Integral Consulting Inc.
200 Washington Street
Suite 201
Santa Cruz, CA 95060

telephone: 831.466.9630
facsimile: 831.466.9670
www.integral-corp.com

MEMORANDUM

To:	Mary Bilse, Environmental Programs Manager and Robert Harary, Director of Public Works, City of Carmel-by-the-Sea
From:	David Revell, Integral Consulting Inc.
Date:	October 4, 2023
Subject:	Carmel Climate Change Vulnerability Assessment, Shoreline and Beach Change Analysis: Seasonal and Long Term
Project No.:	C3016

EXECUTIVE SUMMARY

Carmel Beach is a 1.25-mile-long pocket beach with sand constrained by two rocky headlands—Arrowhead Point in the north and Carmel Point and an offshore reef in the south. As a large pocket beach, the volume of sand is mostly contained between the headlands, where very little sediment is gained or lost within the system. Sediment movement within the system can occur either north or south (alongshore) or off and onshore (cross shore) based on seasonal changes in wave energy and direction and in response to large storm wave events. Note that the movement of sediment in coastal environments is a dynamic and ongoing process. Sediment transport at Carmel Beach will be influenced by sea-level rise and increased storminess, which are long-term factors influenced by climate change. This report focuses only on typical historical conditions and does not project the potential hazard at Carmel Beach due to climate change. This will occur in future tasks.

The following is a highlight of this study's major findings for shoreline and beach change organized by **long-term historical trends** (decadal scale), **seasonal trends** (monthly to annual scale), **storm impacts** (event specific), and **recovery** (both seasonal and long term).

Long-term Historical Trends

- Over the last 80 years, while there have been many observed changes in dry sand beach widths due to a sequence of storm and recovery events, there is no long-term erosion trend as evidenced by a relatively stable average shoreline position derived via satellite measurements. This lack of an erosion trend indicates that there has been a consistent volume of sand in this pocket beach at Carmel Bay.

- The stable beach volume in this area is rather unique in California. Most of the other littoral cells (or beach compartments) have a set of sand sources and a sink (like a submarine canyon) where sand is lost from the beach system.
- On average, dry beach widths were narrower south of 8th Avenue, wider in the north by the Pebble Beach Golf Links, and the widest in the dune-backed areas near the Del Mar parking lot.

Seasonal Trends

- The dry sand beach widths change seasonally, where the narrowest beach widths occur in the spring (after winter storm waves move sand offshore) and the widest beach widths occur in the fall (after small summer waves bring that same sand back onshore).
- The highest range in beach widths occurs around the area of 4th Avenue and Pescadero Canyon (around the offshore rock).
- The beach width remains most consistent in the dune-backed areas near the Del Mar Parking lot, presumably as a result of sand being eroded from the dunes and nourishing that portion of the beach.

Storm Impacts

- The biggest storm impacts occur during strong west swells (often El Niño years), which approach the beach straight on. When erosion is highest, dry sand beach widths are the narrowest as most of the sand is moved from the dry sand beach and into nearshore bars. This erosion and sand transport during storms can expose the sandstone bedrock underlying the sand in some areas resulting in challenges to beach access and damaging coastal armoring. When the beach is narrowest, the waves can break closer to shore, overtop the coastal armoring, and lead to erosion of the cliffs and bluffs.
- The most significant observed cliff erosion ranged between 20–40 ft and was observed following the 1982–1983 El Niño in areas where coastal armoring was already in place.

Recovery

- Recovery of the dry sand beach after large storm events can take a few years. The area south of 8th Avenue usually begins recovery earliest but takes the longest to recover.
- Recovery time varies but is related to waves with smaller wave heights and longer periods and coming from both the north and south angles to the beach.

INTRODUCTION

Purpose of this Study

This study is part of the City of Carmel Coastal Engineering and Hazard Assessment and serves as a technical memorandum to complete the deliverable for Task 2 of the Carmel Climate Change Vulnerability Assessment, Shoreline and Beach Change Analysis: Seasonal and Long Term. This technical memo intends to explain the physical processes that lead to seasonal changes in the beach, document the extent of historic erosion, and quantify changes to the shoreline, cliffs, and dunes.

During this task in the project, large ocean swells associated with the energetic winter storms of 2022–23 caused substantial beach scouring. Examples of these hazardous conditions can be seen in Figure 1 below, where scouring made beach access difficult (see Figure 1, left) and portions of the beach became difficult to navigate (see Figure 22, right).

Figure 1. Left, undermined 12th Avenue stairway following the El Niño Winter of 2015–16 (January 24, 2016). Source: Easton Geology (2016)
Right, the beach scoured down to bedrock near 10th and 11th avenues following strong winter storms of 2022–23 (January 30, 2023). Source: HKA (2023).

These storm events highlighted the need to identify priority locations for repairs (see Task 1 report by Haro, Kasunich & Associates, Inc., Carmel Beach Coastal Protection Assessment). As results from Task 1 were presented and the project progressed, some of the key questions being asked by members of the City of Carmel-by-the-Sea for this task included:

- What is the long-term trend in shoreline change, and is there a narrowing of beach widths?
- What changes do large storm events cause?

- How long does the beach take to recover following large storm events?

This study will serve to provide an understanding for how this beach system changes both seasonally and long term, and these findings will inform sea-level rise and coastal hazard modeling efforts for Task 3, Shoreline and Beach Erosion Exposure Modeling, and improve understanding of potential exposure and vulnerabilities to city infrastructure and development for Task 4, Coastal Hazard and Sea Level Rise Vulnerabilities.

Study Area

This study focuses on Carmel Beach within Carmel Bay, illustrated by the brackets in Figure 2. Carmel Beach is a pocket beach extending between Arrowhead to Carmel Points, the city portion of Carmel Beach encompasses the lower three-fourths of this northern pocket beach (from Pescadero Canyon to Carmel Point), with the Pebble Beach section extending north towards Arrowhead Point[1] (see Figure 2). As the city and non-city portions of Carmel Beach form a connected system, the analysis is focused on both portions.

[1] Named for the golf course located just inland of this location and not to be confused with the actual Pebble Beach, a small pocket beach located in the north of Carmel Bay.

Figure 2. Project Study Area.

Beach Sections and Coastal Access

The city beach is a 22.5-acre public park accessed by locals and visitors alike. It is served by an extensive public access system that includes 10 beach access stairways and four sand ramps. Beach access parking is available at the Del Mar Parking Lot (122 spaces), as well as along Scenic Road (127 spaces) and North San Antonio Avenue in the north (10 spaces) (Shonman and D'Ambrosio 2003) (see Figure 3).

The beach sections referenced in this study emerged from the City's Climate Change Vulnerability Assessment report (2021). One of the priorities of this report was to identify how adaptation options and strategies along the coast may vary for four distinct planning areas within the City (see the areas identified in Figure 3). The planning areas identified include:

- Mostly armored cliffs and bluffs along Scenic Road south of 8th Avenue. Henceforth referred to as **Section 1, South Beach** (Figure 4).
- Unarmored dunes along private property between 8th Avenue and Del Mar Parking Lot. Henceforth referred to as **Section 2, Central Beach** (Figure 5)**.**
- Mostly natural, unarmored North Dunes area. Henceforth referred to as **Section 3, North Dunes** (Figure 6).
- Armored private properties on the cliffs at the north end of the City. Henceforth referred to as **Section 4, North Beach** (Figure 7).

For the sake of brevity, each beach section in this memo will be referred to by section number and/or its short name, South Beach, Central Beach, North Dunes, or North Beach. Also included is the beach section north of the City limits, referred to in this study as **Section 5, Pebble Beach** (Figure 8).

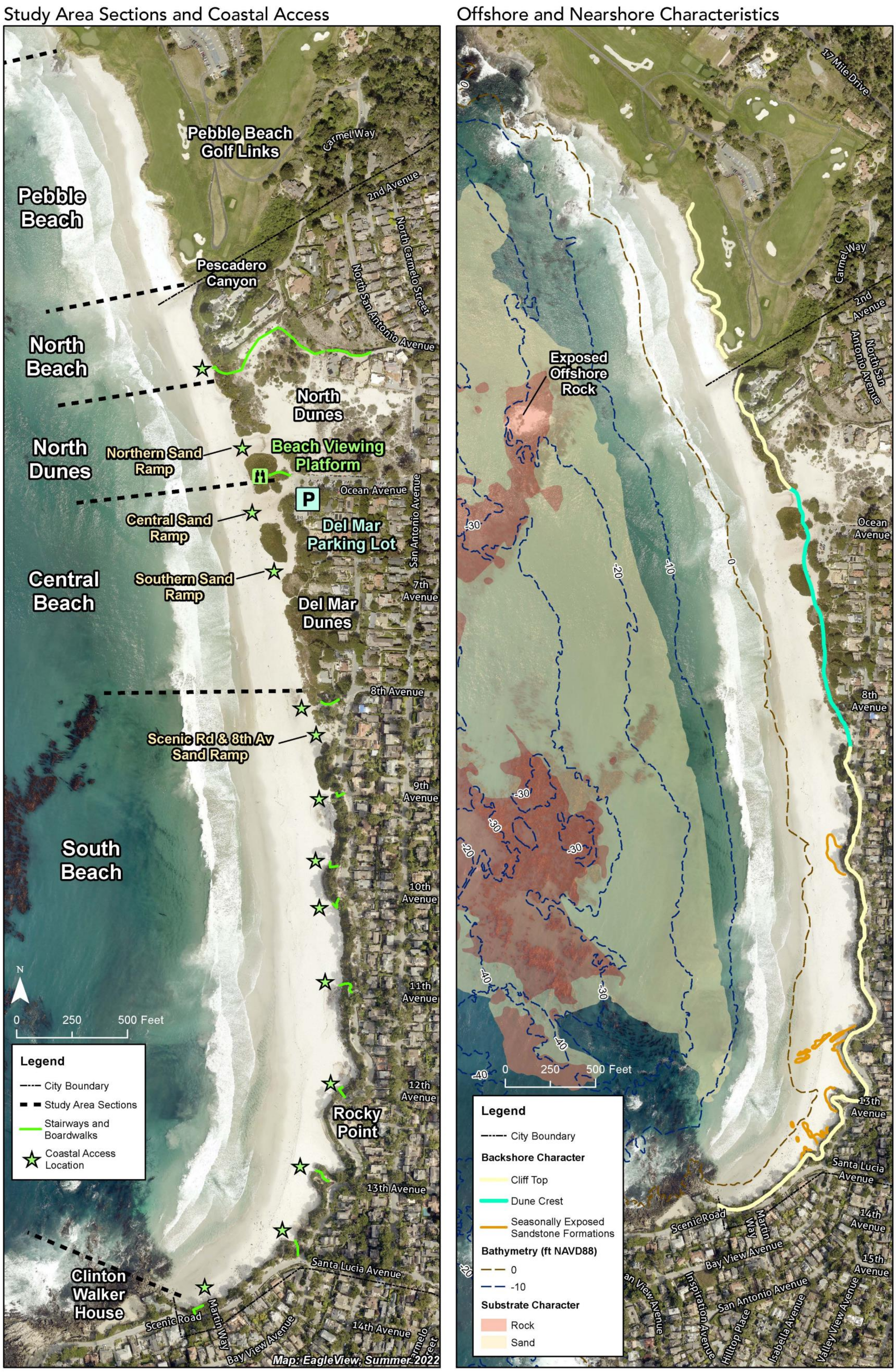


Figure 3. Carmel Beach Sections and Coastal Access (left), and Offshore and Nearshore Characteristics (right)

Figure 4. Section 1, South Beach. Source: California Coastal Records Project (2018)

Figure 5. Section 2, Central Beach. Source: California Coastal Records Project (2018)

Figure 6. Section 3, North Dunes. Source: California Coastal Records Project (2018)

Figure 7. Section 4, North Beach. Source: California Coastal Records Project (2018)

Figure 8. Section 5, Pebble Beach. Source: California Coastal Records Project (2018)

COASTAL PROCESSES AND MORPHOLOGY

The coastal zone is influenced by a multitude of marine forces including tides, waves, and wind, and extends seaward to the point at which waves no longer interact with the seabed. This section will provide an overview of the coastal processes that are pertinent to Carmel Beach. Note that Carmel has cliffs, dunes, and beaches that behave differently and quasi-independently.

Coastal processes that create coastal hazards include tides, waves, and related storm conditions. An important measure of coastal hazards is the total water level (TWL) elevation, which is the combined effect of wave run-up height, storm surge, tides, and sea-level elevations (**Error! Reference source not found.**Figure 9). At Carmel Beach, river discharge is not a contributing factor to TWL in the study area as flows from Pescadero Creek are low, and there is very little interaction with Carmel River and San Jose Creek in the southern Carmel Bay beach compartment due to Carmel Point. A combination of large waves occurring at high tides during storm conditions poses the largest potential threat for coastal erosion. Coastal erosion is comprised of both beach narrowing and cliff retreat. Beach narrowing and cliff retreat are two separate processes, but a narrower beach can lead to increased cliff retreat, which is explained further below. In the future, as sea levels rise, both the wave run-up dynamics and the tidal elevations will change, leading to higher TWLs for longer durations, accelerating both beach narrowing and cliff retreat. Each coastal process is summarized in **Error! Reference source not found.**.

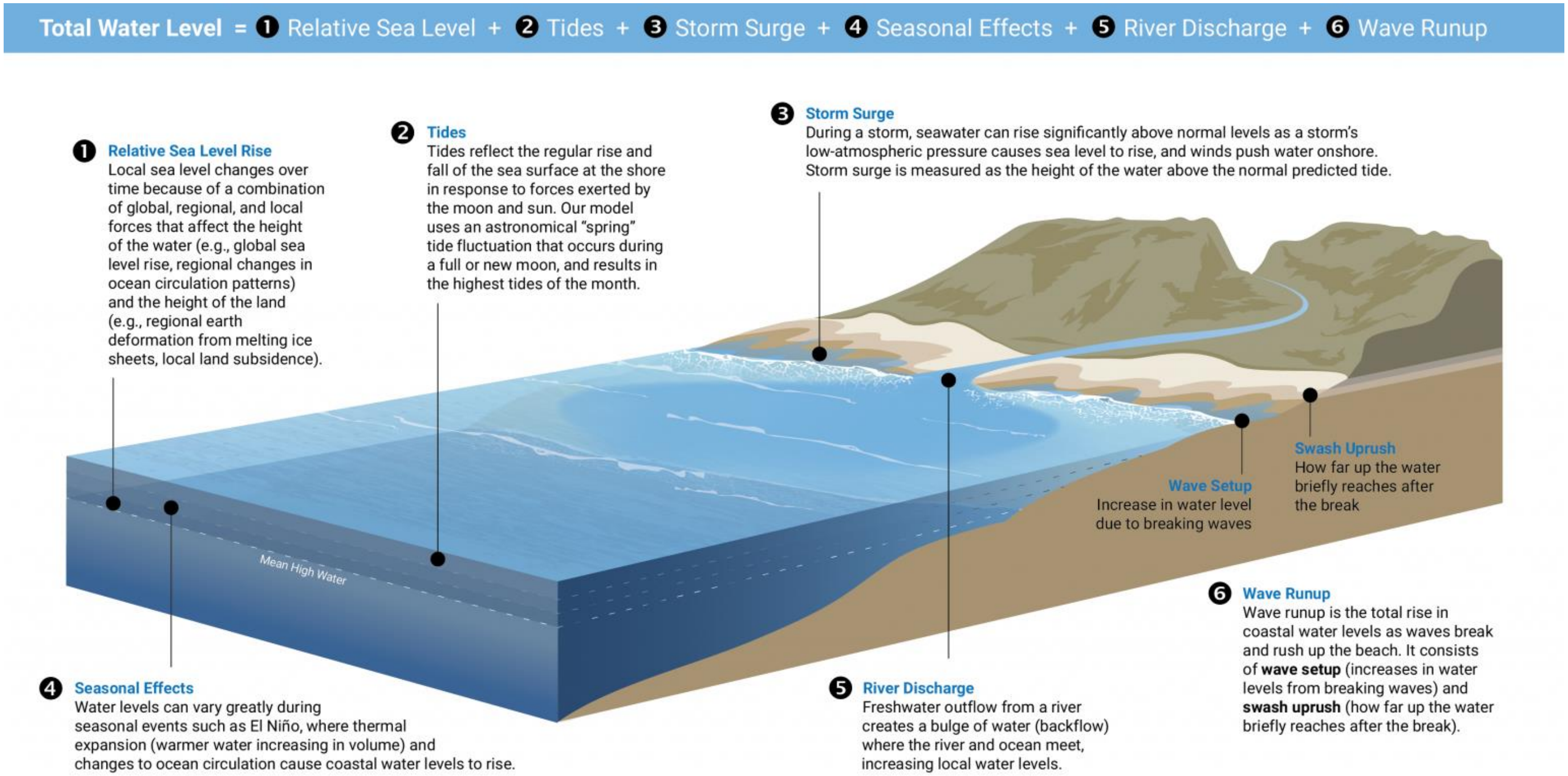


Figure 9. Conceptual diagram of the components of total water level.
Source: Our Coast Our Future Web Platform, Point Blue Conservation Science and USGS (2021).

Tides

Tides in the study area are mixed, predominantly semidiurnal, and are composed of two low and two high-water levels of unequal heights per 24.8-hour tidal cycle. Typically, the largest tide ranges in a year occur in late December to early January when the moon and sun are in alignment and closest in their orbits to the earth. These astronomical high tides are known as “king tides” and often result in coastal flooding unrelated to storm events.

Maximum water levels occur due to astronomical tides, wind surges, wave setup, density anomalies, long waves (including tsunamis), and cyclic El Niño and Pacific Decadal Oscillations. On longer time scales, the tides will reach higher elevations as sea levels rise. The National Oceanic and Atmospheric Administration (NOAA) Monterey tide gauge (Station 9413450) is the closest tide gauge to Carmel with readings extending only to the 1970s, whereas some gauges date back much further. For instance, the San Francisco tide gauges dates back to the mid-1800s. The relative rise in sea level, based on the Monterey gauge, is 1.62 millimeters per year (mm/yr.), based on monthly mean sea level data from 1973–2022, with a 95% confidence interval of 0.70 mm/yr. (Figure 10). This indicates that sea levels have risen 0.3 ft since the early 1970s. These measured local relative sea-level rise trends when compared to the global average provide estimates of land motion. In this case, the land is rising but just not as fast as sea levels.

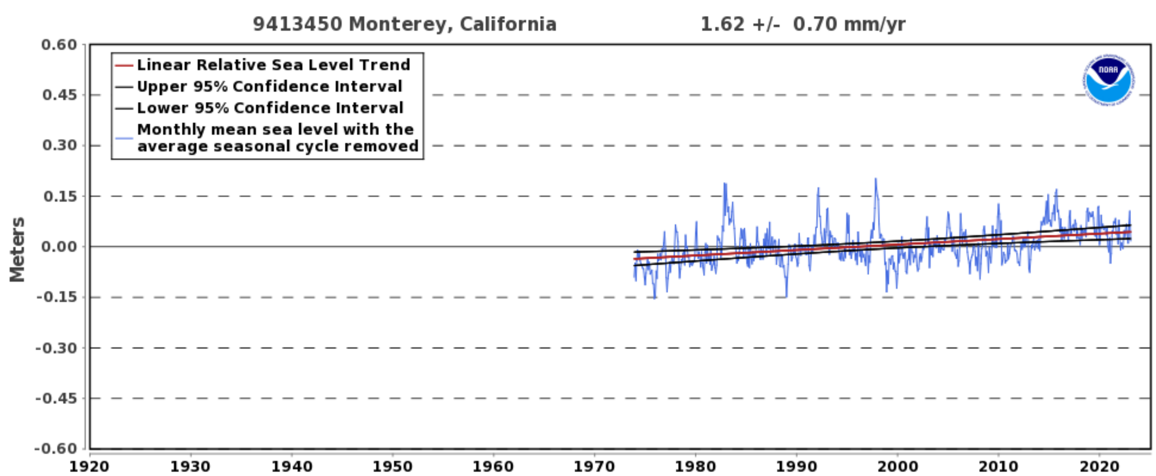


Figure 10. Relative Sea Level Trend for the NOAA Monterey Tide Gauge (NOAA Station 9413450)

Waves

The waves that approach Carmel Beach are characterized by three dominant types depending on their wave source and direction (see **Error! Reference source not found.**)**Error! Reference source not found.**. Most wave energy approaches the study site from the northwest and west (Storlazzi and Wingfield 2005) by waves generated by cyclones in the North Pacific and tends to peak in wave height during the winter months (up to 25 ft). During the summer, southern hemisphere waves produce smaller waves with longer wave periods (greater than 20 seconds). Between April and October, mid-sized and slightly shorter period wind waves also approach Carmel Beach from the northwest (Storlazzi and Wingfield 2005). In general, smaller waves tend to move sand volumes up the beach profile and feed the dry sand beach while larger waves tend to move sand off of the dry sand beach.

The wave climate fluctuates over interannual and longer time periods with ocean-atmosphere oscillations like the El Niño Southern Oscillation (ENSO). These storms tend to follow a more southerly track when El Niño conditions are strongest, resulting in more erosion potential for the study area. El Niño conditions generally occur every three to seven years, with particularly intense events every 10 to 20 years (Storlazzi and Griggs 1998). There are also longer-term climatic oscillations such as the Pacific Decadal Oscillation (PDO). PDO warm phases have been associated with periods of increased storm frequency and intensity, resulting in accelerated erosion rates (Russell and Griggs 2012).

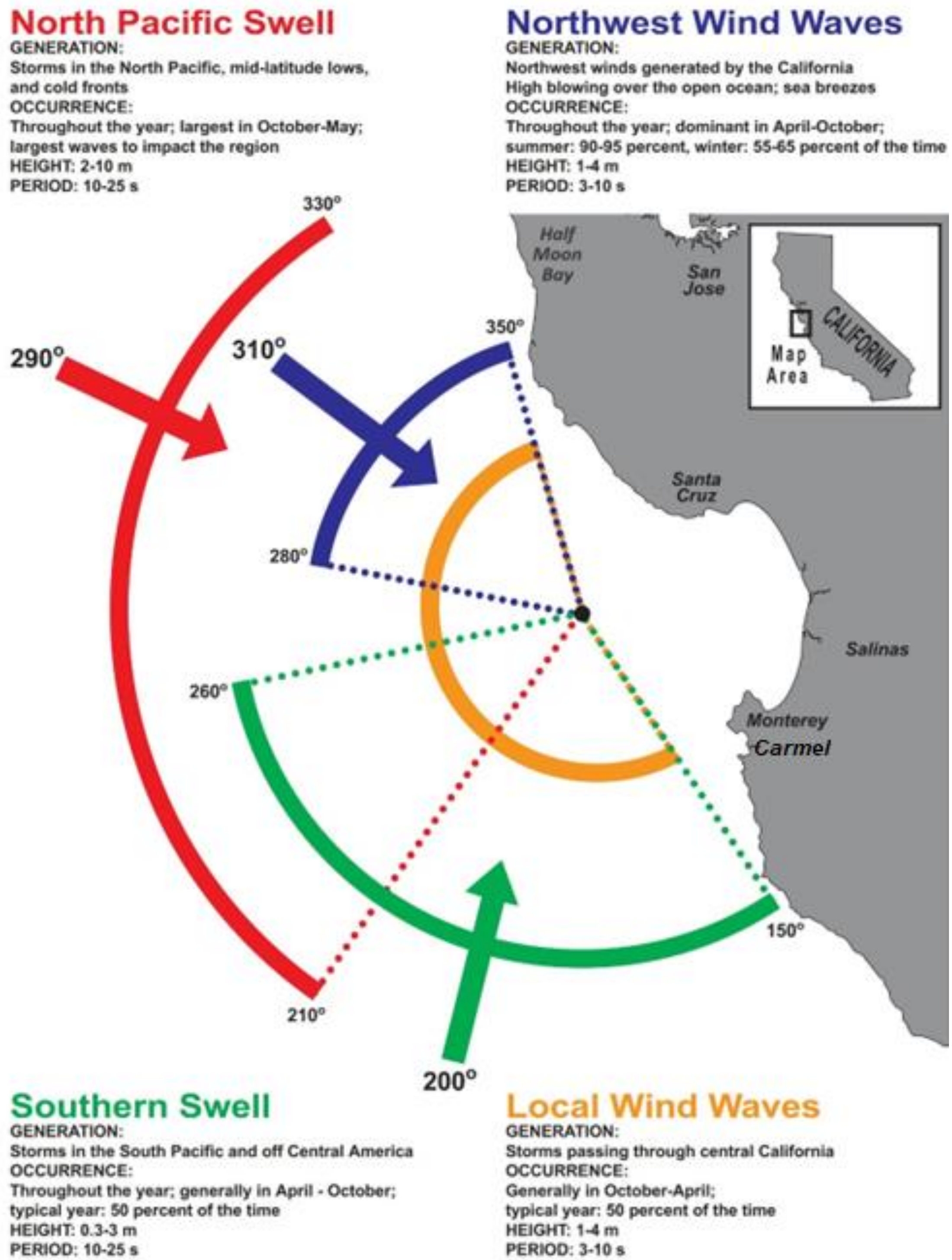


Figure 11. Diagram depicting dominant wave types, directions, and seasons for Carmel Beach and Monterey Bay.
Source: Storlazzi and Wingfield (2005)

FEMA Storm Wave Hazard Zones

The National Flood Insurance Program, administered by the Federal Emergency Management Agency (FEMA), is intended to reduce future flood damage by encouraging local governments to adopt floodplain management regulatory programs. The regulatory Flood Insurance Rate Maps identify base flood elevations according to a 1%-annual-chance TWL elevation at the coast. The base flood elevations are depicted in **Error! Reference source not found.** (right) and vary from 16 to 31 ft. FEMA has determined that the highest wave runup extents between 9th and 11th avenues, and this is the one location where FEMA projects that the current 1%-annual-chance wave runup hazards to overtop the crest of the bluff.

Figure 12. City stormwater and water ponding areas (left), and FEMA 1%-annual-chance storm wave flood extent (right). Water ponding locations represent general areas, and were sourced from differences between winter 2009 and summer 2010 digital elevation models, as well as aerial images from 2003–2022.

Geomorphology

Carmel Beach's sediment originates from the granodiorite formations in the Pacific Grove and Monterey peninsula areas. Additionally, there have been minor contributions from sediment deposition at Pescadero Canyon and erosion of the sandstone cliffs in the central and southern regions of the beach. Eventually, sediment is gradually transported southward through a small channel, making its way out towards the Carmel submarine canyon (Storlazzi and Field 2000). Over the course of geological timescales (i.e., millennia), these sources have contributed to the composition of Carmel Beach.

Over the course of human timescales (i.e., decades to centuries), the sediments in Carmel Bay mostly remain between Arrowhead and Carmel points. Unlike most other California beaches that are located on exposed, open coastlines, Carmel Beach is a pocket beach situated between two headlands. On an open, exposed coastline, a beach can receive sediment from adjacent beaches. At Carmel, however, the headlands impede the delivery of sediment into and out of the beach. Therefore, Carmel receives very little sediment via alongshore littoral transport from the beaches north (Monterey Bay) and south (Carmel River State Beach) (see Figure 2. Project Study Area.Figure 2), and the sediment mostly moves in the cross-shore direction seasonally, as explained below.

Beach Dynamics

A beach is not just the dry sand above the waves; it also includes sediment volumes extending until the offshore. Figure 13 illustrates a cross-shore section of the beach, starting inland and extending offshore. Starting inland, the following describes the different portions of the beach cross section:

- **Backshore**: The dry sand beach starts at the toe of a cliff or dune and extends to the highest of high tides (also known as mean higher high hater [MHHW]). In this zone, the sand might build up to form a berm crest. The dominant force that shapes the beach in this zone is the wind, or aeolian forcing.
- **Nearshore**: This nearshore can also be considered the “surf zone.” This zone extends from the MHHW location on the beach to the offshore point where the sand no longer feels the effects of waves. The dominant force that shapes the beach in this zone are the waves. This section also includes the **beachface**, also known as a foreshore, which is the gently sloping part of a beach that is closest to the water's edge. It is the part of the beach that is typically exposed to the daily rise and fall of tides. The beachface is important in this study because this is the zone that the satellite imagery uses to demarcate the shoreline. The nearshore section also includes sandbars, which are berms of sand that are underwater and in nearshore waters.

- **Offshore:** The offshore portion of the beach is in deeper water. The sediment in this portion does not contribute to the beach since the sediment does not feel wave action at this depth. Dominant forces in this zone are ocean currents.

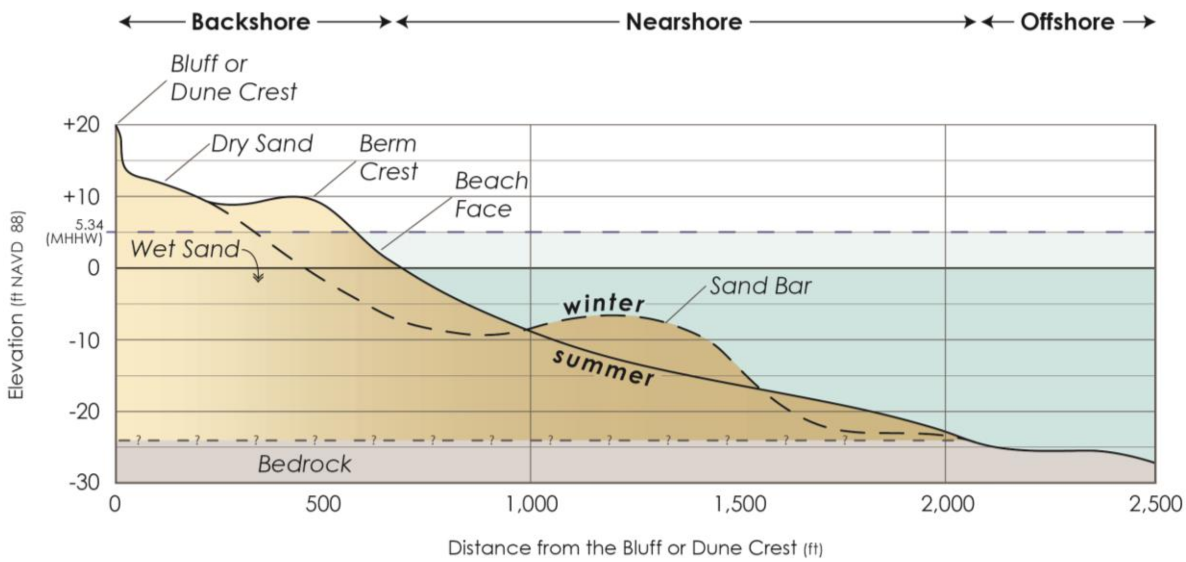


Figure 13. Example of a cross-shore profile showing seasonal change for Carmel Beach. The beach profile changes seasonally with a widening of the beach typically occurring between April and September, and a narrowing of the beach occurring in conjunction with winter storms and large waves, typically occurring in the winter months. The solid black line represents a typical summer profile, with a beach berm forming in spring and summer and a widening of the dry sand beach by as much as 200 ft. The hatched line represents a typical winter profile, with the beach face retreating and a longshore bar developing in the nearshore.
Image adapted from Waves and Beaches by Willard Bascom, 1964 (updated in 2020 by Kim McCoy).

The movement of sediment on and offshore throughout the seasons is influenced by various natural processes, including changes in wave action, tides, and weather patterns. The following is an overview of how sediment can move across the beach profile:

- **Winter season (offshore movement):** During the winter months, storms and strong winds are more common. These weather events generate powerful waves and increased wave energy. Powerful waves can erode the beach face and the backshore, picking up sand and sediment from the beach. Sediment is transported off the beach as the waves carry it away from the shore and onto nearshore sand bars.
- **Spring season (onshore movement):** In the spring, weather patterns often become milder with reduced storm activity. As wave energy decreases, sediment that was transported offshore into nearshore sand bars during the winter begin to

move back toward the shore, which is known as onshore sediment transport. Beaches then experience accretion, where sand is deposited back onto the beachface, widening the shoreline.

- **Summer season (onshore movement and stabilization):** During the summer, waves are typically calmer, and the beach may stabilize as sediment transport slows down. Beaches may reach their widest points during this season, providing ample space for beachgoers and recreational activities.
- **Autumn season (variable conditions):** In the autumn, weather patterns can vary, with occasional storms and changing wave conditions. Sediment movement can be influenced by the specific weather events that occur during this season. Storms can lead to erosion and offshore sediment transport, while calmer periods may promote onshore sediment transport and beach accretion.

Note that the movement of sediment in coastal environments is a dynamic and ongoing process. Sediment transport will also be influenced by long-term factors, such as sea level rise, increased storminess, and changes in the underlying geology. This report focuses only on historical typical conditions, and does not project the hazard of sea level rise and potential erosion in the future.

Cliff Dynamics

The Carmel cliffs are comprised of variable materials, and each material will erode differently depending on its strength and other factors. Three types of material comprise these backshore areas: 1) marine terraces that are generally composed of loose deposits of layered sands, clays, and gravels; 2) dune sands (largely quartz sands) and 3) generally dense sandstone bedrock, often overlayed by deposits of siltstone and claystone (Shonman and D'Ambrosio 2003).

In nearshore waters, sediment pockets overlay and fill areas of sandstone bedrock, which are punctuated by areas of Salinan Block granodiorite (see Figure 3, right). This rock serves as a holdfast for kelp, which is visible in many aerial photos offshore of the South and North Beach areas. Approximately 1,000 ft seaward of the North Beach section near Pescadero Canyon an offshore rock outcrop emerges from the bay, and these rocks can affect wave refraction and breaking wave patterns.

Carmel Beach is backed by sandstone cliffs and sand dunes. The cliff-backed portions make up 64% of the city's backshore and are comprised of sandstone overlayed by loose terrace deposits (see Figure 3, right). The dune-backed portions of the shore comprise 36% of the city's backshore and are comprised of sandstone at an unknown depth and location, overlayed by windblown dune sands and dune vegetation (see **Error! Reference source not found.**, which shows the underlying sandstone exposed).

Figure 14. The exposed sandstone formation, indicated in red, located at the central sand ramp near the Del Mar Parking Lot.

Cliff erosion and bluff failures tend to happen more rarely and are episodic in nature. There are different mechanisms for failure or erosion, and these can be divided into two different types. The first type of failure mechanism is driven by coastal forces (i.e., waves and tides), and will be directly related to whether or not the beach is wide or narrow; a wider beach will protect the cliffs and bluffs from wave exposure. The second type of failure is driven by terrestrial forces (i.e., rain, stormwater, groundwater), and is not affected by beach widths. The two types of failures are detailed below:

Coastal-driven failure mechanisms: Powerful waves, especially during storms, can directly impact terraces and cliffs. The force of the waves and the backshore currents that are created can lead to abrasion of the sandstone rock, undercut the base of the cliffs, and lead to failures and collapse of the terraces above. Tides can also contribute to erosion, especially when powerful waves coincide with high tides. At these times, wave runup can exceed the crest elevation of the coastal armoring, and erosive forces can reach the softer terrace deposits and topsoil. The repeated wetting and drying of the materials in the terrace deposits can also lead to weakening over time. Wind-driven spray from breaking waves can further saturate terrace soils and accelerate failures along the bluff face.

Terrestrial-driven failure mechanisms: Other erosive forces include those from subaerial forces including stormwater runoff and focused sheet flow. This is most pronounced during periods of heavy rainfall, which can saturate the topsoil, lead to runoff that can carry away loose sediments and make terrace areas prone to landslides. In addition, the movement of groundwater within the bluff or terrace can erode materials from within, weakening their structural integrity.

CARMEL BEACH: A BRIEF OVERVIEW AND HISTORY

Carmel Beach is a dynamic landscape featuring a diverse range of cliff and dune formations. These formations have been impacted by human actions that have ultimately shaped the beach into its present state. This section will detail these geomorphic processes and provide an overview of human influences, synthesizing their interplay in the evolution of Carmel Beach.

Figure 15 provides a shore-parallel cross section of the varying vertical cliff and dune formations, as well as a diagram of coastal armoring locations and seasonal beach widths. Along the beach, the contact between the less consolidated softer marine terrace deposits and the dense sandstone basal unit varies but tends to be lower in the Central Beach section between 11th and 8th avenues, and highest in the North Beach and South Beach. Sandstone underlies the terrace for the entirety of the beach, however in the central portion of the beach, remnant windblown Pleistocene sand dunes and dune vegetation overlay the basal sandstone geologic unit (James C. Reynolds and Associates 1986, Shonman and D'Ambrosio 2003).

Since 1958, the City—and to a lesser extent, private homeowners—have built numerous seawalls and riprap revetments to protect portions of the shoreline cliffs and bluffs. Seawalls and revetments protect about 68% of the city's backshore, including a large private seawall in the north and numerous City-maintained seawalls in the south. Riprap revetments can be found throughout the beach, primarily in the wider beach areas in the north of Section 1 as well throughout Sections 2 and 3. The locations and conditions of these are documented extensively in the Task 1 report by Haro, Kasunich & Associates, Inc. (2023). Since the 1960s, the City has often managed sand to improve access along the city's sand ramps and cover the riprap revetments for both appearance and public safety (see Beach Management section below).

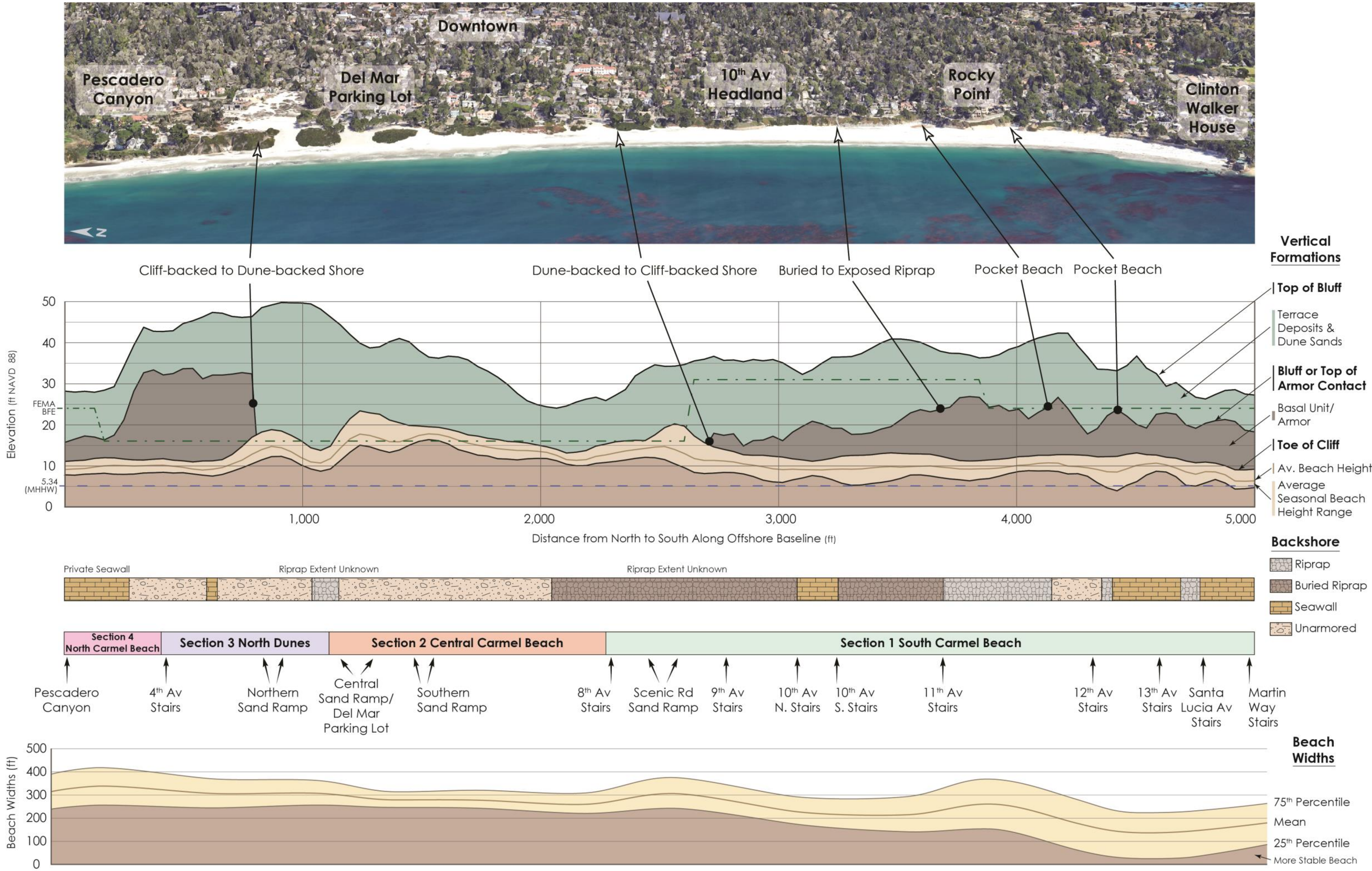


Figure 15. Beach locations (first/top panel), a cross section of the geology (second panel), a depiction of backshore protection (third panel), beach sections (fourth panel), and beach width measurements from CoastSat (fifth/bottom panel). Note that the mean 25th and 75th percentile beach widths are from the entire satellite-derived beach width dataset (years 1984–2021). Approximately half of the linear distance of the city's shoreline protection structures are seawalls; however, as they have been built on many crenulated portions of the backshore, this distribution is not reflected in the figure, which follows a linear path along the foreshore.

Table 1. Beach sections, geomorphology, backshore protection, beach width, and flood height information

Name and Extent	Geomorphology	Backshore Characteristics	Beach Width Range 25th-75th Percentiles	FEMA Flood Elevation
North Beach Pescadero Canyon to 4th Avenue	Sandstone overlayed by terrace deposits up to 45 ft	Private seawall near Pescadero Canyon and unarmored cliffs	Relatively wider beach with some variability 200–400 ft	24 ft (max) 16 ft (min)
North Dunes 4th Avenue to the Central Sand Ramp	Sandstone overlayed by windblown beach sands ranging between 25–50 ft	Mostly unarmored, one sea wall protecting an outfall, and buried riprap	Relatively stable beach 280–310 ft	16 ft
Central Carmel Beach Central Sand Ramp to 8th Avenue	Sandstone overlayed by windblown beach sands ranging between 25–35 ft	Mostly unarmored and some buried riprap (the extent of this riprap is unknown)	Relatively stable beach 280–310 ft	16 ft
South Carmel Beach 8th Avenue to Martin Way	Sandstone overlayed by terrace deposits between 25–45 ft	Mostly armored with riprap and seawalls	The narrowest beach width with the greatest seasonal variability 150–300 ft	31 ft (max) 16 ft (min)

The highest beach widths are found in the central and northern sections of Carmel Beach (between Pescadero Canyon to 8th Avenue), with beach widths of around 300 ft. As higher and wider beaches serve to dissipate storm wave impacts, there is a clear connection between seawall armoring and narrower average beach widths. The average beach width declines south of 8th Avenue, with the lowest average beach width of 100 ft located around the small rocky headland at 13th Avenue. The range of beach widths shows the extent to which seasonal change occurs, indicating that sections that experience the greatest scouring also experience the greatest recovery.

The variability of dry sand beach widths (explained in more detail in the Dry Sand Beach Widths section), is usually due to seasonal changes as opposed to inter-annual changes. The southern section (south of 8th Avenue) has the highest variability in the dataset, with beach widths ranging 175 ft (50–225 ft) between the 25th and 75th percentiles. The northern sections (between Pescadero Canyon and the Central Sand Ramp) also had high variability, generally ranging from 150 ft (between 250–400 ft). The most stable beach section is found in the largely unarmored dune-backed stretches of the Del Mar and North dunes. The beach widths in these sections usually range approximately 50 ft (between 250–300 ft) between the 25th and 75th percentiles.

Beach Management – Sand Redistribution Program, Beach Berm, and Water Ponding

The city's sand redistribution program has involved bulldozing sand from the lower beach (located above high tide line) to the upper beach and is intended to improve public safety and compensate for sand that is naturally pushed downslope by visitors (see Figure 16). This program has been in place since the 1960s and originally operated below the Del Mar parking lot in late spring/early summer. Starting in 1984, the sand redistribution plan expanded, and sand was also bulldozed to cover the riprap revetments (see Figure 17 as a reference from 2003). The total sand redistribution volume varies between 50–100,000 cubic yards depending on conditions (mild winter requires less sand movement than severe winters) (Shonman and D'Ambrosio 2003).

Figure 16. Active Beach Management near the Del Mar Parking Lot
Source: Coastal Records Project (August 2003)

Figure 17. Beach management with sand bulldozed over the riprap revetments near 13th Avenue Source: Coastal Records Project (August 2003).

During the spring and early summer, beach-building process lead to the development of a wide sand berm in the foreshore of the beach. Behind this berm, the sand level will typically be lower. Intermittently, and most often during periods of high tide, wave runup can overtop the berm and settle in the lower areas of the back beach. During fall and early winter, stormwater runoff can also create scour pockets near the city's outfalls and rain and stormwater can settle in these lower areas. Figure 12 (left) shows the locations of the city's outfall network as well as the general locations of water ponding.

BEACH WIDTH DATA AND ANALYSIS METHODS

This study builds on a large body of work including the City's Shoreline Management Plan (2003), Coastal Access and Recreation Element (2003), Coastal Resource Element (2003), Climate Change Vulnerability Assessment (2021), as well as numerous other studies, including those led by Willard Bascom in 1945–47. This study relies primarily on publicly accessible shoreline position data from CoastSat extending from 1984–2021, digital elevation models from 1997–2018, aerial photos from 1941–2022, as well as storm damage photos and firsthand accounts of city staff and residents.

Datasets

The primary datasets used in this analysis include:

- Waves
    - NDBC Buoy Station 46042 (NOAA)
- Shoreline Position
    - CoastSat shoreline positions ~monthly from 1984–2021 (University of New South Wales and USGS)
    - Aerial photographs from 1941–2022 (numerous sources)
- Elevations
    - Digital elevation models, 8 flights from 1997–2018 (NOAA, U.S. Geological Survey [USGS], FEMA, U.S. Army Corp of Engineers, Association of Monterey Bay Area Governments)
    - Beach profile surveys by Willard Bascom, monthly from 1946–47 (archived and sourced from the University of California, San Diego [UCSD])
- Others
    - Reports, historical photos, winter of 2022–23 field visits.

Dry Beach Change Analysis

Seasonal and interannual beach width trends were assessed using satellite-derived shoreline positions between 1984 and 2021. These approximately monthly shoreline positions were sourced from the CoastSat project; an open-source and joint development effort between the Water Research Laboratory of the University of New South Wales in Sydney, and USGS (Vos et al. 2019). CoastSat extracts shoreline positions from Landsat 5, Landsat 7, Landsat 8, Landsat 9, and Sentinel-2 satellite images with a horizontal accuracy of +/- 10 m (33 ft) and provides the largest repository of historical shoreline positions for Carmel Beach with over 15,000 observation records. CoastSat delineates the shoreline as the wet/dry line in each satellite image (see orange shoreline, **Error! Reference source not found.**). Beach widths, therefore, represent the visible dry sand beach and are representative of the distribution of sand across the entire nearshore profile. This wet/dry line was determined at every time step where there was a non-obscured image (usually due to cloudy or foggy weather) available; about monthly or bi-monthly.

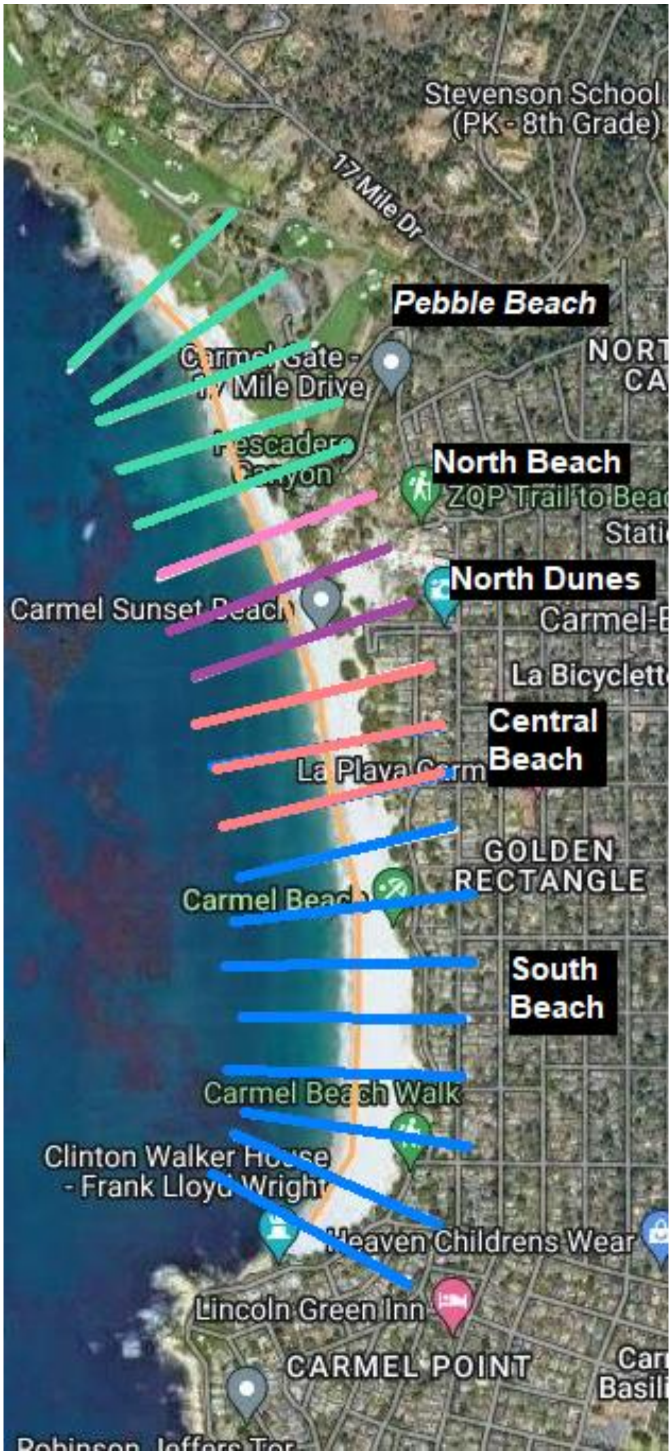


Figure 18. CoastSat transects and groupings based on beach section. Interactive map and data available at: http://coastsat.wrl.unsw.edu.au/

For this study, 18 cross-shore transects were grouped by section: South Beach, Central Beach, North Dunes, North Beach, and Pebble Beach. At each transect, a backshore toe location was determined for the most landward side of the transect, and this toe location was subtracted from the shore position to determine a dry sand beach width for each time step. These dry sand beach widths were then analyzed for overall, seasonal, and interannual trends, and the findings are presented below.

Caveats

The analysis in this report included the years when there was an active sand redistribution program on the City portion of the beach. Therefore, the natural evolution of the beach is not necessarily observed but one that is influenced by the City's redistribution efforts. The sand redistribution program moves sand the lower beach to the upper beach, a process that largely mimics, but speeds up, the natural process of beach width recovery through wind and wave action. The nuances of how this program has influenced the CoastSat shoreline positions cannot be determined. In the data, it may register as the beach building out faster over the long term than it naturally would (i.e., faster recovery rates).

Cliff Erosion Analysis

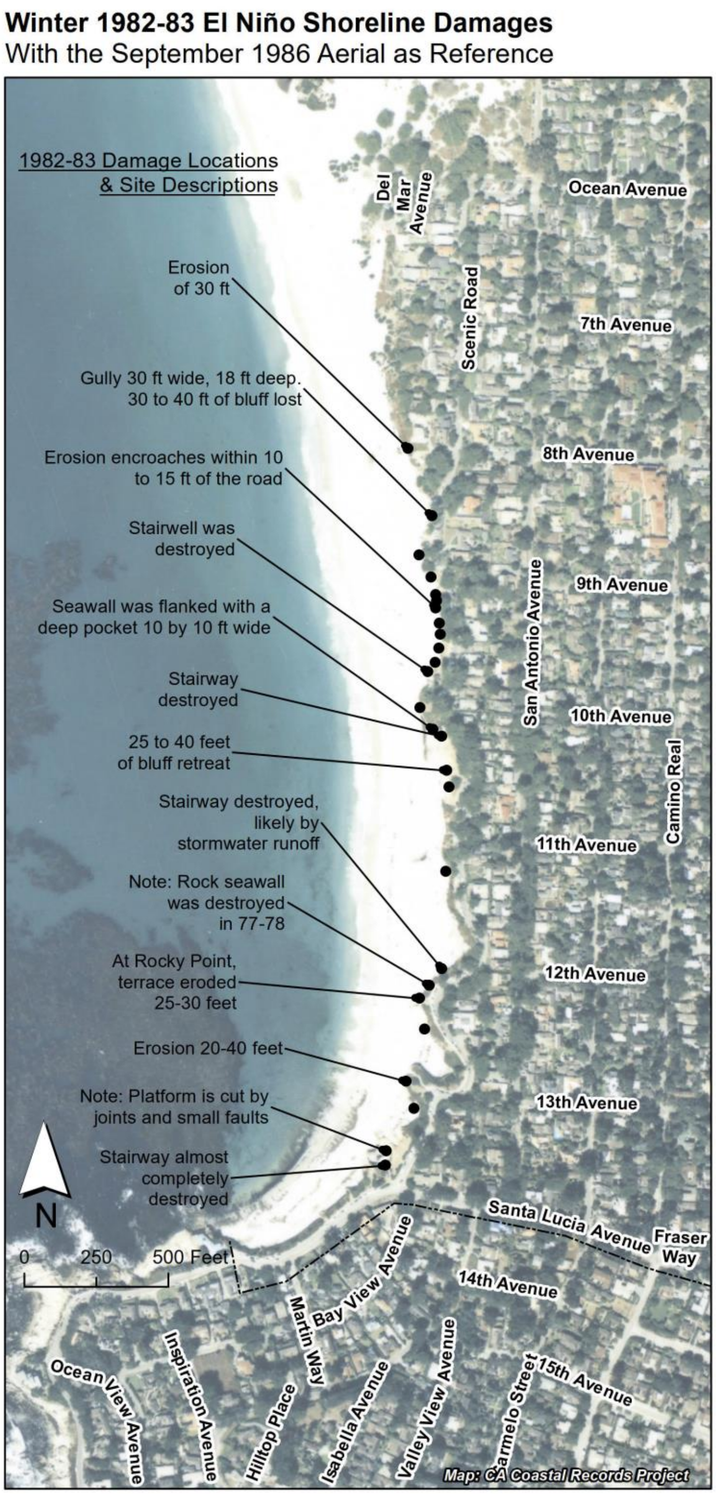
Typically, the evaluation of the long-term trend in cliff erosion is performed by comparing a series of historical aerials and surveys. However, along the City's shoreline, this is made difficult by shoreline protection and recovery efforts including the filling and armoring of eroded areas following storm events. The majority of these occurred following the Carmel Beach Rehabilitation Project (1983–1988), where the City added significant fill material to Carmel's coastal bluffs following erosion events, Scenic Road was repaved, the seaward curb and pedestrian pathway was redesigned (moving the bluff top edge seaward), and the stormwater system was rebuilt and conveyance improved to reduce future erosion (Shonman and D'Ambrosio 2003).

In addition, determining a cliff top position is made difficult due to a lack of georectified and high-resolution historical aerial photographs, as well as obstructions from the dense vegetation along the City's bluffs. However, the unarmored cliffs along the Pebble Beach Golf Links can be used as a proxy for a similar geologic setting, and the results can inform what a long-term erosion rate[2] for the city may have been without human intervention[3].

[2] It is important to note that erosion of an average annual sense can be a bit misleading, since erosion rarely occurs during average conditions, but rather larger failures tend to occur during major storm events.
[3] Cliff face areas along the Pebble Beach Golf Links have been armored as well, however much less so than the city portions of the beach.

The Integral Consulting Inc. (Integral) team analyzed shoreline position change for ~1,000 ft of the largely unarmored cliffs along Pebble Beach, stretching along the 10th fairway to Pescadero Canyon. The team used the Digital Shoreline Analysis System (DSAS) tool from USGS, which enables the calculation of rate-of-change statistics from multiple historical shoreline positions. It provides an automated method for establishing measurement locations, performs erosion rate calculations, and provides the statistical data necessary to assess the robustness of the erosion calculations.

CLIFF EROSION



The cliffs and bluffs along the City's shoreline have endured numerous erosion events, with perhaps the most notable in recent memory being the 1982–83 El Niño winter. As recounted in local media and post-storm surveys, the beach was heavily scoured following a series of storms. This left the bluffs less protected from wave attack and exposed them to considerable amounts of subaerial erosion processes. The City contracted Rogers E. Johnson and Associates to perform a post-storm assessment, and a map of observed damage locations from the assessment can be found in Figure 19 (Rogers E. Johnson and Associates 1984).

Figure 19. Winter of 1982–83 shoreline damages. Observations compiled from Rogers E. Johnson and Associates

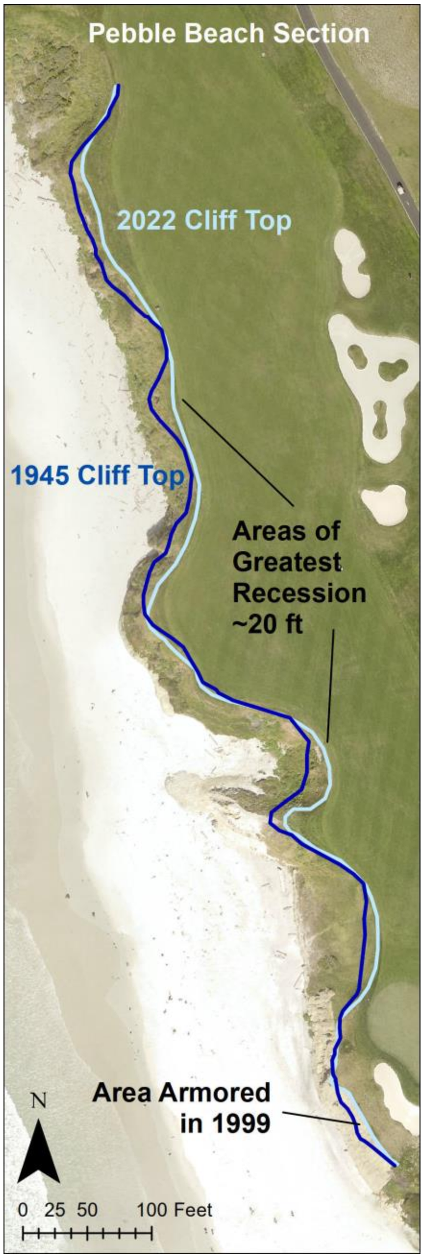


Figure 20. Bluff-top position for the Pebble Beach section along Carmel Beach.

As part of this 1984 assessment, Rogers E. Johnson and Associates calculated the long-term trends in historical erosion between 1908 and 1983. They determined that the northern portion of the beach experienced **4.8 in./yr.** of erosion and the southern portion experienced **3.6–8.4 in./yr.**; with much of this erosion occurring in the winter of 1982–83. This included some major erosion hotspot locations such as 30 ft of bluff loss between 8th and 9th avenues, 25–40 ft of bluff between 10th and 11th Avenue, 20–40 ft of bluff between 9th and 10th avenues, and 30 ft of bluff near Santa Lucia Avenue (Rogers E. Johnson and Associates 1984). It is important to note that the large erosion distances observed during this event occurred on bluffs that already had coastal armoring.

As part of the background investigation, the Integral team reviewed other erosion studies, including the UCSD and Scripps Historical Coastal Erosion Study (Zuzanna and Young 2022) and the USGS Statewide Assessment (Hapke and Reid 2007). The UCSD Scripps Study found negligible (0.0001 in./yr.) erosion between 2010 and 2016, likely due to the very short sample period. The USGS Statewide Assessment is reported for the area from Point Piños to Gorda and shows **11.8 in./yr**. from 1930s to 2002; however, this is for a much wider area of study.

The Integral team used the DSAS tool to determine both an endpoint erosion rate and a linear regression erosion rate for the Pebble Beach section of cliffs. The average bluff top recession from 1945 to 2022 was found to be just over 1 in./yr (as an averaged linear rate), with the greatest erosion occurring at two locations where erosion averaged ~3 in. a year or ~20 ft total (see the areas noted in).

These bluff top erosion rates will be incorporated into the next phase of work projecting future coastal erosion distances exacerbated by sea-level rise.

DRY SAND BEACH WIDTHS: SEASONAL AND STORM EVENT RESPONSE

Seasonal Dry Sand Beach Widths

Analyzing the trends in the CoastSat dataset, the change in dry sand beach widths over time (variability) was mostly due to seasonal, rather than interannual (i.e., between years) changes, with beach widths being the narrowest in the spring months and widest in the fall months (Figure 21). To determine how the beach widths changed throughout the year, the shoreline positions were averaged over each month for all of the years in the dataset, and the results are presented in Figure 21**Error! Reference source not found.**. The sections between 4th Avenue and 8th Avenue (North Dunes and Central Beach) were more stable throughout the year than the other sections, since they had more similar winter and summer beach. The ends of the beach, south of 8th Avenue (South Beach) and north of 4th Avenue (North Beach), were the least stable throughout the year, since they had the narrowest beach width in the winter and widest beach width in the summer. The southern section had the narrowest beach widths overall, particularly in the winter season.

Widening and narrowing along the beach happened at different times for different sections of the beach. Both the extreme north (Pebble Beach) and south were more likely to recover earlier in the year, with beach widths widening beginning in late winter (i.e., March), whereas the central areas of Carmel Beach often recovered later in the year, with beach widths widening in the late spring or summer (i.e., June). The first section of the beach that eroded was Pebble Beach; Pebble Beach began to narrow in the late summer.

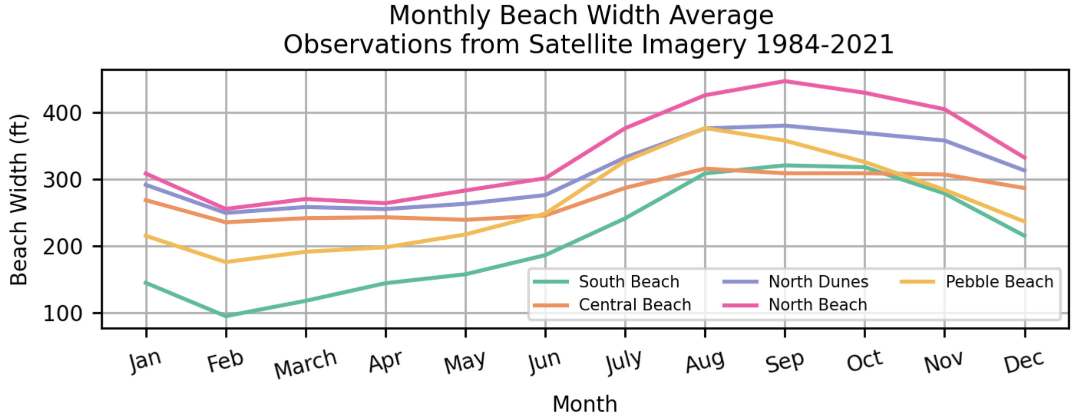


Figure 21. Beach widths were averaged by month for the entire dataset and grouped by beach section. The beach widths show a seasonal oscillation.

Beach Volume Change; Storm Response

During major storms, which are more frequent and intense during El Niño years, large storm wave events can scour and narrow the protective beach. In addition, large storms bring high rainfall, which saturates and weakens coastal bluffs, elevates sea levels causing waves to break closer to shore, and is often accompanied by larger waves leading to more erosion. Storlazzi and Griggs have found that 75% of shoreline erosion and damage has occurred during El Niño winters, and the moderate- to high-intensity El Niños do most of the damage (Storlazzi and Griggs 1998).

Figure 22. In response to winter storms (seen here in 2023), it is common for the steep sand dunes around Del Mar Avenue to scarp on the seaward edge (left), and for scouring to expose the underlying base of sandstone outcroppings (right) and footings of the coastal armoring in the southern areas of the beach.
Source: Integral Consulting (February 1, 2023)

The winter of 1997–98 was a very strong El Niño for California with one of the wettest winters on record. This marks the first major El Niño event where digital elevation surveys are available both pre- and post-storm season. The changes in beach elevation and volumes correspond with the CoastSat dry sand beach width data, with a significant narrowing of areas south of 8th Avenue and much less in the dune-backed Del Mar and North Dunes areas. The North Dunes area even saw some accretion, perhaps explained by sediment eroding from the upland dunes down onto the dry sand beach and foreshore. The maximum scour of sand levels between fall and spring was ~14 ft, with a total of ~300,000 cubic yards of sand moved from the beach into nearshore bars (see Figure 23). By comparison, the City's summer sand redistribution program moves 50,000–100,000 cubic yards of sand depending on conditions (Shonman and D'Ambrosio 2003).

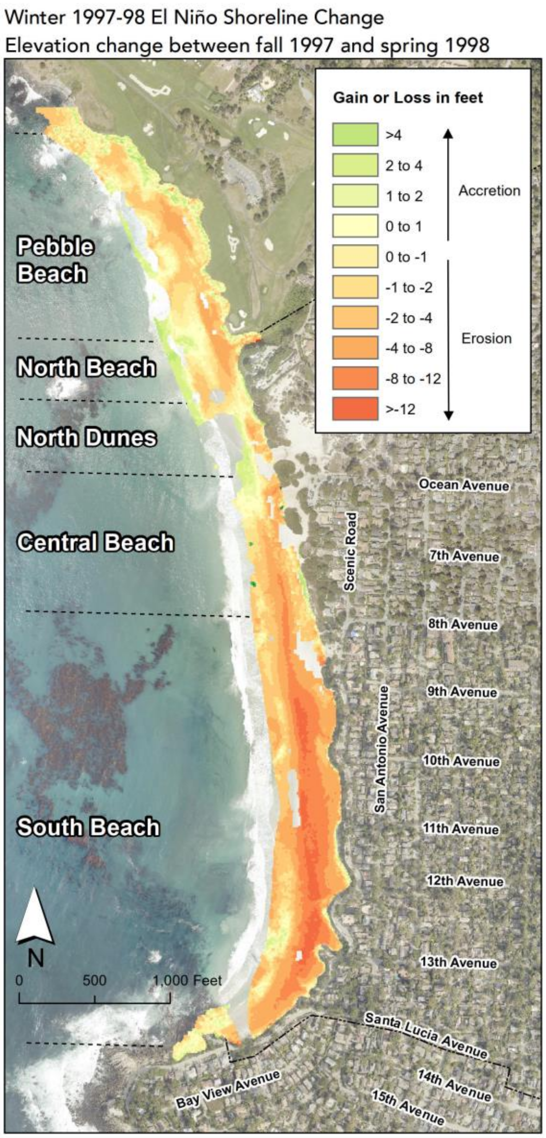


Figure 23. Beach elevation change following the El Niño winter of 1997–98

The beach scouring that occurred in the winter of 1997–98 corresponds with observations and documentation of other El Niño years that have occurred.

Following the 1982–83 El Niño, City staff reported that the level of back beach areas was 4 to 10 ft lower than it normally is in July (Rogers E. Johnson and Associates 1983). In addition, significant erosion took place in the Del Mar Dunes, which led to the placement of engineered revetments, and necessitating the City to restore the dunes to their original size (Shonman and D’Ambrosio 2003).

According to city inspections in January 2016 (another El Niño year), measurements showed that the sand level on the beach along the south side of 12th Avenue had dropped by nearly 6 feet. Sand began to be redeposited at various shoreline sites during February, and this became very noticeable in the coves at 12th and 13th Avenues later in the season (City of Carmel-by-the-Sea 2016).

LONG-TERM DRY SAND BEACH WIDTH CHANGE AND RECOVERY

Overall, while the shoreline was variable both seasonally and in response to large storm events, it showed a mostly stable long-term trend between 1984 to 2021 across all beach sections. To examine any long-term trends in dry sand beach widths, the beach widths were averaged by year, and the results are plotted in Figure 24.

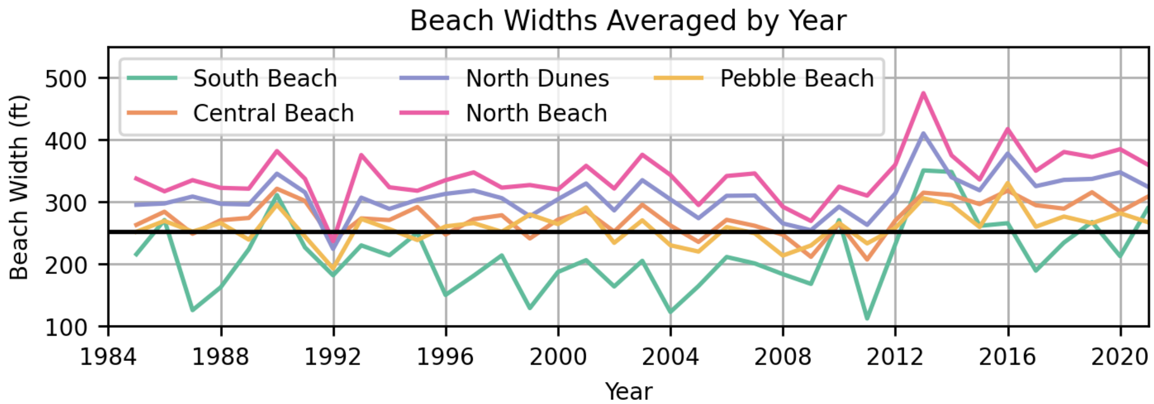


Figure 24. Beach widths were averaged by year for the entire dataset and grouped by beach section. The beach widths are generally stable and deviate about a mean.

The beach widths average about 250 ft without any significant trend (no obvious accretion or erosion) in the 40-year dataset. This provides good evidence that over the last 40 years, the sand volume in the Carmel Bay pocket beach has stayed relatively constant.

Overall, dry sand beach widths are lower for the ends of the beach (Pebble Beach and South Beach), and higher in the central portions, which can also be seen in satellite images of April 1971, October 1976, April 1993, and spring 2006 (Figure 25, Figure 26).

The southern section of the beach has had historically lower beach widths than the other sections, and a particularly good example of a narrow southern beach section can be seen in the spring 2005 image (Figure 26). A particularly narrow beach occurred in 1992 (which is likely related to the 1992 El Niño), and 2009 and 2011, when the beach widths dropped to below average (Figure 26). An example photo of a narrow Carmel Beach can be seen in the spring of 2010 (Figure 25). After 2011, all dry sand beach widths recovered to higher than average, before decreasing after 2013 to below or about average. Example photos of wide beach widths can be seen in September 1986, May 2001, and July 2016 imagery (Figure 25, Figure 26). In recent years, since around 2018, the southern section of the beach has seen wider beach widths than the extreme northern section (Pebble Beach).

Figure 25 and Figure 26 also show that the widest beach widths did not occur in the earliest aerial images of 1941 and 1945, providing additional evidence that sand volumes in Carmel Bay have likely been relatively stable over the last 80 years.

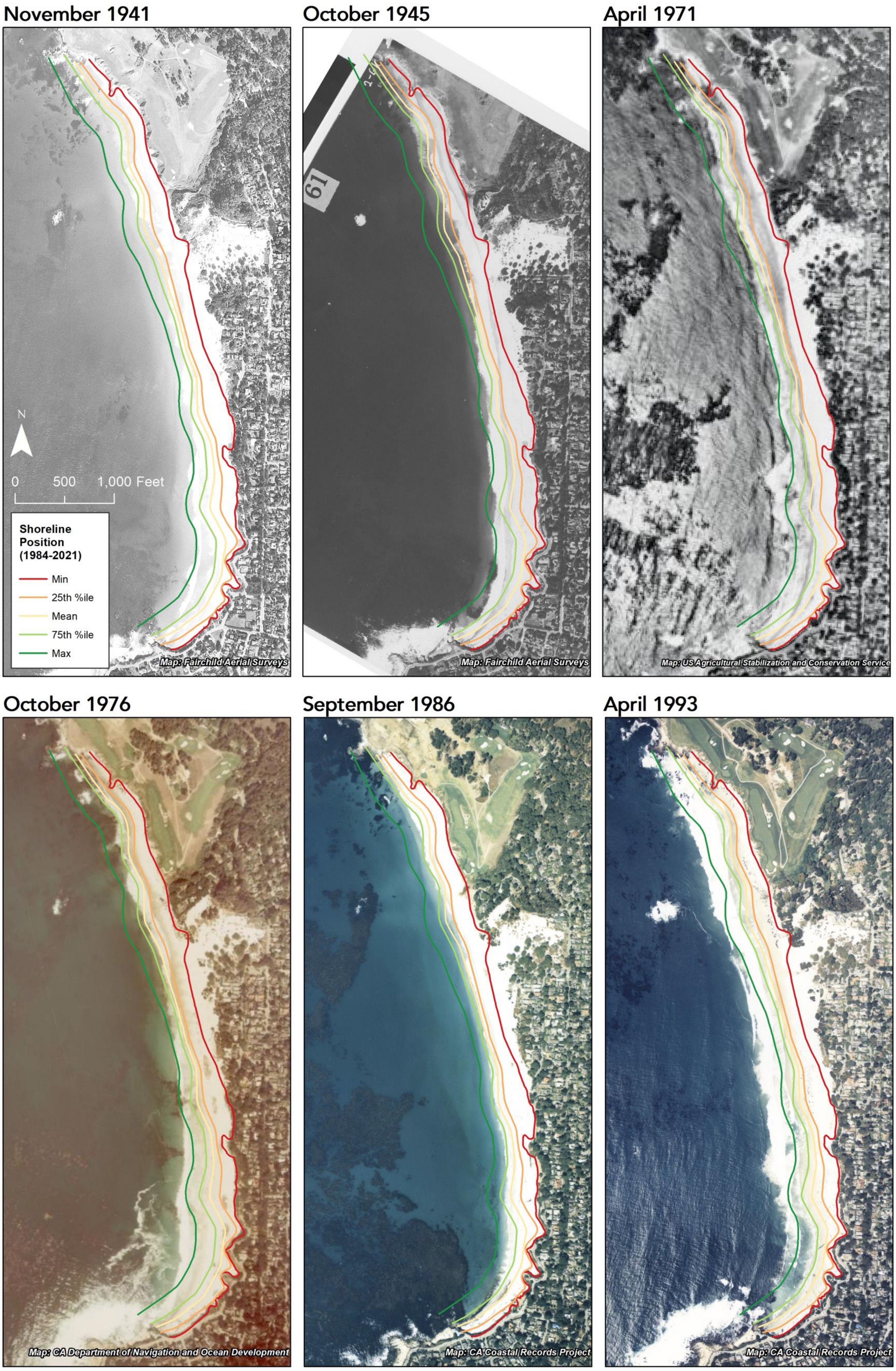


Figure 25. Aerial time series for select years from 1941–1993 with shoreline beach positions from 1984-2021.

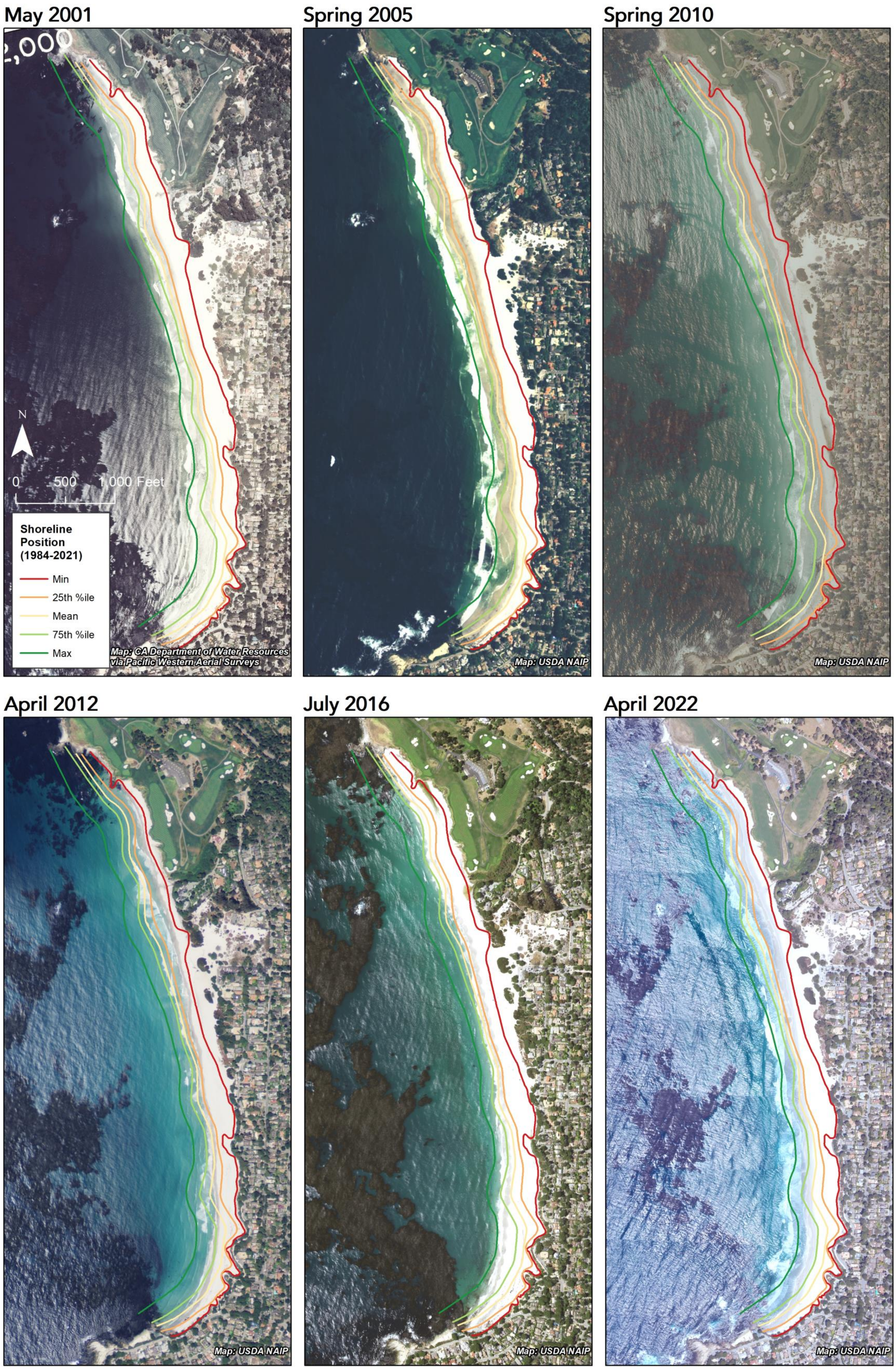


Figure 26. Aerial time series for select years from 2001–22 with shoreline beach positions from 1984–2021.

Beach Width Recovery

Recovery Time Scales and Rates

One of the questions that the Carmel community has been asking, especially after the energetic winter erosion from January and February of 2023, is about the timing of the dry sand beach recovery. To address this question, the recovery time scale was defined annually as the number of days that it took for a beach to build back up from the most eroded position (narrowest beach width) to the most accreted position (widest beach width) for that year. The recovery rate is defined as the speed (measured by the number of days) for the beach to go from narrowest to widest as calculated as the distance the beach recovered divided by the number of days the beach took to recover. Figure 27 shows that higher recovery rates correspond to a lower number of days, meaning that the beach recovered quickly in that specific year. On average, it took the beach ~160 days (about 4 months) at a rate of 1.2 ft/day for the beach to reach its maximum position. Fast recovery rates tended to follow El Niño events, as seen in the years 1993 and 2016, showing that the beach wants to build back up to a mean position.

Interannual recovery for each beach section can also be seen in Figure 24 when beach widths increase. After the 1992 El Niño, beach widths for all beach sections dropped and then recovered the following year (1993), except for the southern portion of the beach. Beach widths for the southern portion of the beach remained narrow until about 2013 when it recovered again. The years 2011–2013 also saw high recovery rates, when beach widths widened until the 2014 El Niño when they narrowed again.

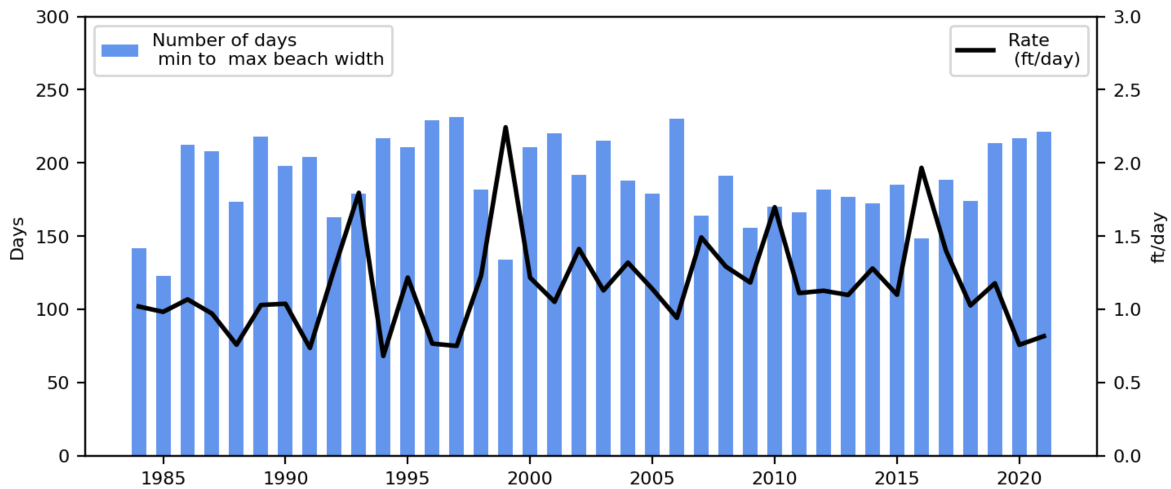


Figure 27. Recovery time scales. Note the sharp peaks in recovery rates around the stronger El Niño years of 1997–98 and 2014–16.

Wave Conditions During Dry Sand Beach Recovery

It is generally understood that beach recovery occurs when waves are smaller and have longer periods. To examine what conditions contributed to high recovery rates, an analysis of the offshore wave conditions that co-occurred with high and low recovery rates was conducted (Table 2). Table 2 divides the wave conditions into three wave directional categories, and then identifies the average wave height and period for each direction. Results show that faster recovery rates corresponded with waves that came from either the north or south and not head-on, and the southern waves have smaller wave heights and longer periods than lower-recovery years. Seasons with lower recovery rates had more waves coming head-on (from a western direction) and larger waves from the north and south.

It appears that a combination of north and south-angled waves, smaller wave heights and longer wave periods are associated with higher recovery rates. However, it is not clear how the relative contributions of the wave direction and smaller wave heights drive physical processes to accelerate recovery rates. A more detailed analysis of recovery events, including spectral information from the wave buoys, and potentially numerical model simulations would be required to determine more specific characteristics and the dynamic details of the recovery process.

Table 2. Wave conditions that co-occur for recovery. Wave data are taken from the Monterey Bay buoy. Each row represents wave information from a different direction. The first row is waves from the northwest/north northwest, the second row is waves from the west. The wave information is the percentage of waves, wave height, and wave period.

	Recovery rate > 1ft/day	Recovery rate 0–1ft/day
Northwest Bin (Waves coming from the north >310 degN)	**13% of waves** Average wave 6.3 ft @ 8.7 seconds	**12% of waves** Average wave 7.2 ft @ 8.7 seconds
West Bin (Waves coming from 240-310 degN, head-on)	**75% of waves** 6.5ft @ 10.8 seconds	**81% of waves** 6.6ft @ 10.7 seconds
Southwest Bin (Waves coming from 180-240 degN, head-on)	**12% of waves** 4.6ft @ 15.5 seconds	**7% of waves** 4.8ft @ 14.4 seconds

CONCLUSIONS

Large storm waves have historically caused dramatic short-term erosion impacts along Carmel Beach that have damaged coastal accessways, narrowed the dry sand beach, and led to the construction of coastal armoring along more than half of the City's backshore. Through analysis of historical reports, aerial and satellite imagery, shoreline position trends, and beach volume changes, Carmel Beach has shown no long-term erosion trend.

This positive finding appears related to a relatively stable volume of sand in this pocket beach constrained in the north by Arrowhead Point, in the south by Carmel Point, and offshore by the granodiorite basal rock.

Based on a 40-year record of approximately monthly shoreline positions, dry sand beach widths vary seasonally and in response to large wave events which narrow the beaches and move sand into nearshore sandbars in the winter and then onshore back onto the dry sand beaches in the summer. An analysis of Willard Bascom's studies on Carmel Beach dating to the mid-to-late 1940s, highlights that this has been occurring for over 80 years.

There has been considerable concern among community members over the future of the dry sand beach and shoreline, especially in response to rising sea levels and potential climate change-induced shifts in weather patterns. Over the short term, the beach will continue to narrow and recover seasonally, and given the stable sand volumes, these seasonal dynamics and storm response and recovery can be expected to continue.

However, as sea levels rise rates accelerate and wave heights increase, various bluff-top and upland resources and infrastructure may be more significantly impacted by erosion, and the narrowing of the beach with additional beach elevation scour caused by more routine interactions with existing coastal armoring may become more frequent and significant.

The extent and potential implications of erosion to Carmel's beaches and bluffs to sea level rise will be explored further in Task 3, Shoreline and Beach Erosion Exposure Modeling. Once this modeling is completed, a vulnerability assessment will be completed to identify potential impacts on the various City assets, infrastructure, and upland development in Task 4, Coastal Hazard and Sea Level Rise Vulnerability.

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ACRONYMS, ABBREVIATIONS, AND DEFINITIONS

backshore	Extreme inland limit of the beach
basal unit	Lower geologic formation of the cliff (sandstone in Carmel)
bluff	Soft unconsolidated materials found in the marine terrace deposits
bluff contact	Location where the bluff meets the cliff
bluff top	Location where there is an identifiable break from the steeper cliff and bluff to the gently sloping inland areas
cliff	Hard consolidated rock under the bluff
CoSMoS	Coastal Storm Modeling System (USGS)
DEM	Topographic Digital Elevation Model
dry sand beach	The portion of the beach that is landward of the mean high water mark
DSAS	Digital Shoreline Analysis System (USGS)
erosion (coastal)	Can refer to either beach narrowing and cliff retreat. For cliffs, this refers to the long-term loss or removal of land due to coastal or terrestrial processes. For beaches, this may refer to either the long-term, short-term, or localized (see scouring) removal of sediments from the beach.
ENSO	El Niño Southern Oscillation
FEMA	Federal Emergency Management Agency
MHW	Mean high water
MHHW	Mean higher high water
MLW	Mean low water
NAVD 88	North American Vertical Datum of 1988 (NAVD 88). The vertical control datum used for surveying.
NOAA	National Oceanic and Atmospheric Administration
PDO	Pacific Decadal Oscillation
scour (beach)	Process by which waves and currents remove sediment from the beach (usually localized)
shoreline	Typically where water meets the land. In this report, it refers to the wet/dry line

toe of the cliff	Location where the dry sand beach meets the base of the cliff
TWL	Total water level. The combined effect of wave run-up height, storm surge, tides, and sea level elevations
USGS	U.S. Geological Survey

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- Moses Cuprill, P.E., Senior Coastal Engineer
- Mark Foxx, P.E., Coastal Engineer

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- Polaris Kinison Brown, Principal Planner
- Anastazia Aziz, AICP, Principal
- Esme Wahl, Associate Planner

City of Carmel-by-the-Sea

- Robert Harary, P.E., Director of Public Works
- Mary Bilse, Environmental Programs Manager
- Javier Hernandez, Project Manager
- Rob Culver, Public Works Superintendent
- Agnes Martelet, Environmental Compliance Manager