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:	February 20, 2024
Subject:	Carmel Climate Change Vulnerability Assessment, Shoreline and Beach Erosion Exposure Modeling and Coastal Hazard and Sea Level Rise Vulnerability
Project No.:	C3016

EXECUTIVE SUMMARY

Integral Consulting Inc. (Integral) working with EMC Planning and Haro Kasunich and Associates (HKA) have been conducting a Coastal Engineering and Hazard Assessment for the City of Carmel-by-the-Sea (City). The following is a synopsis of the major findings for Task 3, Shoreline and Beach Erosion Exposure Modeling, and Task 4, Coastal Hazard and Sea Level Rise Vulnerability.

The scope of work for Task 3 was to project future beach narrowing and cliff and dune erosion hazard extents with sea level rise. The coastal erosion hazard projections include a future without armoring present and one that considers the effect of the existing City's coastal armoring. The hazard exposure modeling in Task 3 was then used to determine what assets and infrastructure were at risk of coastal erosion in the future under armored and unarmored conditions. The vulnerability assessment evaluated erosion hazard exposure to land use and structures, roads and parking, and infrastructure. The differences between hazard extents and vulnerabilities will be useful in Phase 2 of the project when examining the implications of various adaptation strategies and policy implications.

Beach Narrowing (Task 3)

- It is projected that the width of Carmel Beach will narrow between 50 and 60 ft for each foot of sea level rise. Assuming that the location of the backshore does not change, the following typical summer beach conditions are projected:
  - By 2 ft of sea level rise, lateral access to areas south of the 12th Avenue headland may be obstructed.
  - By 3 ft of sea level rise, the southern end of Carmel Beach south of 8th Avenue is projected to be a series of pocket beaches rather than one continuous stretch of dry sand beach. Only during highly recovered conditions will a dry sand beach remain south of 12th Avenue.
  - By 4 ft of sea level rise, the only continuous dry sand beach remaining will be from the North Dunes sand ramps to Pescadero Canyon. In the south, only two small pockets of dry sand beaches are projected to remain around 8th Avenue and 11th Avenue.
  - By 5 ft of sea level rise, only one pocket of dry sand beach around the North Dunes and the 4th Avenue stairs is likely to remain.

Coastal Cliff and Dune Erosion (Task 3)

- Considering coastal armoring in erosion projections, erosion rates are dampened significantly in the near term; however, with increasing sea level rise, the effectiveness of the armoring is reduced, leading to an acceleration in blufftop erosion above the coastal armoring beyond 1 ft of sea level rise.
- In the armored scenario, the following is projected:
  - By 1 ft of sea level rise, the areas with the greatest threat of erosion are the private oceanfront properties near Pescadero Canyon, the dune-backed shore between 4th Avenue and 8th Avenue, the lower cliffs between 8th Avenue and 11th Avenue, and the unarmored cliffs by 12th Avenue.
  - By 2 ft of sea level rise, erosion rates accelerate as coastal armoring is more likely to be overtopped by larger waves. Areas behind seawalls have projected erosion hazard distances of 20 to 40 ft.
  - By 4 ft of sea level rise the highest erosion distance is projected around 12th Avenue, where a combination of factors related to local geology, wave heights, and lack of armoring yields projections of retreat up to 150 ft. Areas of the north dunes around the Del Mar sand ramp also see higher projections of retreat of up to 90 ft, extending to the volleyball courts.

Vulnerability Assessment (Task 4)

The scope of work for Task 4 was to determine the bluff-top assets and infrastructure potentially exposed to coastal erosion for both armored and unarmored backshore conditions. The vulnerability assessment evaluated erosion hazard exposure to land use and structures, roads and parking, and utility infrastructure. For succinctness, the results of only the coastal armored scenario are presented here. See Appendix A for a full suite of tables for both the armored and unarmored scenarios.

- Currently, all the assets and infrastructure along the beach and bluff including 10 coastal access stairways, the Scenic Road walkway, and the stormwater drainage network are exposed to erosion. The public restroom adjacent to the Santa Lucia Avenue stairs is exposed to erosion and will face increased threat from coastal wave flooding in the future.
- By 1 ft of sea level rise, Scenic Road is exposed to erosion in six locations, largely around 12th Avenue and between 10th and 8th Avenues. A wastewater force main near Martin Way is exposed, as well as a wastewater main between 9th and 10th avenues, and a wastewater main under the dunes between 7th and 8th Avenues. Waves overtopping the bluff are expected to be more likely along the southern seawall between Santa Lucia Ave and Martin Way.
- By 2 ft of sea level rise, nearly the entire length of Scenic Road is exposed to erosion, including most of the underground water and wastewater infrastructure. This includes a water main between 8th and 10th avenues. Waves overtopping the bluffs are expected to be more likely between 10th and 11th avenues.
- With between 2 and 4 ft of sea level rise, 44 homes along Scenic Road and near Pescadero Canyon are projected to potentially be exposed to erosion. One additional water main under Scenic Road south of 13th Avenue is exposed to erosion. One additional wastewater force main is exposed to erosion by 8th Avenue. The Del Mar parking lot is exposed to erosion. Waves overtopping the bluffs are expected to be more likely between 9th and 10th avenues.

INTRODUCTION

Purpose of This Study

This study is part of the City of Carmel Coastal Engineering and Hazard Assessment, and this technical memorandum serves to complete the deliverables for Task 3, Shoreline and Beach Erosion Exposure Modeling, and Task 4, Coastal Hazard and Sea Level Rise Vulnerability. This technical memorandum projects long-term beach, cliff, and dune erosion with sea level rise, as well as summarizes the risk to public and private infrastructure and assets. The coastal hazard exposure forecasting was completed using a suite of state-of-the-science models for a range of sea level rise horizons considering a variety of assumptions on historical erosion rates and conditions with and without coastal armoring in place. The vulnerability assessment evaluates the spatial intersection between the projected coastal hazards and the locations of bluff-top infrastructure and assets. Results from the vulnerability assessment are summarized by the likelihood of impact across multiple horizons, near-term (1 ft of sea level rise / 2045–2060), medium-term (2 ft of sea level rise / 2060–2080), and long-term (4 ft of sea level rise / 2080–2100) and are presented in the Task 4 Vulnerability Assessment section.

Study Area

This study focuses on the City-owned portion of Carmel Beach from Pescadero Canyon in the north to Carmel Point in the south. Summaries of hazards and vulnerabilities are organized and divided into four sections, which emerged from the City's Climate Change Vulnerability Assessment Report (City of Carmel-by-the-Sea 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. Results from the hazards modeling and vulnerability assessment will inform the development of adaptation strategies in Phase 2 of this project.

Study Area Sections

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

For the sake of brevity, each 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.

Within each section listed above, erosion projections were conducted on multiple smaller backshore locations. Each of these subsections was organized by their unique orientation, backshore type (armor or unarmored), and backshore characteristics (dune-backed, cliff-backed, vegetated, unvegetated, etc.). In total, 31 separate backshore areas were used to project location-specific erosion hazard zones.

SEA LEVEL RISE

Global sea level rise is a result of human-caused climate change and is driven by the thermal expansion of ocean water and the melting of terrestrial ice as the Earth warms. Global climate models indicate that California will see significant sea level rise during this century, with the exact magnitude depending on factors such as global greenhouse gas emissions and the Earth's energy imbalance, the rate at which oceans absorb heat, land ice melting rates, movement of land-based ice sheets, and local land subsidence or uplift.

According to California's Office of Environmental Health Hazard Assessment, the central coast of California experienced about 8 in. of sea level rise from 1900 to 2020, and the rate is projected to increase over this century (OEHHA 2022). California Ocean Protection Council (OPC) and California Coastal Commission (CCC) both issued guidance documents that are meant to guide local jurisdictions on sea level rise planning. They are:

- State of California Sea-Level Rise Guidance Year 2018 Update, adopted by OPC in 2018
- CCC Sea Level Rise Policy Guidance, certified by the Coastal Commission in 2018.
- Draft State of California Sea Level Rise Guidance: 2024 Science and Policy Update, released in January, 2024[1]

Based on this guidance, this study evaluated a range of sea level rise projections under high emissions (RCP 8.5) using a 1) median scenario, representing a 50% probability that sea level rise will reach 2.0 ft by 2100; 2) likely scenario representing a 66% probability that sea-level rise will reach 3.0 ft by 2100 and; 3) a medium-high risk aversion scenario representing a 0.5% probability that sea level rise will reach 3.9 ft of sea level rise by 2080 (Table 1 and Figure 1).

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[1] In this draft update, some language form the 2018 report have been updated. "Medium-High Risk Aversion" now corresponds to the "High" scenario, and "Likely" corresponds to the "Intermediate" scenario. This updated language corresponds with NOAA's 2022 Global and Regional Sea Level Rise Scenarios for the United States Report.

Table 1. Probabilistic projections for future sea level rise by year for Monterey.

From OPC 2018 Guidance	**Sea Level Rise Rate (ft) Range of Projections**		
Year	**Median** *50% probability SLR meets or exceeds…*	**Likely** *66% probability SLR meets or exceeds…*	**Medium-High Risk Aversion** *0.5% probability SLR meets or exceeds…*
2020	0 (baseline)		
2040	0.3	0.5	0.7
2060	0.7	1.1	2.1
2080	1.3	2.0	3.9
2100	2.0	3.0	6.4

Source: OPC Guidance (2018). Projected sea levels using the Monterey tide gauge. Values have been adjusted by shifting the baseline year from 2000 to 2020. All sea level rise rates are referenced to high emissions scenarios.

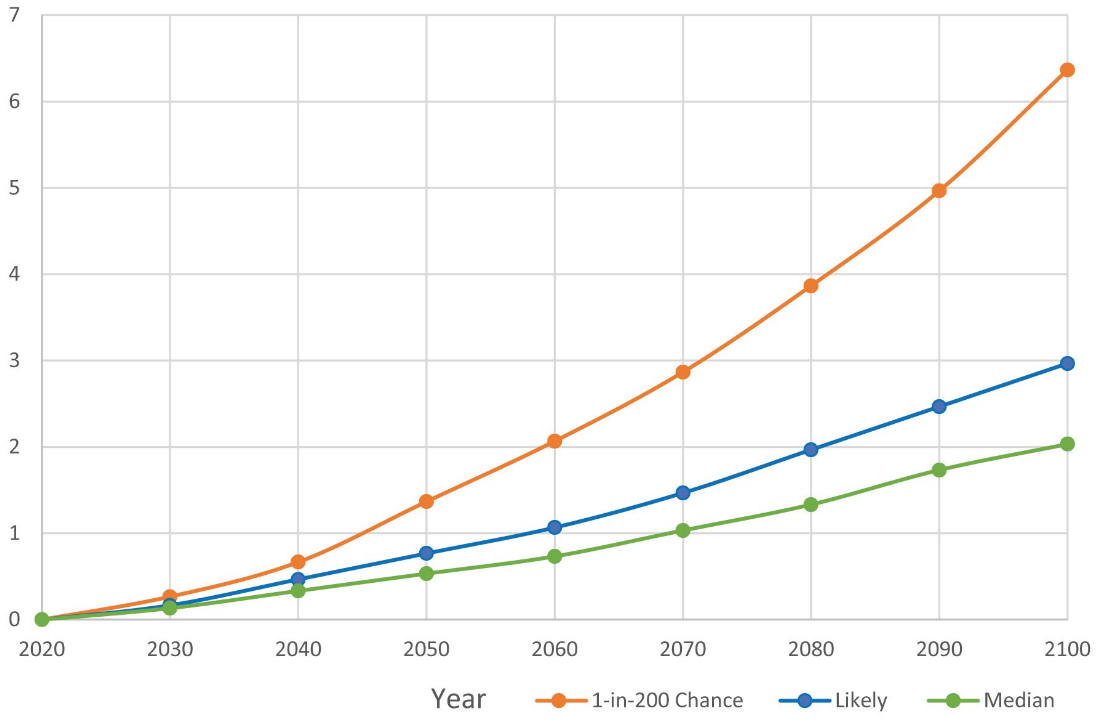

Figure 1. 1-in-200 Chance (Medium-High Risk Aversion), Likely (66% Probability), and Median (50% Probability) rate of sea level rise from 2020 to 2100 under high emissions, based on OPC Guidance (2018, 2024).

COASTAL HAZARDS

This study evaluated the following coastal hazards:

- **Coastal cliff and dune erosion**—includes erosion of the dune-backed areas from 8th Avenue in the south to the volleyball courts in the north, and the cliff-backed sections in the southern and northern sections of the study area.
- **Beach narrowing**—represented by the projected future change in the summer beach widths for each foot of sea level rise.
- **Coastal wave overtopping**—evaluated based on total water level exceedance analysis for above existing coastal armoring and dune and cliff crests along the study area.

Descriptions of these hazards and the forces that influence them are presented below.

Coastal Cliff and Dune Erosion Forces

Coastal erosion is a complex process shaped by various factors resulting in the ongoing retreat of dunes and cliffs. The factors that contribute to erosion encompass marine forces (such as wave energy), terrestrial forces (including rainfall and groundwater flow), and terrestrial conditions (like rock type, grain size, joint density, or the presence of coastal armoring). Together, these elements are the primary influences contributing to coastal cliff and dune retreat.

Two erosion processes occur along the cliff-backed shoreline: the first is erosion of the softer marine terrace deposits (or bluffs) that overlay the sandstone bedrock, and the second involves the long-term erosion of the sandstone bedrock (or cliffs). In conjunction, these processes lead to inland retreat of the bluff-top edge along the cliff-backed shore.

Erosion processes on the dune-backed shoreline are influenced by wind and water, with marine forces such as wave attack being the primary driver of dune crest recession. As waves arrive during winter storms, this wave action can transport sand away from the base of the dune, creating a dune scarp. Over time, a new dune profile will take shape as the slope stabilizes, and accretive forces such as summer waves bring sand to shore and prevailing winds (also known as aeolian transport) bring sand to the dune. If the erosive forces acting upon the dune surpass the constructive accretive forces, the crest of the dune will progressively migrate inland.

Carmel Beach experiences most erosion events in the winter when storms bring intense rainfall and larger waves. During the winter, the sand that is typically on the dry beach during the summer is relocated offshore to form sandbars. For typical winter conditions, these sandbars act as a protective barrier, causing larger waves to break offshore, dissipating much of their energy before reaching the beach. However, during large storms, there is so much wave energy and elevated water levels that the waves will reach backshore and can contribute to erosion. In a natural, unarmored environment, additional eroded sediment from the backshore would be available to replenish the beach during such events. However, in an armored setting, this source of sediment is not available to counterbalance the increased wave energy.

The erosion forces at work involve a complex interplay of marine and terrestrial factors and conditions. The subsequent sections explore these in more detail.

Marine Forcing

Waves and induced currents are the main primary marine influences on erosion. Elevated wave heights, typically associated with winter storms, contribute to increased run-up and higher total water levels. This results in more wave energy being directed toward the back of the beach. Furthermore, local variability in nearshore geomorphology can concentrate wave energy in specific zones and guide water flow, leading to the acceleration of alongshore currents.

Wave Reflection

Waves that reach the seawalls will reflect off the seawalls and travel seaward. At the seawall, the water particles under the reflected wave will move quickly, mobilize sand, and cause scour at the toe of the structure. The amount of scour is proportional to the height of the wave; the higher the wave, the greater the scour. In Figure 2, waves are crashing into the seawall near Martin Way.

Figure 2. Martin Way Stairs (highlighted in yellow) during the El Niño winter of 2023–24. Source: City of Carmel, January 2024

Wave Overtopping

When wave run-up reaches coastal armoring structures, especially vertical seawalls, it can elevate water levels and create wave splash over the seawalls (Figure 3). This wave splash water, especially when driven by onshore winds, can saturate the bluff terraces behind the wall, contributing to bluff failure and erosion behind the seawalls. As sea levels rise, wave run up elevations reach a point where the water that is overtopping is not just a vertical splash but rather a wave (or “green water”), that has horizontal momentum and can further accelerate the erosion of the bluff above the coastal armoring structures.

Figure 3. Wave overtopping on a Carmel seawall (see arrow). Note the directional wave and splash along the wall. Source: City of Carmel January 5, 2023

Inshore and Backshore Currents

The study by Rogers E. Johnson and Associates (Johnson 1983) detailed a swift inshore current that moves horizontally along the beach, typically heading southward where elevations are lower. Inshore and backshore currents have been observed in recent events, illustrated in Figure 4. In the initial panel, waves collide with the seawall, reflecting away from it. The water, attempting to escape, is directed around the seawall. These currents with high particle velocities can more effectively mobilize sand away from the beach.

Figure 4. Rip currents moving away from the shore in the cove at 13th Avenue. Left, the cove fills with water from broken waves. Right, an alongshore current develops, channeling water out of the cove and along the seawall to the south.
Source: City of Carmel, January 2023

Local Conditions

Outcrops and variability of the backshore will affect how currents develop and where wave focusing occurs. A unique contributing factor for Carmel is the orientation of exposed outcrops of sandstone in the beach area (Figure 5). These outcrops are usually buried by beach sand and are only exposed following significant winter scouring events. The Johnson (1983) study notes that deep channels exist between these outcrops that lie perpendicular to the bluffs. These formations may act to direct and focus water flow toward specific locations on the backshore, producing more severe erosion (Figure 6).

Figure 5. Left: Sandstone outcrop between Santa Lucia Ave and 13th Avenue, winter of 2010. Note the perched beach sand atop the sandstone outcrop to the right (orange circle), an indication of the previous summer's sand levels. Right: A scoured beach in January 2023 near 10th Avenue reveals a channel between sandstone bedrock with a gap oriented at an angle to the backshore. Source: City of Carmel.

Figure 6. Focusing of water flow between the gap in the sandstone formation. This leads to a piling up of water in the gap and subsequently higher erosion. Location: Stairs at northern end of 10th Avenue. Source: City of Carmel, January 2023

Terrestrial Forcing and Conditions

Terrestrial forces include rainfall and groundwater flow, as well as terrain and lithological conditions, including variations in geology, profile elevation, beach slope, folding, faulting, and shoreline orientation. As noted in the Johnson (1983) study, two strong sets of fractures which trend in the northwest direction have allowed waves to selectively attack the backshore along these zones of weakness. This process has helped to form the coves and headlands seen in the southern end of the beach. In addition, there are also anthropogenic factors to consider related to land use patterns, stormwater management, irrigation systems, coastal armoring, and recovery efforts. Human and animal foot traffic along informal shoreline trails, or through vegetated dunes (or bluff-cuts) also contributes to erosion along shoreline bluffs and is a persistent problem for the City (Shonman and D’Ambrosio 2015).

Stormwater Runoff Influence

The City’s shoreline is located at the bottom of a hill where stormwater is channeled from the streets above. The City’s stormwater discharges onto the beach through 21 outfalls. During the severe El Niño winter of 1982-83, severe winter storms struck Carmel every 10 days, and the heavy rains overwhelmed the City’s storm drain system and were a major contributor to bluff-top erosion. Although significant upgrades and improvements to the drain system and catch basins were made between 1983 and 1988 following the El Niño storms, the ability of the stormwater system to channel water effectively will be affected by sea level rise, coastal erosion processes, and increases in high-intensity rainfall events due to climate change (Shonman and D’Ambrosio 2003).

Erosion Response

The erosion response of the cliff-backed bluffs and the dunes and beach are different. Bluff erosion occurs episodically, and the bluff does not recover without intervention. In contrast, the sandy beach will recover between storm events as smaller waves bring sand back to the shore. Given enough time and favorable winds, sand dunes can also recover as the beach sand is blow into the dunes. Predominantly sandy areas, like dunes and the beach, will erode gradually over time, while predominantly rocky areas, like the cliffs and bluffs, will erode episodically over time. Figure 7 depicts the different types of erosion depending on the backshore type.

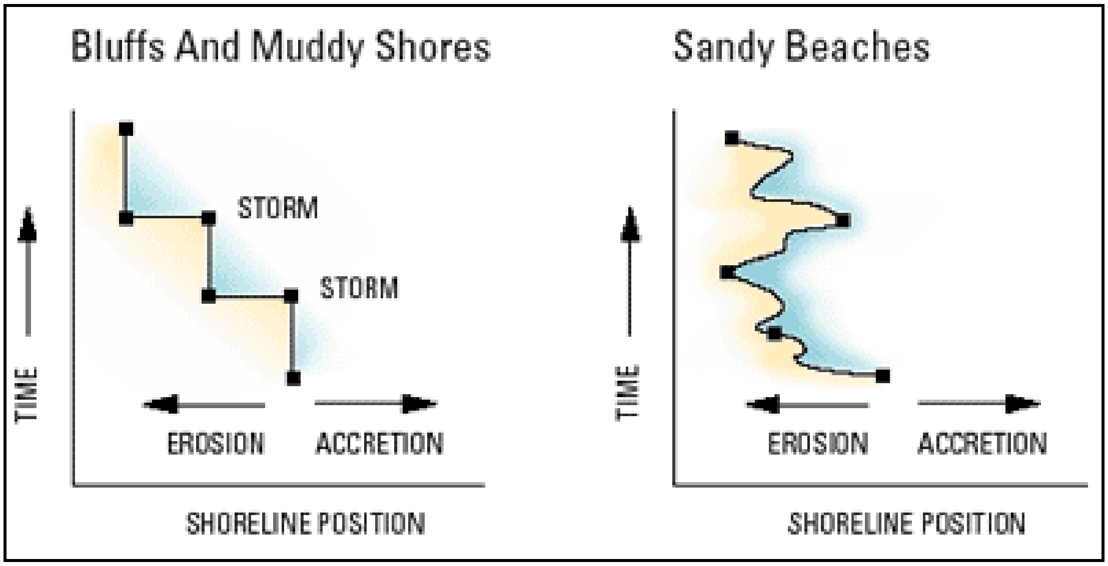

Figure 7. Bluff erosion occurs episodically and only moves inland while sandy beaches can erode during storms and recover during calmer wave conditions time.
Image from the U.S. Geological Survey.

Beach Narrowing

The effect of sea level rise will be the landward migration of the shoreline. On average, Carmel Beach has an offshore slope of approximately 50:1 to 60:1,[2] meaning every foot of sea level rise will result in a 50- to 60-ft landward progression of the shoreline.

It is important to understand that coastal armoring protects what is behind the armor, at the cost of the fronting beach. With increasing sea levels, it is only a matter of time before beaches in front of hard armoring structures will disappear. This is a phenomenon known as coastal squeeze or passive erosion.

Dune Erosion and Scarping

During storm events, the dunes along Carmel Beach can experience substantial erosion. Wave run-up, especially during elevated tides, allows wave energy to reach the backshore and impact the base of the dune. This can result in the removal of sand, leaving a steep dune scarp (Figure 8). The extent of dune erosion at a specific location is influenced by factors such as beach slope, dune vegetation, and, crucially, the location of buried riprap that protects the dune toe from erosion.

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[2] From the 15-m isobath to the toe of the cliff, dune, or coastal armor.

Following significant erosion, the recovery of Carmel’s dunes occurs gradually, facilitated by smaller waves and wind bringing sand back over an extended period. However, because of the longer recovery time of dune systems, they are especially susceptible to increased storm frequencies and sea level rise. Elevated water levels with sea level rise will allow wave erosion processes to act farther up on the beach profile causing an evolution of the dune profile farther inland.

Figure 8. Dune scarp at Del Mar Sand Ramp. The yellow hatched line represents the previous summer’s beach profile. Dune scarping can have a significant impact on beach access. Source: City of Carmel, January 2023

Bluff Terrace Erosion

Bluff terrace erosion is primarily due to two natural processes: 1) wave attack eroding the sandstone bedrock and undermining the bluff, and 2) terrace slumping. Rainfall and saturated soils can cause gullying and slumping that contribute to the recession of the bluff. Slumping can also accelerate erosion of the underlying sandstone during large failure events. Note that as bluffs erode, debris accumulates at the base of the cliff, which can provide some temporary protection from wave attack.

DATA AND ANALYSIS METHODS

This section summarizes this assessment’s methodology and approaches for assessing sea level rise and coastal hazard vulnerabilities.

Coastal Modeling Parameters

The extent of coastal erosion is represented as the landward migration of the bluff or dune crest. Coastal erosion is episodic, not constant, making it difficult to estimate the eroded position of the cliff top for any given time and location. This study projects the average retreat rates associated with a series of these episodic events over time to yield projections for the average bluff or dune crest position in the future.

The models for cliff erosion rely on simplifications of reality and relate cliff retreat to factors such as wave impacts, sea level rise, historical erosion rates, and cross-shore profile geometry. Detailed below are the data sets that contributed to these model parameters. The short-term impacts of these seasonal processes vary spatially, and the processes occur across long time scales; thus, they are extremely hard to predict both spatially and temporally.

Coastal models require historical erosion rates to project future erosion rates. They also require additional parameters to determine terrestrial and marine forcing, including the following:

- **Geomorphic:** bluff-top elevation, contact elevation between terrace and cliff, toe elevation, foreshore beach slope
- **Waves**: total water levels.

Determination of Erosion Rates

Location-specific erosion rates are an important factor in determining erosion projections and were needed given the detailed scale of this study. Unfortunately, data were not available to support an accurate location-specific historical erosion rate assessment and literature was cited to determine average erosion rates across the entirety of Carmel Beach. To arrive at a location-specific erosion rates, the average erosion rates from the literature were adjusted to take into account varying local conditions. For a more detailed explanation of average historical erosion rates and maximum observed failure distances, refer to the Task 2 Report: Shoreline and Beach Change Analysis: Seasonal and Long Term.

An upper and lower bound of potential erosion rates were determined to reflect a more likely and worst-case condition and to account for uncertainty in both spatial accuracy and confidence in the cited literature. The Johnson (1983) study documented locations and extents of failures and computed a long-term erosion rate from 1908 to 1982, and determined that the bluffs eroded between 0.3 and 0.7 ft/yr with an average of 0.4 ft/yr. It should be noted that erosion occurs episodically, not on an average annual basis, and maximum failure distances may reach as far as 30-40 feet, as documented in Johnson (1983) study following the 1982-83 El Niño winter.

To represent a lower bound, this study adjusted the average lower bound to 0.2 ft/yr, which is an average between the erosion rate found for the Pebble Beach Golf Course section of beach (0.1 ft/yr) and the lower bound reported by Johnson (0.3 ft/yr). To represent a worst case, this study used the average of 0.7 ft/yr found by Johnson (1983).

Location-Specific Historical Erosion Rates

To determine site-specific erosion rates for the entire shoreline, the historical erosion rates of 0.2 ft/yr (likely), 0.4 ft/yr (best, representing an average), and 0.7 ft/yr (worst case) were multiplied by an adjustment factor, which was determined based on geological conditions, geomorphic factors, locations with accelerated nearshore currents and historical observations of failures. Projections of erosion using these historical rate assumptions are discussed in the Task 3, Hazard Model Findings section, below.

A site-specific adjustment factor was informed from reports of geological conditions from the Johnson (1983) study, the James C. Reynolds and Associates (Reynolds 1986) soil investigation report noting bluff contact elevations, Carmel Shoreline Assessment Fall 2014 to Summer 2016 (Carmel-by-the-Sea 2016), and from observations made in the field by the Haro Kasunich & Associates, Inc. and Integral team in 2023. These reports and field observations provided a spatially explicit reference for the geological and terrestrial conditions that may contribute to higher erosion rates in certain areas, such as noted locations of jointing, faulting, fractures, and sandstone platforms that may focus wave energy, as well as areas that experience more significant beach scouring. Elements that may inhibit erosion were also factored in, such as the presence of a sandstone platform that may deflect wave energy, a more sheltered shoreline orientation, the presence dune vegetation, and areas that experience less beach scouring. Consideration was also given to the contact elevation of the more erosion-prone terrace deposits. This information was also verified by failure observations that were compiled from site-specific studies, including from Johnson (1983, 1997), and assessments from Shonman and D’Ambrosio (2015). The range of assumed location-specific erosion rates are shown in Figure 9.

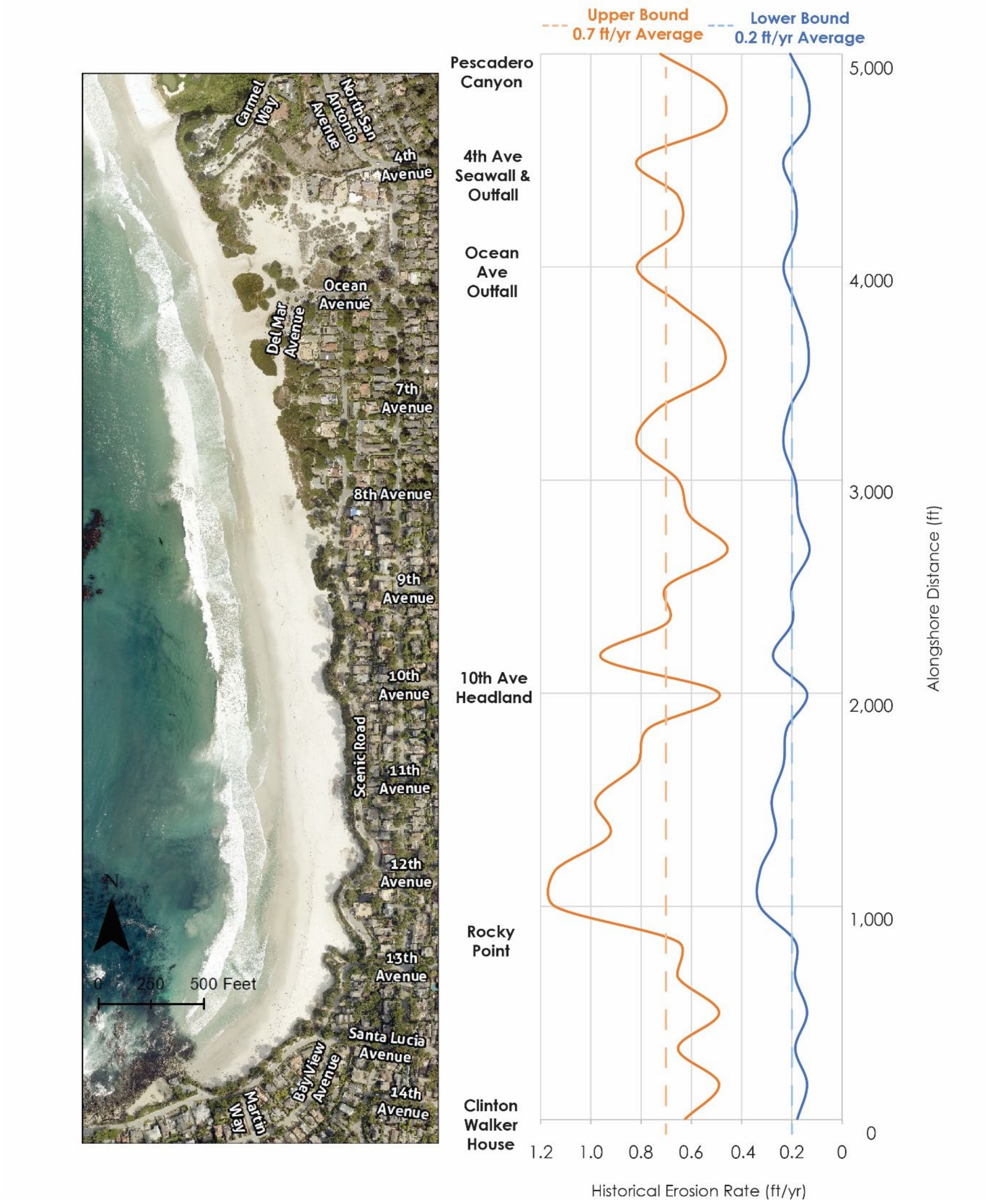

Figure 9. The range of historical erosion rates estimated in this study, which are used to derive future erosion projections by accelerating these rates with sea level rise.

Geomorphic Data (Elevation and Slopes)

Digital elevation models (DEMs) were used to develop cross-shore profiles, which inform the elevations of important cliff and dune features. These data were sourced from the National Oceanic and Atmospheric Administration (NOAA) Digital Coast website and the Association of Monterey Bay Area Governments (AMBAG). Elevation models considered in this study included the following surveys: Federal Emergency Management Agency (FEMA) 2018 (Spring), U.S. Geological Survey (USGS) 2016 (Spring), California ARRA 2010/11 (Winter), AMBAG 2010 (Summer), U.S. Army Corps of Engineers NCMP 2009 (Fall), USGS 1998 (Spring), USGS 1997 (Fall), as well as the USGS CoNED Topobathy from the Coastal National Elevation Database (multiple dates from 2008 to 2015).

Cliff and Dune Feature Locations

Locations of the following cliff features was determined: the toe of the cliff or armoring structure, the top of the armoring structure or the contract between the cliff and the bluff terrace, and the crest of the bluff at the landward edge. These features were manually digitized from high-resolution aerial photographs from EagleView (2022) provided by the City and verified using the 2018 and 2016 lidar DEMs, as well as oblique images from the California Coastal Records Project. The height of all coastal armoring was further verified from site observations as documented in the tables provided in Task 1, Coastal Engineering Assessment.

Cliff Top Elevations

The elevation of the top of the cliff was determined just inland (2 m) of the observed cliff-top location to account for potential positional inaccuracies in the DEMs. Elevations for each transect were determined using available DEMs for each year, and outliers were removed from the data set.

Bluff Contact and Top of Armor Elevations

The contact elevation between the more erosion-resistant sandstone or coastal armoring and the less erosion-resistant terrace was determined using an average elevation from all available data sets while filtering bias errors due to vegetation. The contact elevation was determined manually through interpretation of the change in slope in the DEMs as well as aerial image interpretation. Contact elevation depths were verified with the Reynolds (1986) assessment. Note that the sandstone bedrock dips below an area of dunes at 8th Avenue and reemerges just shoreward of the beach volleyball courts. For the dune-backed sections where the sandstone bedrock is buried by dune sand, a linear interpolation between the known locations of the southern and northern contact elevations was used. This interpolated location is important because once dune erosion reaches this location, then the erosion processes shift to cliff erosion processes.

Cliff Toe Elevations

The elevation of the cliff or armor toe was determined just seaward (5 m) of the observed toe location to account for seasonal changes in beach elevation, which can affect the horizontal toe position. Toe elevations were determined for both winter/spring and summer/fall. For these modeling purposes, the average winter/spring elevation was used, as this season is typically most erosive, and beach sand levels are the lowest. This elevation was calculated from the average of the three lowest elevations found among the available DEMs. The lowest toe elevations were typically found in the 1998 spring (following the El Niño Winter) and 2010 summer surveys, with the 2016 spring and 2018 spring surveys also contributing.

Nearshore Waves and Total Water Levels

Wave properties, including wave height and period, were derived from unpublished data from the USGS (Hegermiller et al. 2017). The time series of nearshore waves along the central California coast, including hindcasted data for 1980–2010 and projected data for 2010–2100, were developed using downscaled regional models. Each subunit in the study area was linked to a nearshore wave data location, with a total of nine wave data points referenced.

An important measure of coastal hazards is the total water level elevation, which is the combined effect of wave run-up height, storm surge, tides, and sea level elevations. For a more detailed discussion of total water level, please see Integral’s Task 2 report, Shoreline and Beach Change: Seasonal and Long Term. For this analysis, total water levels were determined by combining the highest astronomical tide (HAT), CoSMoS Waves, and a wave run-up using the Stockdon et al. (2006) wave run-up equation.

The total water levels were calibrated using FEMA’s flood hazard elevation levels by matching the total water level at each transect to the FEMA flood hazard elevation. To ensure the total water levels matched the flood hazard elevation levels, the foreshore slopes of the transects were adjusted. The final range of slopes was between 6/100 and 14/100 ($\tan\beta$ – 0.06 – 0.14).

Cliff and Dune Erosion Projection Methods

Erosion projections assume that sea level rise will elevate wave energy, intensifying its impact on cliffs, dunes, and armor, and ultimately leading to heightened retreat rates. Peer-reviewed models, described in more detail below, rely on assumptions linking cliff retreat to sea level rise, wave energy, historical cliff behavior, and cross-shore profile geometry. The CoSMoS cliff forecasting tool relies on five different models from Limber et al. (2018). However, not all models within the CoSMoS cliff forecasting tool were appropriate for the study area. This study used two models hand-picked to match the hard rock geologic conditions of the study area, which are detailed below.

Several different scenarios are modeled: 1) unarmored and armored, and 2) high, medium, and low assumptions on historical erosion rates. The erosion model projects erosion distances at 1-year time steps. Erosion distances are mapped in approximately 20-year time periods: 2020–2040 (0–1 ft sea level rise), 2040–2060 (1–2 ft sea level rise), and 2060–2080 (2–4 ft sea level rise). While period of time is used for the erosion modeling, all results are reported by level of sea level rise.

Exceedance Model (Cliff-backed shorelines with Armoring)

This model uses historical erosion rates to project cliff retreat using methods described in ESA (2016), Revell et al. (2011), and Limber et al. (2018). It presumes that the wave energy reaching the bluff will cause the bluff retreat rate to accelerate beyond historical levels. Wave energy reaching the bluff is modeled as the amount of time the total water level exceeds the contact between the terrace and the sandstone, also called "exceedance hours." With sea level rise, the retreat rate will increase proportionally to the increase in exceedance hours. As total water levels were calculated assuming elevated tides and scoured beach profiles, exceedance hours were divided by 4 to account for hours of high wave run up occurring during high tides in the mixed semi-diurnal tide regime (two high and two low tides of unequal height daily). One erosion hazard zone representing the best estimate of future erosion hazards was developed.

Trenhaile Model (Cliff-backed shorelines without armoring)

This model presumes that the distance between wave breaking and the cliff toe (surf zone length) will drive cliff retreat and is described in Trenhaile (2000) and Limber et al. (2018). A shorter surf zone will increase the wave energy available to reach the backshore, and sea level rise will reduce surf zone length and lead to an acceleration of erosion into the future. Unlike the exceedance model described above, this model does not consider the presence of armoring along the backshore. Three erosion hazard zones representing a range of estimates of future erosion hazards was developed.

Dune Erosion Model (Dune-backed shorelines)

This model was conducted using a geometric model of foredune erosion due to sea level rise (Komar et al 1999, Revell et al 2011). This model projected that the dune would intersect the underlying cemented beach deposits and more erosion-resistant sandstone between 2045 and 2060 (or one foot of sea level rise). After one foot of sea level rise, the dominant erosion mode was modeled as a hard cliff-back coast (see Trenhaile model, described above).

Beach Narrowing Projection Methods

A Bruun-type model was used to estimate coastal recession by assuming the conservation of sediment and an equilibrium profile shape. [3] This model shifts the beach profile upward and landward by a distance determined by sea level rise and the geometry of the profile. The baseline for a typical summer beach is the 75th percentile beach location as determined from analysis of the CoastSat data record from 1984 to 2021 and is described in more detail in Task 2. For this analysis, it is assumed that the current armored backshore toe of the cliff or dune location does not retreat inland with sea level rise. This model can be considered a “hold the line” scenario and represents what changes to the beach may occur if the coastal armoring is maintained and no additional adaptation strategies are implemented in the future.

Model Caveats and Disclaimer

The cliff erosion model projections show a band of potential erosion. It is highly unlikely that all of this erosion would occur simultaneously, rather multiple cliff failures would occur along the coast in different locations. The cliff erosion models used in this study do not account for the evolution of nearshore slopes over time, including the beach and shore platform, which are likely to evolve as sea levels rise and erosion forcing conditions change. Additionally, the efficacy of coastal armoring over time and when or if failure of these structures will occur is not considered.

Small variations in initial parameter values can lead to significant variations in model predictions as they are multiplied over long time scales. As a result, the uncertainty in erosion rate projections generally increases over time.

Finally, the future holds many uncertainties that may influence erosion, ranging from potential changes in precipitation, temperature, wave climate, frequency and magnitude of precipitating storm events, and anthropogenic contributions and responses to erosion. Due to the highly uncertain nature of these processes, caution should be used with all erosion projections.

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[3] The conservation of sediment assumption in the Bruun model was justified in Task 2 findings of a stable sand volume in the nearshore system.

Given these disclaimers, however, all efforts have been made to utilize the best available science and methods and carefully document uncertainties. These results represent the state of the practice in coastal cliff erosion projections.

Vulnerability Assessment Methods

The vulnerability assessment analyzes the spatial intersection (or overlay) of the coastal erosion hazard zones with the assets and infrastructure data sets. The study team overlaid all available parcels, structures, roads, and infrastructure data sets with the coastal erosion hazard zones to quantitatively assess both the number and amount of assets affected. For each resource sector, individual data sets had particular reporting criteria, including number, length, and area affected. Data sets were queried, and summary statistics of assets affected were calculated by sea level rise elevation (see Appendix A for tabular results). Results were collated into tables and are interpreted in the Task 4, Vulnerability Assessment, section below. Because of the sensitive nature of utility and infrastructure data, and to respect the privacy of individual residents and landowners, this study does not map the locations of vulnerable assets.

Asset Data

The study team considered and collected all available geospatial asset data from the City, County, and cross-jurisdictional agencies such as CalAm Water and the Carmel Area Wastewater District. The team obtained the most up-to-date data directly from the source at the time of evaluation and performed quality assurance on the data.

TASK 3 HAZARD MODEL FINDINGS

This section provides the analysis and modeling results in the forms of tables of total water levels with sea level rise by backshore section, maps displaying erosion hazard zone projections, and maps of beach narrowing.

Total Water Level Findings

This section reports the progression of total water levels with sea level rise. High total water levels allow wave energy to reach the backshore, overtop coastal armoring and accelerate erosion, and these values are related to how much erosion accelerates in the erosion scenario with armoring. This analysis assumes that the future wave climate is comparable to the historical wave climate and that total water level changes are based primarily on influences from sea level rise. Modeling of total water levels assumes that current backshore location and height of armoring remain consistent throughout the future, and that no additional adaptation strategies are implemented.

Table 1. The percentage of time total water level exceeds the top of armor or sandstone and terrace contact elevation (left) and if total water levels exceed the crest (right) for each sea level rise level. Green indicates very little (<3%), yellow indicates low (3–10%), orange indicates medium (10–20%), and red indicates high levels of exceedance time (>20%). Areas are listed from south to north.

Location *From south to north*	**Water Levels above the Top of Armoring or Sandstone Cliff** *Percentage of days* that the contact elevation is exceeded*			**Water Levels above the Crest of the Bluff or Dune** *Does wave splash exceed crest elevation? (YES or NO)*		
	Sea Level Rise Horizon, feet (years)			Sea Level Rise Horizon, feet (years)		
	1 (2045–2060)	2 (2060–2080)	4 (2080–2100+)	1 (2045–2060)	2 (2060–2080)	4 (2080–2100+)
Section 1 South Beach						
Martin Way to Santa Lucia Ave (Seawall)	**4%**	**8%**	**21%**	**YES**	**YES**	**YES**
Santa Lucia Ave to 13th Ave (Seawall)	**6%**	**16%**	**23%**	**YES**	**YES**	**YES**
13th Ave Headland (Seawall)	**1%**	**3%**	**10%**	**YES**	**YES**	**YES**
13th Ave Cove (Seawall)	**4%**	**10%**	**22%**	**NO**	**NO**	**NO**
13th Ave to 12th Ave (Riprap)	**22%**	**25%**	**25%**	**NO**	**NO**	**NO**
13th Ave to 12th Ave (Seawall)	**<1%**	**<1%**	**2%**	**NO**	**YES**	**YES**
13th Ave to 12th Ave (Unarmored Cliff with Riprap around SW Drain)	**2%**	**5%**	**17%**	**NO**	**YES**	**YES**
13th Ave to 12th Ave (Unarmored Cliff)	**14%**	**21%**	**25%**	**NO**	**NO**	**YES**
12th Ave Cove (Unarmored Cliff)	**<1%**	**1%**	**5%**	**NO**	**NO**	**NO**
12th Ave Cove (Revetment)	**1%**	**2%**	**6%**	**NO**	**NO**	**NO**
12th Ave to 11th Ave (Revetment)	**1%**	**1%**	**4%**	**YES**	**YES**	**YES**
11th Ave to 10th Ave (Buried Revetment)	**15%**	**20%**	**24%**	**YES**	**YES**	**YES**
10th Ave Headland (Seawall)	**13%**	**19%**	**24%**	**YES**	**YES**	**YES**
10th Ave to 9th Ave (Buried Revetment)	**24%**	**25%**	**25%**	**YES**	**YES**	**YES**
9th Ave to 8th Ave (Buried Revetment)	**25%**	**25%**	**25%**	**YES**	**YES**	**YES**
8th Ave Stairs (Buried Revetment)	**12%**	**24%**	**25%**	**NO**	**NO**	**NO**
Section 2 Central Beach						
8th Ave (Buried Revetment under Vegetated Dune)	**<1%**	**3%**	**23%**	**NO**	**NO**	**YES**
8th Ave to 7th Ave (Vegetated Dune)	**<1%**	**<1%**	**4%**	**NO**	**NO**	**NO**
7th Ave (Vegetated Dune)	**0**	**0**	**<1%**	**NO**	**NO**	**NO**
Southern Sand Ramp (Dune)	**0**	**0**	**0**	**NO**	**NO**	**NO**
7th Ave to Ocean Ave (Vegetated Dune)	**0**	**0**	**0**	**NO**	**NO**	**NO**

	Water Levels above the Top of Armoring or Sandstone Cliff *Percentage of days* that the contact elevation is exceeded*			**Water Levels above the Crest of the Bluff or Dune** *Does wave splash exceed crest elevation? (YES or NO)*		
	Sea Level Rise Horizon, feet (years)			Sea Level Rise Horizon, feet (years)		
Location *From south to north*	1 (2045–2060)	2 (2060–2080)	4 (2080–2100+)	1 (2045–2060)	2 (2060–2080)	4 (2080–2100+)
Del Mar Parking Lot (Dune)	**0**	**0**	**0**	**NO**	**NO**	**NO**
Section 3 North Dunes						
Ocean Ave (Buried Revetment under Vegetated Dune)	**0**	**0**	**0**	**NO**	**NO**	**NO**
Ocean Ave (Vegetated Dune)	**0**	**0**	**0**	**NO**	**NO**	**NO**
Northern Sand Ramp (Dune)	**0**	**0**	**0**	**NO**	**NO**	**NO**
Ocean Ave to 4th Ave (Vegetated Dune and Cliff)	**0**	**0**	**0**	**NO**	**NO**	**NO**
Ocean Ave to 4th Ave (Vegetated Dune and Cliff)	**0**	**0**	**0**	**NO**	**NO**	**NO**
Ocean Ave to 4th Ave (Seawall)	**0**	**0**	**0**	**NO**	**NO**	**NO**
4th Ave Stairs (Vegetated Dune and Cliff)	**0**	**0**	**0**	**NO**	**NO**	**NO**
Section 4 North Beach						
4th Ave to Pescadero Canyon (Unarmored Cliff)	**0**	**0**	**0**	**NO**	**NO**	**NO**
4th Ave to Pescadero Canyon (Seawall)	**18%**	**24%**	**25%**	**NO**	**NO**	**YES**

Note: *Percentage of days are tallied by decadal range. The decal ranges used assume a high emissions and medium-high risk aversion sea level rise scenario with 1 ft of sea level rise by the 2040s, 2 ft of sea level rise by the 2060s, and 4 ft of sea level rise by the 2080s.

For the South Beach section, by 1 ft of sea level rise, total water levels during a 100-year storm event are often up to 3 feet or more over the terrace contact elevation. By 2 ft of sea level rise, the total water level is often greater than 5 ft over the crest in most sections.

For the Central Beach section, the total water level is expected to be higher than the crest only at the southernmost areas near 8th Avenue. As elevations rise toward the north, total water levels are not projected to exceed the dune crest or bluff contact elevation by four ft of sea level rise.

The North Dunes and North Beach do not see total water levels higher than the bluff contact or crest elevation except for the low-lying area near Pescadero Canyon. In this area, the total water levels are projected to be 5 ft greater than the top of armor elevation for all sea level rise horizons and projected to be higher than the bluff crest by 4 ft of sea level rise.

Cliff and Dune Erosion Hazard Findings

This section provides maps of the erosion hazard zones (Figures 12 through 16). The maps are organized by the with and without armoring scenarios and split into the north (including the North Dunes, North Beach, and Central Beach), central (including the Central Beach and South Beach), and south (including South Beach) areas. For the with armoring scenario, a range of future erosion probabilities are presented. For the armored erosion projection, only a best estimate scenario relying on a range of erosion baselines and future conditions is presented. For the armored scenario, erosion rates are dampened significantly in the near term due to limited wave splash above the crest of the armoring structures; however, with increasing sea level rise, the effectiveness of the armoring is reduced, leading to more green water horizontal wave run up velocities and an acceleration in bluff-top erosion above the coastal armoring in future.

Hazards Zone Disclaimer

The maps and associated analyses in this section are intended as planning tools to illustrate projected hazard exposure with sea level rise. The contributors and sponsors of this product do not assume liability for any injury, death, property damage, or other effects of erosion or flooding.

Although every effort was made to review all resource sector and infrastructure data used in this study, neither the City nor its consultant, Integral, can verify the completeness of all spatial data. For this reason, we do not accept responsibility for any errors, omissions, or positional inaccuracies. Users of the data displayed in the maps are strongly cautioned to verify all information.


Coastal Cliff and Dune Erosion Projection Without Armoring - North Carmel Beach

Notes: *Erosion distances represent projected long-term time-averaged trends in erosion without coastal armoring. Future erosion distances and bluff crest position may vary from these projections.*

Sea level rise elevations and time periods are based on 2018 OPC guidance and refer to a high emissions scenario with 2020 as a baseline.

Aerial: EagleView, 2022

Figure 10. Map of dune and cliff erosion for the northern beach. Displays erosion hazards without armoring. Hazard zones represent three bands of certainty, most likely, based on the assumption of a low average erosion rate (0.2 ft/yr), best, based on the assumption of an average erosion rate (0.4 ft/yr), and worst case, based on the assumption of a high average erosion rate (0.7 ft/yr).

Coastal Cliff and Dune Erosion Projection Without Armoring - Central Carmel Beach

1 ft of SLR (2045 - 2060)

2 ft of SLR (2060 - 2080)

4 ft of SLR (2080 - 2100+)

Notes: *Erosion distances represent projected long-term time-averaged trends in erosion without coastal armoring. Future erosion distances and bluff crest position may vary from these projections.*

Sea level rise elevations and time periods are based on 2018 OPC guidance and refer to a high emissions scenario with 2020 as a baseline.

Aerial: EagleView, 2022

Figure 11. Map of dune and cliff erosion for the central beach. Displays erosion hazards without armoring. Hazard zones represent three bands of certainty, most likely, based on the assumption of a low average erosion rate (0.2 ft/yr), best, based on the assumption of an average erosion rate (0.4 ft/yr), and worst case, based on the assumption of a high average erosion rate (0.7 ft/yr).

Notes: *Erosion distances represent projected long-term time-averaged trends in erosion without coastal armoring. Future erosion distances and bluff crest position may vary from these projections.*

Sea level rise elevations and time periods are based on 2018 OPC guidance and refer to a high emissions scenario with 2020 as a baseline.

Aerial: EagleView, 2022

Figure 12. Map of dune and cliff erosion for the southern beach. Displays erosion hazards without armoring. Hazard zones represent three bands of certainty, most likely, based on the assumption of a low average erosion rate (0.2 ft/yr), best, based on the assumption of an average erosion rate (0.4 ft/yr), and worst case, based on the assumption of a high average erosion rate (0.7 ft/yr).

Notes: *Erosion distances represent projected long-term time-averaged trends in erosion with coastal armoring. Future erosion distances and bluff crest position may vary from these projections.*

Sea level rise elevations and time periods are based on 2018 OPC guidance and refer to a high emissions scenario with 2020 as a baseline.

Figure 13. Map of dune and cliff erosion for the northern beach. Displays erosion hazards with armoring. Hazard zones in areas where armoring is not present rely on the ‘without armoring’ scenario using the assumption of an average erosion rate (0.4 ft/yr).

Figure 14. Map of dune and cliff erosion for the central beach. Displays erosion hazards with armoring. Hazard zones in areas where armoring is not present rely on the ‘without armoring’ scenario using the assumption of an average erosion rate (0.4 ft/yr).

Notes: *Erosion distances represent projected long-term time-averaged trends in erosion with coastal armoring. Future erosion distances and bluff crest position may vary from these projections.*

Sea level rise elevations and time periods are based on 2018 OPC guidance and refer to a high emissions scenario with 2020 as a baseline.

Figure 15. Map of dune and cliff erosion for the southern beach. Displays erosion hazards with armoring. Hazard zones in areas where armoring is not present rely on the 'without armoring' scenario using the assumption of an average erosion rate (0.4 ft/yr).

Notes: *Erosion distances represent projected long-term time-averaged trends in erosion with coastal armoring. Future erosion distances and bluff crest position may vary from these projections.*

Sea level rise elevations and time periods are based on 2018 OPC guidance and refer to a high emissions scenario with 2020 as a baseline.

Figure 16. Map of dune and cliff erosion for the entire beach. Displays erosion hazards with armoring. Hazard zones in areas where armoring is not present rely on the 'without armoring' scenario using the assumption of an average erosion rate (0.4 ft/yr).

Beach Narrowing Findings

In response to rising sea levels, Carmel Beach will narrow over time without any additional adaptation strategies (Figures 17 and 18). Beaches with no armoring may migrate landward with sea level rise as cliffs and dunes erode naturally. However, if landward migration is inhibited by armoring, beaches will narrow and likely be permanently inundated (Table 2) at some point in the future. This is a phenomenon known as coastal squeeze or passive erosion. A narrative of beach narrowing can be found below in the Task 4, Vulnerability Assessment section.

Table 2. Typical summer dry sand beach remaining with each foot of sea level rise

Sea Level Rise Elevation (ft)	Acres of Dry Sand Beach (typical summer)	Percentage
0	34.2	100%
1	27.4	80%
2	20.7	61%
3	14.1	41%
4	7.6	22%
5	2.6	8%

Notes: The baseline year for sea level rise 2020. Summer dry sand beach acreage is representative of the 75 percentile beach width from 1984 to 2021.

How to Interpret the Hazard Maps

The maps of beach narrowing with sea level rise represent a typical summer beach. Actual summer beach widths may vary. Beach widths are constrained by the current position of backshore toe and are reflective of a “hold the line” scenario.

Summer Beach Width Change Projection - North Carmel Beach

Beach Narrowing by Foot of Sea Level Rise

Sub Tidal	Beach Narrowing	Wet Sand	Dry Sand

Max. Beach Observed (1984-2021)

Toe of the Cliff, Dune, or Armor

Shoreline Features

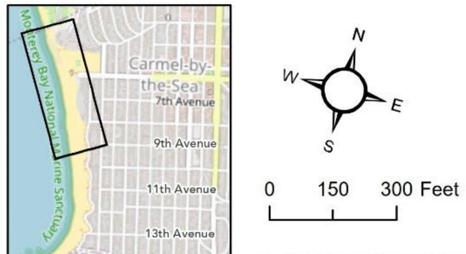
- Coastal Access Location
- Typical Summer Beach (1984-2021)
- Toe of the Cliff, Dune, or Armor (2022)
- Typical Summer Beach Projection - Elevation 1
- Narrowed Summer Beach Projection - Elevation 2

Notes: *Beach changes represent a typical summer beach (75th percentile shoreline position determined using CoastSat data from 1984-2021).*

Sea level rise elevations and time periods are based on 2018 OPC guidance and refer to a high emissions scenario with 2020 as a baseline.

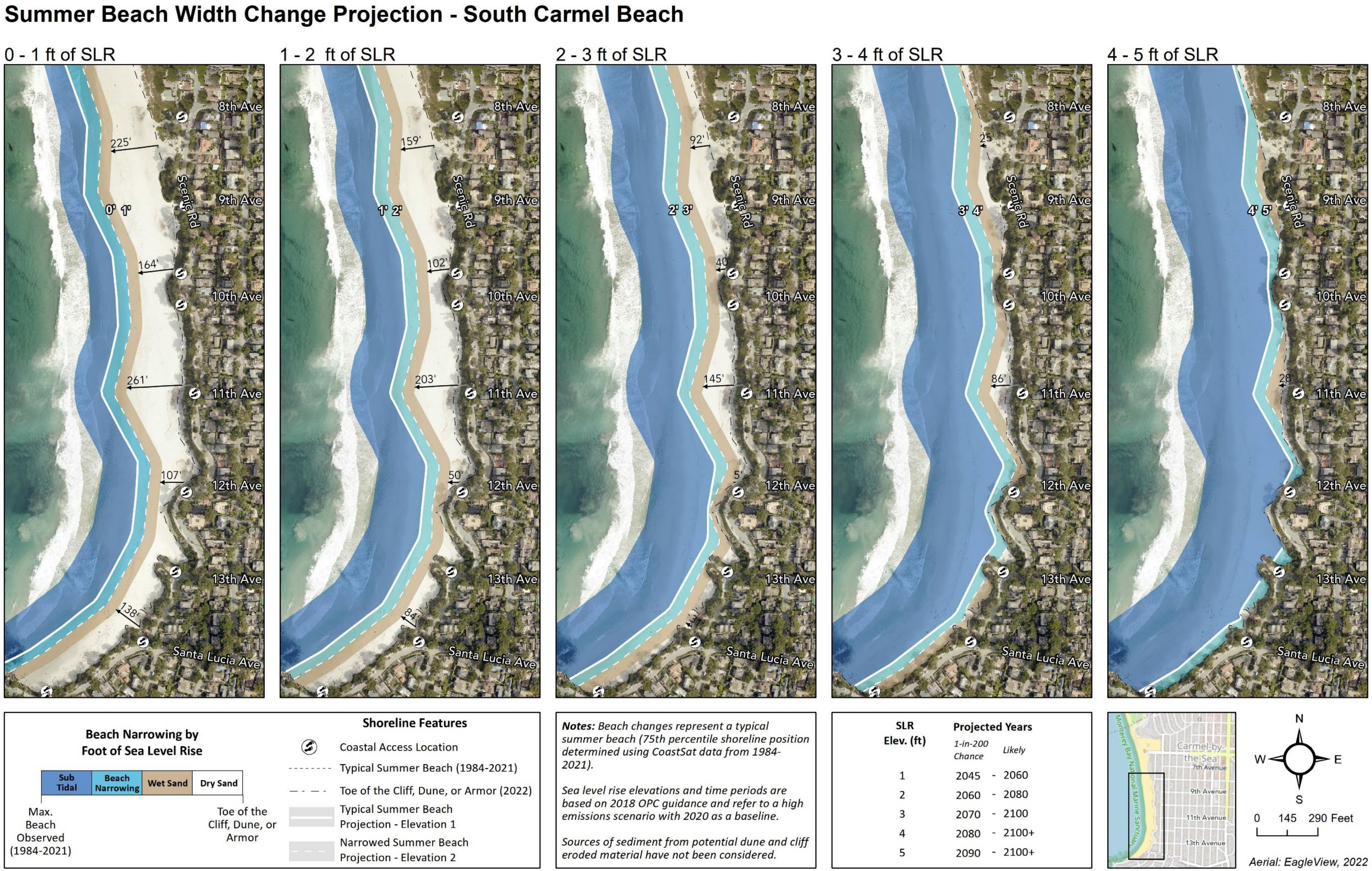
Sources of sediment from potential dune and cliff eroded material have not been considered.

SLR Elev. (ft)	**Projected Years** *1-in-200 Chance*		*Likely*
1	2045	-	2050
2	2060	-	2080
3	2070	-	2100
4	2080	-	2100+
5	2090	-	2100+



Aerial: EagleView, 2022

Figure 17. Summer dry sand beach loss in the northern beach between 0 to 5 ft of sea level rise.



Notes: *Beach changes represent a typical summer beach (75th percentile shoreline position determined using CoastSat data from 1984-2021).*

Sea level rise elevations and time periods are based on 2018 OPC guidance and refer to a high emissions scenario with 2020 as a baseline.

Sources of sediment from potential dune and cliff eroded material have not been considered.

SLR Elev. (ft)	Projected Years *1-in-200 Chance*	*Likely*
1	2045	- 2060
2	2060	- 2080
3	2070	- 2100
4	2080	- 2100+
5	2090	- 2100+

Figure 18. Summer dry sand beach loss in the southern beach between 0 to 5 ft of sea level rise.

TASK 4 VULNERABILITY ASSESSMENT

This section provides a narrative of vulnerabilities to sea level rise by each section of the City's shoreline. The focus of this assessment is on the direct exposure of City infrastructure, property, and structures to coastal erosion and sea level rise. This assessment does not consider the wide range of cascading impacts associated with climate change.

Section 1 South Beach—Scenic Road from 8th Avenue to Martin Way

This section of shoreline is composed of mostly armored cliffs along Scenic Road south of 8th Avenue and extends for ~0.6 mile. The contact elevation between the sandstone cliff and the softer terrace is lower in the north and rises toward the south, before dropping once more around 13th Avenue. This section experiences the most significant variability in seasonal beach width change.

The area between 9th Avenue and 11th Avenue has a FEMA base flood elevation of 31 ft, which is higher than other locations along Carmel Beach (24 ft in the south and 16 ft in the north). The Johnson (1983) study notes that the area around 10th to 12th Avenue is a possible fault zone and reports erosion of 25–40 ft here following the 1982-83 El Niño winter. These factors led to the assumption of a higher historical erosion rate for this section and yielded a higher erosion projection in the future.

The South Beach area is primarily residential, and a pedestrian pathway runs along this ocean-facing side of Scenic Road at the top of the bluff, which is a popular destination for locals and tourists.

Section 1 Vulnerabilities

Current Vulnerabilities

There is a restroom near Santa Lucia Avenue located along the bluffs (Figure 19). The base of the restroom is located at ~24 ft NAVD 88, which is at the same elevation of the FEMA base flood elevation for this area. This restroom will face an increased exposure to coastal wave flooding with sea level rise. The Johnson (1983) study notes that the rock stairway adjacent to this bathroom was almost destroyed in the 1982-83 El Niño storms.

Figure 19. Restroom at Santa Lucia Avenue.

Between 9th and 11th avenues, the FEMA 100-year coastal wave hazard zone extends to the residential properties on Scenic Road; however, none of the homes are exposed. Analysis shows total water level aligns with the FEMA base flood elevations, and additionally shows the potential for wave splash to exceed the bluff crest of the armored coastline between 13th Avenue and Martin Way.

The Scenic Road walkway, which abuts the bluff top edge, is vulnerable to erosion. Erosion could threaten the pathway and related amenities such as benches and signage, and safety features such as crib walls, guardrails, and handrails. The bluffs between 9th and 10th are especially prone to immediate erosion hazards as the contact elevation of the less erosion resistant bluff terrace and dune sands is much lower. Note that significant erosion of this walkway has occurred in the past, as documented in the Johnson (1983) study following the 1982-32 El Niño winter. Erosion distances from that series of winter storm events are depicted in Table 3.

Table 3. Observations of historical erosion events from the 1982-83 El Niño winter.

Observed Erosion from the Johnson 1983 Survey	**Location**
Loss of 20 ft of bluff	North of 8th Avenue
Loss of 30 ft of bluff	Between 8th and 9th Avenues
Loss of 40 ft of bluff	Between 9th and 10th Avenues
Loss of 25 ft of bluff	Between 10th and 11th Avenues
Loss of 30 ft of bluff	Near Santa Lucia Avenue

The stormwater drainage network, which is often buried beneath the bluff terrace and the cliff to drain stormwater to the beach, is likely to be exposed to storm wave flooding and erosion (Figure 20). Failure of a storm drain can also exacerbate erosion from terrestrial scouring during rain events.

Figure 20. Stormwater drainage near 13th Avenue.

There are ten beach access stairways that lead to the beach, and all of these stairways are vulnerable to wave attack, scouring and undercutting of their foundations, and coastal erosion. In addition, the failure of a stairway can exacerbate erosion of surrounding bluffs. Breakaway stair designs such as those just north of 10th Avenue can greatly reduce the potential for stairway failures to contribute to erosion.

Figure 21. Stairway at Santa Lucia Avenue. Note damage to the railing from past storms.

1 ft of Sea Level Rise (2045–2060)

By 1 ft of sea level rise, and without any adaptation measures, the typical summer dry sand beach could be reduced by 20%. Beach narrowing will be experienced most acutely south of 12th Avenue where typical beach widths are much narrower.

The areas with the greatest exposure to erosion include the armored cliffs between 8th Avenue and 11th Avenue and the unarmored cliffs around 12th Avenue. As erosion accelerates, this exposes the Scenic Road roadway to erosion in six probable locations between 8th Avenue and 12th Avenue.

A wastewater force main located under the Scenic Road walkway near Martin Way is likely exposed to erosion, as well as a wastewater main under Scenic Road between 9th Avenue and 10th Avenue, and a sewer main under the dunes near 8th Avenue.

Wave uprush and overtopping of the bluff crest is expected to occur more frequently along the southern seawall between Santa Lucia Avenue and Martin Way, and between 8th Avenue and 11th Avenue.

2 ft of Sea Level Rise (2060–2080)

By 2 ft of sea level rise, and without any adaptation measures, the typical summer dry sand beach could be reduced by 40%, and a loss of lateral beach access to areas south of the 12th Avenue headland may occur in the summer. The coastal erosion hazard modeling indicates that erosion rates will begin to accelerate as coastal armoring is more likely to be overtopped by higher levels of wave splash and wave run up due to elevated water levels. Many areas behind the coastal armor have erosion hazard distances projected to be between 20 to 40 ft. Nearly the entire length of Scenic Road would then be exposed to erosion, including most of the underground water and wastewater infrastructure. By 2 ft of sea level rise, a water main under Scenic Road between 8th Avenue and 10th Avenue may become exposed. In the without armoring scenario, four homes between 9th and 12th Avenues are potentially exposed to erosion.

Wave splash and overtopping of the bluff crest are expected to be more severe between 9th and 10th avenues and may now be experienced between 12th to 13th avenues. In a without armoring scenario, four oceanfront homes would be exposed to erosion.

4 ft of Sea Level Rise (2080–2100+)

By 4 ft of sea level rise, and without implementation of any adaptation measures, the typical summer dry sand beach could be reduced by 80%, and only two small pockets of beach are projected to remain, one 1.5-acre pocket beach around 8th Avenue stairs, and one 1.5-acre pocket beach around 11th Avenue stairs.

Some of the highest erosion distances are projected between 10th and 12th Avenue, where a combination of factors related to wave exposure and local geology[4] yield projections of retreat up to 150 ft.

Between 2 and 4 ft of sea level rise, 42 oceanfront homes along Scenic Road may be exposed to erosion hazards. In the without armoring scenario, 53 homes, for a total of 57, are potentially exposed to erosion. Coastal erosion may threaten the wastewater and water laterals, as well as other utilities that connect with these homes. One additional water main location under Scenic Road south of 13th Avenue could become exposed to erosion, and one additional sewer force main location could become exposed to erosion near 8th Avenue.

Wave uprush and overtopping the bluff crest is expected to be more severe between 9th Avenue and 10th Avenue and may now be experienced at the higher cliffs by 12th Avenue. Along the lower cliffs between Santa Lucia Avenue and Martin Way, and north of 10th Avenue, wave splash above the bluff crest could exceed 5 ft turning that overtopping into a green water wave with more erosion potential.

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[4] The Johnson (1983) study noted that this area may be part of an old fault zone which has more shattered and weakened the rock

Section 2 Central Beach—Private Property Area from Del Mar Parking Lot to 8th Avenue

The central beach extends alongshore for approximately 0.2 mile and is characterized by densely vegetated dunes known as the Del Mar Dunes, which are home to dune scrub habitat and the black legless lizard, a species of concern (City of Carmel 2010). Atop the rear dune are private homes. Although no riprap armoring is visible, armoring is mapped in the City’s Shoreline Management Plan (2004) under the dunes at 8th Avenue. The sandstone bedrock is overlayed by dunes throughout this section, and it is assumed that the contact elevation between the sandstone bedrock and the sand and terrace soils is lower in the south and rises in the north around the Del Mar parking lot. Two coastal access sand ramps are located in this section. The intention of sand ramps is to provide coastal access and allow for access for those with limited mobility.

Section 2 Vulnerabilities

Current Vulnerabilities

Dune erosion was observed in this area during the winter storms of 2022-23 (Figure 22). The Johnson (1983) study notes that the dunes near 8th Avenue eroded 30 ft and formed a 14 ft-high scarp during the 1982-83 El Niño winter. Dune erosion hazards between 0 and 1 ft of sea level rise are projected to cause erosion of 30 to 40 ft in this area, corresponding with the severe winter storm erosion observed in the Johnson study.

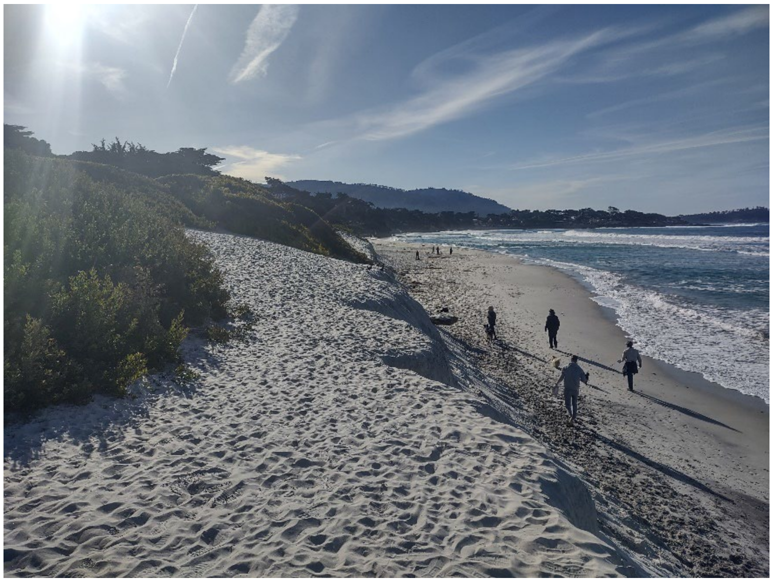

Figure 22. A view looking south over the Del Mar Dunes. A dune scarp is evident along the sand ramp and the dunes. January 2023.

This shoreline section has less immediate bluff-top development than other areas of the City and faces fewer immediate vulnerabilities for the oceanfront homes due to wider setback distances. However, dune erosion and wave flooding could threaten the private coastal accessways, as well as the two coastal access sand ramps south of the Del Mar parking lot and the stairway at 8th Avenue. In addition, the City's stormwater drainage system is vulnerable to dune erosion, and this section also contains private stormwater drain pipes that are exposed to erosion (Figure 23).

Figure 23. Stormwater drain near 8th Avenue fronted by an eroded scarp following winter storms in 2023. Note the riprap boulder on the bottom right.

A gravity sewer line runs from the Del Mar Parking lot to 8th Avenue in front of the oceanfront homes along Scenic Road. This sewer line is located just inland of the dune crest and may be vulnerable to erosion. The depth and condition of the sewer line is unknown; however, exposure and potential failure could cause untreated wastewater to enter nearby homes, and or cause environmental harm to the nearby dune, beach, and ocean habitats.

1 ft of Sea Level Rise (2045–2060)

The foredune area is vulnerable to erosion, and this study projects up to 40 ft of recession with 1 ft of sea level rise. The sand ramps found in this section and Section 3 (North

Dunes) are constructed of bulldozed sand and buried drift logs (Shonman and D'Ambrosio 2003). With accelerating sea level rise, erosion scarping may become more frequent occurrences and the integrity of the sand ramps may be at risk as erosion threatens to expose the buried drift log core.

2 ft of Sea Level Rise (2060–2080)

By 2 ft of sea level rise, and without any adaptation measures, the dune erosion process may shift toward cliff erosion processes as the foredune retreats inland and contact with the underlying cemented beach deposits and sandstone occurs. The threat of coastal storm waves overtopping the dunes and threatening the homes along the backdune remains unlikely. By 8th Avenue, a wastewater lift station located at ~24.5 ft may be exposed to storm wave flooding (Figure 24). A sewer main under the dunes between 7th Avenue and 8th Avenue could be exposed to dune erosion although the condition of the underlying revetment is not well understood presently.

Figure 24. Wastewater lift station near 8th Avenue.

4 ft of Sea Level Rise (2080–2100+)

By 4 ft of sea level rise, and without any adaptation measures, a collection of three homes around Scenic Road and 8th Avenue are exposed to erosion. Under a more severe erosion scenario (worst case), an additional five homes, for a total of eight, could be threatened by erosion between 8th Avenue and Ocean Avenue.

Section 3 North Dunes Area from 4th Avenue to Del Mar Parking Lot

The North Dunes section is a mostly natural, unarmored area that provides numerous recreational opportunities for the public. The section is 0.1 mile long and begins at the public access stairway at 4th Avenue in the north end and extends to the Del Mar parking lot to the south. The northern half of this shoreline section is characterized by a heavily vegetated cliff and bluff. A concrete stormwater discharge outfall is located just south of the 4th Avenue coastal access stairway. The remainder of this section is more open, with clusters of vegetated dunes and trees that extend back to San Antonio Avenue, nearly 1,000 ft from the swash zone. This section is home to a range of dune habitats, including Tidestrom's lupine, a federally and state-listed endangered plant species, and the California black legless lizard, a species of special concern in the state (City of Carmel 2010). The southern portion of this section has a heavily used public bathroom, four popular sand volleyball courts, and a bluff-top viewing platform.

Section 3 Vulnerabilities

Current Vulnerabilities

The bluff-top viewing platform at Ocean Avenue is vulnerable to dune erosion, as is the coastal access stairway at 4th Avenue. A stormwater outfall and seawall just south of 4th Ave is likely exposed to erosion. The Task 1 Coastal Protection Assessment identified this seawall as being a high priority for repair.

Figure 25. Seawall and outfall just south of the 4th Avenue Stairway.

1 ft of Sea Level Rise (2045–2060)

This dune backed shoreline is susceptible to significant dune erosion, and this study projects between 15 and 30 ft of recession with 1 ft of sea level rise, and 0.18 acre of North Dunes Habitat area exposed to erosion. Large storm events could cause additional dune erosion and scarping. Coastal access at the northern sand ramp could be impacted unless a consistent supply of sand is maintained.

2 ft of Sea Level Rise (2060–2080)

By 2 ft of sea level rise, and without any adaptation measures, this dune-backed area may transform into a cliff-backed shoreline restricting access to the beach. An additional 0.33 acre of dune habitat would be exposed to erosion, for a total of 0.52 acre.

4 ft of Sea Level Rise (2080–2100+)

By 4 ft of sea level rise, and without any adaptation measures, an additional 0.64 acre of dune habitat is exposed to erosion, for a total of 1.16 acres.

The Del Mar parking lot could be exposed to coastal erosion. In the unarmored and worst-case erosion scenario, the public restroom and the beach volleyball courts are also likely exposed to erosion.

Two water storage tanks located near the Del Mar parking lot and may also be exposed to erosion. While the exact spatial locations were not available, maps referenced in the Shoreline Management Plan (2003) show that both likely fall within the erosion hazard zone.

With no additional adaptation implementation, this is one of the last areas of Carmel Beach that can expect to maintain a dry sand beach with up to 5 ft of sea level rise.

Section 4 North Beach—Private Properties from Pescadero Canyon to 4th Avenue

The North Beach is a 400-ft stretch of coast that makes up the very northern portion of the City Beach study area and consists of private properties on top of the bluffs. The bluff increases in elevation from about 20 ft near to Pescadero Canyon to approximately 50 ft just north of the 4th Avenue stairway. The upland area of this section is composed of just two oceanfront private parcels. The northern parcel maintains its own seawall and the southern parcel is unarmored.

Section 4 Vulnerabilities

Current Vulnerabilities

A private seawall (Figure 26) is vulnerable to wave attack and overtopping.

Figure 26. Privately owned seawall near Pescadero Canyon.

1 ft of Sea Level Rise (2045–2060)

In the armored erosion scenario, wave uprush and splash along this seawall are above the top of the armor height, yielding an erosion distance of 30 ft by 1 ft of sea level rise. Erosion distances are only projected to be just over 20 ft along the higher unarmored property due to the higher cliff and bluff terrace contact elevation.

2 ft of Sea Level Rise (2060–2080)

By 2 ft of sea level rise, and in a without armoring scenario, one home is potentially vulnerable to erosion.

4 ft of Sea Level Rise (2080–2100+)

By 4 ft of sea level rise, and in a with armoring scenario, both homes are potentially vulnerable to coastal erosion.

With no adaptation implementation, this is one of the last areas of Carmel Beach that can expect to maintain a dry sand beach with up to 5 ft of sea level rise.

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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
dunes	Areas where wave action and onshore winds have led to sand deposition, located landward of the beach
erosion (coastal)	Can refer to either beach narrowing or 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.
FEMA	Federal Emergency Management Agency
green water	Occurs when waves break onto or over the coastal armoring and the overtopping volume is relatively continuous
NAVD 88	North American Vertical Datum of 1988 (NAVD 88). The vertical control datum used for surveying.
NOAA	National Oceanic and Atmospheric Administration
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
splash	Occurs when waves break seaward of the coastal armoring, or where the armoring is high in relation to the wave height, and overtopping is a concentrated stream of water droplets

toe of the cliff	Location where the dry sand beach meets the base of the cliff
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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APPENDIX A. SECTOR VULNERABILITY FINDINGS

This section provides a series of tables indicating the extent of hazard impacts to land Use and structures, roads and parking, and utilities and infrastructure. Findings are organized by the two erosion hazard zone scenarios, one for a **with** coastal armoring where erosion rates are reduced, and one for a **without** coastal armoring scenario, where erosion is modeled without consideration of armoring. A best estimate on future erosion rates are reported for both. Both scenarios are reported using the best estimate for

Land Use and Structures

Parcels

Reported as noncumulative area across horizons

Parcels	**With Coastal Armoring Scenario**				
	Existing (Bluff and Beach)	SLR (ft)			
Parcel Type		**1**	**2**	**4**	**Total**
Public (sq ft)	290,913	42,358	45,179	43,338	421,787
Residential (sq ft)	20,764	4,713	15,397	152,622	193,496

Parcels	**Without Coastal Armoring Scenario**				
	Existing (Bluff and Beach)	SLR (ft)			
Parcel Type		**1**	**2**	**4**	**Total**
Public (sq ft)	290,913	49,645	39,009	42,243	421,809
Residential (sq ft)	20,764	4,713	26,206	201,011	252,694

Reported as the number of parcels at the first instance of contact with the hazard zone

Parcels	**With Coastal Armoring Scenario**				
	Existing (Bluff and Beach)	SLR (ft)			
Parcel Type		**1**	**2**	**4**	**Total**
Public	9				9
Residential	3		29	40	72

Parcels	**Without Coastal Armoring Scenario**				
	Existing (Bluff and Beach)	SLR (ft)			
Parcel Type		**1**	**2**	**4**	**Total**
Public	9				9
Residential	3		38	33	74

Buildings

Reported as the number of structures at the first instance of contact with the erosion hazard zone

Buildings	**With Coastal Armoring Scenario**			
	SLR (ft)			
Building Type	**1**	**2**	**4**	**Total**
Public Restroom	1			1
Residences*		0	43	44

Buildings	**Without Coastal Armoring Scenario**			
	SLR (ft)			
Building Type	**1**	**2**	**4**	**Total**
Public Restroom	1			1
Residences*		5	54	59

**Excludes garages and the wastewater lift station structure (included in the wastewater section building)*

Roads

Roads and Parking	**With Coastal Armoring Scenario**		
	SLR (ft)		
	1	**2**	**4**
Scenic Road (ft)*	702	3,113	3,463
Ocean Ave Parking Lot (sq ft)*			2,149
Scenic Road (sq ft)*	2,864	56,877	96,067

Roads and Parking	**Without Coastal Armoring Scenario**		
	SLR (ft)		
	1	**2**	**4**
Scenic Road (ft)*	1,497	3,226	3,475
Ocean Ave Parking Lot (sq ft)			2,149
Scenic Road (sq ft)*	6,432	70,762	98,517

** Lengths and areas are cumulative across sea level rise horizons. Length of Scenic Road is measured from the oceanfront curb*

Utilities and Infrastructure

Stormwater

Stormwater	**With Coastal Armoring Scenario**				
	Existing (Bluff)	SLR (ft)			**Total**
		1	**2**	**4**	
CDS Separator	2			1	3
Inlets	1	3	10	11	25
Junctions	1		1		2
Manholes	3		2	2	7
Outfalls	17	2		2	21
Culverts		1	1	1	3
Drains (ft)*	1,391	1,888	2,891	3,581	

Stormwater	**Without Coastal Armoring Scenario**				
	Existing (Bluff)	SLR (ft)			**Total**
		1	**2**	**4**	
CDS Separator	2			1	3
Inlets	1	7	11	7	26
Junctions	1		1		2
Manholes	3		2	2	7
Outfalls	17	2		2	21
Culverts		1	1	1	3
Drains (ft)*	1,391	2,034	2,940	3,590	

**Lengths are cumulative across sea level rise horizons. Does not include private stormwater infrastructure.*

Wastewater

Wastewater Infrastructure	**With Coastal Armoring Scenario**			
	SLR			
	1	**2**	**4**	**Total**
DCO (cleanout)	1			1
Manhole		5	4	9
Pump Station			1	1
Sewer Main (ft)*	381	2,155	4,164	
Forced Main (ft)*	51	479	805	

Wastewater Infrastructure	**Without Coastal Armoring Scenario**			
	SLR			
	1	**2**	**4**	**Total**
DCO (cleanout)	1			1
Manhole	1	4	5	10
Pump Station			1	1
Sewer Main (ft)*	406	2,564	4,390	
Forced Main (ft)*	338	553	805	

**Lengths are cumulative across sea level rise horizons*

Water

Water	**With Coastal Armoring Scenario**		
	SLR (ft)		
	1	**2**	**4**
Hydrants	1	0	0
Water Main (ft)*	0	439	1,870

Water	**Without Coastal Armoring Scenario**		
	SLR (ft)		
	1	**2**	**4**
Hydrants	2	0	2
Water Main (ft)*	0	737	2,072

**Lengths are cumulative across sea level rise horizons. Does not include two water storage tanks located near the Del Mar Parking Lot. Water irrigation pipes are not included*