Ocean Beach, San Francisco, CA.

Newkirk et al, 2018. Newkirk, Sarah, Sam Veloz, Maya Hayden, Walter Heady, Kelly Leo, Jenna Judge, Robert Battalio, Tiffany Cheng, Tara Ursell, Mary Small. 2018. *Toward Natural Infrastructure to Manage Change in California*. California's Fourth Climate Change Assessment, California Natural Resources Agency. Publication number: CCCA4-CNRA-2018-011. https://www.energy.ca.gov/sites/default/files/2019-12/Oceans_CCCA4-CNRA-2018-011_ada.pdf

Olmsted, R., and N. Olmsted 1979. Ocean Beach Study: A Survey of Historic Maps and Photographs.

Revell and others 2011. Revell, D.L., Battalio, R., Spear, B., Ruggiero, P, and Vandever, J. 2011. A Methodology for Predicting Future Coastal Hazards due to Sea level Rise on the California Coast. Journal of Climatic Change 2011 109 (Suppl 1): S251–S276, DOI 10.1007/s10584-011-0315-2, 10 December 2011 # Springer Science+Business Media. https://research.fit.edu/media/site-specific/researchfitedu/coast-climate-adaptation-library/united-states/west-coast-amp-hawaix27i/california---statewide/Revell.--2011.--Methodology-for-Predicting-SLR-Hazards-Along-California-Coast.pdf

Ruggiero and others 2001. RUGGIERO, P.; KOMAR, P.D.; MCDOUGAL, W.G.; MARRA, J.J., and BEACH, R.A., 2001. Wave Runup, Extreme Water Levels and the Erosion of Properties Backing Beaches. Journal of Coastal Research, 17(2),407-419. West Palm Beach (Florida), ISSN 0749-0208.

SPUR, AECOM, ESA PWA, Nelson\Nygaard, Sherwood Design Engineers, Phil D. King, PhD, 2012, Ocean Beach Master Plan, Prepared for State of California Coastal Conservancy, San Francisco Public Utilities Commission, and the National Park Service, Available online [1/23]: https://issuu.com/oceanbeachmasterplan/docs/obmp_document_full/11 .

Schwarz et al 2019. Schwarz, C.; Brinkkemper, J.; Ruessink, G. Feedbacks between Biotic and Abiotic Processes Governing the Development of Foredune Blowouts: A Review. J. Mar. Sci. Eng. 2019, 7, 2. https://doi.org/10.3390/jmse7010002

Thornton et al 2007. E.B. Thornton, J. MacMahan, A.H. Sallenger, Rip currents, mega-cusps, and eroding dunes, Marine Geology, Volume 240, Issues 1–4, 2007, Pages 151-167, ISSN 0025-3227

USGS 2006 Hapke CJ, Reid D, Richmond BM, Ruggiero P, List J. 2006. National Assessment of Shoreline Change Part 3: Historical Shoreline Change and Associated Coastal Land Loss Along Sandy Shorelines of the California Coast. U.S. Geological Survey Open File Report 2006-1219.

USGS 2007. Hapke CJ, Reid D, Borelli M. 2007. National Assessment of Shoreline Change Part 4: A GIS Compilation of Vector Cliff Edges and Associated Cliff Erosion Data for the California Coast. U.S. Geological Survey Open File Report 2007-1112.

Vandebroek, E.E. and Battalio, R.T., 2013. Historic Shoreline Locations at Ocean Beach, San Francisco, Figure 1 in “San Francisco: A Test Case for Coping with Rising Seas” by Molly Samuel, prepared for KQED Science. Published online at Quest, The Science of Sustainability.

Abbreviations and Definitions

dune	Sand mound formed by wind inland of a beach
toe	Bottom of a slope
crest	Top of a slope
Large wood	Tree trunks of branches, dead, placed to emulate natural wrack formations which are suppressed due to interventions such as deforestation
Wrack	Material washed up and deposited on the beach by wave runup. Typically refers to organic materials such as large wood, other dead vegetation such as branches and kelp. Can also include undesirable treated wood and trash.
Natural shore infrastructure	Natural or nature-based features that provide benefits such as erosion and flood risk reduction
geomorphology	The shapes and dynamic characteristics of natural formations: In this report, beaches, dunes and surfzone
Bio-geomorphology	Geomorphology induced by living organisms interacting with physical processes: In this report, the effect of plants on dune morphology.

OCEAN BEACH ANALYSIS AND PLANNING SEGMENTS
OBMP SEGMENTS

NOB	North Ocean Beach – south to Lincoln Way
MOB	Middle Ocean Beach – south to Sloat Blvd
SOB	South Ocean Beach – south to Fort Funston

SUNSET RESILIENCE (THIS STUDY) SEGMENTS

Reach A	North Ocean Beach – south to Lincoln Way
Reach B	Lincoln Way to Noriega Street
Reach C	Noriega Street to Santiago Street
Reach D	Santiago Street to Sloat Blvd.
OBMP	Ocean Beach Master Plan (Spur and others 2012)

TIDES AND DATUMS

MHHW	Mean Higher High Water
MSL	Mean Sea Level
MLLW	Mean Lower Low Water
NAVD	North American Vertical Datum

COASTAL ENGINEERING – MORPHOLOGY TERMS

Dune toe	the seaward extent of the dune where it meets the beach
beach	Dry beach between MHHW and dune toe
Shoreline	Typically the MHHW shoreline
SWL	Still Water Level meaning the ocean level not affected by waves
RWL	Reference Water Level, typically synonymous with SWL
DWL	Dynamic Water Level, the elevation of oscillating wave setup above the ocean level, which is a maximum at the shore
Wave Setup	The increase in water level driven by breaking wave momentum, which oscillates and is correlated with large wave sets (groups). Wave setup is sometimes segregated into the average and dynamic components.
R, Wave runup	The uprush of water resulting from waves breaking nearshore. Wave runup consists of the wave setup and wave swash components. Runup is a varying parameter and the contemporary typical practice is to use "$R_{2\%}$" which is the runup exceeded only 2% of the time during a given wave event. (not the same as a 2% annual recurrence which is a 50-year event)
TWL	Total Water Level which is the elevation of wave runup added to the ocean SWL.
MOP	CDIP MOnitoring and Prediction (MOP) System https://cdip.ucsd.edu/documents/index/product_docs/mops/mop_intro.html#:~:text=CDIP%20provides%20public%20access%20to%20its%20monitoring-based%20wave,the%20continental%20shelf%20and%20the%20Southern%20California%20Bight.
CDIP	Coastal Data Information Program
Rip current	Current generally flowing seaward from shore, essentially draining water transported shoreward by breaking waves.
Rip embayment	A landward-concave indentation of the shoreline and depression of the surf zone sea floor scoured by a rip current
LIDAR	Light Detection And Ranging; a method of mapping elevations of the land surface.

Appendix C: Detailed conceptual model of beach-dune interactions at Ocean Beach (Peter Baye)

Peter R. Baye, Ph.D.
Coastal Ecologist, Botanist
33660 Annapolis Road
Annapolis, California 95412

(415) 310-5109 botanybaye@gmail.com

M E M O R A N D U M

To: Ellen Plane, Jeremy Lowe, SFEI
Cc: Bob Battalio, ESA
Date: December 12, 2023 (Final; edited draft of January 2023)
SUBJECT: General and reach-specific conceptual models of beach-dune interactions at Ocean Beach, basis for recommendations on climate change adaptation and resilience

OUTLINE

1. Introduction and Summary

This memorandum provides conceptual models for foredune evolution and maintenance processes and history at Ocean Beach, under the influence of native and non-native vegetation, and local beach processes. The conceptual models summarized are aimed at informing practical applications in adaptive management of Ocean Beach under foreseeable decades of sediment supply and climate forcing (Pacific sea level rise, increased intensity and duration of coastal storms, extreme droughts and thermal events affecting vegetation, variations in beach sand supply alongshore) and intensive urban recreational uses of the beach. They also provide the basis for design of potential alternatives to mitigate climate change impacts on the beach, foredune zone, and Great Highway, by engineered adaptive modifications of Ocean Beach, including bio-engineering (vegetation management as a tool for modifying geomorphic processes and landform evolution) and strategic sand placement.

The models below are based on a review and synthesis of the current global scientific literature on beach and foredune geomorphic evolution under the influence of vegetation, applied to long-term field observations at Ocean Beach (1984-present) and review of available historical aerial imagery on Google Earth (supplemented by other archival aerial photos provided by SFEI). They focus on vegetation influences on sand deposition and erosion rates, patterns, processes, and resultant landforms, and beach controls of wind-blown (aeolian) sand supply to foredunes, which can constrain foredune development, as well as cause overwhelming dune mobility and onshore migration. They also include description of relevant beach processes influencing foredunes, which in themselves may or may not be subject to short-term engineering control, but may be used as indicators for near-term prediction and anticipation (forecasting) of changes in dune sand supply, or elevated erosion risks, in practical, real-time monitoring programs supporting adaptive management.

Peter R. Baye Ph.D.
Coastal Ecologist, Botanist
(415) 310-5109
botanybaye@gmail.com

2. Conceptual Model Components for Ocean Beach Foredune Vegetation and Geomorphic Process Interactions

Globally, foredunes are shore-parallel dune landforms formed by the interaction between wind transport of beach sand and sand-trapping, burial-tolerant perennial coastal dune vegetation. Foredunes are the primary topographic feature landward of the backshore, capable of restricting storm wave runup, and releasing accumulated sand back to the beach during storm erosion events. On the Pacific U.S. coast, foredune morphology varies from discontinuous and irregular hummocks, mounds, or blowouts, to continuous, linear ridges.

Foredune ridges were not natural features of Ocean Beach prior to 1870. Native dune vegetation behind Ocean Beach formed only sparsely distributed dome-like hummock dunes under prostrate, broad-leaved perennial dune vegetation, within an unstable landscape of mostly barren, landward-migrating desert-like transverse dunes. In the 1870s, dune stabilization of Golden Gate Park commenced with large-scale transplanting of dune-stabilizing Mediterranean European marram grass (European beachgrass) imported from Gascony, France. The City's dune stabilization extended to wood crib walls along segments of Ocean Beach, where it was used to develop high, narrow, steep artificial European-style foredune ridges. Subsequent sand and other fill embankments along Great Highway were fronted with marram grass foredunes, perched on artificial fill.

Along Ocean Beach's artificial sand embankments and seawalls today, there are only a few existing dominant modern foredune vegetation types: unmanaged of prostrate mats of iceplant, and stands of marram grass - both non-native and invasive - are the most extensive, and provide what little dune stabilization and dune-building vegetation there is. Of the two native foredune vegetation types favored by environmental policies of the City and County of San Francisco, California, and National Park Service, only beach wildrye vegetation provides significant sand-trapping and high dune-building capacity for the higher rates of wind-blown sand transport from Ocean Beach, where segments of wide dry backshore beach provide abundant supply. Other native broadleaf foredune species are prostrate mat-forming types, like iceplant, and have limited capacity to trap and stabilize high rates of wind-blown sand, or build high foredunes needed for the tight "coastal squeeze" foredune space seaward of Great Highway infrastructure.

Marram grass is still abundant as a legacy of the 1985 sand embankment project construction, but as an invasive non-native species, it is generally prohibited from active planting or use today in California. The remnant stands of marram are weakened by decades of chronic unmanaged recreational trampling, causing and maintaining permanent dune destabilization and massive blowouts, especially at Noriega and Judah St. crossings. Marram grass has unmatched ability to build high, narrow, steep foredune ridges under high rates of foredune sand accretion – the basic reason for its original introduction. Though beach wildrye is reported to build lower foredunes than both American and European species of *Ammophila* in the Pacific Northwest, at Ocean Beach, it has built closely equivalent high foredune ridges with slopes and crest elevations similar to adjacent marram foredunes near Irving St, since the 1990s. (See Appendix)

Even more important for resilience to foredune blowout resistance and recovery (vegetative self-repair) marram has less capacity for extensive, rapid lateral (creeping) vegetative spread than native beach wildrye, which allocates much more growth towards rapid, extensive vegetative spread, making it superior at re-colonizing foredune gaps and incipient blowouts. Unlike marram grass, which generally outcompetes native foredune plants in the Central Coast (in part by smothering competitors with excessive dune sand accretion, trapped by its stiff, tall, dense canopy) beach wildrye is compatible with mixed stands of associated native species. In addition, beach wildrye has greater capacity to tolerate short-term root exposure to elevated beach sand salinity from wave runup or overwash, compared with marram grass.

The two dune grasses also differ in their responses to intensive foot trampling for beach access and recreation. Beach wildrye allocates a high proportion of its growth towards extensively creeping rhizomes that vegetatively spread well-spaced small clusters of shoots into bare sand gaps, rapidly colonizing open sand in erosion scars or bare paths. Marram, in contrast, allocates most growth to dense leafy shoots in large tussocks, and relatively little to short-creeping rhizomes, which are less efficient at colonizing sand gaps and blowouts. These ecological engineer species differ in the way they shape Ocean Beach foredunes and their responses to sand accretion and disturbance: the unmanaged beach wildrye section of foredune has resisted large blowout destabilization for over 3 decades, and protects downwind segments of Great Highway from sand burial. The prevailing marram foredunes, in contrast, have developed extensive blowouts in response to unmanaged trampling pressure. Iceplant vegetation in the landward sand embankment flats has demonstrated low resilience (rapid destabilization) in response to foredune blowout migration.

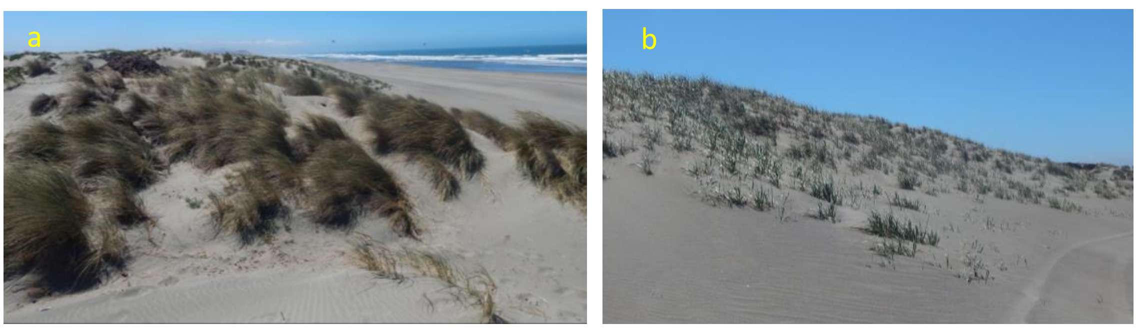


Figure 1. Marram grass and beach wildrye foredune morphology at Ocean Beach. (a) Marram grass foredune in Reach B, under high rates of dune sand accretion, forms dense erect tussocks and hummocky dune topography with gaps and unvegetated shadow dunes among them, at high risk for blowout development. (b) Beach wildrye (American dunegrass) foredune in adjacent Reach B segment, also under high rate of dune sand accretion, forms a broader, relatively smooth to undulating (not hummocky) foredune slope of similar height, with more evenly dispersed smaller shoot clusters creeping down towards the backshore. Foot trails in beach wildrye have been slower to develop early stage blowouts, because rhizome growth rapidly recolonizes trampled path edges. .

2.1. Biogeomorphic functional traits of Ocean Beach foredune vegetation

Research on both Pacific and Atlantic U.S. coasts has demonstrated that foredune plant morphology, growth habit, and patterns of spread (colony type) strongly influence the geomorphic processes and patterns of foredunes - shape, size, stability, resilience, and accretion rates. These biogeomorphic traits are not based on native or non-native species status or historical "natural" conditions. They vary among species and ecologically similar groups of species (functional groups or guilds), and include:

- **Leafy shoot density, cover, and height** (shoots/unit area, total above-ground area of biomass). The shoot structure and density of leafy shoot is a porous obstacle to wind, providing drag (friction) to surface air flow. This causes significant reduction in sand-transporting wind velocity at and below the canopy, reducing its competence to transport sand. This causes wind-blown sand to deposit and accumulate in the slowed airflow zone within the canopy. Short canopies provide only shallow zones of slowed airflow. Taller, denser leafy canopies provide thick zones of still or slowed airflow, and sand deposition. Regeneration of shoots at the accreted sand surface restores the canopy for serial sand-trapping and dune accretion events. (see Appendix)

- **Ratio of lateral spread to vertical growth**. Plant growth (biomass) allocation to lateral below-ground shoot and root spread versus above-ground erect (vertical shoot) biomass and structure; influence on foredune width:height ratio. (see Appendix)

- **Sand burial tolerance** (sand accretion depth as % plant height, or absolute accretion thickness above surface). Plant responses to burial rates above threshold of tolerance: mortality and reduction in density, cover. Sand burial tolerance varies with species, seasonal development, and rate of burial. (see Appendix)
- **Plant responses to sand burial rates below threshold of tolerance**: growth stimulation or inhibition, or stimulation after recovery from temporary inhibition.

- **Below-ground biomass (root + rhizome) and shear strength**; "sod" strength (substrate stabilization, deflation resistance; scarp and slump-block coherence, shear strength). The capacity for foredune sand substrates to develop near-vertical slopes in response to storm wave erosion, and the ability to form coherent slump-blocks, depends on additional shear strength provided by stratified root and rhizome systems, and sand moisture. Root systems that are spreading and fibrous, stratified throughout the foredune as it builds vertically (e.g. dune grasses), provide higher shear strength than deep taproots with little shallow lateral branching (e.g., dune shrubs and tap-rooted broadleaf plants).

2.2. Foredune geomorphic responses to interactions between vegetation and wind-blown sand transport at Ocean Beach

The following geomorphic feedback processes in foredunes, including the mixed foredune and artificial sand embankment at Ocean Beach, are directly conditioned by dominant vegetation types, and are important functions for resilience to erosion.

- **Foredune shape** (height:width ratio, "hummockiness", continuity or crest linearity, relict scarp features, relict slump block features),
- **Foredune size, crest elevation, slopes**
- **Vertical accretion rate and sand trapping capacity**

- **Resistance to initiation of blowouts**
- **Blowout reversal and recovery** (self-repair)
- **Wave erosion morphology**: vertical scarp, slump blocks
- **Post-storm erosion recovery process:** sequence of vegetated slump blocks interact with dune ramps (Christiansen and Davidson-Arnott 2004), and lateral vegetative spread

Figure 2. Slope failure of unconsolidated sand in response to wave erosion at the toe. (a) Avalanche failure without slump blocks in the scarp of an artificial sacrificial sand berm (designed to erode and nourish the beach) at South Ocean Beach; (b) Avalanche failure of a natural ancient dune (bluff) at Fort Funston south of Ocean Beach, January 2016.

2.3. Foredune vegetation dynamics: conceptual model components for Ocean Beach settings. The cycle of foredune initiation, accretion, storm wave scarp erosion, and post-storm foredune scarp recovery at Ocean Beach is mediated by vegetation dynamics described below. Destabilization of foredune vegetation and formation of mobile dune blowouts are mediated by vegetation interactions with trampling, onshore wind-blown sand transport, and storm wave scarp erosion.

2.3.1. Dominant dune-forming vegetation. The long-term patterns and rates of foredune accretion are strongly influenced by the interactions between the growth form and growth rates of dominant vegetation, rates of onshore wind-blown sand transport, and wave erosion. Species-specific plant traits that physically influence dune sand trapping an accretion in foredunes are shoot height and growth form (e.g., prostrate and short, or tall and erect; grass-like or broadleaf; clumped, shrubby, or widely creeping), shoot density, sand burial tolerance and post-burial recovery, and the rate of lateral vegetative (clonal) spread. Additional traits that influence post-storm dispersal and spread of foredune plants include seedling or vegetative fragment tolerance to sand salinity or seawater immersion. The morphological and physiological plant traits that influence development of sedimentary landforms (ecogeomorphic traits) are summarized below for the most influential existing foredune vegetation at Ocean Beach, and are provided in Appendix 1.

- **Beach wildrye** (syn. American dunegrass, *Leymus mollis; Elymus mollis*): ***An extensively and rapidly creeping tall perennial native dune grass with typically small shoot***

Peter R. Baye Ph.D.
Coastal Ecologist, Botanist
(415) 310-5109
botanybaye@gmail.com

clusters. In foredunes, it forms relatively low-density, semi-open vegetation stands with moderately high sand trapping capacity (circa 20-30 cm depth), and wider, gently sloped (more dissipative to wave runup) foredune windward slopes and coalesce to broad ridges relatively quickly. It is functionally most similar to American beachgrass (North Atlantic US coast)*, Ammophila breviligulata*.

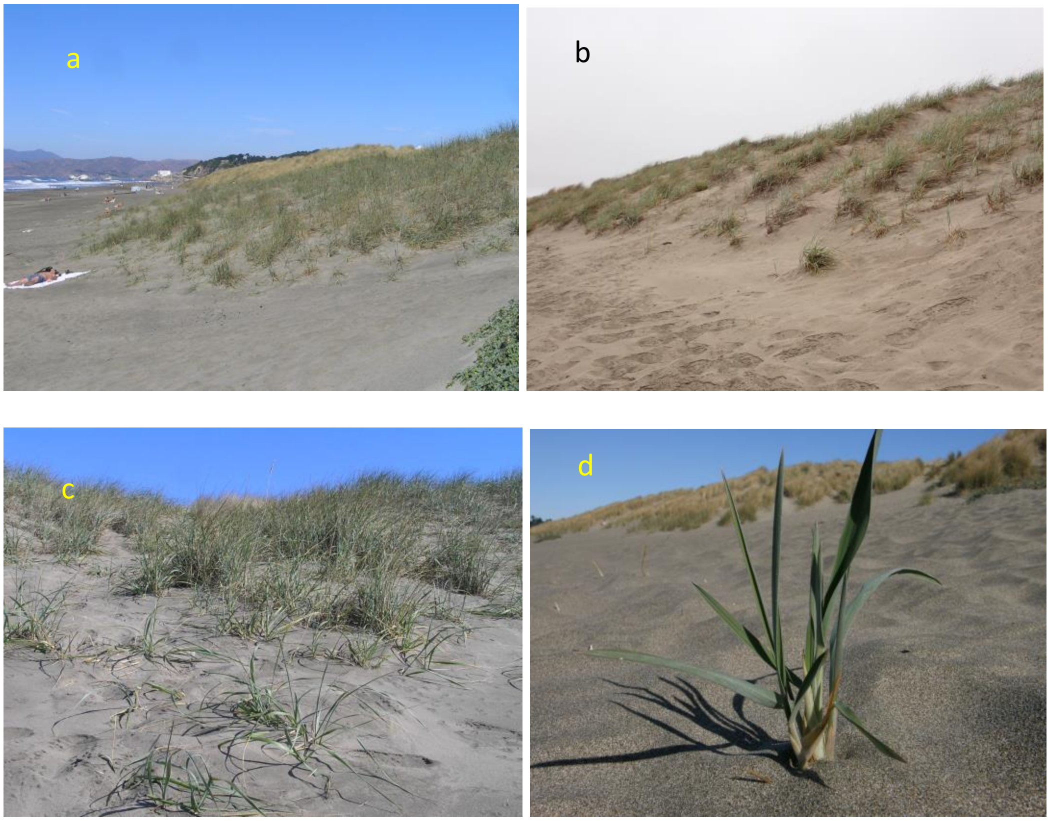


Figure 3. Beach wildrye, *Leymus mollis*, at Ocean Beach. (a) Beach wildrye foredune patch in Reach B, near Irving in October 2006, over 10 years after initial establishment in early 1990s, in a gap between marram grass-dominated foredunes, spreading in the gap down to the beach. (b) The beach wildrye foredune in July 2022 coalesced to a continuous high foredune ridge, matching the dimensions and elevations of adjacent marram foredunes, and keeping pace with dune sand accretion without developing mobile dunes or landward blowouts, over 30 years. (c) Growth habit of beach wildrye in accreting foredunes shapes the foredunes it forms: dispersion of widely spaced, spreading shoot clusters with broad, lax leaves. (d) New shoot cluster emerging from a rhizome tip turning upward through the sand at the leading edge of the colony in early winter, over 2 m from the nearest parent plant.

- **Marram grass** (syn. European beachgrass, *Ammophila arenaria*)***. A taller and stiffer, short-creeping, perennial grass*** with very high tolerance to sand burial. Marram forms dense, clumped semi-evergreen stands or tussocks with erect shoots and leaf blades that confer very high sand trapping capacity (40-60+ cm depth), and steeper, narrower, more hummocky foredunes. Accreting hummocks are slower to coalesce to a continuous foredune than widely creeping foredune grasses of temperate North

American, European, or Asian coasts, such as *Leymus mollis, L. arenarius, A. breviligulata*, or *Calammophila baltica*.

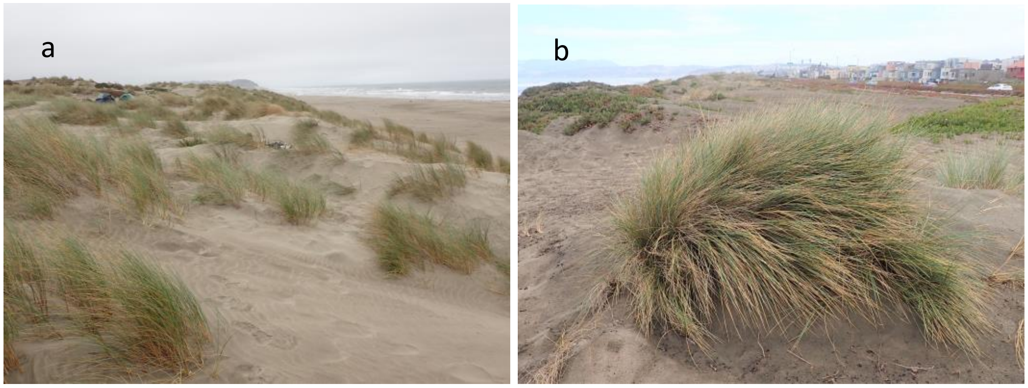


Figure 4. Marram grass, *Ammophila arenaria*, at Ocean Beach. Tussock growth pattern of marram grass in accreting foredunes of Ocean Beach develops from high growth allocation to dense vertical shoot branching and relatively infrequent, short-creeping lateral spread by rhizomes, under moderate to high rates of sand accretion. Tussocks leave unstable sand gaps with active wind-blown sand transport between tussocks, slow to coalesce into continuous foredune ridge under trampling pressure. (a) Reach B; (b) Reach D.

- ***Mat-forming prostrate broadleaf perennial dune plants*** form *low broad discontinuous foredunes, not ridges, with gaps between mounds or hummocks,* and with relatively low sand accretion capacity.

c

Figure 5. Iceplant, *Carpobrotus edulis* and *C. edulis* x *chilensis* at Ocean Beach. (a) Iceplant mats are readily overwhelmed by dune sand accretion, and slow to recover from burial. Overwhelming sand burial occurs here at the top of the sand embankment of Reach D, after years of stability (causing marram grass decline and shift to iceplant dominance) followed by rapid dune blowout and dune lobe formation. (b) Iceplant shoots elongate through sand burial depths of about 20 cm, but with sharply reduced shoot density and spread, leaving unstable bare sand while dunes deposition is active. (c) Stable old iceplant mats on artificial sandy fill placed in the mid-1980s, undergoing overwhelming sand burial at the seaward edge by foredune blowouts, which replace it with more burial-tolerant marram grass.

- **Broadleaf prostrate perennial forbs.** Native perennial broadleaf herbaceous dune plants with prostrate growth habits composed the historic dominant native vegetation of Ocean Beach, which was very sparse and patchy within a landscape of open, mobile dunes extending from the beach to the interior dune field. The most abundant and geomorphically important two species of seaward foredunes were beach-bur (*Ambrosia chamissonis*) and yellow sand-verbena (*Abronia latifolia*); see Appendix. Their prostrate growth habit with extensive lateral branching minimally trapped and stabilized foredune sand, and generated broad, mounded dune landforms. The taproot structure of the plants – lacking a network of fine lateral roots in upper sand layers to bind sand and increase shear strength - provided minimal below-ground stabilization of foredune sand. The limited foredunes these species formed were subject to very rapid destabilization when undermined and eroded by waves. Broadleaf prostrate dune forbs still occur spontaneously at Ocean Beach, but they are infrequent.

- ***Annual to short-lived perennial* pioneer beach/foredune plants** contribute to relatively minor, transient or seasonal sand accretion in the backshore beach. They support little or no multi-year (perennial) foredune building. The most common short-lived perennial/facultative annual plant at Ocean Beach is non-native sea-rocket, *Cakile maritima.* The native prostrate perennial beach saltwort, *Extriplex leucophylla* (syn. *Atriplex leucophylla*) similarly provides minor and self-limiting foredune and backshore beach accretion in transient low embryo foredune mounds.

Peter R. Baye Ph.D.
Coastal Ecologist, Botanist
(415) 310-5109
botanybaye@gmail.com

2.3.2. Foredune vegetation, erosion, and recovery processes

Foredune blowout resistance, initiation and vegetative "self-repair": Foredune blowouts are unvegetated, wind-eroded troughs or bowl-shaped depressions in foredunes, with depositional dune lobes downwind. Continuous perennial vegetation cover inhibits blowout initiation and development. Breaks (gaps) in perennial vegetation cover on the windward slope and especially the crest of the foredune (where wind flow accelerates) initiate blowouts. The susceptibility of foredunes to blowout initiation depends in part on the continuity of above-ground vegetation canopy cover sheltering the sand surface, resisting wind erosion at the surface. Blowout susceptibility also depends on below-ground resistance to deflation, provided by highly variable near-surface root systems of dominant dune plants: wide-spreading networks of shallow lateral roots and rhizomes of foredune grasses provide significant shear strength to unconsolidated sand. In contrast, deep taproots with little near-surface lateral branching provide little below-ground resistance to blowout initiation by surface erosion, or undermining of scarps by wave erosion. Chronic trampling and denudation of foredune vegetation at fixed locations, such as pedestrian access points or crossings, is an important social ecological control of blowout initiation and development. Vegetative recolonization of blowouts is an important "self-repair" process that is defeated by chronic footpath trampling at fixed locations.

At Ocean Beach, chronic trampling of foot trails across the foredune zone is the primary initial cause of blowouts, and also the primary sustaining cause of unvegetated sand in blowouts, since trampling inhibits vegetative re-stabilization (self-repair) of mobile sand in early stage blowouts. Large blowouts are associated with major stoplight crosswalks (e.g., Lincoln, Judah, Noriega). Foredune crest blowout *initiation* is relatively more inhibited by extensively creeping perennial dune grasses, and *blowout self-repair* (negative feedback, gap recolonization and accretion) is facilitated by extensively creeping dune grasses, such as beach wildrye.

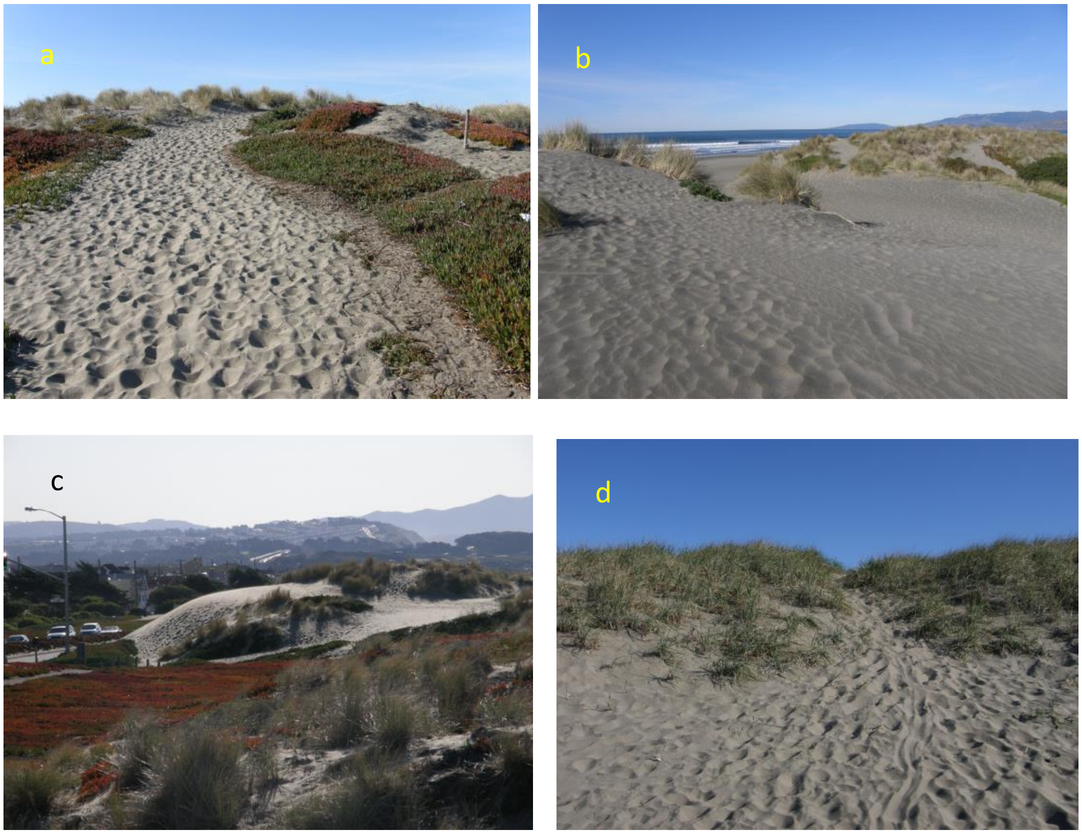


Figure 6. Dune blowout development stages around foot trails crossing Ocean Beach foredunes, Judah-Irving, December 2011. (a) Denuded trampled foot trail fringed by iceplant at Great Highway, on the sheltered (downwind) side of the foredune. (b) Denuded top of trampled foredune with scattered marram grass hummocks near mouth of blowout. (c) Blowout lobe (lobate dune) migrating across iceplant mats to Great Highway, NW to SE direction of deposition and migration at Judah St. (d) Trampled smaller foot trail (between stoplights) through beach wildrye foredune with strong lateral creeping vegetative spread, inhibiting blowout development; incipient blowouts remained small at this location in 2022.

Peter R. Baye Ph.D.
Coastal Ecologist, Botanist
(415) 310-5109
botanybaye@gmail.com

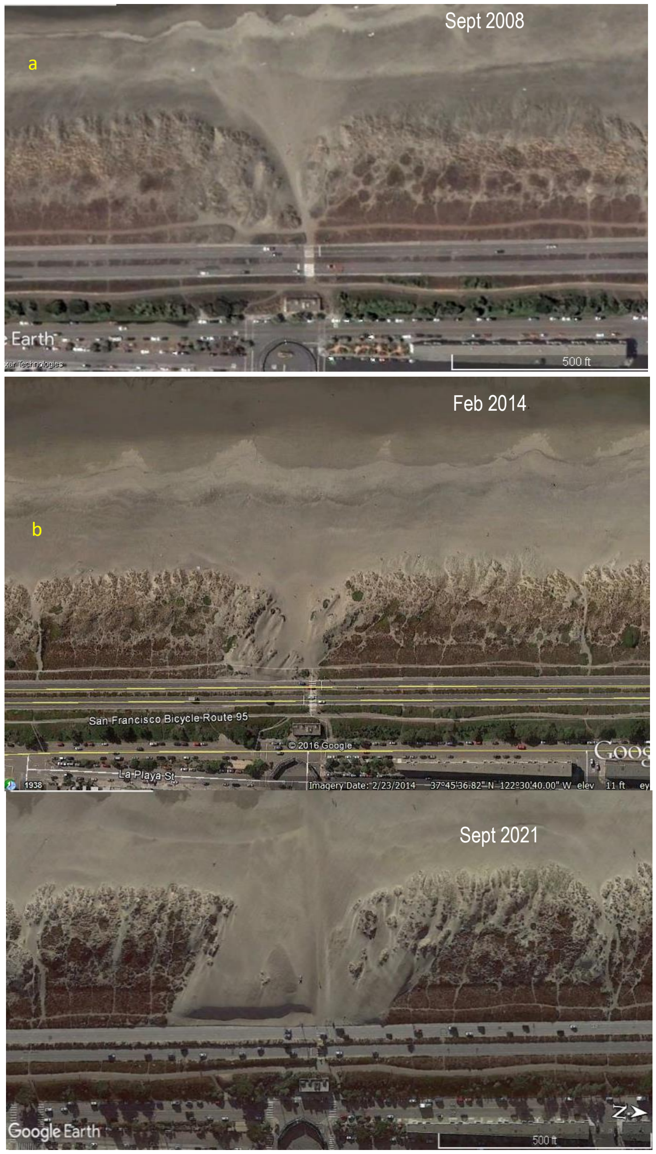


Figure 7. Foredune blowout development from denuded foot trails to fully destabilized migrating blowout dunes at Judah St., 2008-2021. (a) 2008: Funnel-shaped foot trail, narrow at crosswalk in linear path through iceplant flats, fanning out between the foredune crest and beach. (b) 2014: Migrating dune lobes travel SE from the wide trampled, denuded mouth of the widened trail on the windward side of the foredune. (c) 2021: massive unvegetated blowout detached and widened beyond original foot trail, with slipface (avalance slope) where it is mechanically excavated at the Great Highway roadside. Both marram grass and iceplant are overwhelmed by deep sand burial and trampling, masking the original blowout initiation pattern and process. Adjacent foredunes north and south of the blowout remain sufficiently vegetated (despite small foot trail dissection) to inhibit full blowout development.

***Episodic, event*-driven foredune evolution**

- *Foredune sand accretion* occurs primarily during *brief seasonal episodes* (hours to days) of high-velocity dry onshore or oblique onshore winds (aeolian sand transport rate = cube function of wind velocity at sand surface), interacting with wide backshore (supratidal) and continuous drained foreshore (upper intertidal beachface) sand fetch.

- *Foredune wave erosion with scarp activation or retreat* occur primarily during infrequent extreme high storm wave erosion events during high tides and depleted beach profiles, often concentrated opposite rip current embayments.

- *Foredune blowout wind erosion* is also activated primarily during brief seasonal episodes of high velocity dry onshore winds, but denudation of vegetation by trampling (priming of blowout troughs in paths and foredune crests) at Ocean Beach is chronic, occurring year-round.

Foredune scarp erosion, regeneration ("self-repair") and failure: processes applicable to Ocean Beach

- **Wave-cut foredune scarps are activated by wave erosion** undercutting the toe of the foredune scarp, with slope failure above; final stages of foredune scarp slope failure usually generates frequent *vegetated sand slump blocks,* oriented sub-vertically by rotational slope failure.

- **Sand slump block coherence during rotational slope failure** (sliding down slope intact with rotation) depends on *sufficient shear strength* generated by shallow *dune grass root and rhizome networks*; deep vertical tap-rooted native broadleaf perennials and shrubs provide limited, low shear strength to slump blocks.

Figure 8. Foredune vegetation below-ground structure (roots, rhizomes) strongly influences sand shear strength and geomorphic slope processes in response to wave-cut scarp erosion. (a) Stratified vertical series of buried foredune crest surfaces, each with dense, tough, fibrous mats of laterally spreading rhizomes and roots of marram grass, maintain high sand shear strength and allow persistent near-vertical scarp slopes to persist. (b) Foredune scarp slope failure under dense, stratified marram grass vegetation typically includes significant frequency of slump blocks with embedded viable shoots and rhizomes entrained from the

crest, supporting vegetative regeneration of the foredune windward slope. (c) Tap-rooted native foredune broadleaf vegetation develops unstable erosional scarps: deep, thick singular crowns and little lateral root branching near the surface provide little shear strength to foredune sand, and result in non-cohesive sand with avalanche failure in scarps, instead of vegetated slump blocks and recovery.

- **Foredune vegetative dispersal in the scarp** is gravity-driven, with vegetative propagules sources from the crest of the foredune transported downslope as *vegetated slump blocks with intact, rooted, embedded clone fragments.* The slump slope is the foundation for deposition of subsequent dune ramps.

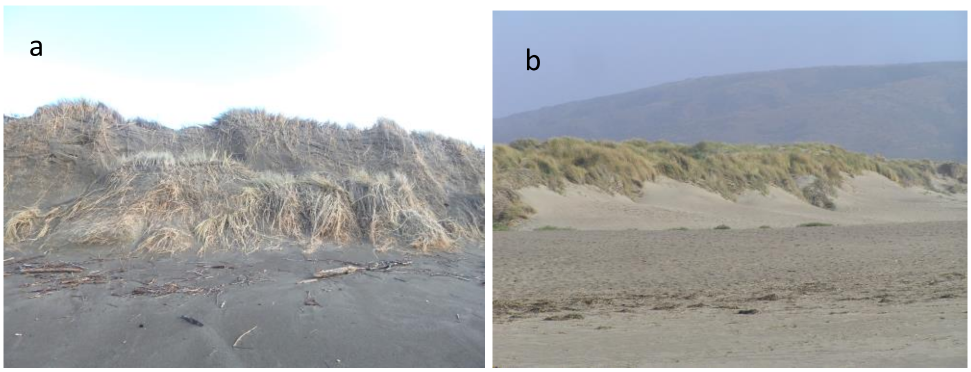


Figure 9. Vegetated foredune recovery process under rhizomatous, creeping dune grass. (a) Marram grass embedded in rotational failure of slump blocks in foredune scarps following storm erosion, with intact rooted vegetation (Manchester Beach, Mendocino County). (b) Foredune ramp accretion re-buries fragmented marram grass and facilitates regeneration and spread, with gradual recovery of vegetated foredune ramps (Sand Point, Lawson's Landing, Marin County). This foredune scarp recovery process is typical of other rhizomatous burial-tolerant foredune grasses.

- **Topographic steering and deflection of onshore wind and sand transport in the scarp/ramp slope**: the *steep scarp and partially filled dune ramp slope deflects onshore winds alongshore*, and inhibits dune sand transport over the scarp crest. Until the dune ramp overtops the scarp crest, dune ramp sand transport is switched to shore-parallel, temporarily suspending increase in foredune crest accretion and elevation gain. When the ramp fills the slope to the crest, over-crest dune sand transport is resumed under both shore-normal and oblique onshore winds. (Figures 9. 10). Shore-parallel deflection of dune ramp sand transport also applies to seawall reaches of Ocean Beach at times.

- **Embedded viable slump-block vegetative dune grass clones regenerate in place and spread radially** on the slumped scarp slope, when partially buried by the accreting dune ramp. (Figure 9.). This process applies only to creeping perennial foredune grasses, and does not occur to a significant extent with tap-rooted broadleaf foredune perennial forbs.

- **Lateral spread of sand-accreting, creeping dune grasses in the coalesced dune ramp/slump block slope** can regenerate ("self-repair") the vegetated seaward slope of the accreting foredune, with sufficient (circa 3+ yr) intervals between active scarp erosion events. The regenerated post-scarp foredune morphology is trimmed to a *sharply linear crest with a relatively steep seaward slope* until/unless sufficient sand accretion rates restore hummocky foredune topography. (Figure 9).

- **Vegetation gaps at the foredune crest** - denuded or destabilized vegetation at the crest of the foredune (e.g., blowouts, intensively trampled dune areas) eliminate foredune scarp recolonization by vegetation, the first step in biogeomorphic "self-repair" processes. Gaps maintain a positive feedback of erosion, with persistent barren, unstable foredunes or blowouts. Foredune crest vegetation integrity and the slumped scarp slope are integral to biogeomorphic foredune self-repair, a critical zone for urbanized foredune management. Note that wave-cut scarps per se do normally initiate blowouts in well-vegetated foredunes with creeping dune grasses.

2.4. Foredune topography and vegetation steer local wind direction dune sand transport patterns. Airflow across the beach and foredune includes interactions between wind, topography and vegetation; wind direction and speed high above the foredune is not the same as airflow near the sand or vegetation surface. Foredune (and scarp) topography steers and deflects onshore winds that transport sand in ways that are important for dune accretion and sand management.

- Oblique onshore wind approach interacts with vegetated foredune scarp morphology – steep vegetated scarp crests, and partial bare sand dune ramps - to *deflect sand transport alongshore* rather than directly onshore across the foredune crest. This is indicated by ripple crest long axes in the dune ramp near right angles to the crest line. Steepened windward foredune slopes act as switches steering slightly oblique wind approach shore to alongshore sand transport

- Oblique onshore wind flowing over sloping, vegetated foredunes is deflected landward, with acceleration over the crest, facilitating foredune crest zone accretion.

Figure 10. Foredune ramps deposited in near-vertical wave-cut scarps at Ocean Beach, with wind ripples indicating surface wind deflection alongshore. (a) Foredune ramp below steep relict iceplant-covered scarp crest, steering oblique onshore winds parallel with the crest, transporting sand alongshore in the ramp, with ripples nearly perpendicular to the crestline; Vicente Avenue, May 2022. (b) Wave-cut and wind-eroded moist (cohesive) scarp in hydraulically deposited sand berm south of Sloat Boulevard, with basal dune ramp exhibiting wind ripples perpendicular to the scarp crestline; March 2021.

Foredune ramps are wedges of wind-blown sand accreted in foredune scarps (sand ramp fills in foredune scarps; gently sloping aeolian ramps, sparse or no vegetation). As they grow, they extend to the scarp crest, and facilitate aeolian sand transport over the dune crest. A critical height of the sand ramp facilitates transport over the crest of the scarp, and switches sand transport direction from parallel with the ramp, to deflection over the crest, when oblique onshore winds interact with the ramp/scarp.

Dense continuous foredune vegetation in the windward slope intercepts most onshore aeolian sand transport until the vegetation canopy is mostly buried by accreted dune sand, and no longer provides significant roughness and drag.

In addition, the foredune windward slope causes significant acceleration of wind velocities (compression of wind-streams) at the crest, increasing capacity to erode and transport sand there, and increasing risk of blowouts. At the toe of the foredune, onshore wind velocities are slower than at the crest and windward mid-slope, favoring deposition along the toe of the vegetated slope, or the bare dune ramp. Blowout gaps in the foredune intercept alongshore aeolian sand transport, and accelerate winds to jet-like flows (funnel and intensify wild velocity, locally intensifying aeolian sand transport).

Supporting literature for this section: Bauer *et al*. 2012, Biel *et al*. 2019, de Carvalho *et al*. 2016, Christiansen and Davidson-Arnott 2004, Davidson-Arnott *et al*. 2012, Goldstein *et al*. 2017; Hacker *et al*. 2019, 2012; Hesp 2002, 2016; Hesp. *et al*. 2002, 2009; Hesp 1988, 2002; Nordstrom *et al.* 2007; Seabloom *et al.* 1994, 2012, Walker *et al.* 2006, van Kuik *et al*. 2022, Zarnetsky *et al.* 2012.

3. Conceptual Model Components for Beach-Foredune Interactions at Ocean Beach

3.1. Backshore beach wrack and evolution of embryo foredunes

3.1.1. Biogeomorphic attributes of drift-line/wrack debris deposits. Wrack (organic detritus and woody debris stranded in the zone of highest annual wave runup) performs important biogeomorphic functions in the backshore, related to foredune evolution, as well as beach habitats.

- *Winter storm high tide wave runup deposit debris and plant propagules* (seed, regenerative vegetative fragments; native and non-native). Winter storm waves deposit organic wracks, foredune plant propagules (seeds, viable dormant vegetative

Peter R. Baye Ph.D.
Coastal Ecologist, Botanist
(415) 310-5109
botanybaye@gmail.com

fragments), and driftwood at the landward end of the backshore, beyond the reach of summer (growing season) high tides and salinity. Winter rains leach desalinize winter storm wrack deposit and sand, supporting seedlings and regenerating fragments of dune and beach plants with limited salt tolerance.

- *Beach topography and stable storm wrack deposit positions*. High wrack line positions on spring-summer Ocean Beach profiles are the ones that contain buoyant organic marine and terrestrial debris, seeds, and viable vegetative propagules that can regenerate colonies of embryo foredune plants. These position reflect relict storm high wave runup limits on the winter storm beach profile, which are followed by post-storm beach accretion and growth of the berm profile. Persistent wrack deposits are inhibited by scarps or steep slopes; unstable wracks below scarps (wave reflection, backwash seaward transport and reworking dominant) generally do not establish plant growth. Vegetative propagules are dormant and salt-insensitive in winter, followed by rains that desalinize seawater-inundated sand, followed by protection by self-burial of moist wind-blown sand deposition (see next)

- *Wrack roughness, deflation resistance, wind-blown trapping, self-burial.* Wrack deposit embedded in sand inhibit surface erosion by wind, and the roughness of porous wrack obstacles to wind flow causes local sand deposition. Wracks, including driftwood and seaweeds, typically bury themselves or deposit shadow dunes in their lee. The surface stabilization and sand accretion of wrack deposits provide sheltered sites favorable to establishment of beach and foredune vegetation. The coarser and more abundant the woody debris in wracks, the more it provides a nucleus for rapid dune sand deposition around juvenile plants. Sand shadow deposits around coarse woody debris raises local beach surface elevations, and the threshold for injurious seawater inundation during high tide and wave events. Sand accretion around coarse wrack deposits thereby reduces the local risk of high tide seawater flooding during the growing season that can otherwise limit embryo dune vegetation establishment.

  Driftwood supplies to Ocean Beach today are scarce relative to prehistoric conditions, when riparian woodland along tributary streams discharged woody debris loads to the Bay, exiting the Golden Gate on ebb tides. High woody debris loads from forested watersheds still deposit large driftwood wracks around beaches at river mouths north and south of San Francisco Bay (e.g., San Gregorio Creek, Pescadero Creek, Russian River, etc.) Modern driftwood sources from urbanized, leveed San Francisco Bay, and its flood control channels, are limited by debris removal maintenance and obstructions at bridges. The low frequency of large driftwood logs and wood jams in Ocean Beach wrack zones may be a constraint on post-storm recovery of embryo foredunes.

  Decay of buried marine macroalgal wracks (seaweeds) in backshore beach wracks provides locally enriched subsurface nutrient and moisture patches in otherwise nutrient-deficient silicic beach sand. Decay of labile, soft organic matter also reduces the surface roughness. Mixtures of coarse woody debris, marine macroalgae and herbaceous vascular plant litter in wracks provides physical wind and wave runup shelter, sand surface accretion or stabilization, and local “hot spots” of elevated substrate nutrient availability and moisture that support pioneer plant colonization.

3.1.2. Wrack, plant colonization, and embryo foredune evolution

Winter storm wrack deposits above summer high tide and wave runup elevations serve as the nuclei for initiation the earliest stages of foredune development, “embryo foredunes”. These consist of pioneer colonies of perennial vegetation capable of spreading, trapping sand and regenerating through sand burial cycles, building foredunes. The early stages of embryo foredunes have little topographic relief (typically less than a meter above the beach), but if they survive winter storm erosion, they continue to accrete, coalesce, and grow into incipient foredunes with substantial topography (1-2 m).

Embryo and incipient foredunes may be partially eroded by wave-cut beach scarps, which shape them into relatively linear patterns as they vegetatively regenerate and resume sand trapping. In the absence of scarps, diffuse wrack-patterned embryo foredune vegetation patches arise on the beach where trampling is relatively less intensive. Intensive trampling from recreational beach use eliminate most scattered embryo foredune vegetation, particularly around the foot trail crossings from Great Highway that radiate as fan-shaped mouths at the beach.

The early stages of plant colonization in winter wrack deposits (seedling and resprouts stage) are highly inconspicuous, in contrast with established vegetation with contrasting green cover that is visually obvious. Seedlings and vegetative resprouts of fragments are highly vulnerable to damage and mortality from trampling, beach vehicles, beach grading, filling, or grooming. Unmanaged trampling, degrades or eliminates the wrack zone of pioneer beach and foredune vegetation recolonization during inconspicuous early stages of development. Plant mortality risks decline with increasing plant size, especially clonal (vegetatively creeping and rooting) plants.

Distinct stages of embryo foredune development that are important for adaptive management at Ocean Beach can be reduced to the following:

- *Beach and foredune vegetation pioneer establishment* in wrack-sheltered microhabitat, subsidized moisture and nutrient retention in otherwise low-fertility beach sand) pioneer colonization of beach by perennial foredune species varies according to growth form
  - clonal (creeping) perennial dune-building grasses = vegetative fragments (shoots, rhizomes)
  - tap-rooted broadleaf plants = seedlings
  - *size-dependent plant survivorship*, resilience; all small young plants are sensitive to crushing (vehicle tracks), foot trampling, winter storm wave erosion, or spring-summer seawater flooding (wave runup) during early stages of development.

- *Initial sand accretion*: When canopies of pioneer beach plant colonies (patches) provide sufficient vegetative roughness to trap and retain wind-blown sand in low dune mounds or hummocks, embryo foredunes are precariously established. While small and low-relief, they are vulnerable to trampling or vehicle damage, and winter storm erosion.

- *Embryo foredune accretion transition to incipient foredune stage*. If embryo foredunes persist through multiple episodes of wind-blown sand accretion and vegetative recovery (burial/regeneration cycles), they begin to coalesce and develop sufficient topographic relief to restrict winter wave runup or cause wave reflection and scarps during erosion phases. Plant growth habits and architecture influence embryo foredune shape and size:
    - *Indeterminate* radial clonal spread is driven by lateral creeping rhizome growth, limited by the growing season duration and subsequent wave erosion during the winter storm season. Radial clonal spread is conducive to coalescence of embryo foredunes, either as irregular clusters of mounds, or as a continuous linear incipient foredune ridge. The rate of coalescence depends on the rate of lateral vegetative spread. Most foredune grasses are indeterminate clonal plants; at least one broadleaf native foredune plant (silvery beach pea) is also indeterminate and clonal, but it is extirpated in San Francisco.
    - *Determinate* (self-limited) radial growth is driven by lateral branching of unrooted shoots on tap-rooted prostrate broadleaf dune plants. These form wide dome-shaped dune mounds with mats of leafy shoot connected to a single massive crown and deep tap-root, with few or no near-surface branch roots.

Ecological functions of wracks and embryo foredunes*.* In addition to their geomorphic role in embryo foredune development, macroalgal wrack and beach vegetation provide microtopographic relief and wind-shelter, cryptic cover, native invertebrate abundance and diversity, and invertebrate prey items of shorebirds in the backshore. Backshore refuge (roost) habitat, supratidal foraging habitat for the federally listed Pacific population of western snowy plover. Wrack deposits and embryo foredunes provide alternative backshore roost and foraging habitat during high recreational beach use and disturbance of the foreshore swash zone (wetted intertidal beachface, preferred foraging habitat in undisturbed beaches). *Beach grooming or grading and unmanaged trampling in the wrack zone degrades* the supratidal foraging and roost habitat of wintering western snowy plovers at Ocean Beach.

Peter R. Baye Ph.D.
Coastal Ecologist, Botanist
(415) 310-5109
botanybaye@gmail.com

Figure 11. Wrack deposits and embryo foredunes. (a) Driftwood provides backshore sand surface stabilization (shadow dunes, deflation obstacles) and shelter (protection for establishing perennial dune vegetation; beach wildrye shown; Manchester Beach, Mendocino). (b) Low-relief hummocky embryo foredunes develop around nuclei of vegetation patches (nebhka) in a wide backshore (Sand Point, Lawson's Landing, Marin County). (c) Western snowy plover, a special-status beach wildlife species, cryptic among wrack deposits in backshore beach, MacKerricher State Park, Mendocino Co.

Supporting literature for this section: Dugan *et al.* 2011; Grilliot *et al.* 2019, Hesp 1989, Hilton & Konlechter 2011; Murphy *et al.* 2021; Nordstrom *et al*. 2007, 2011.

3.1.3. Dynamic seaward limits of perennial foredune vegetation

The seaward limit of perennial foredune vegetation in embryo foredunes and foredune ridges is controlled by factors that differ on prograding, wide beaches (e.g. Reach A, Ocean Beach), and stable to retreating beaches that are subject to recurring episodes of erosion and profile recovery (e.g., Reaches B-D).

Seaward limit of perennial foredune vegetation on stable or retreating beaches. The seaward limit of perennial foredune vegetation on stable or retreating beaches is generally limited by physical constraints of winter storm wave erosion in the backshore zone, which undercuts or scours out the regenerative structures of perennial dune-building vegetation (rhizomes, shoot crowns, buds, roots), often in a linear or crenulate pattern. Wave-cut beach or incipient foredune scarps trim and shape foredune ridges to relatively linear shore-parallel patterns (Hesp 1989, 2013; Figures 9, 12). If creeping perennial vegetation is dominant in the foredune zone, its spread (rhizome creep) proceeds from the scarp in embryo or incipient foredunes, after dune ramp deposition infills scarps. This typically results in a linear foredune ridge aligned with the relict scarp.

Peter R. Baye Ph.D.
Coastal Ecologist, Botanist
(415) 310-5109
botanybaye@gmail.com

Figure 12. Beach scarp retreat into incipient foredunes dominated by beach wildrye leaves a straightened, linear scarp line, outcropping or dangling connected viable rhizomes with regenerative buds, and bud-bearing rhizome fragments deposited in upper wrack lines. Post-storm recovery of the scarp facilitates development of a linear low foredune ridge. Ten Mile Dunes, MacKerricher State Park, Mendocino County, December 2015.

The position of the seaward limit of foredunes on stable or retreating beaches is effectively the relict landward limit of maximum scarp retreat from the antecedent storm profile phase. The position of the winter storm erosional scarp in the beach or foredune profile is a function of storm wave runup during extreme high tides (Ruggiero *et al*. 2001). It is not necessarily related to a threshold beach elevation relative to tidal datums, or horizontal distance from tide lines or beach morphological features during the growing season (calm weather beach profile), but it may correspond with threshold backshore width (McLean and Shen 2006) that may influence wave runup. The position of the seaward limit of embryo foredunes on stable or retreating beaches is not directly related to tidal datums (cf. non-analogous traditional tidal salt marsh zonation models).

Young stands of perennial vegetation in embryo foredunes have limited direct or indirect influence on the limit of storm wave runup (e.g., roughness, drag of above-ground shoots), since scarp retreat processes on beach and embryo foredune substrates are driven by wave undercutting at the toe of the scarp at beach level, below the root zone and shoot canopy, followed by slope failure (avalanche or slump failure). In contrast, stratified relict root/rhizome systems (formed by vertical sequences of dune accretion and vegetative recovery) of mature foredunes surfaces can significantly increase shear strength of well-developed foredunes under wave attack, and provides substantial erosion resistance relative to unconsolidated sand (Figures 8,9; Feagin *et al.* 2015).

Seaward limit of perennial foredune vegetation on wide, prograding beaches. On prograding beaches (such as Reach A and the northern end of Reach B of Ocean Beach), in contrast, winter storm wave erosion is often not the limiting factor for seaward foredune position as the zone of storm wave erosion shifts seaward of the wrack deposition zone and embryo foredunes. On prograding beach profiles, perennial foredune vegetation spread (especially creeping vegetative [clonal] spread) itself can be a driver of seaward foredune position, and it can be constrained by biological, physical or anthropogenic factors rather than winter storm erosion.

On prograding beaches with intensive recreational management, trampling of seedlings and early-stage vegetative regeneration in the winter wrack zone (Section 3.1.2), can cause high mortality even complete denudation of vegetation in the storm wrack/embryo foredune zone of the backshore, masking the position of the potential incipient foredune zone. Complete denudation of backshore vegetation is also the result of mechanical grading or beach grooming. Intensive trampling of the backshore beach during spring, when physical root injury from trampling can be most severe (limited root development, warming temperatures, high leaf evapotranspiration), can also "foot-prune" (shear, sever, crush) soft, fragile young creeping below-ground shoots and roots of foredune grasses early in development (Figure 6), and thus inhibit or prevent expansion to the backshore -- without visible traces of this cause later in the growing season.

On prograding beach segments with less intensive trampling in the backshore, embryo foredune vegetation dieback may also occur from non-erosional wave overtopping (ephemeral seawater flooding, sand salinization during spring high tides and high wave runup) during the sensitive spring-summer growing season. In the absence of rainfall that leaches salt from supratidal sand, dry-season seawater flooding of the backshore causes saline or hypersaline substrate conditions, which is injurious or lethal to beach and foredune vegetation. At Ocean Beach, wave runup and salinization of the winter wrack/embryo foredune zone during the spring high tides of summer months is very infrequent and local, compared with the widespread and intensive impacts of recreational trampling (all reaches) and beach grading (reaches A and C).

The rate of foredune scarp retreat, and the post-storm and landward scarp position in the profile, are influenced by the duration of the high storm wave action at extreme high tides, and the volume of foredune sand available for release to the scarp (foredune dimensions). Therefore, the seaward limit of the embryo foredune zone would be expected to retreat as a dependent function of beach profile retreat.

Embryo foredunes and wrack zone pioneer beach vegetation can also be limited by wave erosion that does not result in defined beach scarps, but erodes by scouring surface sand down below the depth of regenerative perennial structures of vegetation (shoot crowns, buds, rhizomes, roots; top 20-60 cm of sand). Conversely, depositional high wave overwash of the embryo foredune zone can also contribute to significant sand accretion in the backshore and foredune zone (Cohn *et al*. 2018), which would facilitate growth of embryo foredunes.

Where drift-lines reinitiate embryo foredunes in the backshore seaward of the (relict) foredune storm scarp when the post-storm beach profile recovery is complete, they may be vulnerable to renewed scarp undercutting and retreat below the depth of active root and rhizome zone of foredune grasses. The most reliable *field indicator* of the (temporarily) potential local stable position of embryo foredune zone is the *most recent highest relict winter outer wrack line that supports vegetative regeneration of perennial foredune and backshore plant species*.

3.2. Beach Processes driving variability in Ocean Beach foredune sand accretion and erosion rates

3.2.1. Backshore sand fetch and supply to foredune sand accretion

Dry dune sand transport rate is a cube function of wind velocity, so most of the annual onshore dune sand transport load is transported by *relatively few days of high-velocity dry season onshore winds* (Davidson-Arnott *et al*. 2005) and often spring (March-May) and fall (Sept-Oct) months at Ocean Beach. Supratidal, dry backshore beach width is generally the primary source of wind-blown sand to foredunes.

Variation in the width of backshore beach exposed to oblique to shore-normal onshore winds above the threshold for wind transport of sand (sand deflation fetch) is a primary driver of variation in foredune accretion and size (Houser and Mathew 2010). It is also the most important and useful rapid assessment metric for near-term (seasonal) prediction of the potential maximum local (seasonal) rate of onshore aeolian sand transport to the foredune (Davidson-Arnott and Law, 1996, Aagaard *et al*. 2004). Dominant northwest winds (high velocity dry winds) at Ocean Beach are oblique to the shore, significantly increasing sand fetch to the foredune zone of north Ocean Beach from the wide backshore.

Narrow dry backshore beach zones, which can develop after storm erosion or migration of rip current embayments, inhibit local foredune sand accretion. Wide dry backshore zones supply relatively high potential rates of onshore wind-blown sand transport during brief high onshore wind events (esp. NW gales – often occurring in spring and fall). Processes and patterns of backshore width variability are discussed in 3.2.3.

Figure 13. Wide, prograded (growing seaward) backshore beach segments of North Ocean Beach. (a) south of Lincoln to Irving, a wide dry persistent backshore beach provides exceptionally large dry sand fetch for aeolian sand accretion in marram and beach wildrye foredunes, 2011. (b) Extremely wide prograded beach plain and low-relief transverse dunes (like giant wind-ripples, up to 3-4 in a series, up to a meter in relief, nearly shore-parallel) seaward of the O'Shaughnessy seawall, at the northernmost end of Ocean Beach; July 2022.

Peter R. Baye Ph.D.
Coastal Ecologist, Botanist
(415) 310-5109
botanybaye@gmail.com

3.2.2. Foreshore sand fetch and resistance to deflation.

The foreshore (intertidal beach: low tide sand flat, bars, troughs, and beachface) can also supply wind-blown sand to the foredune, but it has some inherent restrictions that often reduce its contribution relative to the supratidal backshore beach. In addition to the tidal submergence of the foreshore reducing the time the sand surface can interact with wind, the surface moisture content, mineral composition, and coarse sediment (shell, pebble) of the foreshore can significantly reduce wind deflation even under high onshore winds. These constraints are directly observable and can be identified to estimate changes in potential foreshore wind-blown sand supply, in addition to the variable width (fetch) of the continuous sandy foreshore zone at low tide. The wetted intertidal foreshore in some conditions, however, can rapidly deflate in short periods of emergence, and sustain significant wind-blown sand transport to the backshore (Jackson and Nordstrom 1997)

Moist, cohesive sand inhibits deflation by raising the shear stress threshold for wind transport, and wet (surface saturated) sand is adhesive to rolling or saltating sand grains, effectively non-erodible by wind (Cornelis *et al*. 2004, Davidson-Arnott *et al*. 2008). Surface-saturated sand may act as a sediment trap for wind-blown sand. Surface sand moisture content or saturation vary with tidal drainage and beach groundwater depth, which are influenced by intertidal beach elevations and morphology:

- Concave, erosional intertidal beach profiles with wide wet or poorly drained foreshore zones, supply significantly less wind-blown sand to foredunes than well-drained, high intertidal sand foreshores.

- Surface-saturated, "glassy" flat intertidal sand areas (beachface or low tide terrace) with emergent shallow beach groundwater, or depressions saturated to flooded (intertidal troughs or runnels; 3.2.3.) eliminate sand fetch, and may act instead as surface traps for any onshore wind-blown sand seaward of them.

- Convex or higher elevation accretional beach profiles with wide, well-drained, high intertidal beachface slopes dry rapidly when tidally emergent, and can deflate rapidly during high onshore winds.

Conspicuous dark heavy mineral lag deposits and pebble or shell lag deposits may develop in the foreshore of some Ocean Beach segments (particularly south of Noriega), and these may also strongly inhibit sand deflation. Blackish magnetite (iron) sand layers concentrate during and shortly after prolonged wave erosion events that lower foreshore elevations. The high density of metallic sand significantly raises the threshold wind velocity for transport for a given grain size, and small heavy metallic grains are relatively cohesive when moist. Thin laminations of fine heavy mineral sands in quartz-dominated foredunes, compared with thick layers in the foreshore (up to about a foot) in the beachface, reflect the limited transport to foredunes.

Pebble and shell lags, concentrated at the surface by selective sand deflation or wave deposition, form an armored intertidal surface at least locally, which also inhibits wind transport of sand below them. Shell and pebble lags may be natural variations in local beach sediment size, or they may be increased by offshore beach nourishment sources that include a high content of very coarse sediment.

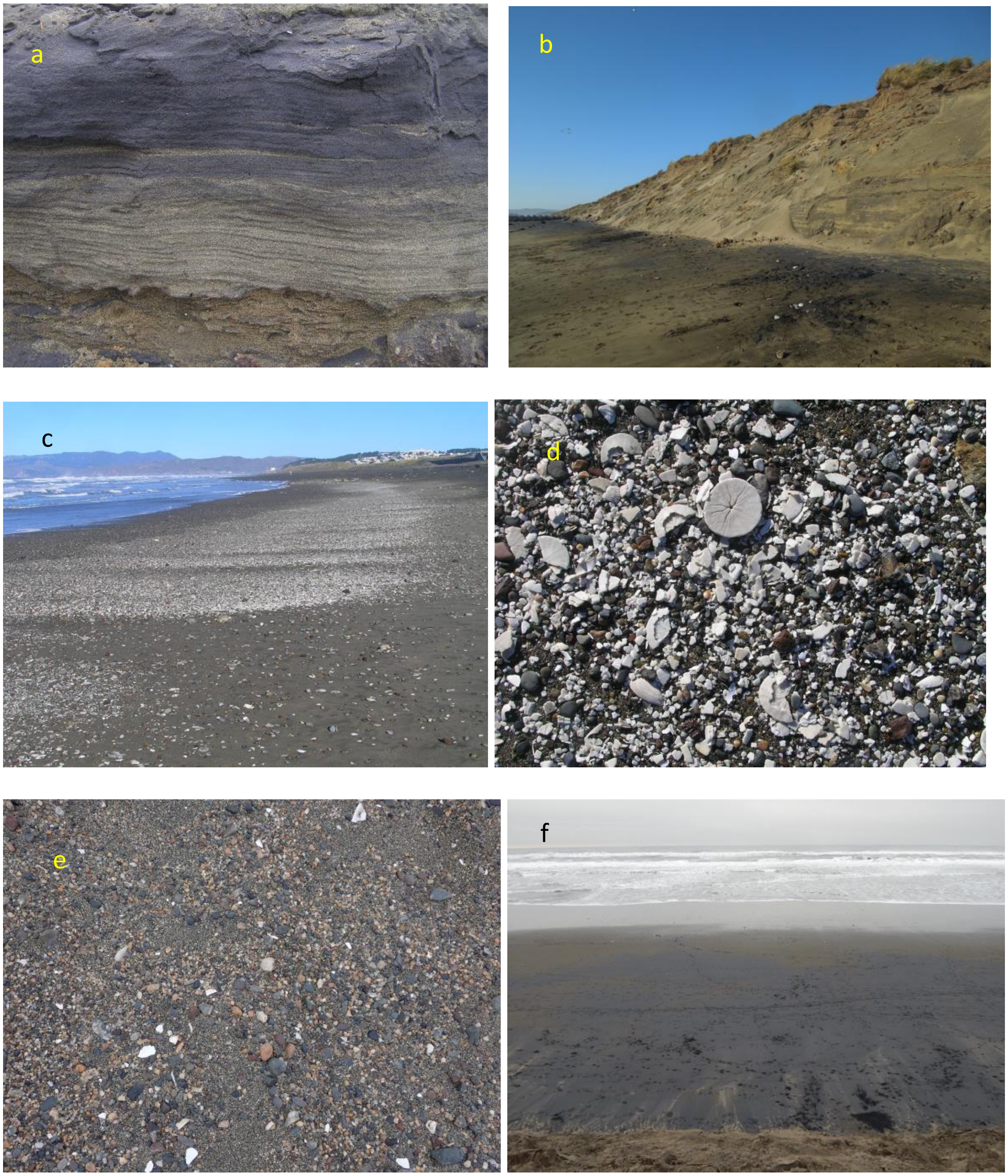


Figure 14. Foreshore sand deflation resistance components at Ocean Beach: heavy mineral sand lag, shell and pebble lags, and wetted beachface. (a-b) Magnetite sand concentrates during storm erosion of beachface surfaces, where it is deposited in early post-storm beach profile recovery stages, as well as in dunes during extreme high wind velocities. (c-d) Shell lag armor surfaces develop on eroded foreshore beach surfaces, especially south of Noriega. (e) Coarse sand dredged from San Francisco Bay commercial

sand mining is used as a deflation-resistant cap of some sand berms south of Sloat. (f) Wet intertidal beach sand, saturated above the swash zone (mirror-like wet surface), restricts wind deflation.

Supporting literature for this section: Anthony *et al*. 2009, Bauer *et al.* 2009, Davidson-Arnott & Law 1990, He *et al*. 2022, Jay et al. 2022, Sarre 1988, Vanhee *et al*. 2002

3.2.3. Beach progradation form and processes – continuous and step changes in beach width affecting dune sand fetch).

The width of the backshore beach – sand deflation fetch - grows during periods of calm weather (non-storm) constructive swell, which can occur in any season, but prevails in the dry season. Natural beach widening (progradation, seaward growth) and its potential dune sand supply usually develop continuously and gradually, but at Ocean Beach, significant discontinuous and irregular patterns of beach widening occur some years in some reaches. These can correspond with predictable local or temporary significant variations in foredune sand supply or erosion. Monitoring of these patterns of beach change driving wind-blown sand supply (seasonal forecasting) can guide adaptive management actions that require lead time for planning and coordination, materials, workforce, or mobilization of equipment. (e.g., brush fence or mat material stockpiling, staging, scheduling for installation).

- **Ridge and backshore runnel welding sequence – abrupt morphological change of foreshore to backshore beach**. Onshore migration of accreting intertidal bars and troughs (slipface ridges and runnels) that finally weld with the backshore cause foreseeable, abrupt significant increases in dry sand backshore fetch that supplies foredunes with wind-blown sand. Predictable sequence recurrent in Reach A, sometimes Reach B:

    - Stage 1. Shore-detached ridge and runnel. Intertidal ridge (bar) accretion, transition to slipface morphology (high convex bar with steep landward depositional slope) and emergence to upper intertidal elevations, seaward of *backshore runnel* (linear upper intertidal trough, wet or flooded when ridge is intertidally emergent, with longshore rip current circulation and outlets). *Stage 1 constrains wind-blown sand transport to the backshore and foredune.*

      In Stage 1, the wet/flooded runnel intercepts onshore aeolian sand transport and segments beach sand fetch from foreshore. Runnels may form ephemeral shallow beach lagoons when outlets are choked and impounded by accreted sand. The ridge migration onshore may be slow or arrested before it flattens or erodes in place (steep high waves), or accretes and migrates on shore, proceeding to Stage 2.

    - Stage 2. Ridge accretes and welds to backshore; runnel fills. Onshore migration of ridge and runnel, terminating with elevated ridge welded to backshore, sand accretion filling runnel. When the bar top coalesces with the backshore beach, a continuous dry supratidal sand fetch abruptly increases. Time scale: weeks to months anticipation of potential foredune sand accretion rate increase. *Stage 2* *abruptly amplifies potential wind-blown sand transport to the backshore and foredune.*

Figure 15. Transient migrating intertidal ridge and runnel morphology at Ocean Beach. This infrequent but important beach state initially reduces backshore sand fetch, and later increases it after sand bars emerge and weld with the backshore beach, from Lawton north beyond Lincoln. (a) Onshore-migrating emergent ridge (berm) impounds a series of backshore runnel lagoons, some of which drain through shallow rip channel outlets. The flooded and wetted backshore acts as a trap for windblown sand. December 2022. (b) Flooded and wet sand of the backshore runnel occupies areas that are usually dry sand, open fetch for dune sand transport in summer. July 2006. (c-d) Long shore-parallel runnel partially draining on an ebbing tide, separating the emergent ridge from the backshore zone. December 2022.

(supporting literature: Carter 1986; Aagard *et al*. 2004, Anthony *et al*. 2009, He *et al.* 2002, Masselink *et al*. 2006; Oblinger and Anthony 2008, Vanhee *et al*. 2002)

- **Continuous berm progradation.** Gradual seaward progradation of berm crest or multiple berm crests, no significant wetted runnels or lagoons segment dune sand fetch. Continuous backshore beach progradation – berm accretion or multiple berm sequences with no intervening runnels – is prevalent in Reach in Reach A (N of Lincoln) and B.

3.2.4. Variability in Ocean Beach mega-cusp and rip embayment position (oblique bar/trough morphology) and "hot spot" locations of foredune storm wave erosion

Beach morphology influences patterns of foredune erosion by storm waves in Monterey Bay (Thornton *et al.* 2007), and similar alongshore variation in beach morphology (transient oblique attached bars, troughs, mega-cusps, crescentic beaches, and associated rip embayments) likely exerts similar effects on local backshore and foredune erosion patterns at other beaches (Houser and Mathew 2010), as well as Ocean Beach.

Narrow backshore beach widths and greater storm wave runup closer to the dune toe correspond with contemporary rip embayment positions, which may be transient and migrate alongshore. Reduced storm wave runup, beach and foredune erosion are associated with wide profile zones associated with mega-cusps or oblique attached bars (Thornton *et al*. 2007, Houser & Mathew 2010, Keijsers *et al*. 2014), which may also be transient and migratory, or relatively persistent seasonally. Foredune scarps persist longer than rip embayment positions, so time lags between rip embayment positions and intensified scarp erosion locations are expected, and weaken short-term correlations among them after scarps form.

Episodic foredune and backshore erosion is related to the position of rip embayments where wave energy propagates farther shoreward with less dissipation, and where the backshore is narrower, allowing storm wave runup to reach the foredune toe over short distances. The alongshore migration of rip embayments and bars moves the position of storm wave erosion hotspots, such that persistent foredune erosion patterns can lag behind the morphology that created them. The formation of relatively persistent large rip embayments can be used as an indicator of locally increased storm wave erosion vulnerability in the backshore and foredune zone, and may have forecasting utility for adaptive management (e.g., sand placement).

Figure 16. Large rip embayments and mega-cusps (beach protuberances) at Ocean Beach.
(a) Large, deep rip embayment at mid-tide brings surf within reach of the sand embankment scarp near Sloat. (b) Large beach mega-cusp and adjacent rip embayments (one of a series alongshore) near Taraval. June 2012.

4. Ocean Beach Reaches: integrated conceptual models

This section provides a synthesis of component beach-dune conceptual models applied to each reach of Ocean Beach, distinguished by significant variations in beach and foredune morphology and dynamics (beach width, dynamic bar, trough, mega-cusp and rip embayment, foredunes, blowout dunes, vegetation), topography, and coastal engineering structures (seawalls, sand embankments, remnant fills)

4.1. Reach A, Balboa to Lincoln (O'Shaughnessy seawall prograded beach plain)

- Prograded wide backshore, no vegetation; maintained by intensive daily year-round unrestricted recreational trampling throughout the backshore, and episodic sand grading (excavation and removal to Sloat "backpass" management). Potential foredune zone is unoccupied.
- No rhythmic beach topography, mega-cusps, rip embayments; linear shore, homogeneous erosion/accretion pattern. Episodic ridge and runnel formation and migration, but low net change in sand fetch when welded to backshore because of permanently wide unvegetated backshore.
- Wide unvegetated trampled backshore maintains maximum sand fetch; low-relief transverse dunes, indistinct at ground level but conspicuous from aerial imagery, raise topographic relief (high elevation backshore). Likely net wind-blown sand transport southward.
- Dune ramp formation at seawall; aborted development of ramps due to beach grading and backpassing. No significant wind-blown sand accretion downwind of seawall (contrast with Reach B-D). No interception of onshore wind-blown sand by foredune vegetation; no foredune growth or topography.
- Rare or no wave runup at seawall; largely vestigial structure
- Wide backshore beach often attracts wintering western snowy plovers in this reach.

4.2. Reach B, Lincoln to Noriega (Accreted Foredune over sand embankment)

- Backshore gradient alongshore: wide backshore beach narrowing southward.
- Episodic ridge and runnel formation, welding to backshore; moderate variability in high sand fetch.
- Vegetated foredunes accreted over 1985 constructed sand embankment.
  Partially vegetated and destabilizing foredune at north end where maximum sand fetch northwest. Continuously vegetated accreting foredunes middle of reach. Unvegetated unstable dune south at Noriega.
- Trampling impacts to foredune vegetation over decades destabilize and devegetate foredunes in vicinity of maximum access (Lincoln/Golden Gate Park and Judah crosswalks, O'Shaughnessy promenade/Lincoln); variable incipient blowouts at smaller social foot trails between, progressively increasing to blowouts.
- Foredune slopes gentlest and widest within accreting native widely creeping beach wildrye vegetation; associated with least blowout development (self-repair).
- Foredune slopes highest, and most hummocky with gaps within marram grass vegetation; associated with high blowout size and frequency.
- Limited embryo foredune and incipient foredune space, high trampling impacts (existing).

- Large blowouts evolved to massive lobate mobile dunes at Noriega & Judah; permanent loss of dune crest vegetation and permanent unrestricted trampling eliminates vegetative recovery process (gravity-driven slumping and self-burial of vegetation). Dune lobes and slipfaces migrate over Great Highway during gales. Lobate dune slipface removed mechanically from road during active migration (gales).

4.3. Reach C, Noriega to Santiago ("New" seawall)

- Variable backshore width and sand fetch; alternating irregular prograded (mega-cusp) and rip embayment position.
- Embryo foredune vegetation and incipient foredune ridge up to 2007; seasonal grading prevents re-establishment of vegetation beyond seedling/resprouts stage. Narrow zone for embryo foredune or incipient foredune, high frequency of scarp retreat or erosional wave runup.
- Denuded wide backshore beach and dry sand mound placement = wide dry sand fetch = high rate wind-blown sand transport (NW to SE). Frequent dune ramps overtopping seawall; transport and accretion over walkways and Great Highway. Ramp profile seaward of excavated trench below seawall launches saltation bedload to suspended sand load over Great Highway.
- High frequency of foreshore with shell/pebble lag, heavy mineral lag, high moisture or saturated sand = sand deflation resistance, reduced wind-blown sand accretion, higher storm wave impact.
- During wide backshore beach phases, western snowy plovers establish high tide roost habitats in this reach.

4.4 Reach D, Santiago to Sloat (Sand embankment with retreating or climbing foredunes)

- Typical narrow backshore, limited sand fetch; foreshore up to scarp toe at embankment. Intermittent wide backshore, fetch increase. High erosion from storm wave attack.
- Compressed space or none for transient embryo foredunes (mega-cusp); high frequency of scarp erosion to toe of embankment (rip embayment).
- Foredune trampling and scarp erosion during low wind-blown sand supply phase 1990s-2010s) reduced marram, increased iceplant dominance; reduced capacity for resilient biogeomorphic response to renewed recent dune sand accretion.
- High frequency blowouts and transgression to Great Highway under dominant iceplant cover, patchy marram.
- Iceplant dominance at crest of scarp; slumps of iceplant downslope dominate new dune ramp; weak spread and sand trapping.
- Mega cusp and rip embayment zone; variable backshore width.
- High frequency of foreshore with heavy mineral lag, high moisture or saturated sand = sand deflation resistance, reduced wind-blown sand accretion, higher storm wave impact.

LITERATURE CITED

Aagaard, T., Davidson-Arnott, R., Greenwood, B. and Nielsen, J., 2004. Sediment supply from shoreface to dunes: linking sediment transport measurements and long-term morphological evolution. Geomorphology, 60(1-2): 205-224.

Aagaard, T., Kroon, A., Andersen, S., Sorensen, R.M., Quartel, S. and Vinther, N., 2005. Intertidal beach change during storm conditions; Egmond, The Netherlands. Marine Geology 218, 65-80.

Anthony, E.J., Ruz, M.H. and Vanhée, S., 2009. Aeolian sand transport over complex intertidal bar-trough beach topography. Geomorphology, 105(1-2):95-105.

S. M. Arens, H. M. E. Van Kaam-Peters, and J. H. Van Boxel. 1995. Air flow over foredunes and implications for sand transport. Earth Surface Processes And Landforms 20(3):15-332

Bauer, B.O., Davidson-Arnott, R.G.D., Hesp, P.A., Namikas, S.L., Ollerhead, J. and Walker, I.J., 2009. Aeolian sediment transport on a beach: Surface moisture, wind fetch, and mean transport. Geomorphology, 105(1-2):106-116.

Bauer, B.O., Davidson-Arnott, R.G., Walker, I.J., Hesp, P.A. and Ollerhead, J., 2012. Wind direction and complex sediment transport response across a beach–dune system. Earth Surface Processes and Landforms, 37(15), pp.1661-1677.

Bauer, B.O., Hesp, P.A., Smyth, T.A., Walker, I.J., Davidson-Arnott, R.G., Pickart, A., Grilliot, M. and Rader, A., 2022. Air flow and sediment transport dynamics on a foredune with contrasting vegetation cover. Earth Surface Processes and Landforms, 47(11):2811-2829.

Biel, R.G., Hacker, S.D. and Ruggiero, P., 2019. Elucidating coastal foredune ecomorphodynamics in the US Pacific Northwest via Bayesian networks. Journal of Geophysical Research: Earth Surface, 124(7):1919-1938.

Carter, R.W.G., 1986. The morphodynamics of beach-ridge formation: Magilligan, Northern Ireland. Marine Geology, 73(3-4):191-214.

Christiansen, M.B. and Davidson-Arnott, R., 2004. Rates of landward sand transport over the foredune at Skallingen, Denmark and the role of dune ramps. Geografisk Tidsskrift-Danish Journal of Geography, 104:31-43.

Cohn, N.; Ruggiero, P.; de Vries, S.; Kaminsky, G. 2018. New insights on the relative contributions of marine and aeolian processes to coastal foredune growth. Geophys. Res. Lett. 45:4965–4973.

Davidson-Arnott, R.G.D., Bauer, B.O., Walker, I.J., Hesp, P.A., Ollerhead, J. and Chapman, C., 2012. High-frequency sediment transport responses on a vegetated foredune. Earth Surface Processes and Landforms, 37(11):1227-1241.

Davidson-Arnott, R.G. and Law, M.N., 1990. Seasonal patterns and controls on sediment supply to coastal foredunes, Long Point, Lake Erie. Coastal dunes: form and process, pp.177-200.

Davidson-Arnott, R.G.D. 2005. Conceptual model of the effects of sea level rise on sandy coasts. Journal of Coastal Research 21: 1166–1172

Davidson-Arnott, R.G., Yang, Y., Ollerhead, J., Hesp, P.A. and Walker, I.J., 2008. The effects of surface moisture on aeolian sediment transport threshold and mass flux on a beach. Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group, 33(1):55-74.

de Carvalho, A.M.C.; Ellis, J.T.; Lamothe, M., and Maia, L.P., 2016. Using wind direction and shoreline morphology to model sand dune mobilization. Journal of Coastal Research, 32(5), 1005–1015.

Dugan, J.E., Hubbard, D.M., Page, H.M. and Schimel, J.P., 2011. Marine macrophyte wrack inputs and dissolved nutrients in beach sands. Estuaries and Coasts, 34(4):839-850.

Feagin, R.A., Figlus, J., Zinnert, J.C., Sigren, J., Martínez, M.L., Silva, R., Smith, W.K., Cox, D., Young, D.R. and Carter, G., 2015. Going with the flow or against the grain? The promise of vegetation for protecting beaches, dunes, and barrier islands from erosion. Frontiers in Ecology and the Environment, 13(4):203-210.

Goldstein, E.B., Moore, L.J. and Durán Vinent, O., 2017. Lateral vegetation growth rates exert control on coastal foredune hummockiness and coalescing time. Earth Surface Dynamics 5(3): 417-427.

Grilliot, M.J., Walker, I.J. and Bauer, B.O., 2019. Aeolian sand transport and deposition patterns within a large woody debris matrix fronting a foredune. Geomorphology, 338, pp.1-15.

Hacker, S.D., Zarnetske, P., Seabloom, E., Ruggiero, P., Mull, J., Gerrity, S. and Jones, C., 2012. Subtle differences in two non-native congeneric beach grasses significantly affect their colonization, spread, and impact. Oikos, 121(1):138-148.

Hacker, S.D., Jay, K.R., Cohn, N., Goldstein, E.B., Hovenga, P.A., Itzkin, M., Moore, L.J., Mostow, R.S., Mullins, E.V. and Ruggiero, P., 2019. Species-specific functional morphology of four US Atlantic coast dune grasses: Biogeographic implications for dune shape and coastal protection. Diversity, 11(5):82.

He, Y., Liu, J., Cai, F., Li, B., Qi, H. and Zhao, S., 2022. Aeolian sand transport influenced by tide and beachface morphology. Geomorphology, 396:107987.

Hesp, P.A., Walker, I.J., Namikas, S.L., Davidson-Arnott, R., Bauer, B.O. and Ollerhead, J., 2009. Storm wind flow over a foredune, Prince Edward Island, Canada. Journal of Coastal Research SI 36:312-316.

Hesp, P., 2002. Foredunes and blowouts: initiation, geomorphology and dynamics. Geomorphology, 48(1-3):245-268.

Hesp, P.A., 1989. A review of biological and geomorphological processes involved in the initiation and development of incipient foredunes. Proceedings of the Royal Society of Edinburgh, Section B: Biological Sciences, 96:181-201.

Hilton, M. and Konlechner, T. 2011. Incipient foredunes developed from marine-dispersed rhizome of *Ammophila arenaria*. Journal of Coastal Research SI 64:288-292.

Houser, C. and Mathew, S., 2011. Alongshore variation in foredune height in response to transport potential and sediment supply: South Padre Island, Texas. Geomorphology, 125(1):.62-72.

Jackson, N.L. and Nordstrom, K.F., 1997. Effects of time-dependent moisture content of surface sediments on aeolian transport rates across a beach, Wildwood, New Jersey, USA. Earth Surface Processes and Landforms 22(7):611-621.

Keijsers, J.G., Poortinga, A., Riksen, M.J. and Maroulis, J., 2014. Spatio-temporal variability in accretion and erosion of coastal foredunes in the Netherlands: regional climate and local topography. PloS one, 9(3):e91115

Masselink, G., Kroon, A. and Davidson-Arnott, R.G.D., 2006. Morphodynamics of intertidal bars in wave-dominated coastal settings—a review. Geomorphology, 73(1-2):33-49

McLean, R. and Shen, J.S., 2006. From foreshore to foredune: foredune development over the last 30 years at Moruya Beach, New South Wales, Australia. Journal of Coastal Research, 22(1):28-36.

Mullins, E., Moore, L.J., Goldstein, E.B., Jass, T., Bruno, J. and Durán Vinent, O., 2019. Investigating dune-building feedback at the plant level: Insights from a multispecies field experiment. Earth Surface Processes and Landforms, 44(9):1734-1747.

Oblinger, A. and Anthony, E.J., 2008. Surface moisture variations on a multibarred macrotidal beach: implications for aeolian sand transport. Journal of Coastal Research, 24(5):1194-1199.

Nordstrom, K.F., Jackson, N.L., Hartman, J.M. and Wong, M., 2007. Aeolian sediment transport on a human-altered foredune. Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group, 32(1):102-115.

Nordstrom, K.F., Jackson, N.L. and Korotky, K.H., 2011. Aeolian sediment transport across beach wrack. Journal of Coastal Research, (59): 211-217.

Sarre, R.D., 1989. Aeolian sand drift from the intertidal zone on a temperate beach: potential and actual rates. Earth Surface Processes and Landforms, 14(3): 247-258.

Sarre, R.D., 1988. Evaluation of aeolian sand transport equations using intertidal zone measurements, Saunton Sands, England. Sedimentology, 35(4):671-679.

Seabloom, E. W., and A. M. Wiedemann. 1994. Distribution and effects of *Ammophila breviligulata* Fern (American beachgrass) on the foredunes of the Washington coast. Journal of Coastal Research 10:178–188

Seabloom, E.W., Ruggiero, P., Hacker, S.D., Mull, J. and Zarnetske, P., 2013. Invasive grasses, climate change, and exposure to storm-wave overtopping in coastal dune ecosystems. Global change biology, 19(3):824-832.

Thornton, E.B., MacMahan, J. and Sallenger Jr, A.H., 2007. Rip currents, mega-cusps, and eroding dunes. Marine Geology, 240(1-4):151-167.

van Kuik, N., de Vries, J., Schwarz, C. and Ruessink, G., 2022. Surface-area development of foredune trough blowouts and associated parabolic dunes quantified from time series of satellite imagery. Aeolian Research 57:100812.

Vanhée, S., Anthony, E.J. and Ruz, M.H., 2002. Aeolian sand transport on a ridge and runnel beach: preliminary results from Leffrinckoucke beach, northern France. Journal of Coastal Research, (36 (10036):732-740.

Walker, I J., P.A. Hesp, R. G. D. Davidson-Arnott and J. Ollerhead. 2006. Topographic steering of alongshore airflow over a vegetated foredune: Greenwich Dunes, Prince Edward Island, Canada. Journal of Coastal Research 22(5): 1278-1291

Zarnetske, P.L., Hacker, S.D., Seabloom, E.W., Ruggiero, P., Killian, J.R., Maddux, T.B. and Cox, D., 2012. Biophysical feedback mediates effects of invasive grasses on coastal dune shape. Ecology, 93(6):1439-1450.

Additional local historical references on Ocean Beach foredune development and Golden Gate Park dune stabilization

McClintock, E. 2001. The Trees of Golden Gate Park and San Francisco. Heyday Books, Berkeley, CA. [Golden Gate Park dune stabilization history]

McLaren, J. 1914. Gardening in California: Landscape and Flower. A.M. Robertson Philopolis Press, San Francisco. [Golden Gate Park dune stabilization and marram grass introduction history; author was second superintendent of Golden Gate Park]

APPENDIX

Principal Foredune and Beach Plant Species of Ocean Beach –
Summary of Key Biogeomorphic Functional Traits affecting Foredune Development

1. Iceplant (*Carpobrotus edulis, C. edulis* x *chilensis*) –

- prostrate, low mat-forming creeping (clonal) perennial evergreen succulent/subshrub.
- *Low sand trapping and dune building capacity* – short canopy (to ca. 20 cm), slow burial recovery (vegetative re-emergence) rate, and low sand burial tolerance.
- *Foredune form*: dome-like mounds or undulating wide foredunes, relatively low height, slow accretion.
- Cover *declines* under rapid or deep (>30 cm) sand burial above canopy height.
- Salt tolerance
    - High foliar tolerance to salt spray
    - Low root salt tolerance during spring-summer growing season (injury or mortality high if flooded by seawater from wave runup during dry season, active growth).

Figure A-1. Prostrate iceplant mats in backdune and foredune vegetation, San Francisco Ocean Beach, and Half Moon Bay, San Mateo County. The low, prostrate growth habit of iceplant forms gently sloping or low mounded dune forms under low rates of sand accretion. It has low capacity to trap sand, build, or stabilize dunes under high rates of sand accretion

2. Marram grass (*Ammophila arenaria*)

- Broom-like, tall (0.75-1.0 m seed-head culms, leafy tillers) upright stiff dense grass tussocks, mostly short-creeping clonal perennial grass, with new growth seasonal clones clustered close (<1 m) to the parent.
- *Highest global sand trapping and dune building capacity of any foredune plant*, rapid burial recovery of vigorous sand burial-conditioned stands; readily maintains foredune accretion rates > 0.5 m/yr, up to ca. 1 m/yr.
- *Foredune form:* high, narrow steep foredune ridge, often crested or hummocky, in Central CA up to ca. 15-20 m high.
- Sand accretion responses

Peter R. Baye Ph.D.
Coastal Ecologist, Botanist
(415) 310-5109
botanybaye@gmail.com

    - Live cover, vigor (growth rate, size) and dominance *increase* under rapid or deep (>30 cm) sand burial; rapid recovery from complete canopy burial during active growth or after dormancy.
    - Live cover, vigor (growth rate, size) density and dominance *decline significantly* after dune stabilization; *stabilization increases mortality and reduces capacity to trap sand* (lag in growth reinvigoration, recovery after resumed sand accretion after long stabilization)
- Salt tolerance
    - High foliar tolerance to salt spray
    - Low root salt tolerance to seawater flooding during spring-summer growing season (salt injury or mortality high if flooded by seawater from wave runup during dry season, active growth).
- Reproduction and propagation
    - No significant seedling recruitment on beach, and none in dunes
    - *Almost all vegetative growth and reproduction* by fragmentation (rhizomes, shoots

Figure A-2. Marram grass in foredunes. (a) Tussocks (clumps) with tall culms bearing seed-heads, formed under moderate rates of sand accretion. (b) Hummocks and shadow dunes formed under high rates of sand accretion. (c) Rhizomes and roots exposed in a scarp, showing stratified vertical rhizomes (regenerating after sand burial) and horizontal rhizomes and roots (developed 1-2 ft below the contemporary sand surface)

3. Beach wildrye / American dunegrass (*Leymus mollis*)

- Lax broad leaf blades, small clusters of vegetative shoots or seed-head culms widely spaced at low density; widely creeping clonal perennial, long rhizomes, new seasonal clones 2-2.5 m from the parent, rapidly spreading into beach or dune gaps. Most rhizomes grow and elongate below ground in summer, followed by peak emergence of tips in fall.
- *Moderately high sand trapping and dune building capacity*, relatively rapid burial recovery (higher in moist beach or dune setting); readily maintains foredune accretion rates > 0.3 m/yr, up to ca. 0.5 m/yr.
- *Foredune form:* usually broad, gently sloping foredune ridge or hummocks, in Central CA up to ca. 2-5(6) m high.
- Sand accretion responses:

Peter R. Baye Ph.D.
Coastal Ecologist, Botanist

(415) 310-5109
botanybaye@gmail.com

  - Cover, vigor (growth rate, size) and dominance can maintain under rapid or deep (>30 cm) sand burial; rapid recovery from complete canopy burial during active growth or after dormancy.
  - Cover, vigor (growth rate, size) density and dominance *decline* after dune stabilization; dune *stabilization increases mortality and reduces capacity to trap sand* (lag in growth reinvigoration, recovery after resumed sand accretion after long stabilization)
- Salt tolerance
  - Not a true halophyte; salt-tolerant glycophyte, but with high effective salt tolerance in rhizome-connected clone networks of plants growing through patchy elevated substrate salinity, or across salinity gradients extending from low-salinity sand. Individual, isolated plants or severed clone fragments have lower salt tolerance.
  - Dormant plants in winter are tolerant of seawater inundation, followed by rainfall leaching of salts.
  - Moderate to low tolerance of elevated sand salinity during the growing season, depending on substrate moisture. Moderate *root* salt tolerance to seawater flooding during spring-summer growing season (limited salt injury or mortality high if flooded by seawater from wave runup during dry season, active growth).
  - High tolerance to salt spray
- Reproduction and propagation
  - Seed production: very low, ecologically insignificant production of viable seed (often sterile). Extremely low rate of seedling recruitment on beach, none in dunes
  - *Almost all vegetative spread, and new colonization of beach habitats,* occurs by clonal fragmentation and dispersal during storm erosion events (rhizomes, shoots), followed by establishment in wracks and embryo foredunes, or slumped foredune scarps.

Peter R. Baye Ph.D.
Coastal Ecologist, Botanist
(415) 310-5109
botanybaye@gmail.com

Figure A-3. Beach wildrye (American dunegrass; *Leymus mollis*, syn. *Elymus mollis*) growth patterns control sand accretion rates and patterns, and foredune shape. (a) continuous canopy of beach wildrye, with attached persistent dead leaves from the previous season, form a near-surface roughness zone (low-velocity "sand stilling" wind zone) acting as a trap for blowing sand, efficient for about 20-30 cm burial depth, depending on shoot height and density. (b) Growth habit of emerging young shoots in widely spaced small clusters, with broad, lax leaf blades (North Fort Funston). (c) Early winter emergence of rhizome tips at the ends of long, spreading rhizomes, rapidly extending the vegetative colony at the foredune toe to the adjacent backshore (Ocean Beach, Irving St.). (d) Long intact rhizomes are exposed by shallow backshore beach erosion, revealing colony structure and spread rates within the growing season (Crissy Field, San Francisco)

Figure A-4. Beach wildrye: vegetative tussock and flowering culms. Summary of published common name synonyms, and global distribution.

4. **Sea-rocket** (*Cakile maritima*)
   - Annual or short-lived perennial succulent broadleaf plant, forming low, wide dome-shaped plants or colonies about 0.2-<0.5 m high. Non-native, common in backshore beach, lower foredune or sand bluff slope (not invasive at Ocean Beach).
   - Low to moderate tolerance of gradual sand burial. Low capacity for dune building, near maximum plant height (<0.5 m). No significant long-term sand stabilization capacity.
   - Salt tolerance – moderately high root salt tolerance to seawater flooding during spring-summer growth season.
   - Reproduction: high seed production and high rate of germination, emergence on backshore beach, and high mortality where trampled on trails and backshore beach areas with high recreational use. Sporadic, infrequent seed dispersal and establishment in foredunes.

Peter R. Baye Ph.D.
Coastal Ecologist, Botanist
(415) 310-5109
botanybaye@gmail.com

Figure A-5. Sea-rocket. (a) Colony established in winter wrack deposition zone of the backshore at Lawsons Landing at the mouth of Tomales Bay, July 2008. (b) Winter dune sand accretion in sea-rocket patches forming hummock dunes and shadow dunes at Doran Beach, Bodega Bay, December 2019. These sea-rocket sand mounds do not persist and initiate embryo foredunes unless they are associated with perennial foredune plants. (c) sea-rocket in flowering and immature fruiting stage.

5. Prostrate native mat-forming perennial foredune forbs: beach-bur, *Ambrosia chamissonis*, and yellow sand-verbena, *Abronia latifolia*

- Prostrate lateral non-rooting branches emerge from enlarged shoot crowns at shallow depths below the dune surface, and do not form clones. Central crowns and branches attach to massive deep tap-roots, subject to erosion in unstable dunes or foredune scarps. Taproots with little lateral branching near the dune surface provides minimal resistance to wind or wave erosion from above or below.
- Prostrate growth habit limits sand accretion and stabilization to shallow increments between intervals of shoot-re-emergence, about 10-20 cm thickness within the shoot canopy. Low annual sand accretion capacity relative to tall foredune grasses. Rapid sand accretion overwhelms and passes over the sand-saturated, buried shoot canopy.
- Low substrate salt tolerance.

Figure A-6. Immature *Abronia latifolia* establishing on the backshore beach, exhibiting short, prostrate evergreen fleshy shoots and leaves, and a long, tapered, taproot with a shoot crown.

Peter R. Baye Ph.D.
Coastal Ecologist, Botanist
(415) 310-5109
botanybaye@gmail.com

Figure A-7. *Abronia latifolia* dome-shaped hummock, and inflorescence.

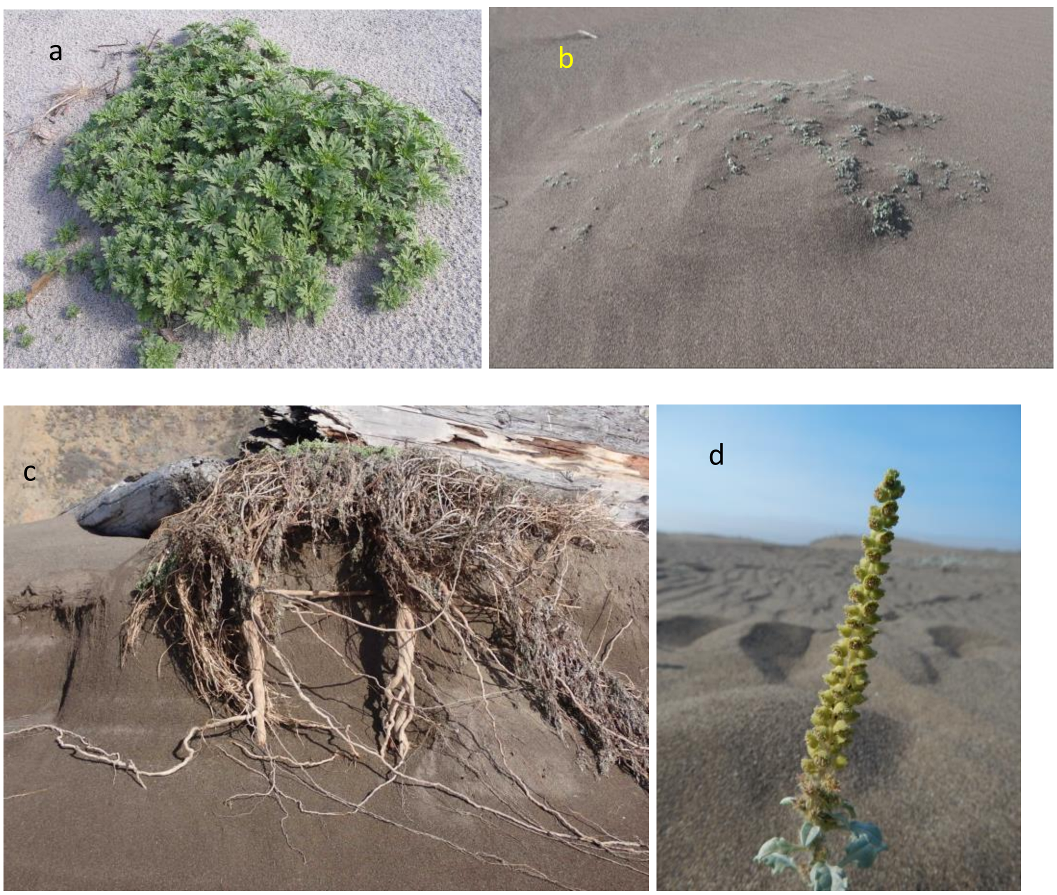


Figure A-8. ***Ambrosia chamissonis***. a. Emergent young vegetative plant at surface of beach. b. Prostrate shoot canopy of a plant in the backshore beach buried with wind-blown sand, saturating its capacity to trap and stabilize sand. c. Taproots with sparse lateral roots in the upper sand horizons are exposed by wave erosion, and provide no significant resistance to erosion. d. Inflorescence typical of ragweed genus, produced in summer.

Appendix D: Detailed Conceptual Design Drawings (Peter Baye)

Reach A (North of Lincoln)

NOTES

Shift sand backpass quarrying to seaward end of backshore beach profile:

- coarser (medium) wave-deposited beach sand, more stable
- troughs trap onshore-blown sand, reduce net wind fetch
- troughs emulate natural backshore runnels (elongated pools)

Establish new foredune zone seaward of seawall:

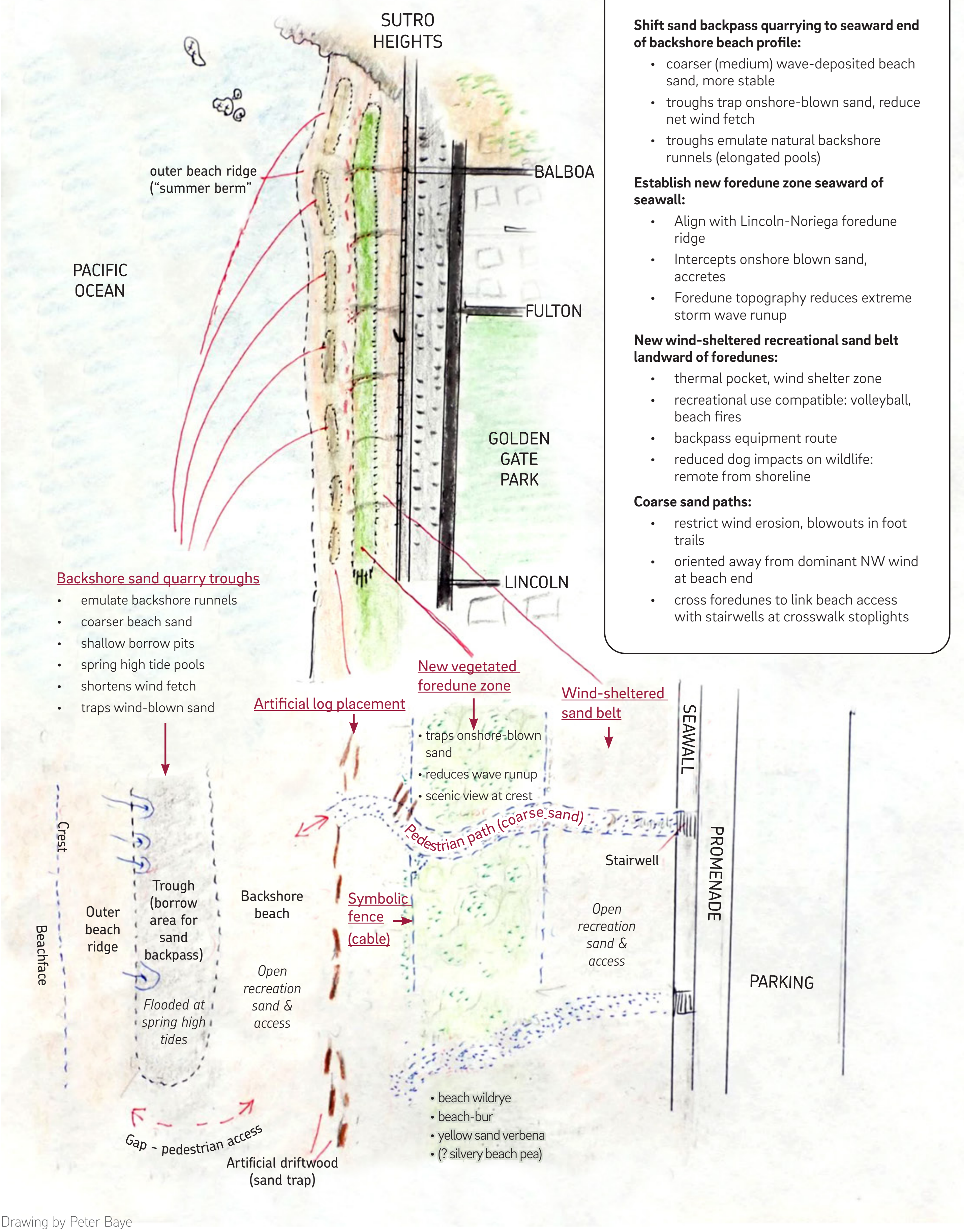
- Align with Lincoln-Noriega foredune ridge
- Intercepts onshore blown sand, accretes
- Foredune topography reduces extreme storm wave runup

New wind-sheltered recreational sand belt landward of foredunes:

- thermal pocket, wind shelter zone
- recreational use compatible: volleyball, beach fires
- backpass equipment route
- reduced dog impacts on wildlife: remote from shoreline

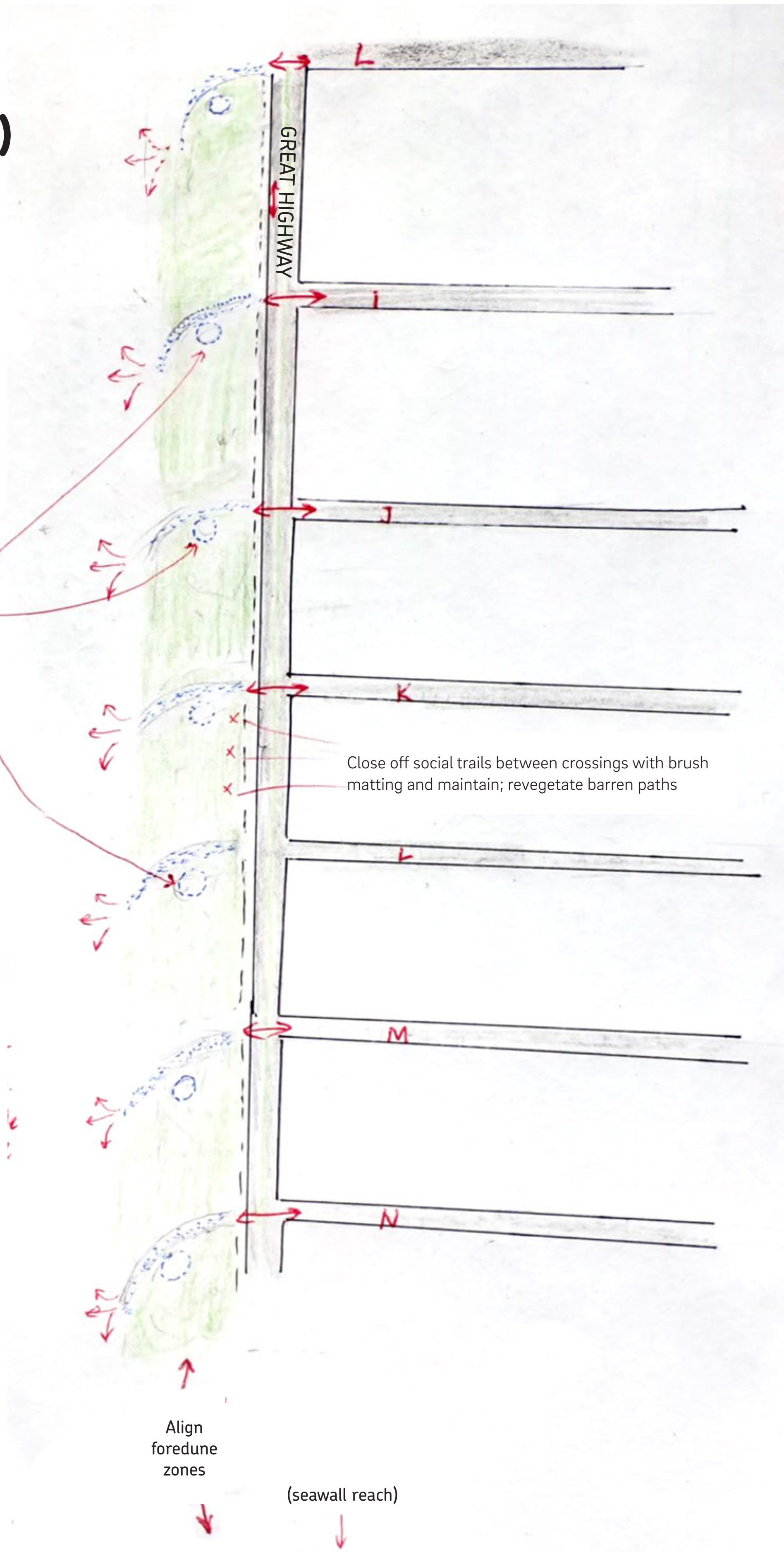
Coarse sand paths:

- restrict wind erosion, blowouts in foot trails
- oriented away from dominant NW wind at beach end
- cross foredunes to link beach access with stairwells at crosswalk stoplights



Drawing by Peter Baye

Reach B
(Lincoln to Noriega)



Major crosswalk (stoplight) trail alignment

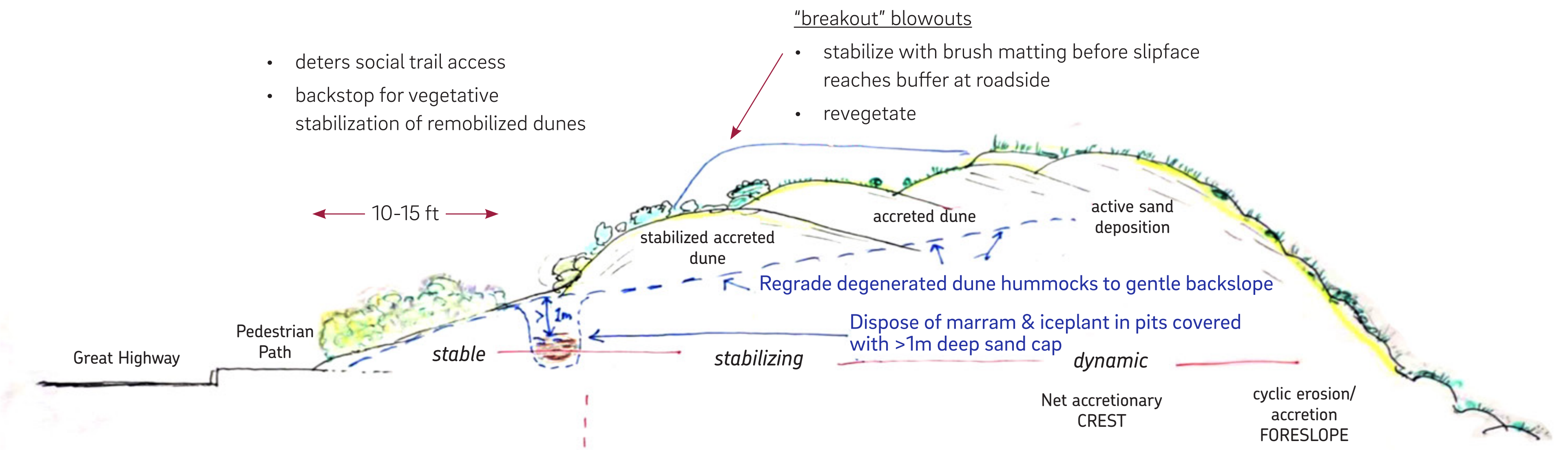
- restrict social trail network between stoplights using brush matting
- Coarse sand footpaths inhibit wind erosion of sand in trampled, bare paths
- coarse sand viewpoints at topographic highs at dune crest for surf viewing - resist sand erosion in concentrated trampling spots, discourage off-trail viewing search

Foredune rehabilitation

1. Regrade degenerated blowouts, marram & iceplant dune hummocks to create gently undulating slope (Fall)
2. Excavate pits to dispose of scraped marram grass and iceplant mats. Bury >1m deep under sand cap.
3. Place brush matting to provide temporary sand stabilization and discourage trampling of vegetation
4. (Winter) Wet, cool weather dormant planting of beach wildrye and associated pioneer species among brush matting
5. Establishment phase: maintain paths, brush matting to deter trampling.
6. Stabilization phase: Plant additional backdune and transitional foredune species landward of foredune crest in zones of low sand accretion (see cross-section for Reach B).

Drawing by Peter Baye

Reach B
(Lincoln to Noriega)
Cross-section



Roadside Dune Scrub Buffer

- **Pioneer: partial/recently stabilized**
  - *LUPINUS CHAMISSONIS* (SILVERY CHAMISSO LUPINE)
  - *LUPINUS ARBOREUS* (YELLOW BUSH LUPINE)
- **Late/mature stabilized**
  - *LUPINUS CHAMISSONIS* (SILVERY CHAMISSO LUPINE)
  - *ERICAMERIA ERICOIDES* (MOCK-HEATHER)
  - *PHACELIA DISTANS*
  - *AMSINCKIA SPECTABILIS*
  - *CHORIZANTHE CUSPIDATA*

  Dune annual forbs (spring-summer)

Transitional Foredune-Backdune

- **Co-dominants**
  - *ABRONIA LATIFOLIA* (YELLOW SAND-VERBENA)
  - *AMBROSIA CHAMISSONIS* (BEACH-BUR)
  - *ARTEMISIA PYCNOCEPHALA* (DUNE SAGE)
- **Clonal grasses (Co-dominants)**
  - *POA DOUGLASSII* (DOUGLAS' DUNE BLUEGRASS)
  - *LEYMUS PACIFICUS X TRITICOIDES* (PACIFIC WILDRYE - LOCAL HYBRID)
- **Sub-dominants**
  - *ERIOGONUM LATIFOLIUM* (DUNE BUCKWHEAT)
  - *LUPINUS CHAMISSONIS* (SILVERY CHAMISSO LUPINE)
  - *ERIGERON GLAUCUS* (BEACH DAISY)
  - *FRAGARIA CHILOENSIS* (BEACH STRAWBERRY)

Foredune

- **Dominant**

  LEYMUS MOLLIS (*ELYMUS MOLLIS*) (BEACH WILDRYE)

- **Sub-dominants**
  - *ABRONIA LATIFOLIA* (YELLOW SAND-VERBENA)
  - *AMBROSIA CHAMISSONIS* (BEACH-BUR)
  - *LATHYRUS LITTORALIS* (SILVERY BEACH PEA)*

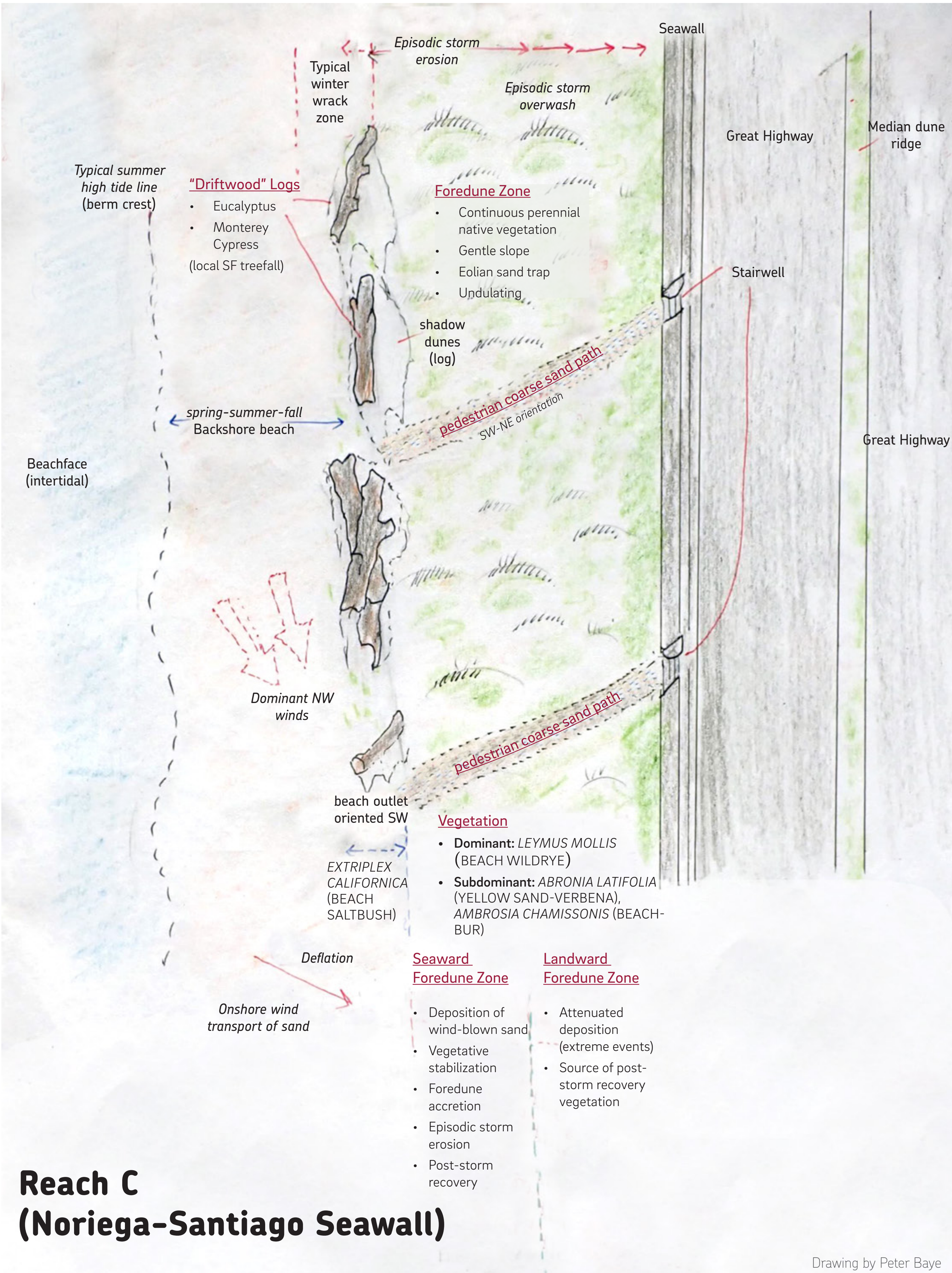
**if approved by GGNRA for reintroduction from Half Moon Bay (extirpated SF native)*

- *fixes nitrogen*
- *provides ground layer roughness for enhanced sand trapping*

Embryo Foredunes

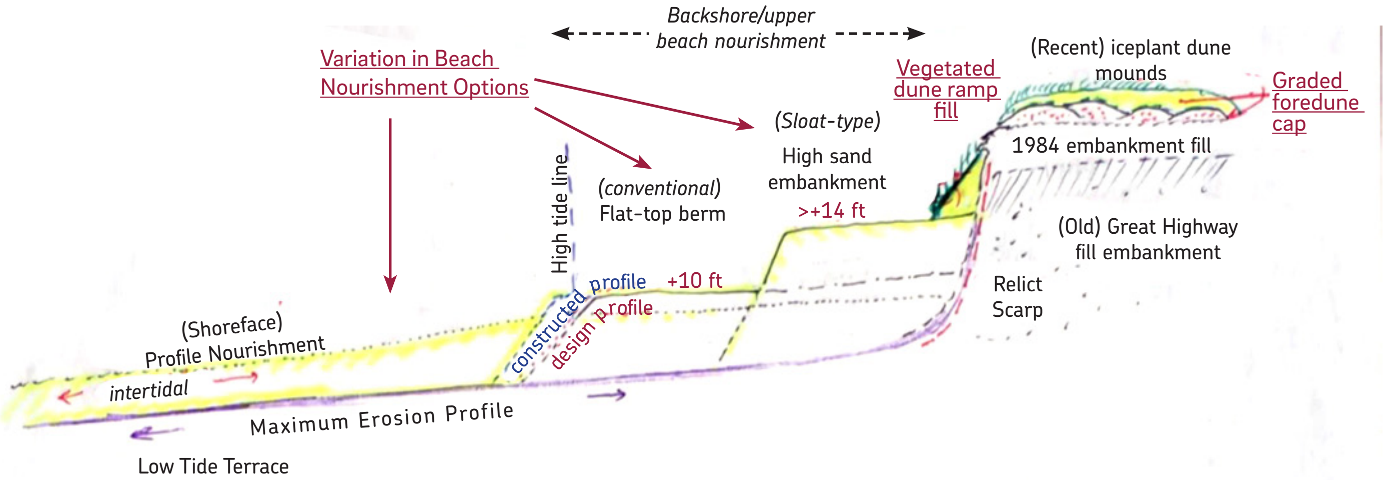
- *EXTRIPLEX CALIFORNICA* (BEACH SALTBUSH)

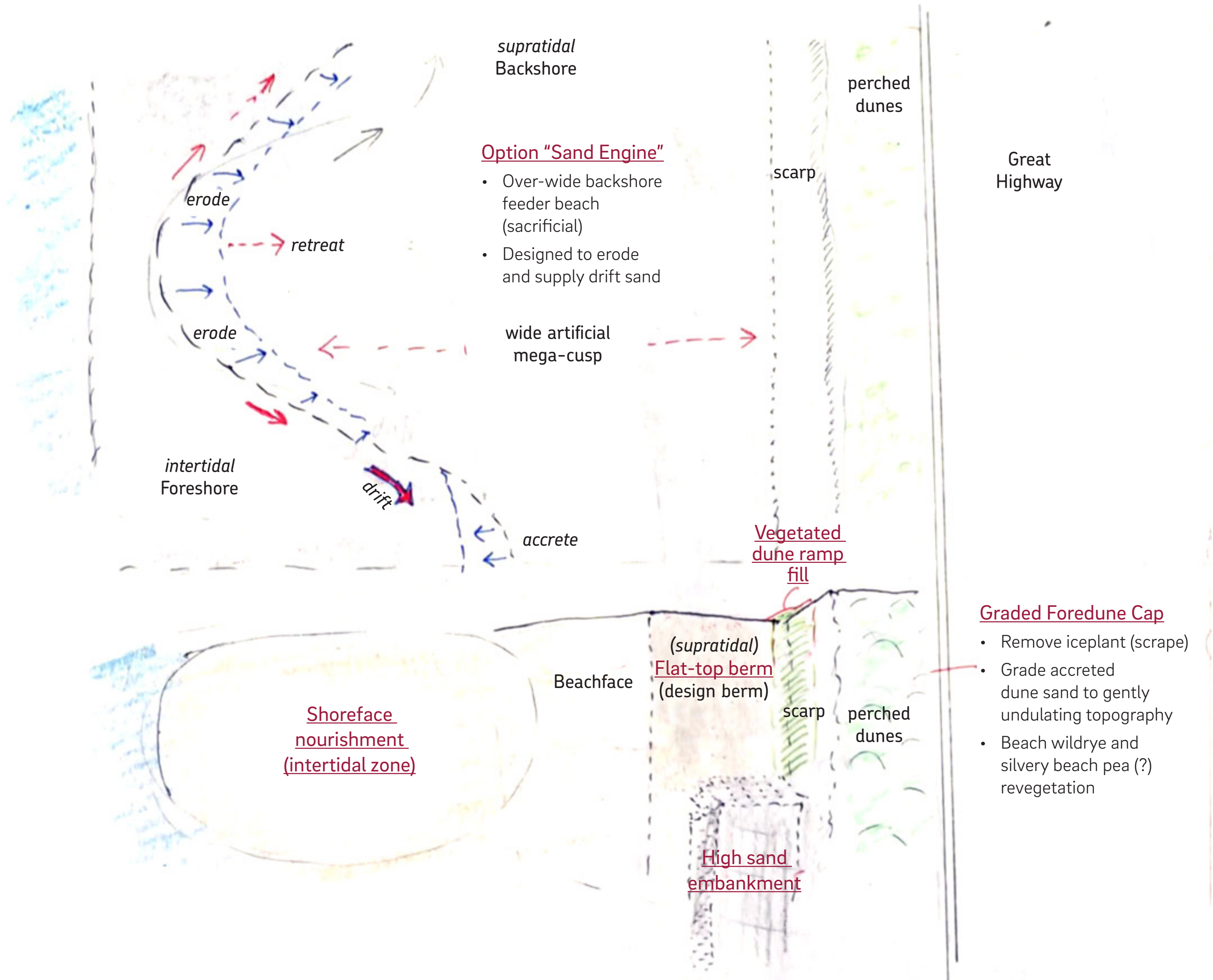
Drawing by Peter Baye



Reach C (Noriega-Santiago Seawall)

Drawing by Peter Baye

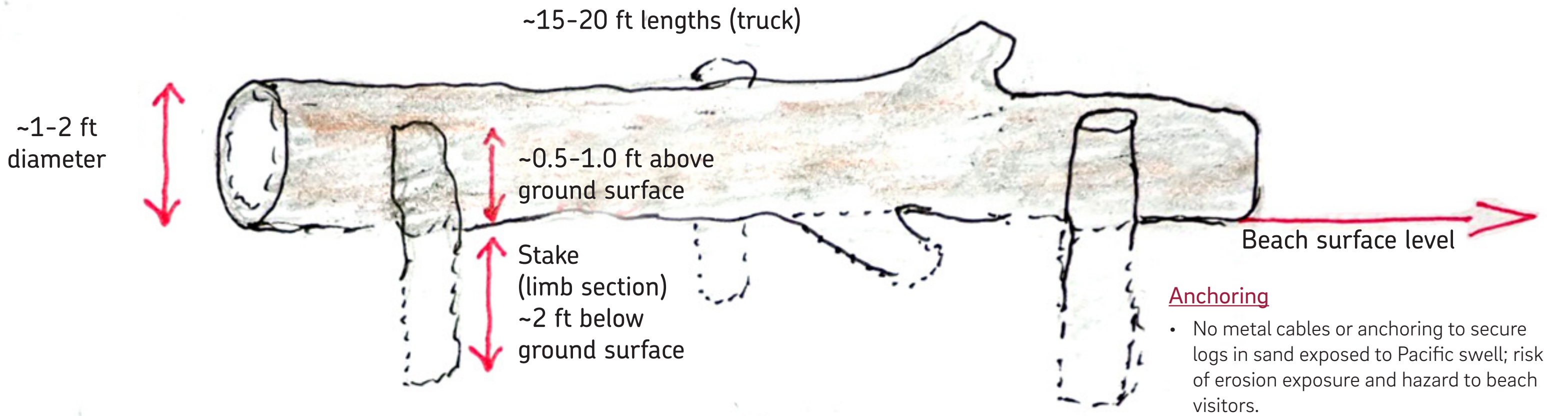




Reach D (Santiago-Sloat)

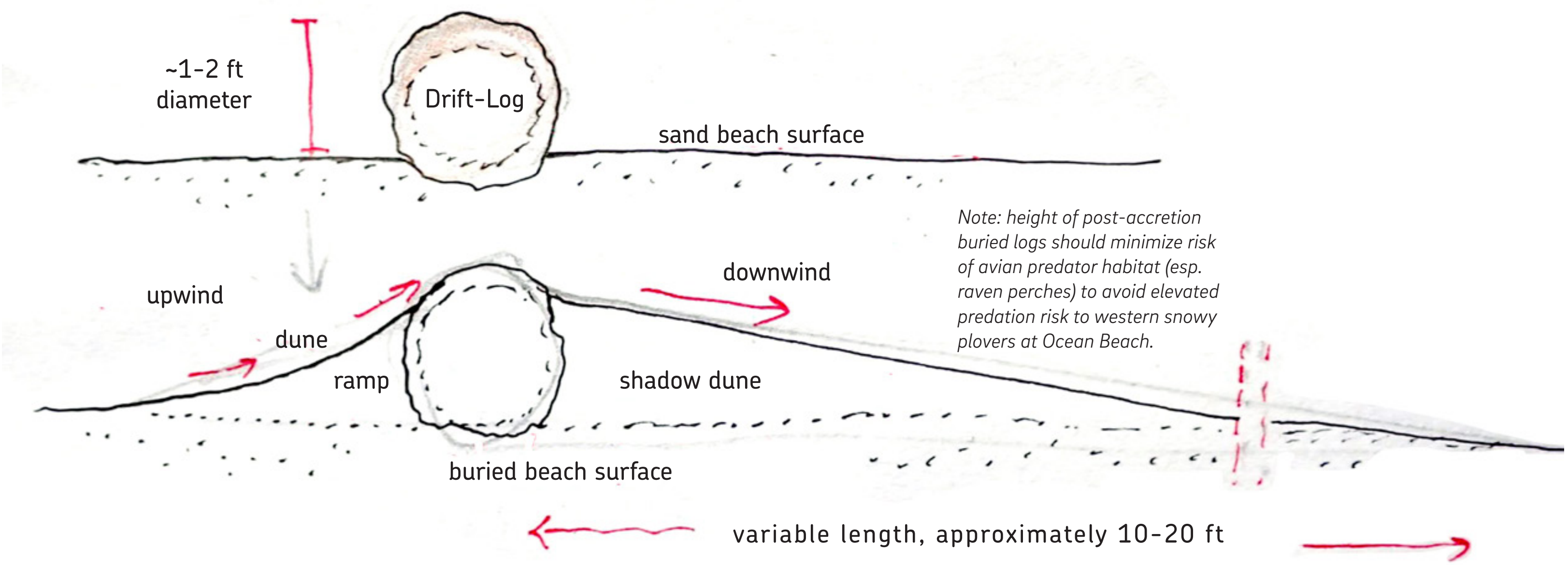
Drawing by Peter Baye

“Driftwood” Logs: Cross-Section



Anchoring

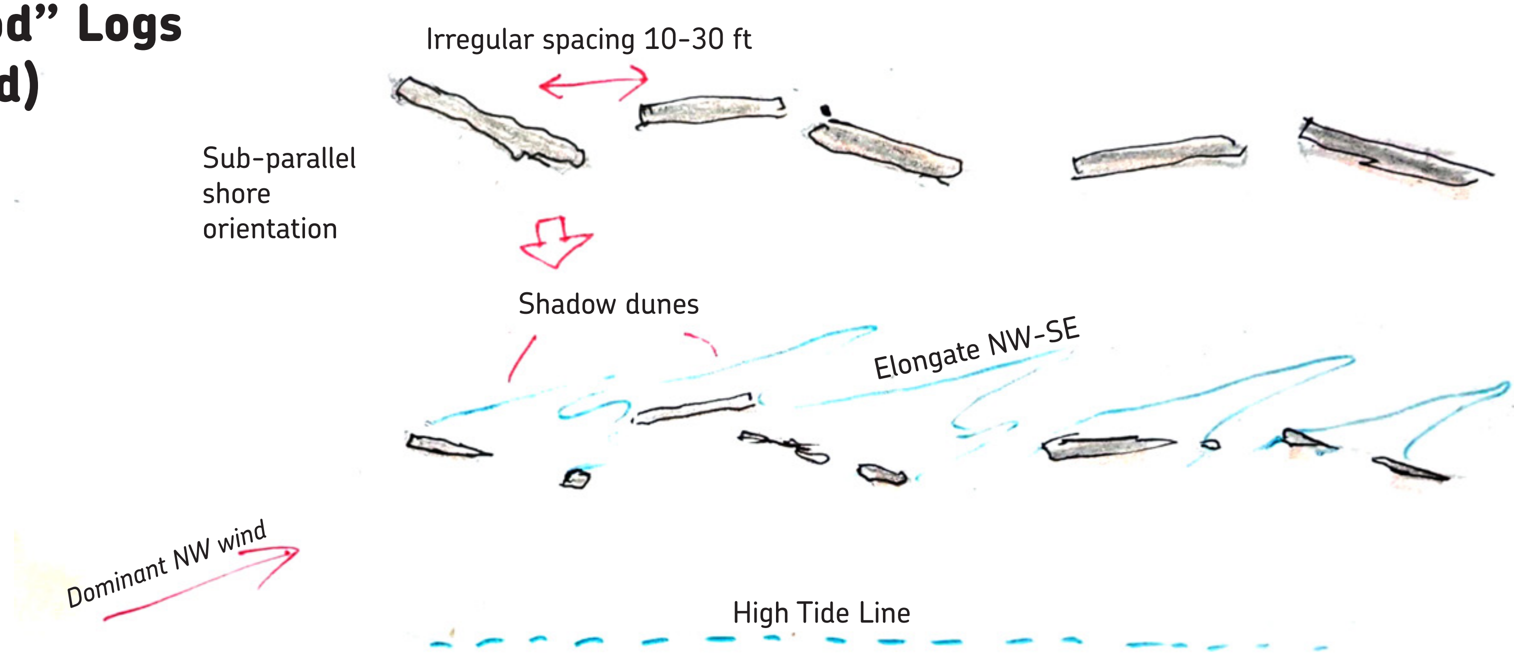
- No metal cables or anchoring to secure logs in sand exposed to Pacific swell; risk of erosion exposure and hazard to beach visitors.
- Instead, log stakes reduce potential for rolling with high swash or wave bore runup, but release logs for shoreward transport during extreme high wave action and high tide.

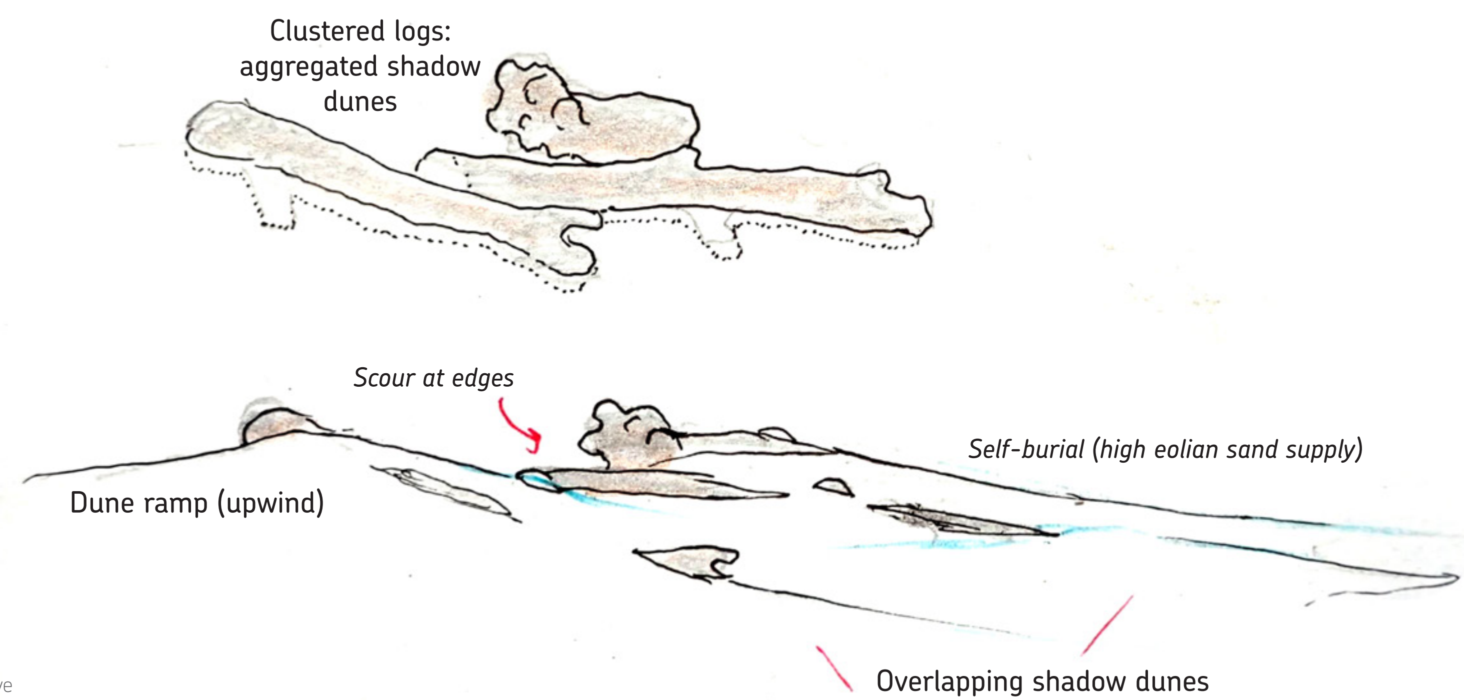


Note: height of post-accretion buried logs should minimize risk of avian predator habitat (esp. raven perches) to avoid elevated predation risk to western snowy plovers at Ocean Beach.

Drawing by Peter Baye

“Driftwood” Logs (continued)





Drawing by Peter Baye