FINAL

Sea Level Rise Risk, Hazards, and Vulnerability Assessment, City of Manhattan Beach

Prepared for
City of Manhattan Beach

May 2021

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Photo by Juliette Finzi Hart

CHAPTER 1

Introduction

Future sea level rise is expected to create a permanent rise in ocean water levels that would shift the water's edge landward. If no action is taken, higher water levels would increase erosion of the beach, cause a loss of sand, and result in a narrower beach. Additionally, the combination of higher ocean water levels and beach erosion could result in greater flooding and damage during coastal storms.

The City of Manhattan Beach is updating its Local Coastal Program (LCP), a planning document that regulates development in the City's coastal zone and establishes a long-range vision for the community. The California Coastal Act, passed in 1976, provides for coastal jurisdictions to adopt an LCP to ensure local implementation of the resource-protection policies of Coastal Act. The City of Manhattan Beach's current LCP Land Use Plan (LUP) was certified by the California Coastal Commission (CCC) in 1981 and amended in 1992-1994. In 2019, this study was commissioned as part of the City's comprehensive update to its LCP to address anticipated sea level rise and its effects on coastal erosion and flooding. The first phase of work includes this Sea Level Rise Risk, Hazards, and Vulnerability Assessment (Vulnerability Assessment) that highlights existing conditions and future vulnerability of the City of Manhattan Beach to projected sea level rise, coastal flooding, and erosion. The findings of this Vulnerability Assessment will be used to develop a range of potential adaptation strategies that address the potential future impacts from sea level rise and storms. The second phase of work will include development and analysis of a sea level rise adaptation plan and policies that the City will ultimately include in the Climate Action and Adaptation Plan (CAAP), Local Hazards Mitigation Plan, and LCP-LUP update.

This Vulnerability Assessment is a planning-level assessment that will inform the development of the CAAP and related LCP-LUP policies to be developed in the second project phase. The Vulnerability Assessment utilizes available coastal hazard mapping products and site-specific analysis discussed in Section 2.3 and Chapter 3. This Vulnerability Assessment relies on reasonable assumptions and engineering judgement to simplify the analysis where needed. It builds on previous studies, including the prior regional Vulnerability Assessment developed by the South Bay Cities Council of Governments (2019) and the Los Angeles County Public Beach Facilities Sea-Level Rise Vulnerability Assessment (Noble Consultants – G.E.C. Inc. 2016).

1.1 Study Area

The Vulnerability Assessment study area consists of Manhattan Beach's 2.1-mile shoreline, extending from 45th Street to 1st Street. The geography in the study area consists of low-lying sandy beaches and backshore areas[1].

The beach is 300 to over 400 feet wide in places; however, it has not always been so wide. In 1938, Dockweiler Beach was nourished with approximately 1.8 million cubic yards of sand from the construction of the Hyperion Sewage Treatment Plant on sand dunes. Multiple beach nourishments followed, adding over 30 million cubic yards of sand to upcoast beaches, including Dockweiler Beach, Venice Beach, and El Segundo. Sand nourishment of upcoast beaches combined with a net southward sediment transport caused by waves and currents towards Manhattan Beach deposited enough sand to widen the beach by approximately 250 feet from the 1940s to the 1970s.The construction of numerous breakwaters, groins, and jetties in Santa Monica Bay has reduced sediment transport. Specifically, the groin at El Segundo Marine Terminal reduces sediment transport southward towards Manhattan Beach, limiting deposition on the beach. But King Harbor at Redondo Beach, south of Manhattan Beach, limits sediment transport from leaving the city's shoreline, where it would otherwise be lost to the Redondo Submarine Canyon. This allows Manhattan Beach to retain sand on the beach.

Today, Manhattan Beach's coastline is largely urbanized, developed by residential and commercial properties. Much of this development is located on what was once large sand dunes. There are some sand dunes remaining, including at Sand Dune Park at the northern end of Manhattan Beach, and planning for the restoration of dunes north and south of Bruce's Beach with Los Angeles County Beaches and Harbors and The Bay Foundation will help improve this habitat. Other habitats include sandy beach, which support unique ecological communities, including invertebrate communities, shorebirds, and pinnipeds, and provides essential ecosystem functions such as food webs that are prey for birds and fish. Two species of concern use the sandy beach: The California Grunion uses the beach for spawning and the Western Snowy Plover overwinters at the beach (Ryan et al. 2014).

Other important coastal features include the 928-foot long Manhattan Beach Pier (Pier). The Pier was built in 1920 and is a state historic landmark, as it is the oldest concrete pier on the West Coast (Manhattan Beach Historical Society). Manhattan Beach coastal amenities also include the Marvin Braude Bike Trail, The Strand pedestrian walkway, parking, restrooms, lifeguard towers, beach volleyball courts, stormwater outfalls, and concession stands.

[1] Backshore areas are areas of a beach that extend inland from the limit of high water to the extreme inland limits of the beach, including dunes that are in the coastal floodplain now or may be in the future based on erosion and sea level rise. Backshore areas are typically only affected by waves during exceptional high tides or severe storms.

1.2 Key Terms and Definitions

The following terms are used throughout the document based on the definitions included in this section:

Coastal flooding refers to flooding due to waves and high water levels originating from the ocean.

Coastal storm events impact the shoreline through higher water levels due to storm surge, large waves, and/or elevated river flows, all of which are commonly associated with low-pressure weather systems. Planning and analysis often occurs for the "100-year storm," which is the storm estimated to have a 1% chance of occurring in any given year.

Coastal storm flooding refers to coastal flooding that occurs during coastal storm events.

Tidal inundation refers to coastal flooding during regular high tides under non-storm conditions.

Coastal erosion refers to loss of sandy beaches, dunes, and the low-lying backshore along the shoreline through natural processes such as waves, wind, or tides.

Rainfall events impact the City through flooding originating from precipitation.

1.3 Existing Coastal Hazards

Manhattan Beach is currently vulnerable to storm flooding, wave impact, and erosion. In the past, extreme coastal flood events have caused significant damage along the coastline. This section describes significant extreme coastal events that have occurred since the 1980s, as well as recent King Tides and erosion events. Events are characterized based on news and technical reports. In the future, coastal impacts from these types of events will increase in intensity and frequency due to sea level rise and climate change.

1.3.1 Coastal Storms

Manhattan Beach has experienced numerous coastal storm events over the past few decades that caused flooding and erosion damage. In the late fall and winter of 1982/1983, California experienced an El Niño that produced significant precipitation, strong winds, and high surf along southern California. The storms damaged coastal structures and eroded beaches. Waves reached the Pier deck and damaged the iconic Pier (**Figure 1-1**). The Pier deck, Roundhouse Aquarium, and lifeguard station at the beginning of the Pier were completely replaced (Manhattan Beach Historical Society). Other notable El Nino seasons occurred in 1998 and 2010. In 2017, surf reached 15 feet at El Porto Beach in North Manhattan Beach (Daily Breeze 2017).

Source: Manhattan Beach Historical Society

Figure 1-1: Photos from the 1982/83 El Nino showing the huge waves at the Manhattan Beach Pier

1.3.2 King Tides

King Tides refer to the highest tides of the year, which occur naturally and predictably when the gravitational pull of the sun and moon align. King Tides provide a preview of future conditions with sea level rise. The California King Tides Project[2] is an initiative that has documented recent King Tides around the country. As a part of a larger statewide effort to document King Tides and a changing coastline, in 2020, the University of Southern California (USC) Sea Grant[3] hosted two Urban Tides Beach Walk events in Manhattan Beach as part of the Urban Tides Project. Photos of King Tides captured by the public, such as those taken at the Urban Tides Beach Walk, can be shared with the California King Tides Project and uploaded to its California King Tides Map. The goal of these ongoing projects is to create a comprehensive record of coastal change and sea level rise, and demonstrate to the public what the coast will look like during average daily tides in the coming decades. **Figures 1-2** and **1-3** below show King Tide conditions in 2020.

[2] Learn about the California King Tides Project at https://www.coastal.ca.gov/kingtides/learn.html

[3] Learn about USC Sea Grant at https://dornsife.usc.edu/uscseagrant/directors-welcome/

Source: The Beach Reporter 2020

Figure 1-2: Wave watchers attend an Urban Tides Beach Walk to view and document a King Tide along Manhattan Beach, 2020

Source: Juliette Finzi Hart 2019

Figure 1-3: King Tide Combined with Stormwater Outflow Flood under the Manhattan Beach Municipal Pier on January 17, 2019

1.3.3 Existing Adaptation Strategies

Some adaptation strategies have already been implemented in Manhattan Beach to reduce vulnerabilities to coastal hazards along the City's shoreline. There are also other adaptation strategies used by adjacent jurisdictions, such as building seasonal sand berms, beach nourishment, and wetlands restoration. A full suite of potential adaptation strategies will be presented in the Adaptation Plan.

Shoreline Armoring

Approximately 23% of the Manhattan Beach coastline is protected by coastal armoring structures such as rock revetments (north end of El Porto Beach, **Figure 1-4**) and concrete sea walls (El Porto Beach and near the Pier, **Figures 1-5** and **1-6**). While sea walls and revetments provide protection to existing shoreline development, these structures can contribute to beach erosion and accelerate beach loss. Seawall and revetment construction is regulated by the Coastal Act (Section 30235) and the policies and regulations of the Manhattan Beach LCP-LUP. The permit application process for shoreline protection devices is complex and lengthy.

An inventory of shoreline protective devices was developed in 2005 by NOAA for the entire California coastline, which ESA updated for this study by interpreting aerial imagery and oblique shoreline photography from the California Coastal Records project[4]. **Figure 1-7** shows the location of existing shoreline protective devices in Manhattan Beach.

Source: Eric Hecht, February 2020, Google Streetview

Figure 1-4: Existing Rock Revetment at North End of El Porto Beach

Source: Google Streetview

Figure 1-5: Existing Seawall at El Porto Beach

[4] Access the CA Coastal Records project at https://www.californiacoastline.org/

Source: Google Streetview, Mosa Al Sadiq, April 2019

Figure 1-6: Existing Seawall at the Pier

SOURCE: California Coastal Commission 2015

Figure 1-7
Shoreline Armoring Locations

ESA

Beach Dune Restoration

Dune restoration is recognized as a natural way of mitigating backshore erosion, as well as maintaining a wider beach by creating an additional source of sand at the back of the beach, while increasing local sand retention. When dunes are allowed to form and create natural features, away from recreation areas, they provide a cost-effective buffer of protection from sea level rise and storm erosion. The Manhattan Beach Dune Restoration Project[5], led by The Bay Foundation in partnership with Los Angeles County Department of Beaches and Harbors, City of Manhattan Beach, and California State Coastal Conservancy, is currently finalizing the planning stage for restoring dunes at Bruce's Beach (as of January 2021). The project, expected to be implemented beginning in fall 2021, will enhance and expand approximately three acres of existing dunes from 36th Street to 23rd Street. The goal of this dune restoration project is to increase the resiliency of the beach through the restoration of sandy beach and foredune habitat, implement nature-based protection measures against sea level rise and coastal storms, and increase engagement of the community through enhanced beach experiences. The restoration project will include removing non-native plants and seeding and planting native vegetation, which will increase sand retention while building dunes over time. The project will also include strategic installation of various types of fencing and installation of educational features like interpretive signage. This demonstration site will serve as a model for the region, showing that heavy recreational use of beaches and meaningful habitat restoration are not incompatible goals.

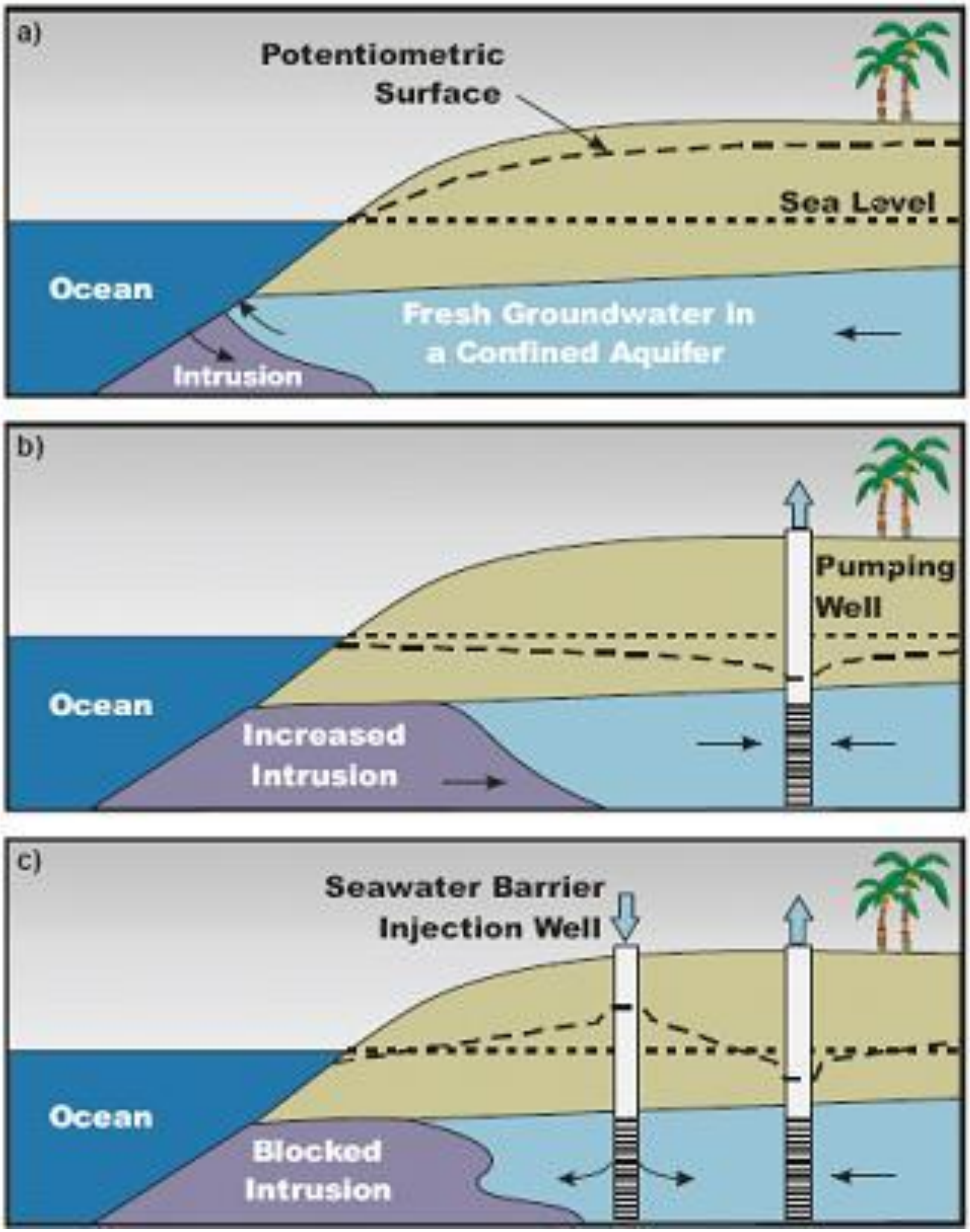
Groundwater Injection

Manhattan Beach has two active groundwater wells used for drinking water: Well 11A and Well 15. Well 11A is located on the southwest corner of Manhattan Beach Boulevard and Green Lane and has a design capacity of 1,800 gallons per minute (AKM Consulting 2010). Well 15 is located on the southwest corner of Manhattan Beach and Vail Avenue and has a design capacity of 1,600 gallons per minute (AKM Consulting 2010). Both wells pull from the deep aquifer rather than the shallow groundwater table.

As a result of pumping out large amounts of fresh groundwater along the coast, salt water from the ocean began to intrude into the spaces left by removal of the groundwater, moving salt water into the groundwater basin in the 1940s (Figure 1-8). In the early 1950s, the West Coast Basin Barrier Project (WCBBP) was constructed to prevent ocean water from intruding into the underlying aquifers of the West Coast Groundwater Basin, which spans from just south of Ballona Creek through Long Beach. As shown in Figure 1-8, the WCBBP injects mostly recycled water into the groundwater basin to push salt water back towards the ocean. In Manhattan Beach, the injection wells are located between Valley Drive and North Ardmore Avenue. The WCBBP is operated by the West Basin Municipal Water District.

As sea levels rise, the higher water levels will drive more salt water into the groundwater table, moving salt water further inland and increasing groundwater levels. If salt water moves too far inland, it could impact the water quality of the water pumped out of the wells. To avoid this, increased injection pumping could be required to maintain the water supply.

[5] https://www.santamonicabay.org/explore/beaches-dunes-bluffs/beach-restoration/manhattan-beach-dune-restoration-project/manhattan-beach-dune-restoration-project-faq/



Source: West Basin Municipal Water District

Figure 1-8: Salt Water Intrusion and Barrier Wells

CHAPTER 2

Sea level Rise Projections

Information on current science and state guidance on sea level rise is discussed in the following sections.

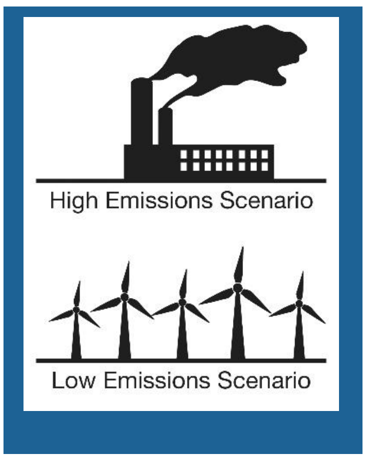
2.1 Sea Level Rise

The two major climate change processes that result in sea level rise are melting of land-based ice (e.g., glaciers and ice sheets) and thermal expansion caused by warming of the ocean (i.e., warmer water molecules take up more space than cooler water molecules). Additionally, vertical land motion can impact the relative amount of sea level rise at the coast. For example, if the land is moving up due to plate tectonics or other geological processes, sea level rise will appear to be less than in other places where the land is stable or moving down, (e.g., like the land subsidence in coastal Louisiana).

Sea levels at the Santa Monica Pier tide gage, which is the closest NOAA tide gauge to Manhattan Beach, have increased by 0.51 feet in the last 100 years (see plot at top of page; NOAA Tides and Currents Station #9410840). However, the rate of sea level rise is expected to increase over time due to the effects of climate change and global warming.

Sea level rise not only increases typical tidal water levels, but it also raises storm water levels. The flood extent due to storm surge and waves is made worse by sea level rise and flooding can occur further inland. Additionally, higher sea levels combined with riverine flooding or water coming from a stormwater outfall can increase flooding by backing up water into the channel or pipe.

2.2 Regional Sea Level Rise Projections[6]



In 2018, the California Ocean Protection Council (CA OPC) updated the *State of California Sea Level Rise Guidance* (CA OPC 2018), which includes projections for sea level rise at various locations along the coast of California through 2150. The guidance is based on the science update prepared by the CA OPC and the California Natural Resources Agency, in collaboration with the Governor's Office of Planning and Research, the California Energy Commission, and the California Ocean Science Trust (Griggs et al. 2017). The CA OPC Guidance presents different sea level rise values based on two global greenhouse gas emissions scenarios:

High Emissions Scenario – This scenario assumes a future where there are no significant local or global efforts to limit or reduce emissions. This scenario assumes "high population and relatively slow income growth with modest rates of technological change and energy intensity improvements, leading in the long-term to high energy demand and GHG emissions" (Riahi et. al 2011).

Low Emissions Scenario – This scenario assumes more aggressive emissions reduction actions corresponding to the aspirational goals of the 2015 Paris Agreement, which calls for limiting mean global warming to less than 2 degrees Celsius and achieving net-zero greenhouse gas emissions in the second half of the century. This scenario is considered challenging to achieve and would include updated climate policies, concerted action by all countries, and a shift to a lower emissions service and information economy. The low emissions scenario is not possible through 2050 based on the current global emissions trajectory.

The 2018 CA OPC Guidance provides a range of probabilistic projections of sea level rise, which was an update specifically designed to help inform decision-makers. However, these projections may underestimate the likelihood of extreme sea level rise, particularly under high-emissions scenarios, so an extreme scenario, called the H++ scenario, was also included in the guidance. The H++ scenario assumes rapid ice sheet loss on Antarctica, which could drive rates of sea level rise 30-40 times faster than the sea level rise experienced over the last century. The updated guidance also identified different risk aversion

[6] A sea level rise projection is a scientific estimate of how much sea level rise is expected to occur over time based on varying assumptions.

projections that correspond to different levels of risk tolerance. These levels are represented as low, medium-high, and extreme risk aversion:

- The low risk aversion projection is appropriate for adaptive, lower consequence projects (e.g., unpaved coastal trail).
- The medium-high risk aversion projection is appropriate as a precautionary projection that can be used for less adaptive, more vulnerable projects or populations that will experience medium to high consequences as a result of underestimating sea level rise (e.g., coastal housing development).
- The extreme risk aversion projection is appropriate for high consequence projects with little to no adaptive capacity and which could have considerable public health, public safety, or environmental impacts (e.g., coastal power plant, wastewater treatment plant, etc.).

Table 2-1 shows the CA OPC 2018 projections for Santa Monica Bay with the risk scenarios identified in the blue boxes. Available sea level rise projections use the year 2000 as a baseline. Since 2000, sea levels are estimated to have increased by just over an inch[7], but sea level rise is expected to accelerate in the coming decades.

While the CA OPC Guidance provides projections through 2150, it is important to note that sea level rise is expected to continue for centuries, because the earth's climate, cryosphere[8], and ocean systems will require time to respond to the emissions that have already been released to the atmosphere. Although sea level rise is typically presented as a range in the amount of sea level rise that will occur by a certain date (e.g., 1-2 feet of sea level rise by 2050), it can also be presented as a range of time during which a certain amount of sea level rise is projected to occur (e.g., 1.5 feet of sea level rise between 2040 and 2070). Even if emissions are reduced to levels consistent with the low-emissions-based projections, sea level will continue to rise to higher levels, just at a later date.

[7] This estimate is based on applying the rate of historic sea-level rise of 1.55 mm/yr published by NOAA Tides and Currents at Station #9410840 over a 20-year period (2000 to 2020).

[8] The cryosphere is the portions of the Earth's surface where water is in solid form, like glaciers and ice caps.

Table 2-1: Sea Level Rise Projections for Santa Monica Bay

		Probabilistic Projections (in feet) (based on Kopp et al. 2014)					H++ scenario (Sweet et al. 2017) *Single scenario
		MEDIAN	LIKELY RANGE		1-IN-20 CHANCE	1-IN-200 CHANCE	
		50% probability sea-level rise meets or exceeds...	66% probability sea-level rise is between...		5% probability sea-level rise meets or exceeds...	0.5% probability sea-level rise meets or exceeds...	
				Low Risk Aversion		Medium - High Risk Aversion	Extreme Risk Aversion
High emissions	2030	0.4	0.3 -	0.5	0.6	0.8	1
	2040	0.6	0.4 -	0.8	0.9	1.2	1.7
	2050	0.8	0.6 -	1.1	1.3	1.9	2.6
Low emissions	2060	0.9	0.6 -	1.2	1.5	2.3	
High emissions	2060	1.1	0.8 -	1.4	1.8	2.6	3.8
Low emissions	2070	1.0	0.7 -	1.4	1.9	3.0	
High emissions	2070	1.3	1.0 -	1.8	2.3	3.4	5.1
Low emissions	2080	1.2	0.8 -	1.7	2.3	3.8	
High emissions	2080	1.7	1.1 -	2.3	2.9	4.4	6.5
Low emissions	2090	1.3	0.8 -	2.0	2.7	4.6	
High emissions	2090	2.0	1.3 -	2.8	3.5	5.5	8.1
Low emissions	2100	1.5	0.9 -	2.3	3.1	5.5	
High emissions	2100	2.3	1.5 -	3.3	4.3	6.8	10.0
Low emissions	2110*	1.6	1.0 -	2.4	3.3	6.1	
High emissions	2110*	2.5	1.8 -	3.5	4.5	7.2	11.7
Low emissions	2120	1.7	1.0 -	2.7	3.8	7.3	
High emissions	2120	2.9	2.0 -	4.0	5.2	8.5	14.0
Low emissions	2130	1.9	1.1 -	3.0	4.2	8.3	
High emissions	2130	3.2	2.2 -	4.5	5.9	9.8	16.3
Low emissions	2140	2.0	1.1 -	3.2	4.7	9.4	
High emissions	2140	3.5	2.4 -	5.1	6.7	11.3	18.9
Low emissions	2150	2.2	1.1 -	3.6	5.3	10.8	
High emissions	2150	3.9	2.6 -	5.7	7.6	12.9	21.7

SOURCE: CA OPC 2018

2.3 State Planning Guidance

Flooding:

The Beach Reporter 2016

Wave runup:

Pepperdine Digital Archives

Erosion:

Kuhn and Shepard 1984
City of Oceanside

The CCC updated their *Sea Level Rise Policy Guidance* in 2018 (CCC 2018). The guidance recommends using the CA OPC sea level rise projections at various planning horizons to assess vulnerability and conduct adaptation planning. The guidance provides a step-by-step process for addressing sea level rise and adaptation planning in updated LCPs (CCC 2018).

State planning guidance calls for considering a range of scenarios (CA OPC 2018; CCC 2018) to bracket the range of likely impacts. Scenario-based analysis promotes the understanding of impacts from a range of potential outcomes and identifies the amount of sea level rise that would cause these impacts.

The CCC Guidance recommends that long-term, community-wide planning efforts evaluate, at a minimum, the "medium-high risk aversion" projection. The extreme risk aversion projection is to be used to evaluate critical facilities. As part of the CCC funding for this study, the City is required to consider both the medium-high and extreme risk aversion projections.

Additionally, Senate Bill 379 requires that Cities update the safety elements of their general plans to include climate adaptation and resiliency strategies. According to the Office of Planning and Research (OPR) General Plan Guidelines, jurisdictions must identify a set of adaptation and resilience goals, policies, and objectives, based on the information analyzed in the vulnerability assessment. The requirements of Senate Bill 379 have five distinct steps, including reviewing existing plans, conducting a vulnerability assessment, developing adaptation goals, creating implementation measures, and updating the safety element with adaptation and resilience considerations.

2.4 CoSMoS Modeling Scenarios

The Coastal Storm Modeling System (CoSMoS)[9] was developed by the United States Geologic Survey (USGS) with state funding for use in sea level rise planning. The interactive tool is available through the Our Coast Our Future platform (ourcoastourfuture.org, click 'flood map'). The modeling effort focused on evaluating flood hazards associated with sea level rise and various storm conditions, as well as shoreline and bluff erosion. Coastal hazards were mapped for the Manhattan Beach coastline at a high resolution with CoSMoS 3.0 in 2016. A total of 40 scenarios were run combining sea level rise and storm type: ten sea level rise amounts (0 to 2 meters at 0.25 meter increments and 5 meters) were modeled with four coastal storm conditions (100-year, 20-year, and 1-year events and no storm) and two management scenarios ("hold the line", where existing structures remain intact rather than erode, and "let it go", where no management actions are taken and erosion

[9] Details on the USGS CoSMoS model are accessible online at: https://www.usgs.gov/cosmos

progresses beyond existing structures). Model results can be viewed through the Our Coast Our Future platform linked above. Hazard modeling outputs include the extent of inundation, flooding, wave run-up, and long-term erosion (see photo box to the left). GIS data for these outputs were downloaded[10] for Manhattan Beach and processed for use in the vulnerability assessment.

[10] CoSMoS hazard maps are accessible online at: https://www.sciencebase.gov/catalog/item/5633fea2e4b048076347f1cf

CHAPTER 3

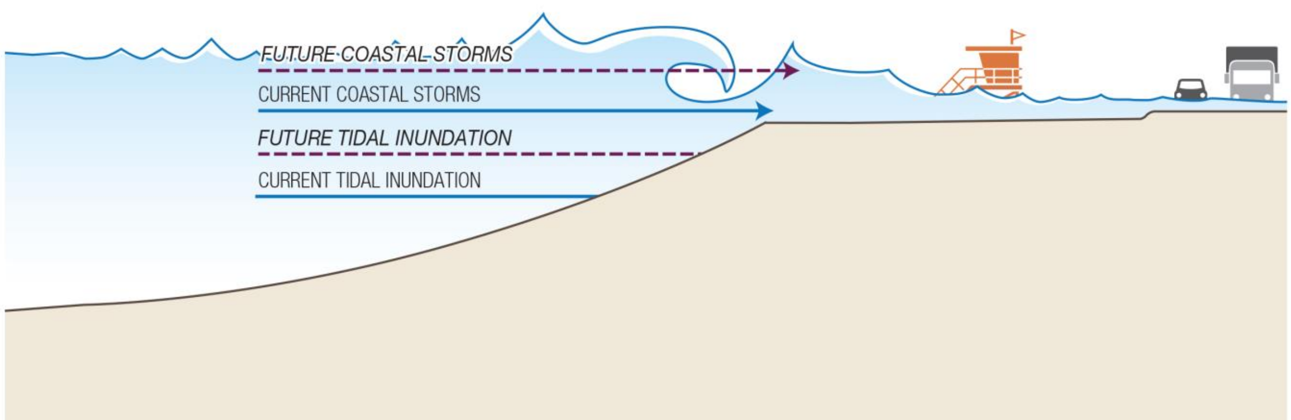
Potential Future Hazards

> *A small storm today may cause limited damage, but with higher sea levels in the future, the same storm event could potentially have a much larger impact.*

Future sea level rise is expected to create a permanent rise in ocean water levels that will shift the water's edge landward. Higher water levels will increase erosion of beaches and result in a narrower beach, if no action is taken. Additionally, the combination of higher ocean water levels and beach erosion would mean that coastal storms will potentially cause greater and more frequent flooding and damage, because reduced beach width is less effective at reducing wave energy, and waves positioned at a higher elevation allow for a deeper reach landward. For example, a small storm event under today's sea levels may not reach the backshore nor cause any damage, but with higher sea levels, the same event could potentially reach further inland and have a much larger impact. Higher water levels at the coast also impact the storm drain system during extreme rainfall events, by backing up water into the system or delaying drainage until low tide. Sea level rise can also increase groundwater levels and the salinity of groundwater, which can cause flooding during rain events or impact drinking water resources. This section identifies five future hazards: tidal inundation, storm flooding, extreme rainfall events, beach erosion, and groundwater hazards associated with sea level rise. This section also discusses the underlying data sets and assumptions associated with the processes for each hazard and methods used to map or analyze each hazard.

3.1 Tidal Inundation and Coastal Storm Flooding

Coastal storm flooding refers to potential impacts from a coastal storm that happens infrequently, whereas tidal inundation refers to the extents of regular tides that occur day-to-day (**Figure 3-1**). As sea levels rise, the extent of tidal inundation will gradually increase with infrequent, extreme events causing more dramatic flooding. These events include higher water levels due to storm surge and ocean waves and are commonly associated with low-pressure weather systems. For example, the probability of an extreme El Niño event occurring could increase from roughly once every 20 years to once every 10 years by 2100 (Cai et al. 2014, South Bay Cities Council of Governments 2019).



NOTE: Sea, tide, and storm surge levels are for illustrative purposes only and do not depict actual or projected levels.

Figure 3-1: Conceptual Shoreline Cross-Section Showing Tidal Inundation and Coastal Storm Flood Hazards

Coastal inundation and storm flooding and erosion results from the USGS CoSMoS model were used to determine potential impacts of sea level rise in Manhattan Beach for typical tides and extreme storm conditions. The USGS modeled and mapped future daily inundation and episodic coastal storm flooding extents for four storm scenarios:

- No flood (regular inundation from the average daily high tide)
- 1-year coastal storm flood event (on average occurs every year)
- 20-year coastal storm flood event (5% chance of occurring each year)
- 100-year coastal storm flood event (1% chance of occurring each year)

These four storm scenarios were analyzed with CoSMoS under ten sea level rise scenarios, including existing sea level:

- 0 meters (existing sea level)
- 0.25 meters
- 0.50 meters
- 0.75 meters
- 1.0 meters
- 1.25 meters
- 1.50 meters
- 1.75 meters
- 2.0 meters
- 5.0 meters

Five sea level rise scenarios, in addition to existing conditions, were mapped for Manhattan Beach (0, 0.75, 1.25, 1.75, 2.0, and 3.0 meters) for the “let it go” scenario where no management actions would be taken and erosion can progress beyond existing structures. These sea level scenarios were evaluated considering the “no flood” (i.e., typical tidal inundation) and “1% annual chance coastal storm flood” scenarios (100-year event). Note that the 3.0-meter sea level rise scenario was only modeled in CoSMoS for tidal inundation and not for any of the coastal storm events, so the 1% annual chance coastal storm flood event is not mapped for 3.0 meters of sea level rise.

The tidal inundation scenario was used to map areas where inundation is a regular event to depict how daily inundation could potentially change in the future with sea level rise (**Figures 3-2 and 3-3**). The 1% annual coastal flood event was chosen to represent the potential impacts from an extreme coastal storm. **Figures 3-4 and 3-5** show the maximum modeled flood extent (i.e., the upper range of the CoSMoS uncertainty bounds, which includes uncertainty due to vertical land motion changes, model performance and elevation measurements) to understand the full range of potential exposure. For context, FEMA flood mapping through the National Flood Insurance Program also provides coastal flooding extent and floodwater elevations for a 1% annual chance coastal storm event under current conditions without future sea level rise. FEMA does not model or map coastal storm events with sea level rise, so this Coastal Vulnerability Assessment does not use FEMA flood hazard data.


Figure 3-2
Tidal Inundation with Sea Level Rise in North Manhattan Beach
45th St
Rosecrans Ave
The Strand
Highland Ave
Marine Ave
N
W
E
S
Current Day
75 cm (2.5 ft) SLR
125 cm (4.1 ft) SLR
175 cm (5.7 ft) SLR
200 cm (6.6 ft) SLR
300 cm (9.8 ft) SLR (H++ proxy)
08/07/2019
Geographic Information System
CITY OF MANHATTAN BEACH

Figure 3-3
Tidal Inundation with Sea Level Rise in South Manhattan Beach

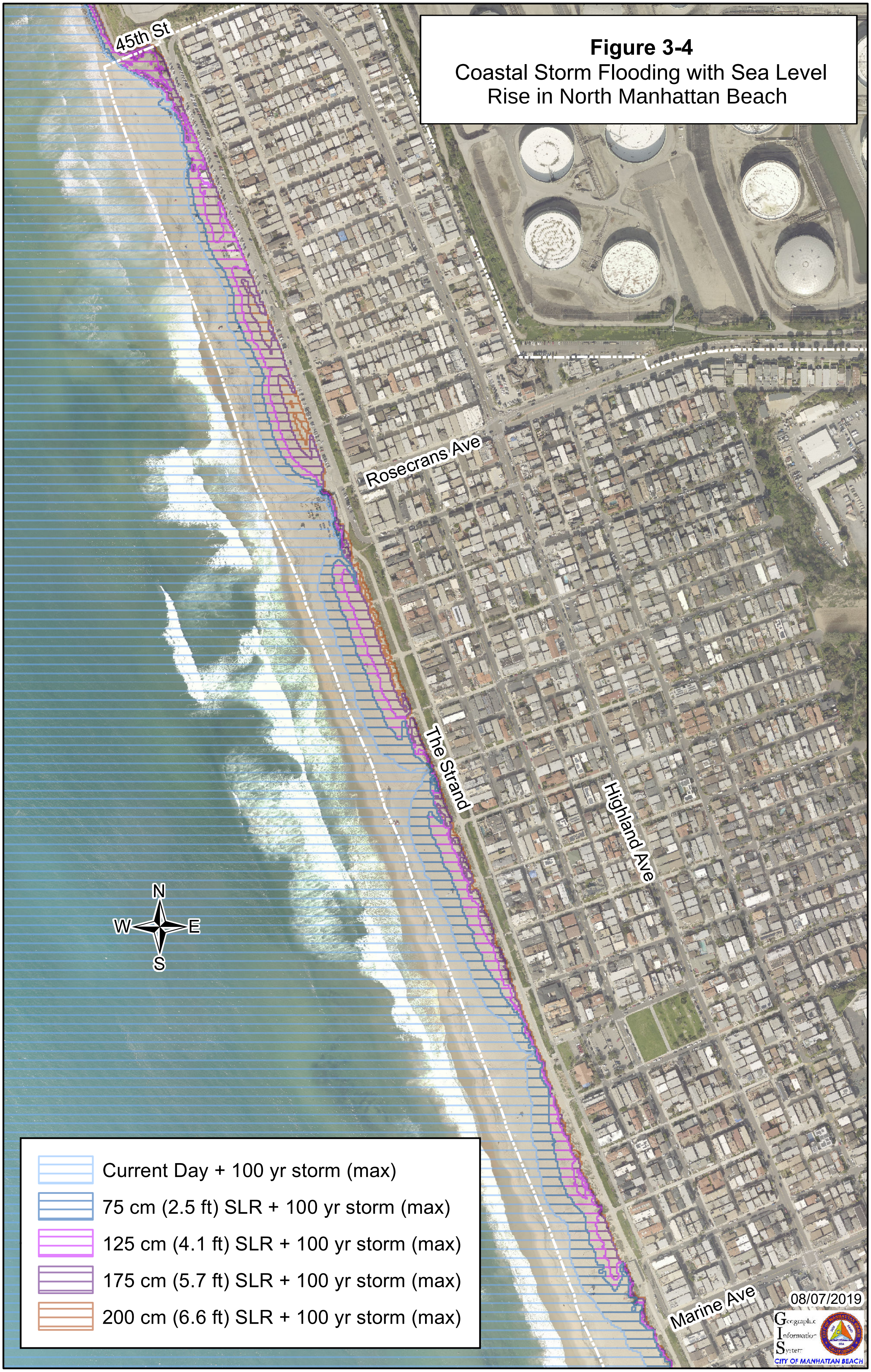


Figure 3-4
Coastal Storm Flooding with Sea Level Rise in North Manhattan Beach
45th St
Rosecrans Ave
The Strand
Highland Ave
Marine Ave
N
W
E
S
Current Day + 100 yr storm (max)
75 cm (2.5 ft) SLR + 100 yr storm (max)
125 cm (4.1 ft) SLR + 100 yr storm (max)
175 cm (5.7 ft) SLR + 100 yr storm (max)
200 cm (6.6 ft) SLR + 100 yr storm (max)
08/07/2019
Geographic Information System
CITY OF MANHATTAN BEACH

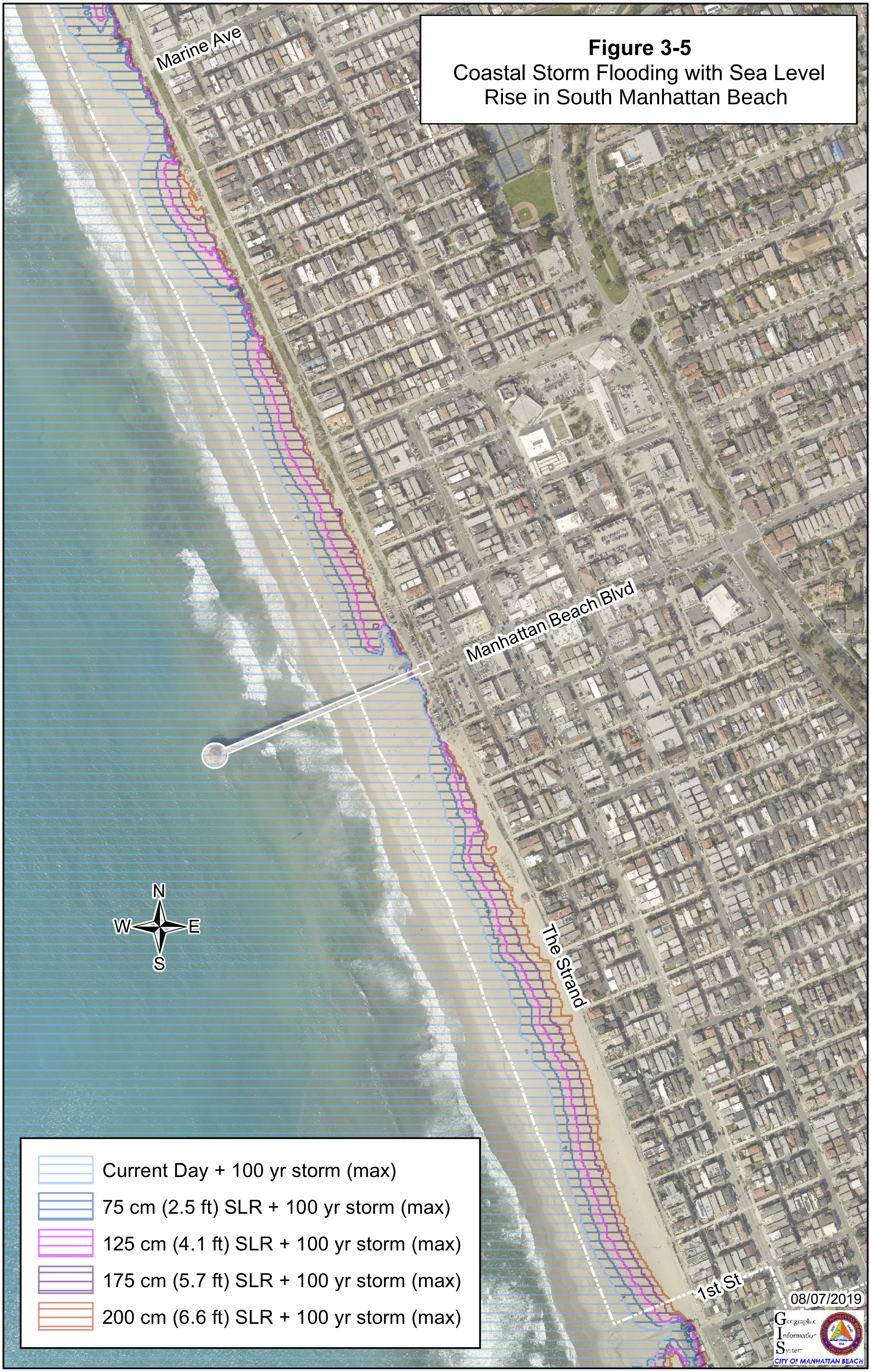
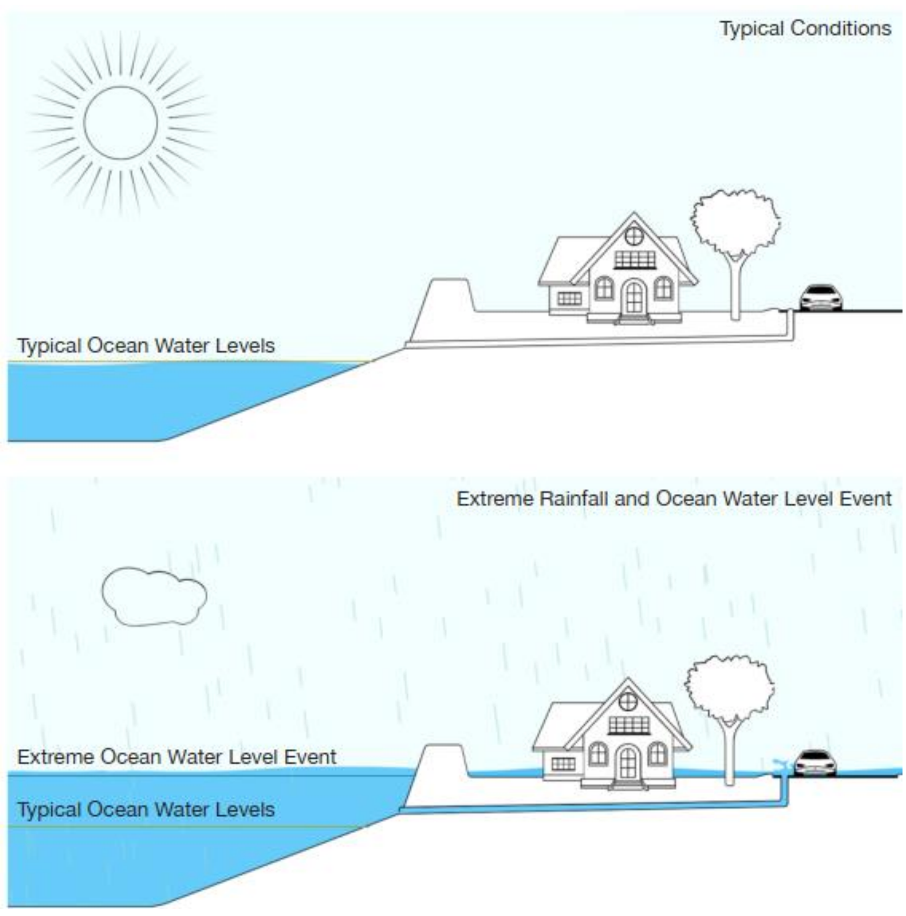


Figure 3-5
Coastal Storm Flooding with Sea Level Rise in South Manhattan Beach
Marine Ave
Manhattan Beach Blvd
The Strand
1st St
N
W
E
S
Current Day + 100 yr storm (max)
75 cm (2.5 ft) SLR + 100 yr storm (max)
125 cm (4.1 ft) SLR + 100 yr storm (max)
175 cm (5.7 ft) SLR + 100 yr storm (max)
200 cm (6.6 ft) SLR + 100 yr storm (max)
08/07/2019
Geographic Information System
CITY OF MANHATTAN BEACH

3.2 Extreme Rainfall Events

Higher sea levels could increase inland flooding, because higher ocean water levels will limit the storm drain system from draining to the ocean. This could result in water backing up into the drains.

Stormwater infrastructure in coastal cities is usually designed to drain rainfall based on a fixed ocean water level (i.e., the design usually assumes sea water levels are low enough to allow full drainage from the pipes). However, the co-occurrence of extreme rainfall and high ocean water levels can lead to increased flood risk. With rising sea levels, Manhattan Beach may experience increased flooding from rainfall events due to the blockage of the outfalls by higher-than-normal coastal water levels moving up into the storm drain system. In this situation, reduced outflow capacity at the ocean outlet may propagate through the system leading to extensive flooding inland (**Figure 3-6**).



Source: NOAA

Figure 3-6: Stormwater Flooding from Backed Up Drainage System

3.2.1 Existing Conditions

A hybrid hydrologic-hydraulic model was developed to determine the vulnerable parts of the Manhattan Beach storm drain system. The hydrologic model simulated extreme rainfall events and the associated stormwater runoff generated overland. The generated runoff was then routed through the drainage system and via the storm drain outfalls to the beach and Pacific Ocean in the hydraulic model. Appendix A provides additional details on the model set up.

When two variables, such as ocean water levels and rainfall, are considered, the return period for a combined scenario is different than the return period for each variable. For example, the chance that the 100-year ocean water level (i.e., the water level with a 1% chance of occurring each year, including storm surge) occurs at the same time as the 100-year rainfall event is less than 1%. Additionally, there are a variety of combinations of ocean water level and rainfall amount that will result in a 1% chance event. For example, a typical ocean water level with an extreme amount of rainfall could result in a 100-year event or an extreme ocean water level with a typical amount of rainfall could result in a 100-year event. **Table 3-1** provides various combinations of ocean water level and 2-hr rainfall that could result in a 100-year event for Manhattan Beach (see Appendix A for additional information on this analysis). The different combinations were modeled in the hybrid hydrologic-hydraulic model to determine how vulnerable the city is under the different scenarios.

Table 3-1: Manhattan Beach Co-Occurrence Hazard Scenarios

RETURN PERIOD	SCENARIO	2-HR RAINFALL (IN/HR)	OCEAN WATER LEVEL (FT ABOVE TYPICAL HIGH WATER)
100-year event	Most likely combo	1.0	1.1
	Rainfall dominated	1.1	0.2
	Ocean water level dominated	0	1.2

Model results for existing conditions (i.e., current climate conditions) showed that the stormwater system can pass the current 25-year rainfall event with limited flooding, but that the 50- and 100-year rainfall events would result in widespread flooding even without a higher coastal water level. Figure 3-7 shows an example of the stormwater drainage system and reported flooding during a storm in 2004. During these events, water is expected to back up into the system and flood through maintenance holes because the pipes cannot move the water to the ocean quickly enough.

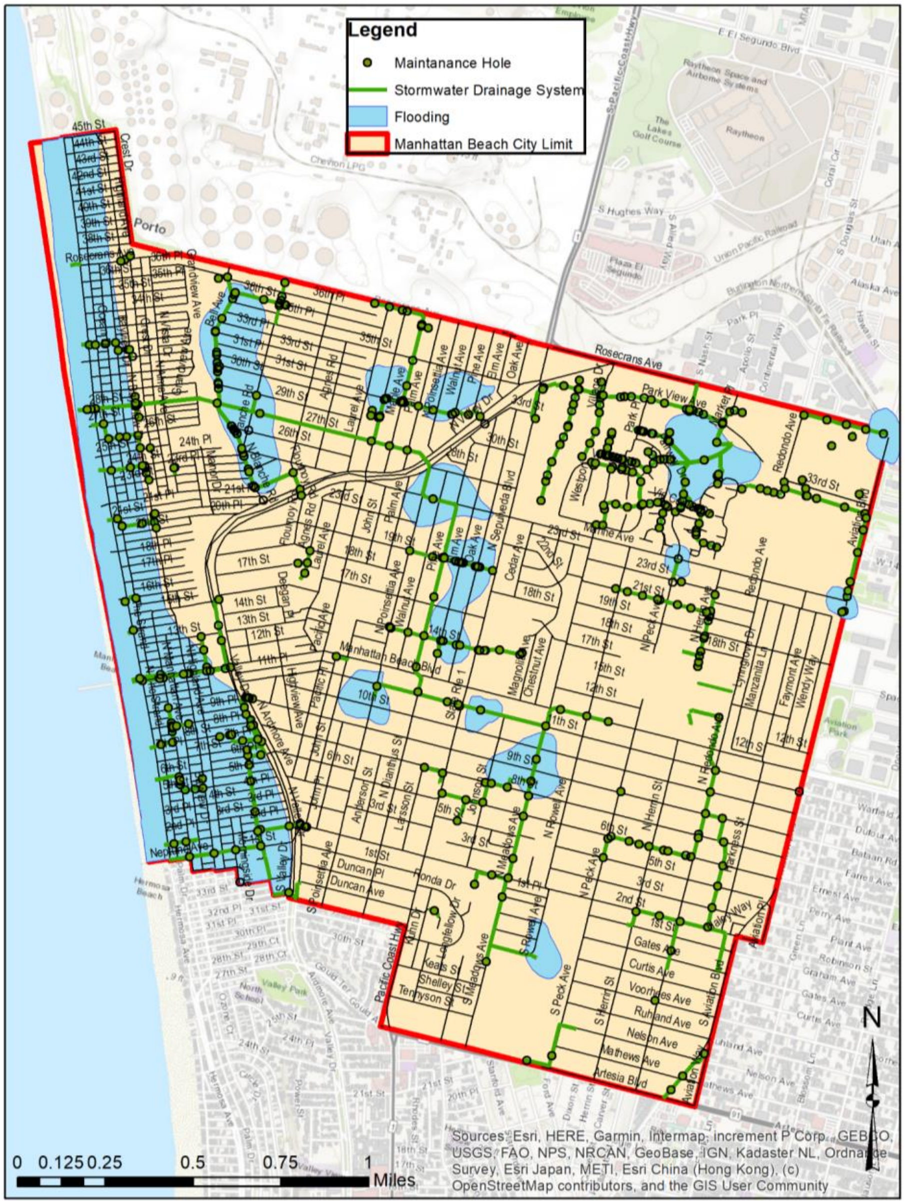


Figure 3-7: Manhattan Beach Storm Drain System and Reported Flooding During a 2004 Rainfall Event

Without sea level rise, for the extreme coastal storm events, the model showed no flooding through the storm drain system since the city elevations increase rapidly from the coast. The most-likely compound flooding scenario (i.e., the scenario during which a relatively high rainfall event coincides with an above-average coastal water level) showed similar results to the extreme coastal water level event (e.g., no flooding) due to sharp increase in land elevations moving away from the coast.

3.2.2 Future Conditions

Chapter 2 discusses the expected increases in sea level rise in the future. Climate change not only alters ocean water levels, but also alters climate patterns, resulting in changes to precipitation. Multiple studies have been conducted to estimate the potential impact of climate change on rainfall. Various models suggest modest changes to overall precipitation by the end of the century (Feng et al., 2019; Polade et al., 2017; Swain et al., 2018), but with the possibility of seasonal variation, (i.e., wetter in winter and drier in fall and spring) (Polade et al., 2017). In particular, atmospheric rivers (corridors in the atmosphere that transport water vapor and are the most significant driver of extreme rainfall events in California) are projected to increase by most current climate models (Gershunov et al. 2013, Dettinger 2011). This increase in atmospheric river frequency is expected to change rainfall frequency, intensity, and timing depending on the season and location. **Table 3-2** shows how the rainfall in the scenarios in Table 3-1 is expected to change by 2100 (see Appendix A for further details). In 2100, the 2-hour rainfall event is expected to be 0.3 in/hr greater than the current 2-hour rainfall event for the most likely rainfall/sea water level combination and 0.4 in/hr higher for the rainfall dominated scenario.

Table 3-2: Manhattan Beach Future Rainfall

RETURN PERIOD	SCENARIO	CURRENT 2-HR RAINFALL (IN/HR)	FUTURE (2100) 2-HR RAINFALL (IN/HR)
100-year event	Most likely combo	1.0	1.3
	Rainfall dominated	1.1	1.5

The hybrid hydrologic-hydraulic model was used to evaluate how an increase in sea level and rainfall would result in an increase to the vulnerability of the storm drain system. The model results showed that future sea levels without a rainfall event are not expected to lead to substantial flooding of the stormwater system, primarily because the storm drain system is elevated enough above the outfalls. **Figure 3-8** shows two outfalls from which stormwater drains into the ocean. The upward slope away from the coast limits the penetration of ocean water level into the stormwater system.

However, the flooding caused by the co-occurrence of high ocean water levels and increased intensity of rainfall storms is expected to get worse in the future. As an example, at the ocean end of the system, the maximum flood rate coming out of a flooded maintenance hole under the current most likely 25-yr compound scenario is estimated at 19.7 cubic feet per second (cfs). The model estimates this would increase to 28.5 cfs in combination with 4.2 feet of sea level rise. In combination with 9.2 feet of sea level rise, the maximum flood rate increases to 41.2 cfs, indicating that both the flood frequency and magnitude will increase.

Figure 3-8: Stormwater Outfalls onto the Beach that Drain Higher Areas of the City

3.3 Beach Erosion

Without action, sea level rise is expected to erode beaches, squeezing them against existing infrastructure on the backshore (Vitousek et al., 2017). The CoSMoS shoreline erosion projections are shown in **Figures 3-9** and **3-10**. Since beaches are a major recreational asset for the City, they were analyzed in additional detail. A two-line shoreline evolution model was used to track shoreline and backshore erosion (the two "lines"), and thus beach width, through time. This model will also be used as a tool to analyze potential adaptation strategies in the Adaptation Plan, which is something CoSMoS does not provide. Details on the shoreline evolution modeling are discussed in Appendix B.

The existing beach widths were determined in Google Earth by measuring the distance between development and the water line along the CoSMoS model transects[11]. This estimate was then compared to the distance measured between the mean high water[12] (MHW) shoreline and the backshore location based on the profiles[13] used in the CoSMoS model. The historic erosion rates from CoSMoS were used as the baseline for the two-line modeling. In general, historic erosion rates in Manhattan Beach show net accretion over time (i.e., beach widening), likely due to the extensive beach nourishment in Santa Monica Bay and the construction of sand retention structures downcoast of the City. To estimate conservatively high future erosion, the baseline historic erosion rate was set to zero erosion in the two-line model (i.e., historic beach widening was not projected forward and the beach width was assumed to be stable without sea level rise). **Table 3-3** presents the beach erosion over time, if no action is taken.

Table 3-3: Beach Width Evolution

YEAR	TOTAL BEACH WIDTH (FT)	% LOSS
2020	370	0%
2030	360	2%
2040	350	5%
2050	330	11%
2060	310	16%
2070	290	22%
2080	260	29%
2090	230	37%
2100	200	47%

Note, Table 3-3 provides the average beach width over time and does not account for erosion during episodic storm events. Typical seasonal oscillations of the shoreline are around 30 feet in Southern California and large coastal storm events can erode the beach by as much as 100 feet.

[11] The model transects are lines perpendicular to the shoreline that were used to model wave runup and erosion.
[12] The average of the two high tides each day from 1983 to 2001.
[13] The model profiles are a cross-section of the beach (i.e., elevations and distance inland) at each of the model transects.

Path: U:\GIS\GIS\Projects\19xxxx\D190512 Manhattan Beach\03 MXDs Projects\CoSMoS shorelinesNorth.mxd, lsheehan 12/15/2020

SOURCE: USGS

Figure 3-9
Shoreline Erosion with Sea Level Rise
in North Manhattan Beach

ESA

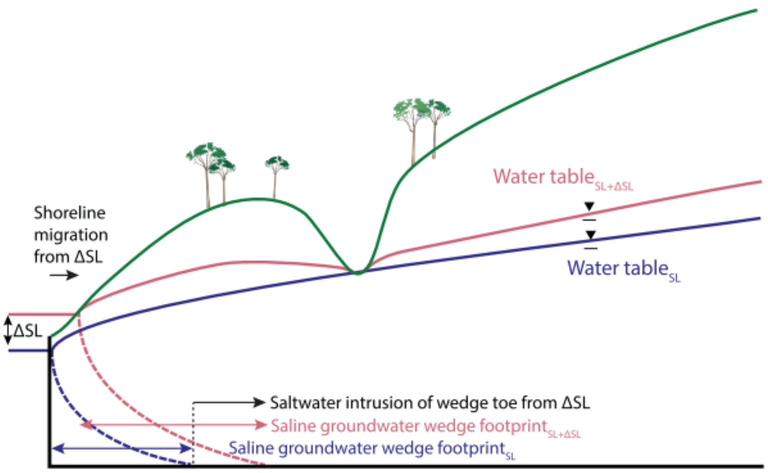
SOURCE: USGS

Figure 3-10
Shoreline Erosion with Sea Level Rise
in South Manhattan Beach

ESA

3.4 Groundwater Hazards

Rising sea levels can impact coastal groundwater both by increasing groundwater levels and the intrusion of salt water into coastal aquifers (**Figure 3-11**). Higher sea levels cause inland intrusion of denser salt water, which can raise unconfined salt water tables and also force overlying freshwater to rise up. As the water table rises, it can rise above the ground surface, flooding low-lying areas or it can infiltrate and damage shallow infrastructure, such as basements, building foundations, and gas lines. Additionally, the intrusion of salt water can impact the drinking water supply.



Source: Befus et al. 2020

Figure 3-11: Changes to the Groundwater Table with Sea Level Rise

Higher groundwater can damage buried infrastructure and building foundations, flood basements and other below-ground structures, and flood low-lying areas. A conservative way to estimate the rise in groundwater is to assume it rises linearly with sea level rise. In areas with streams and rivers, this approach is overly conservative because the groundwater can drain out along the low-lying stream or river bed, lowering the total amount of rise in groundwater elevation, as shown in Figure 3-11.

Using the data from Befus et al. 2020, the depth to groundwater was evaluated across Manhattan Beach. While there is not expected to be any emergence of groundwater leading to backshore ponding in Manhattan Beach, it is possible that groundwater could impact underground infrastructure, such as sewer and electrical lines. Under existing conditions, the model results showed that the groundwater table is 5-20 feet below the beach, except at the edge of the water, where the groundwater table is closer than five feet to the surface. With 3.3 feet (1 meter) of sea level rise, the model showed groundwater levels under the beach would increase 3.2 feet. With 6.6 feet (2 meters) of sea level rise, the groundwater would increase 6.4 feet and with 9.8 feet (3 meters) of sea level rise, it would increase 9.6 feet. The model showed that the groundwater in Manhattan Beach would increase slightly less than the amount of sea level rise (e.g., 9.8 feet of sea level rise translates to 9.6 feet of rise in the groundwater). Because the land slopes up quickly from the beach, the groundwater under most of the city is deep and there is limited risk to inland flooding.

CHAPTER 4

Vulnerability Assessment

Understanding the risk of not taking action is the first step in planning for sea level rise.

This section uses the future hazards described in Chapter 3 to identify the assets (e.g., beaches, stormwater outfalls, etc.) and communities potentially at risk from sea level rise. To develop an effective adaptation plan and policies to address sea level rise vulnerability, the risk of not taking action must be understood first. For this reason, this Vulnerability Assessment includes a “do nothing” or “no action” scenario in which the City or other asset managers do not respond to sea level rise. This scenario assumes the existing armoring would not be maintained, per the “let it go” scenario. In reality, the City will likely take action (and already has, see Section 1.233). As a next step, the City will develop adaptation measures to reduce future and current vulnerabilities and assess these measures in an Adaptation Plan.

Each asset was analyzed to determine the potential exposure to the different hazards and consequences, and the sensitivity and adaptive capacity of the asset to the potential hazard, as per the CCC guidelines. The following boxes describe in further detail the information contained within this section. The CCC guidelines also recommend consideration of land use constraints (e.g., how land use patterns may impact potential sea level rise vulnerability), which will be analyzed and presented in the Adaptation Plan.

Exposure to hazard and the consequences are evaluated based on the type of hazard an asset would potentially be subject to under future conditions and the timing at which this hazard is expected to potentially occur. An example of low consequence would be infrequent storm flooding of a parking lot. An example of high consequence would be tidal inundation of an emergency response facility.

Sensitivity to hazard is defined as the asset's level of impairment if flooded temporarily or permanently, or if affected by erosion or waves. Highly sensitive assets would lose their primary function if exposed to any degree of flood or erosion whatsoever. Assets with low sensitivity would not be majorly impacted by inundation or erosion.

Adaptive Capacity is the asset's ability to change and respond to a hazard. Low adaptive capacity assets would take a long time to be operational, once impacted. High adaptive capacity assets would bounce back more quickly.

An asset's vulnerability depends on its potential exposure to hazards and the consequences of that exposure (higher exposure or consequences results in higher vulnerability), the sensitivity of the asset (higher sensitivity results in higher vulnerability), and the adaptive capacity of the asset (lower adaptive capacity results in higher vulnerability).

The final Section 4.5 discusses socioeconomic impacts and analyzes environmental justice as it relates to sea level rise in Manhattan Beach.

4.1 Beaches and Associated Facilities and Events

Beaches, their associated facilities, and events on the beach are at risk for tidal inundation, coastal storm flooding, and erosion. Beaches are a major recreational asset of Manhattan Beach and the region. Associated facilities include the Marvin Braude Trail, parking lots, public restrooms, concession stands and beach rentals, beach access points, and lifeguard towers. Additionally, major events, such as beach volleyball tournaments, are held on the beach throughout the year. Access to sandy beach would become more limited with rising sea levels, affecting not only beach activities, but also beach access, safety logistics (lifeguards, fire), management practices (trash, grooming, etc.) and sandy beach habitat.

4.1.1 Hazards and Consequences

As discussed in Section 3.3, 60 feet of beach is expected to be lost by 2060 with just under half of the beach width lost by 2100 (Table 3-3). Additionally, episodic storm events could damage infrastructure even sooner. Events that depend on the beach, such as volleyball tournaments, will be compromised by beach erosion over time. For example, the City used to have four volleyball courts east to west near the Pier, but due to recent erosion, now only has three. With 6.6 feet of sea level rise, daily wave runup is expected to reach the courts closest to the ocean. The current site plans for the Manhattan Beach Open and the Charlie Saikley 6-person volleyball tournaments would need to be updated before 6.6 feet of sea level rise to maintain the emergency vehicle lane between the ocean and the courts.

Currently, development along the beach only rarely, if ever, experiences wave damage during coastal storm events. **Table 4-1** presents the beach facility hazards and the amount of sea level rise expected for the hazard to occur.

Table 4-1: Beach Facility Hazards, Consequences, Sensitivity and Adaptive Capacity

ASSET	WAVE RUNUP FLOODING DURING A 100-YR EVENT[1]	COASTAL STORM INUNDATION DURING A 100-YR EVENT	TIDAL INUNDATION DURING A TYPICAL DAY	CONSEQUENCES	SENSITIVITY	ADAPTIVE CAPACITY
Marvin Braude Trail through El Porto Beach	4.9-6.6 ft of SLR	Some spots with 4.9-5.7 ft of SLR	n/a	Low	Low	High
Public restroom building between 43rd and 42nd St.	4.9-6.6 ft of SLR	4.9-5.7 ft of SLR	n/a	Medium	Low	Medium
Food stand and beach rental building at El Porto Beach	Now	3.3-4.1 ft of SLR	6.6-9.8 ft of SLR	Medium	Medium	Medium
Public restroom and maintenance building at the end of Rosecrans Ave.	0-1.6 ft of SLR	3.3-4.1 ft of SLR	6.6-9.8 ft of SLR	Medium	Low	Medium
Marvin Braude Trail in places from 32nd to 17th St.	4.9-6.6 ft of SLR	n/a	n/a	Low	Low	High
Beach access using the steps from the Pier down to the beach	Now	Now	6.6-9.8 ft of SLR	Low	Low	High
Public restrooms at the Pier	1.6-3.3 ft of SLR	3.3-4.1 ft of SLR	n/a	Medium	Low	Medium
Lower Pier parking lot	4.9-6.6 ft of SLR	n/a	n/a	Low	Low	High
Marvin Braude Trail near 10th St.	4.9-6.6 ft of SLR	n/a	n/a	Low	Low	High
Lifeguard towers	Now	Some now, some with 3.3-4.1 ft of SLR	6.6-9.8 ft of SLR	High	Low	High

SLR = sea level rise
n/a = no flooding through 9.8 ft of SLR
1. This represents wave flooding above the coastal storm inundation. See sidebar in Section 2.3 for photo examples.

The consequences of the Marvin Braude Trail or parking lots flooding during a storm are low. Pedestrian and bicyclists within the coastal zone would lose mobility due to inundation of segments of existing trails and parking would decrease under flooded conditions. However, once dry, these facilities would provide public access again. During a more dramatic storm event, the trail or parking lots could experience impacts such as cracking or potholes which could require repair and a longer impact to access.

The increased frequency of flooding for the restroom and food stand and rental buildings during storm events could lead to water damage and other flood related damages, as well as disrupted access to and from the buildings, so they would have medium consequences as a result of flooding. Some of these buildings could experience daily inundation between 6.6 and 9.8 feet of sea level rise, which would have higher consequences.

The consequences of the lifeguard towers flooding would be high, since they are needed for public safety. Flooding and erosion could impact emergency response capabilities and response time. Additionally, decreased sandy beach area could impact emergency response routes and transportation (i.e., driving on the beach).

The consequences of the beach access from the Pier flooding are low since there is additional beach access in the vicinity. However, increased flooding of any magnitude in this area could pose a safety hazard to the community.

The Manhattan Beach Municipal Pier is specifically designed and intentionally located to be in the potential hazard zones. However, over time, the exposure of the structure to waves and large storm events will increase. Additionally, the assets at the pier (e.g., Roundhouse Aquarium) will experience more frequent wave overtopping with sea level rise.

Beaches, which are dynamic ecosystems already subject to dramatic cycles of erosion and accretion, tend to be resilient to coastal storm events. However, sea level rise will lead to long-term erosive trends. The consequence of the beach flooding is low, but erosion, which would cause a narrowing of the beach, would be of high consequence and could lead to impacts to biodiversity, community composition, ecological function, and wildlife populations. Additionally, the narrower beach could lead to impacts to sand accumulation, wrack retention, and nutrient cycling. A smaller beach would also reduce the area for mobile intertidal animals that spend most of their time in the lower intertidal zone, but move during high waves and storm conditions.

4.1.2 Sensitivity

The sensitivity of the Marvin Braude Trail or parking lots flooding are low because access would be temporarily impaired, but the damage would be low compared to other types of development. The restroom facilities are expected to have low sensitivity to occasional flooding since access would be impacted, but flooding is not expected to cause major damage. Because flood levels in the restrooms would be low, impacts to mechanical or plumbing systems are not expected.

The food stands and rentals buildings are expected to have medium sensitivity since long-term operational interruptions could occur if mechanical or plumbing systems are flooded.

The sensitivity of the lifeguard towers flooding would also be low, as they are designed to be above the water and can be relocated.

The sensitivity of the beach access from the Pier to flooding is low since access would be temporarily impaired, but damage would be minimal. The Pier would have low sensitivity as access from the beach would cease during flood events, but access from the road would maintain operations on a short-term basis.

Events on the beach would have high sensitivity to flooding or erosion because the event could not be held without dry beach space.

The beach habitat would have low sensitivity to flooding, which is typical for a dynamic ecosystem, but would have high sensitivity to erosion, if the sensitive upper intertidal zone were lost. Loss of beach width would result in smaller upper intertidal zones, which would strongly reduce intertidal biodiversity, decrease the prey available for birds and fish and eliminate nesting habitat for species of concern (California Grunion and Western Snowy Plover) (Myers et al. 2019).

4.1.3 Adaptive Capacity

The Marvin Braude Trail and parking lots are expected to have high adaptive capacity, meaning they could return to normal operations very quickly after a periodic or temporary flood event. A more extreme event could lead to the need for repairs, but this is expected to be infrequent. The restrooms and food stand and rentals building, on the other hand, would have medium adaptive capacity as it could take some time to restore access and operations and the facilities cannot be easily relocated.

The lifeguard towers would have high adaptive capacity because they could be easily relocated to prevent future flooding.

The adaptive capacity of the beach access from the Pier is high since access would be temporarily impaired, but would allow for access once waters recede. The Pier would have medium adaptive capacity as damage from waves and flooding could disrupt operations until repairs are made.

Events on the beach would have high adaptive capacity because they could be relocated prior to the event.

The beach habitat would have high adaptive capacity since Manhattan Beach has a wide beach that is expected to remain, although narrower. The beach is expected to maintain some upper intertidal zone habitat through 2100, which will help maintain biodiversity and ecosystem functions. Dune restoration will increase the adaptive capacity of the beach, while also reducing the hazard exposure for coastal infrastructure, such as the Marvin Braude Trail.

4.1.4 Vulnerability Summary

The most vulnerable assets among the beach and associated facilities include:

- Food stand and beach rental building at El Porto Beach, because the building is threatened under existing conditions and could experience tidal inundation between 6.6 and 9.8 feet of sea level rise, water damage could disrupt operations, and the facilities cannot be easily relocated.
- The Manhattan Beach Municipal Pier, because it is threatened under existing conditions, flooding and wave damage could disrupt operations and require long-term repair, and it is intentionally located over the water, which puts it in a hazard zone.

Lower vulnerability assets that should still be considered in future adaptation planning include:

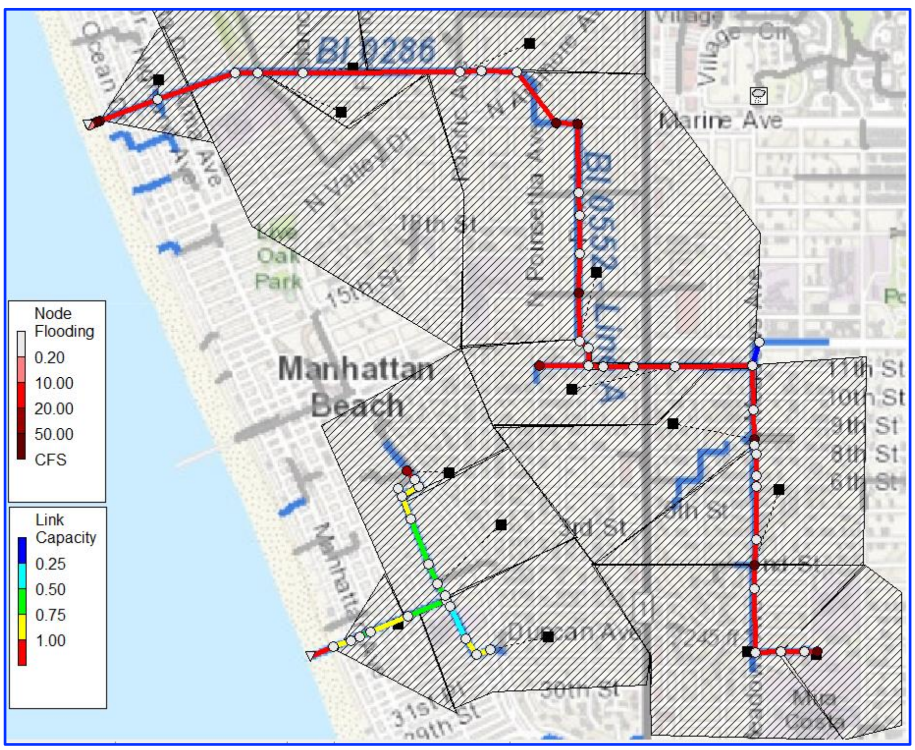
- Public restrooms (specifically the restrooms at Rosecrans Avenue. which are expected to be vulnerable to storm waves by 1.6 feet of sea level rise, storm flooding by 4.1 feet of sea level rise, and tidal inundation by 9.8 feet of sea level rise),
- Marvin Braude Trail (vulnerable to storm waves between 4.9 and 6.6 feet of sea level rise),
- Lifeguard towers (vulnerable to storm waves now and tidal inundation by 9.8 feet of sea level rise), and
- Major beach events (vulnerable to daily wave run up by 6.6 feet of sea level rise).

4.2 Storm Drain System

The storm drain system in Manhattan Beach conveys excess rainfall to four main outlets (and other minor local outlets that drain smaller watersheds). Two of these major outlets are located on the eastern side of Manhattan Beach and, therefore, do not drain to the ocean. The other two major outlets drain to the coast and could be affected by higher ocean water levels and increased precipitation. One of these major outlets drains a smaller catchment, with an area of around 350 acres. The other outlet drains a larger watershed with an area of around 1,790 acres (encompassing ~70% of Manhattan Beach).

4.2.1 Hazards and Consequences

As discussed in Section 3.2.2, extreme rainfall combined with high ocean water levels is expected to increase the flooding in the city from the storm drain system. **Figure 4-1** shows the results of the hybrid hydrologic-hydraulic model for a 25-year compound flooding scenario (e.g., rainfall and ocean water level) with 9.2 feet of sea level rise. The color of the pipelines represents how full the pipe is flowing. Red lines represent the pipe is at capacity, while yellow, green, and blue lines show that the pipes still have capacity. The circle nodes represent maintenance holes and the different shades of red indicate flooding. The figure shows that several nodes are expected to flood in this scenario, which would impact the City’s ability to get water out of the city.



Note: Hatched areas indicate catchment drainage areas, not flooding extent.

Figure 4-1: Storm Drain Pipe Capacity and Maintenance Hole (Node) Flooding Rates Under the 25-year Compound Scenario with 9.2 feet of Sea Level Rise.

The storm drain outfalls could also be threatened by beach erosion and vulnerable to sand blockage with sea level rise as the beach profile adjusts (more sand at higher elevations) to keep up with higher water levels.

Increasing groundwater levels due to sea level rise could impact stormwater discharges if the resulting water levels cause infiltration into stormwater pipes or inundation at discharge points. Because rainfall is low in Southern California, leading to a low groundwater recharge rate, and soils are relatively permeable in the city, groundwater effects in Manhattan Beach are expected to be minor. Based on data from Befus et al. 2020, the USGS analyzed potential groundwater impacts to the stormwater system in Manhattan Beach by extracting the depth to groundwater at the outfall locations shown in **Figure 4-2**. Further detail is presented in **Appendix C**.

Figure 4-2: Stormwater Outfall Locations

The analysis results showed that the outfalls at 28th Street (#7) and 1st Street (#22) are currently within 5 feet of the groundwater table. In addition to groundwater levels reaching the outfalls with 5 feet of sea level rise, the 28th Street outfall is expected to be inundated by the tides with 6.6 feet of sea level rise, and the 1st Street outfall would be inundated by the tides with 9.8 feet of sea level rise.

The analysis showed the outfalls at 27th Street (#8) and just north of the Pier (#15) would be within 6 feet of the groundwater table with 3.3 feet of sea level rise. The majority of the rest of the outfalls would be within 7 feet of the groundwater table with 6.6 feet of sea level rise, except the outfalls at 24th Street (#9), 21st Street (#11), north and south of 18th Street (#12 and #13), 9th Street (#17), and 2nd Street (#21). These would all be within 7 feet of the groundwater table with 9.8 feet of sea level rise, except for the outfalls at 24th Street and 9th Street. The groundwater model uses annual average recharge to determine the typical groundwater table, so the actual water table could be significantly higher following unusually wet periods (there is a lag between rainfall inputs and groundwater table response). However, the model does not include the effects of stormwater management systems, which would limit groundwater recharge and water table rise due to storms, and widespread development in Manhattan Beach may also reduce groundwater recharge from rainfall. As a result, the groundwater table is not expected to rise much higher than shown in the model.

The consequences of increased water levels at the downstream end of the storm drain system would be medium as backwater effects due to downstream flow blockage or constriction would increase flooding at the maintenance holes during major rain events. Flooding would be expected to become more frequent and more extensive and could cause inland property damage. Failure of the storm drain system could cause impacts to water quality by flooding streets and other areas that could contribute additional contaminants to the stormwater.

4.2.2 Sensitivity

Due to the upward slope away from the coast, ocean water levels have limited penetration into the stormwater drainage network. Higher sea levels without a rainfall event do not lead to substantial flooding. However, the co-occurrence of extreme rainfall and coastal storm events, including storm surge, can lead to increased flood risk. With rising sea levels, Manhattan Beach is expected to experience flooding from rainfall events that the storm system has previously been designed to handle due to the blockage of the outfalls by higher-than-normal coastal water levels. Therefore, the storm drain system's sensitivity to sea level rise is medium.

4.2.3 Adaptive Capacity

The storm drain system has low adaptive capacity. The limited capacity of the pipes already results in inland flooding during a 50- or 100-year rainfall event. Increasing the capacity of the pipes would require replacing the pipes throughout the system, which would be an extensive undertaking.

The outfalls that are expected to be tidally inundated with sea level rise (at 28th Street and 1st Street) extend the furthest onto the beach and have relatively gentle slopes moving inland across the beach. These outfalls could potentially be moved inland and upslope to discharge above the ocean/groundwater levels (i.e., by removing the downstream section of the storm drain pipe/shortening the storm drain pipe).

4.2.4 Vulnerability Summary

The stormwater drainage system has medium-high vulnerability because the system already floods during extreme rainfall events and will flood more frequently with climate change and sea level rise. The vulnerability is medium-high because the consequences of failure would be medium, the sensitivity of the system to sea level rise is medium, and the system has low adaptive capacity.

4.3 South Bay Cities' Main Sewer Trunk Line

The South Bay Cities' main sewer trunk line runs along the beach from the north end of Manhattan Beach to just north of the Pier, where the line begins to run under the development, rather than the beach.

4.3.1 Hazards and Consequences

Beach erosion is not expected to reach the sewer line under 6.6 feet of sea level rise, but water levels during a 100-year storm could extend to the sewer line between 27th and 32nd Streets and around Marine Avenue. Higher water levels could limit access to the line for maintenance and operation or inundate maintenance holes and increase flows in the system that the treatment plant would then have to process. These storm impacts would be temporary.

Assuming the sewer line is 6 feet below the ground surface, groundwater could rise to just under the pipe with 9.8 feet of sea level rise, based on the data from Befus et al. 2020 (USGS, Appendix C). Rising groundwater could place unanticipated buoyancy forces on the buried line, potentially leading to leaks and/or pipe failure. Additionally, groundwater infiltration to the line could increase flows in the system that the treatment plant would then have to process.

Consequences of sea level rise impacting the sewer system are high, since failure of the wastewater system could result in major impacts to water quality and human health at the beach. However, the risk of hazards is low, since potential impacts are not expected until 6.6 feet of sea level rise (temporary flooding) and greater than 9.8 feet of sea level rise (groundwater impacts).

4.3.2 Sensitivity

The sewer line is likely not highly sensitive to occasional extreme coastal storm events flooding the beach on top of the pipe. These events would limit access for maintenance and could inundate maintenance holes, increasing flows in the system, but would pass once the water levels dropped. The sensitivity of the sewer line to groundwater impacts is uncertain and could be studied to help plan for future adaptations.

4.3.3 Adaptive Capacity

The sewer line has low adaptive capacity. Rerouting the line out of the coastal area would be an extensive undertaking and would likely require additional pump stations to convey wastewater to the treatment plant.

4.3.4 Vulnerability Summary

The sewer line has medium to high vulnerability with 6.6 feet of sea level rise because the consequences of failure would be high, the sensitivity of the system to sea level rise is low to medium, and the system has low adaptive capacity.

4.4 Coastal Structures

Parts of the Manhattan Beach coastline are protected by coastal armoring structures, such as rock revetments (north end of El Porto Beach, **Figure 1-4**) and sea walls (El Porto Beach and near the Pier, **Figures 1-5** and **1-6**).

4.4.1 Hazards and Consequences

Tidal inundation is expected to reach the rock revetment on the north end of El Porto Beach with 9.8 feet of sea level rise. Coastal storm inundation during the 100-year event will impact the revetment and sea wall in El Porto Beach sooner, with 4.1 feet of sea level rise. The sea wall at the Pier is already exposed to coastal storm inundation during the 100-year event with no sea level rise and the impacts to the sea wall are expected to increase over time.

The consequences of the revetment or sea wall overtopping at El Porto Beach would be inundation of the Marvin Braude Trail. Overtopping of the sea wall at the Pier would result in flooding of the parking lot. Since the trail and parking lot are low sensitivity assets, the consequences of failure of the coastal structures is low.

4.4.2 Sensitivity

The coastal structures are specifically designed and intentionally located to be in the hazard zones. However, over time, the exposure of the structures will likely increase, so that riprap that experiences occasional flooding today could experience deeper floodwaters and stronger wave action in the future. Increased water levels and wave-runup during storms can cause damage to the coastal structures and incremental reduction in the level of flood and erosion protection and/or increased maintenance costs. Coastal structures have a medium sensitivity to sea level rise.

4.4.3 Adaptive Capacity

The adaptive capacity of coastal structures is medium to high, because they are typically designed to be in the hazard zones and can be maintained or repaired after storm events.

4.4.4 Vulnerability Summary

Coastal structures in Manhattan Beach have medium-low vulnerability with future sea level rise because the consequences of failure would be low, the sensitivity of the system to sea level rise is medium, and the system has medium to high adaptive capacity.

4.5 Socioeconomic Impacts and Environmental Justice Analysis

Vulnerable communities experience heightened risk and increased sensitivity to climate change and have less capacity and fewer resources to cope with, adapt to, or recover from climate impacts. These disproportionate effects are caused by physical (built and environmental), social, political, and/or economic factor(s), which are exacerbated by climate impacts. These factors include, but are not limited to, race, class, sexual orientation and identification, national origin, and income inequality (ICARP, 2021). Additionally, historic inequity in land use and zoning policies, underinvestment in vulnerable communities and lack of meaningful engagement in planning and policy making have created disparities in how prepared communities are to adapt to the impacts of climate change (APEN, 2019). Many individuals experience multiple and intersecting vulnerabilities which can make them particularly at risk with regard to climate change. For example, black and Hispanic mothers are more likely to be single heads of household and are also more likely to be low-income, live in flood prone areas, and have health issues that can be exacerbated by climate change.

Vulnerable communities across the City of Manhattan Beach include homeless individuals, elderly, children, visitors, and seasonal residents. Additionally, certain census tracts compared to the City as a whole have the following vulnerable populations: low-income families, unemployed/underemployed, renters, low-income homeowner and renter housing burden, single parent household, linguistically isolated households, disabled individuals, and uninsured individuals.

Within the City, census tracts 6202.01 (El Porto), 6203.05 (north of Manhattan Beach Boulevard), and 6209.04 (south of Manhattan Beach Boulevard) are all located in the coastal zone. The discussion below notes where there are populations within these census tracts that have a higher concentration of a vulnerable population. While coastal hazards are not expected to directly impact any residences in the city, roads or major infrastructure during this study's planning horizon (i.e., 2100), these populations will be important to consider and prioritize in the future as sea level rise continues beyond 2100.

4.5.1 Elderly

Within the City of Manhattan Beach, 15% of people are 65 years old or older. In particular, south of Manhattan Beach Boulevard, 18% of people are 65 years old or older. Older adults may be less mobile and may be less able to evacuate in the event of flooding or another climate event.

4.5.2 Visitors and Seasonal Residents

Due to its well-known beaches, Manhattan Beach is a popular destination for visitors and seasonal residents. Visitors and seasonal residents are less likely to receive information regarding potential climate impacts as well as programs and policies to reduce impacts such as evacuation plans and routes etc. Therefore, seasonal residents and visitors may be less prepared and more vulnerable to climate change impacts such as flooding.

Additionally, visitors from surrounding areas may increase in the future as other beaches are lost. Los Angeles County estimates that Redondo Beach and Torrance Beach may be completely eroded by 2100. This will likely increase the demand for beach access at Dockweiler State Beach, Manhattan Beach, and Hermosa Beach, which are expected to lose about half their width, but maintain around 200-foot wide beaches by the end of the century. (LA County 2016).

4.5.3 Unemployed/Underemployed

Compared to the City of Manhattan beach where 76% of people aged 25-64 are employed, south of Manhattan Beach Boulevard, 69% of people in this age group are employed. Unemployed or under employed individuals may be more vulnerable to the impacts of climate change as they may have less access to financial and other resources, which may make adaptation to climate change more difficult (HPI, 2021).

4.5.4 People with Disabilities

Data from the South Bay Cities Council of Government Vulnerability Assessment for Manhattan Beach suggests that between 20 and 30% of the adult population between 17th Street and Manhattan Beach Boulevard (Block Group 6 within Census Tract 6203.05) has a physical or mental disability, which is significantly higher than the percentage of adults with a disability in other portions of the city. Individuals with disabilities may experience the effects of climate change more intensely than other groups due to discrimination, marginalization, and other social and economic factors. Additionally, certain disabilities may prevent individuals from being mobile, which may impact their ability to evacuate in the event of flooding (SBCCOG, 2019)

4.5.5 Low Income

Compared to the City as a whole where 9% of individuals have an income below 200% of the federal poverty threshold, within El Porto, 15% of individuals have an income below 200% of the federal poverty threshold (200% of the federal poverty level is often used to measure poverty in California due to high costs of living). Low-income households and individuals are more likely to live in inadequate housing and are more likely to live in areas that are already disproportionately impacted by pollution, health problems, and natural disasters. Low-income communities have less access to financial resources and are more likely to be uninsured, which makes adaptation and recovery from coastal hazards more difficult. Additionally, low income households often do not have access to vehicles, which can make evacuating more difficult (HPI, 2021).

4.5.6 Low-Income Homeowner Housing Burden

Compared to the city as a whole where 8% of low-income homeowners spend more than 50% of their income on housing costs, 12% of low-income homeowners south of Manhattan Beach Boulevard pay more than 50% of their income on housing costs. High housing costs and housing instability reduce a household's access to financial resources and may make a household more likely to be uninsured, all of which makes adaptation and recovery from coastal hazards more difficult (HPI, 2021).

4.5.7 Homeless

Homeless neighbors are more exposed to extreme heat, air pollution, and flooding and are at an increased risk for dehydration, sunburn, respiratory and cardiovascular diseases as well as displacement. Homeless individuals are also less likely to have access to healthcare, financial resources, or reliable transportation.

4.5.8 Renters

Compared to the City of Manhattan Beach as a whole, where 70% of housing units are occupied by homeowners, within El Porto, 74% of housing units are occupied by renters and north of Manhattan Beach Boulevard, 50% of housing units are occupied by renters. Renters, especially low-income renters, have a reduced ability to prepare homes and properties for coastal hazards. Additionally, low-income renters often spend a disproportionate amount of their income on housing costs and are at an increased risk of displacement during natural disasters. Renters also do not have access to information regarding the flood risk of rented properties and often do not have insurance to cover losses from natural disasters (HPI, 2020).

4.5.9 Single Heads of Household

Approximately 25% of households in El Porto are led by a single parent as compared to 11% of households across the city as a whole. Households lead by a single parent are vulnerable to the impacts of coastal hazards as they have only one wage earner to support household financial needs and only one parent to perform family and house care duties (HPI, 2020).

4.5.10 Children

Roughly 6% of the population of the City of Manhattan Beach is under 5 years of age. Children under the age of 5 are particularly affected by heat waves, pollution, undernutrition, vector borne diseases, as well as respiratory and cardiovascular diseases due to anatomical, cognitive immunological, and psychological differences between children and adults (HPI, 2020; Lawrence et al., 2018)

4.5.11 Linguistically Isolated Households

Data from the South Bay Cities Council of Government Vulnerability Assessment for Manhattan Beach suggests that between 5 and 10% of households between 17th Street and Manhattan Beach Boulevard do not have an adult that speaks English, which is significantly higher than the percentage of linguistically isolated households in other portions of the city. Households without an English speaker at home are considered to be linguistically isolated and may have more difficulty accessing information about evacuation. Linguistic isolation can increase vulnerability during climate events such as flooding (SBCCOG, 2019).

4.5.12 People Lacking Health Insurance

Data from the South Bay Cities Council of Government Vulnerability Assessment for Manhattan Beach suggests that between 9 and 18% of individuals between 17th Street and Manhattan Beach Boulevard do not have health insurance, which is significantly higher than the percentage of uninsured individuals in other portions of the city. Having health insurance greatly improves health outcomes by connecting people with the necessary medical care. Individuals without access to healthcare are more vulnerable to the health impacts of flooding and the mental health impacts of climate change (SBCCOG, 2019).

4.5.13 SB 535 and AB1550 Disadvantaged and Low-Income Communities

SB 535 and AB 1550 require the State of California to invest certain percentages of climate cap and trade mitigation funds to identified disadvanted and low-income communities. CalEPA developed a tool called CalEnviroscreen for assessing what constitutes a disadvantaged community. A “disadvantaged community” is defined as the top 25% highest scoring census tracts based on the results of the California Communities Environmental Health Screening Tool. A “low-income community” is defined as a census tract with median household incomes at or below 80% of the statewide median income or with median household incomes at or below the threshold designated as low income by HCD’s State Income Limits.

The City of Manhattan Beach does not contain any disadvantaged communities as defined by SB 535 and CalEnviroScreen, nor any low-income communities as defined by AB1550. However, there are both disadvantaged and low-income communities north and east of the city, who may rely on the coastal resources and amenities within Manhattan Beach. This may increase the consequences of coastal hazard impacts to certain assets, like parking lots and restrooms, since these assets allow visitors to access the coastal resources. The City should prioritize maintaining and improving coastal access resources, such as trails, visitor-serving amenities, public parking, EV charging stations, bike racks, and other mixed-modal facilities for non-residents as part of the adaptation planning process.

4.5.14 Proposition 68 Disadvantaged Communities

Proposition 68, passed in 2018, authorizes $4.1 billion for state and local parks, natural resources protection, climate adaptation, water quality, and flood protection. Projects that benefit disadvantaged and severely disadvantaged communities are given priority for funding. A severely disadvantaged community is defined as a census block group with a median household income less than 60% of the California statewide average. A disadvantaged community is a census block group with a median household income less than 80% of the California statewide average. Other State grant funding opportunities also use these same definitions.

The City of Manhattan Beach does not contain any disadvantaged or severely disadvantaged communities as defined by Proposition 68. However, there are both disadvantaged and severely disadvantaged communities just east of the city in Redondo Beach and Lawndale. These communities may rely on the coastal resources and amenities within Manhattan Beach. This may increase the consequences of coastal hazard impacts to certain assets, like parking lots and restrooms, since these assets allow visitors to access the coastal resources. The City should prioritize maintaining and improving coastal access resources, such as trails, visitor-serving amenities, public parking, EV charging stations, bike racks, and other mixed-modal facilities for non-residents as part of the adaptation planning process.


Photo by The Bay Foundation

CHAPTER 5

Conclusions

With anticipated sea level rise, Manhattan Beach's current vulnerabilities to coastal flooding and erosion are projected to increase in frequency, intensity, and extent. As discussed in Section 1.2, past, extreme coastal flood events have caused significant damage along the City's coastline, without the impact of sea level rise. Future sea level rise is expected to create a permanent rise in ocean water levels that will increase erosion of beaches and result in more damaging coastal storm events. Higher water levels at the coast and increased rainfall will also impact the storm drainage system during extreme rainfall events by backing up water into the system and delaying drainage until low tide. Sea level rise will also increase groundwater levels, which can impact buried utilities.

Manhattan Beach's vulnerable assets include beaches and associated facilities and events, the storm drain system, the South Bay Cities' main sewer trunk line, and coastal structures. **Table 5-1** summarizes the grades for each asset's exposure to hazards and consequence, sensitivity to the hazards, adaptive capacity, and overall vulnerability. If no action is taken, sea level rise could result in major impacts to the City. However, the City and other asset managers are taking action by conducting this study and by planning for sea level rise, including the existing adaptation strategies (Section 1.3.3) and implementing other strategies (i.e., beach dune restoration). As a next step, the City will develop adaptation measures to reduce future vulnerabilities and assess these measures in an Adaptation Plan.

Table 5-1: Manhattan Beach Vulnerability Summary

ASSET	EXPOSURE & CONSEQUENCE	SENSITIVITY	ADAPTIVE CAPACITY	VULNERABILITY
Beaches & Associated Facilities and Events				
Marvin Braude Trail through El Porto Beach	Low	Low	High	**Low**
Public restroom building between 43rd and 42nd St.	Medium	Low	Medium	**Medium-Low**
Food stand and beach rental building at El Porto Beach	Medium	Medium	Medium	**Medium**
Public restroom and maintenance building at the end of Rosecrans Ave.	Medium	Low	Medium	**Medium-Low**
Marvin Braude Trail in places from 32nd to 17th St.	Low	Low	High	**Low**
Beach access using the steps from the Pier down to the beach	Low	Low	High	**Low**
Restrooms at the Pier	Medium	Low	Medium	**Medium-Low**
Lower Pier parking lot	Low	Low	High	**Low**
Marvin Braude Trail near 10th St.	Low	Low	High	**Low**
Lifeguard towers	High	Low	High	**Medium-Low**
Municipal Pier	Medium	Low	Medium	**Medium-Low**
Beach events	Low	High	High	**Medium-Low**
Beach habitat	Medium	Low	High	**Medium-Low**
Storm drain system	High	Medium-Low	Low	**Medium-High**
South Bay Cities' main sewer trunk line	Medium	Low	Low	**Medium**
Coastal Structures	Low	Medium	Medium-High	**Medium-Low**

The following are the assets most vulnerable to sea level rise hazards (i.e., received an overall vulnerability ranking of medium-high or medium):

- **Storm drain system:** Under existing conditions without sea level rise, the current 25-year rainfall event causes inland flooding in the system. Extreme rainfall combined with high ocean water levels in the future is expected to increase the flooding in the city from the storm drain system.
- **Food stand and beach rental building at El Porto Beach:** This building already experiences flooding under a 100-year coastal storm event, and the frequency and intensity of flooding is expected to increase in the future.
- **South Bay Cities' main sewer trunk line:** The South Bay Cities' main sewer trunk line runs along the beach from the north end of Manhattan Beach to just north of the Pier. The 100-year coastal storm event is expected to reach the pipeline with 6.6 feet of sea level rise, placing buoyancy forces on the line, which could lead to leaks and/or pipe failure.

These planning-level analyses and results are approximate and intended solely for the purpose of assessing potential future coastal vulnerabilities and informing the development of the CAAP, updates to the Local Hazards Mitigation Plan, and related

LCP-LUP policies. Only assets identified through available geo-spatial data sets have been considered, so additional assets may need to be evaluated in the future.

In the next steps of the LCP-LUP preparation process, adaptation measures to reduce future vulnerabilities will be identified and assessed, and the CAAP will be developed. The CAAP will consider potential climate adaptation measures that include a range of accommodation, protection, and retreat strategies. Costs for no action and adaptive management strategies will be estimated and compared to inform adaptation planning.

CHAPTER 6

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Appendix A

Multi-Hazard Confluence Modeling of Manhattan Beach's Stormwater Infrastructure

City of Manhattan Beach Climate Resiliency Program

Multi-Hazard Confluence Modeling of Manhattan Beach's Stormwater Infrastructure

Executive Summary

ESA
WaClim LLC
Water & Climate Solutions

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EXECUTIVE SUMMARY

Background

Characterizing the frequency and return period (i.e. recurrence interval) of extreme events is fundamental to local level planning, adaptation, and risk management. Coastal cities, like Manhattan Beach, are typically exposed to multiple extreme (and even non-extreme) flooding hazards (or flood drivers) such as ocean water levels, waves, precipitation, and rainfall, or surface, runoff. In coastal systems, the flood drivers are often tied together or are dependent on one another (e.g., a storm event that drives both high ocean water levels and extreme precipitation), which can lead to compound events in which the simultaneous or sequential occurrence of extreme or non-extreme events may lead to an extreme impact (e.g., flood inundation, infrastructure failure). In Manhattan Beach, combined extreme precipitation and high ocean water levels can have a multiplier effect leading to flood inundation and damages to infrastructure.

Current trajectories of SLR point to an increase greater than 3 ft (1 m) over the 21st century. By changing coastal dynamics characteristics, this rise amplifies flood risk in the region, altering design heights and posing uncertainties in required flood risk allowances.

Physically, SLR adds to the height of future storm tides, reduces pressure gradients that are important for transporting surface runoff (here, urban floodwater) to the ocean, and enables greater upstream wave propagation. Projected future SLR further complicates coastal flood hazard analysis by introducing a non-stationarity change in the flood risk over time (i.e., continuously changing risk over an unknown period of time adding to uncertainties in future flood risk).

Current procedures for local rainfall and flood frequency analysis methods do not consider the effect of dynamic ocean water levels. Similarly, frequency analysis procedures for ocean water levels do not account for terrestrial factors such as surface runoff or direct precipitation into urban areas (also known as pluvial flooding). Ignoring the interactions between these drivers is expected to underestimate the overall flood risk and their impacts on local infrastructure. In this report, the individual drivers of flooding (here, rainfall and ocean water level) are investigated under current and future climate scenarios. Then, current and future flood drivers are used for multi-hazard confluence modeling of Manhattan Beach's stormwater infrastructure.

Key Findings

Climate change is expected to increase frequency and intensity of extreme rainfall events and storm-driven floods: NOAA Atlas 14 volume 6 provides precipitation frequency estimates for California, frequently used for design and risk assessment purposes (gray lines in Figure 1). Results show that climate change is expected to increase the likelihood of extreme rainfall events in Manhattan Beach. Figure 1 displays current Intensity-Duration-Frequency (IDF) curves (grey lines based on NOAA) and projected future IDF curves for 25-, 50-, and 100-year events under representative concentration pathways (RCP) 4.5 (top) and 8.5 (bottom). The curves for the future scenarios are on top of the current IDF curves, indicating an expected increase in frequency and intensity of rainfall with climate change.

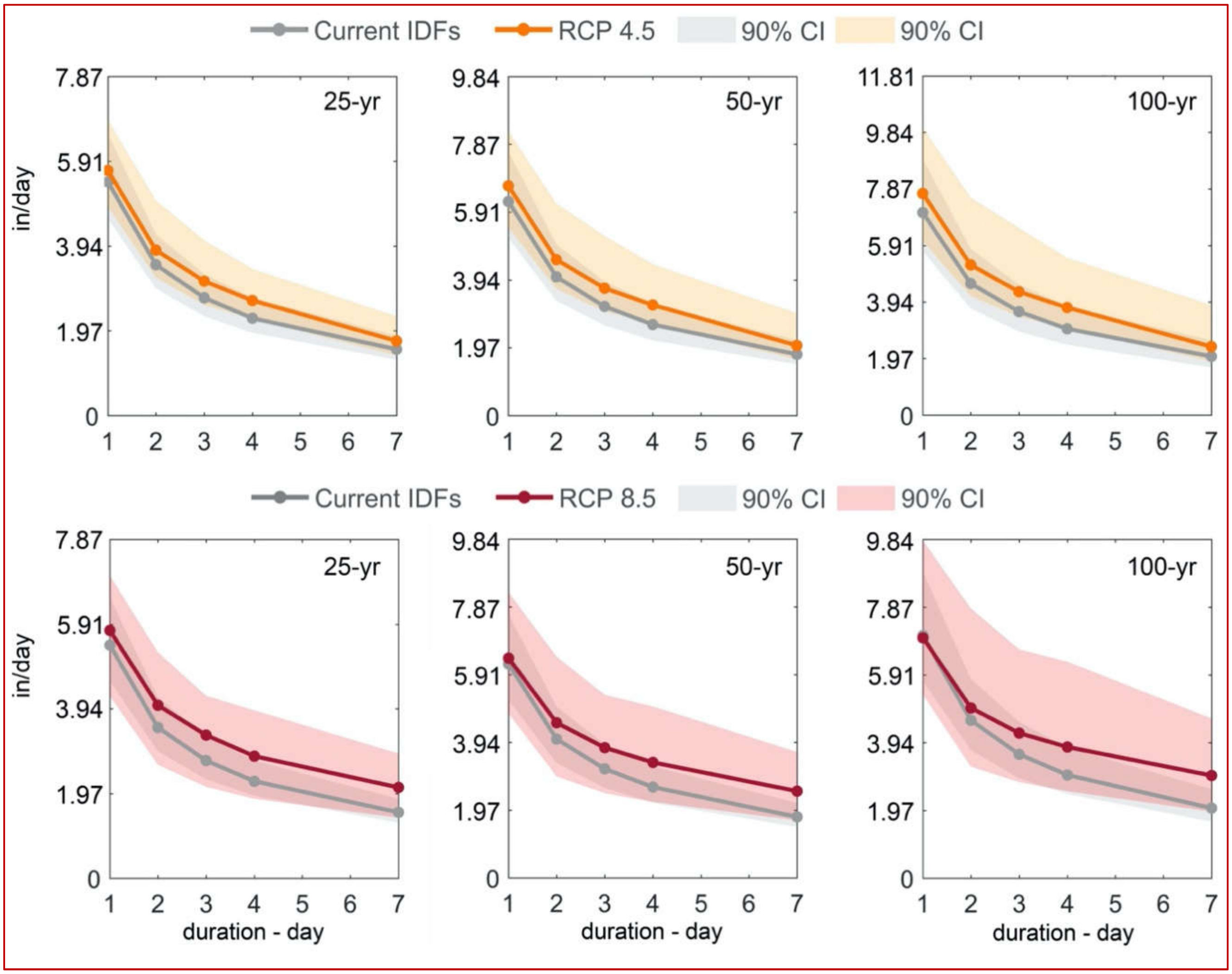


Figure 1: Estimated IDF curves for 25-, 50-, and 100-year rainfall events based on all available downscaled CMIP5 climate model simulations under RCPs 4.5 (top) and 8.5 (bottom). The grey lines indicate the current IDF curves available from NOAA whereas the shaded areas represent the 90% confidence intervals.

Widespread urban flooding is expected under current 50-yr and 100-yr storms: Model simulations for current 25-, 50-, and 100-yr return periods show that the Manhattan Beach's stormwater infrastructure cannot convey the excessive rainfall generated by 50-yr and 100-yr storms, leading to widespread flooding, even without a significant contribution from the coastal water levels. The system reaches its capacity under a 25-yr rainfall event with limited flooding across the city. Under 50-yr and 100-yr storm-dominated scenarios, all the links of network N1 (larger network in Figure 2) reach their maximum capacity at the 9th hour of the simulation (the most extreme time-step during the modeled extreme storm), and the majority of maintenance holes experience surcharge and extensive flooding. While the network N2 (smaller network in Figure 2 that drains near the pier) performs slightly better under the same scenarios, flooding would be expected in Valley Drive and conduits near (and upstream of) the cross-section of 6th and N. Ingleside Drive. as they reach their maximum capacity.

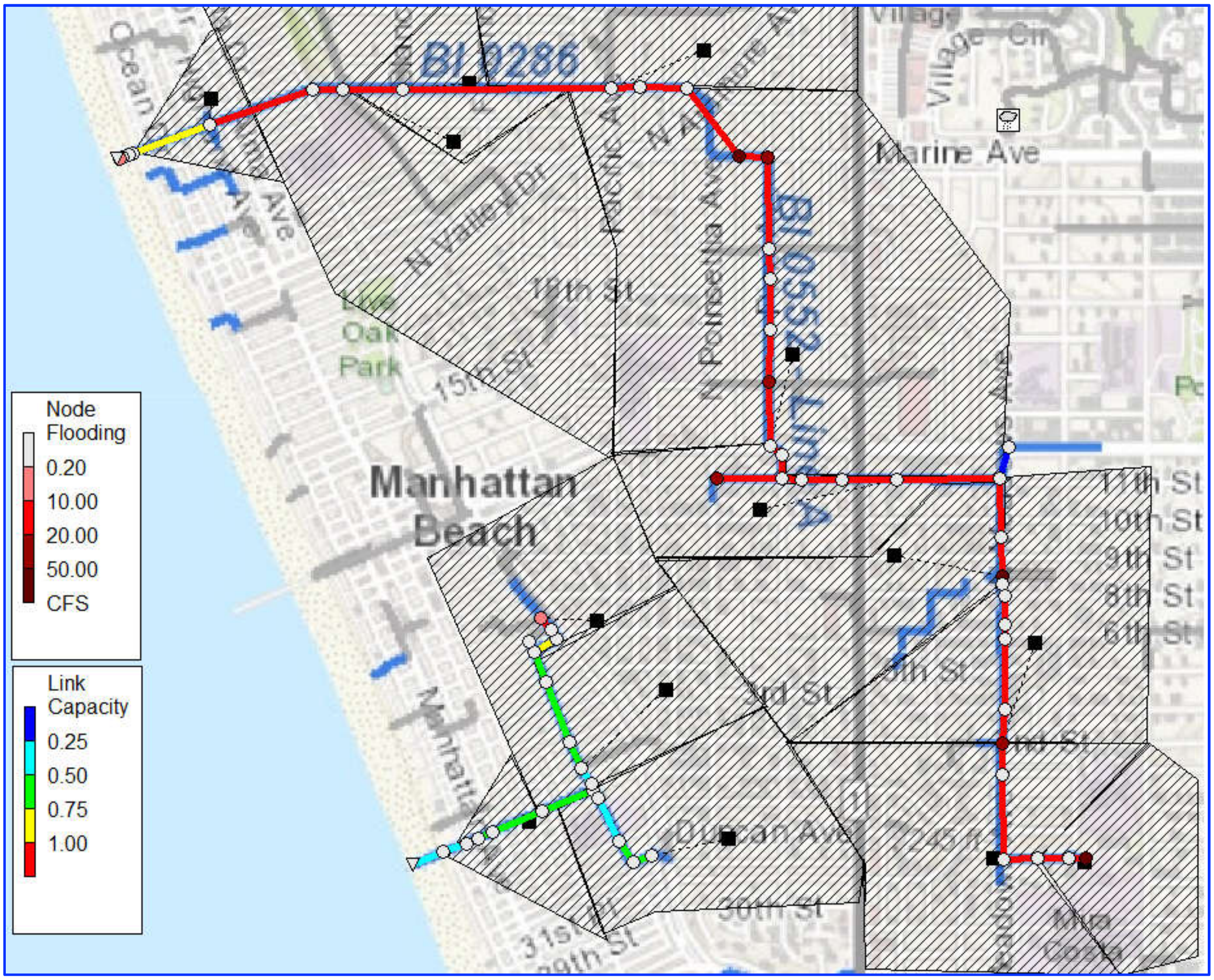


Figure 2: Map of the simulated status of the network under the univariate storm-driven 100-yr flood (e.g., rainfall alone with no extreme ocean water level or future extreme ocean water levels) at the 9th hour (the most extreme time-step during the simulation).

Figure 3 shows part of the N1 network (larger network in Figure 2 - see the red line) under current 25-yr (left) and future 25-yr storms — see the technical report for more details and alternative scenarios. As shown, the simulated water levels (blue lines) are higher in the right panel (future climate) relative to the left panel (current climate) indicating more flooding is expected in a warming climate.

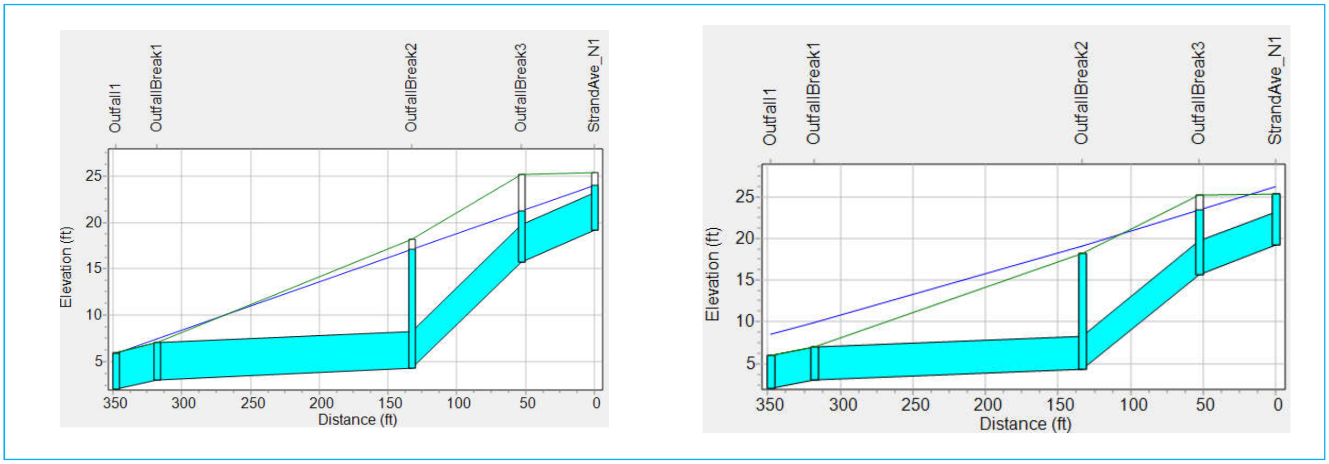
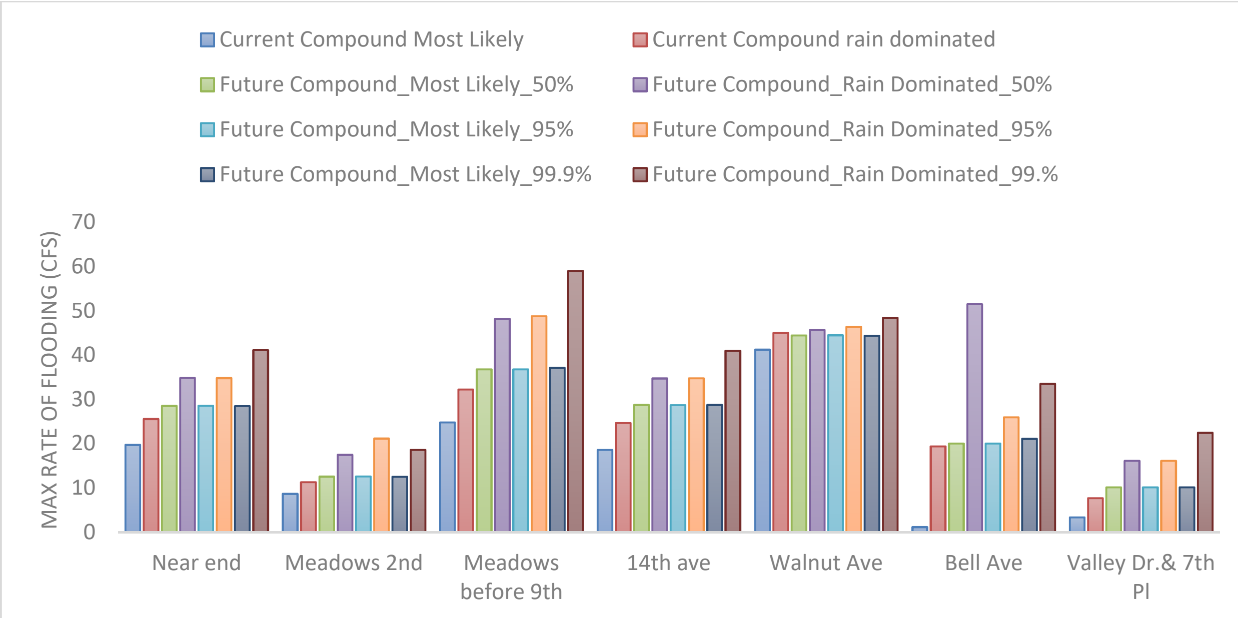


Figure 3: Part of the N1 network (larger network in Figure 2) under current 25-yr (left) and future (RCP8.5) 25-yr (right) storms (right column).

Future sea levels without a rainfall storm do not lead to substantial flooding in the stormwater infrastructure system: After investigating a wide range of current and future SLR scenarios, it was concluded that SLR alone (without a rainfall storm) does not lead to substantial flooding of the stormwater network primarily because of elevation difference between the outfalls and the rest of the system, as shown in profile views in Figure 3. The below pictures show two outfalls from which stormwater drains into the ocean. The upward slope away from the coast limits the penetration of ocean water level into the stormwater drainage network.

Compound high ocean water level scenarios and rainfall storms can cause widespread flooding: Stormwater infrastructure in coastal cities is usually designed to drain rainfall based on a fixed ocean water level (i.e., the design usually assumes ocean water levels are low enough to allow full drainage from the pipes). However, the co-occurrence of extreme rainfall and high ocean water levels can lead to increased flood risk. With rising sea levels, the model showed that Manhattan Beach will experience flooding from rainfall events that the storm system has previously been designed to handle due to the blockage of the outfalls by higher-than-normal coastal water levels. In this situation, reduced outflow capacity at the ocean outlets will propagate through the system leading to flooding inland. Figure 4 shows the estimated maximum flood rate for various 25-yr (top) and 100-yr (bottom) compound flooding scenarios. The percentiles in the labels correspond to the percentiles of the future sea levels. Higher percentiles indicate higher sea levels from the ensemble of future projections (see the technical report for the exact values of the selected scenarios). For example, the chance that the 100-yr ocean water level (i.e., the water level with a 1% chance of occurring each year) occurs at the same time as the 100-yr rainfall event is much less 1%. There are a variety of combinations of ocean water level and rainfall amount that will result in a 100-yr event. For example, a typical ocean water level with an extreme amount of rainfall could result in a 100-year event or an extreme ocean water level with a typical amount of rainfall could result in a 100-year event. Figure 4 shows both the most likely combination of ocean water level and rainfall that would correspond to a 25- and 100-yr event and also a rainfall dominated scenario, where the ocean water level is less extreme. As shown, considering future sea levels, the maximum flood rate increases with higher amounts of projected future SLR. The x-axis in Figure 4 shows the last 7 nodes in the stormwater drainage network where sea level impact is noticeable.



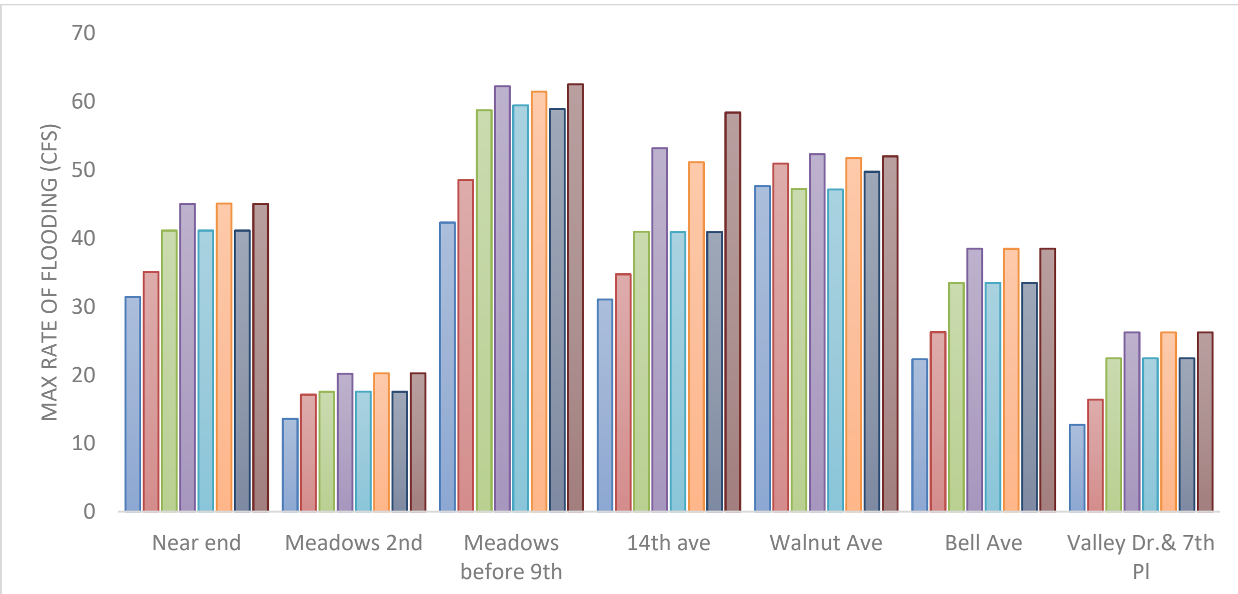


Figure 4: Estimated maximum rate of flooding under various 25-yr (top) and 100-yr (bottom) compound flooding scenarios (percentiles in the labels correspond to the percentiles of the future sea levels).

Figure 4 highlights the impacts of SLR on local flooding in the coastal part of the stormwater drainage system. Comparing the current compound coastal flooding (blue bars) with future compound coastal flooding with 50th percentile of future sea levels (green bars) one can see significant increases in the maximum flood rate. As an example, at the near end of the system, the maximum flood rate under current most likely 25-yr compound scenario is estimated at 19.7

cfs which increases to 28.5 cfs under future most likely 25-yr compound flood scenario with 50th percentile of future sea levels. For the same 25-yr scenario but under 99th percentile of future sea level projections, the maximum flood rate increases to 41.2 cfs.

In summary, the interactions between SLR and extreme rainfall is expected to exacerbate flooding in coastal areas. Even under a future 25-yr compound flooding scenario but extreme future sea levels (e.g., 99th percentile), the system reaches its capacity and flooding in coastal part of the system in inevitable. In Figure 5, areas around the red lines are expected to get flooded due to overflow of the drainage system. However, pluvial flooding in other areas can also occur due to accumulation of direct rainfall due to poor drainage.

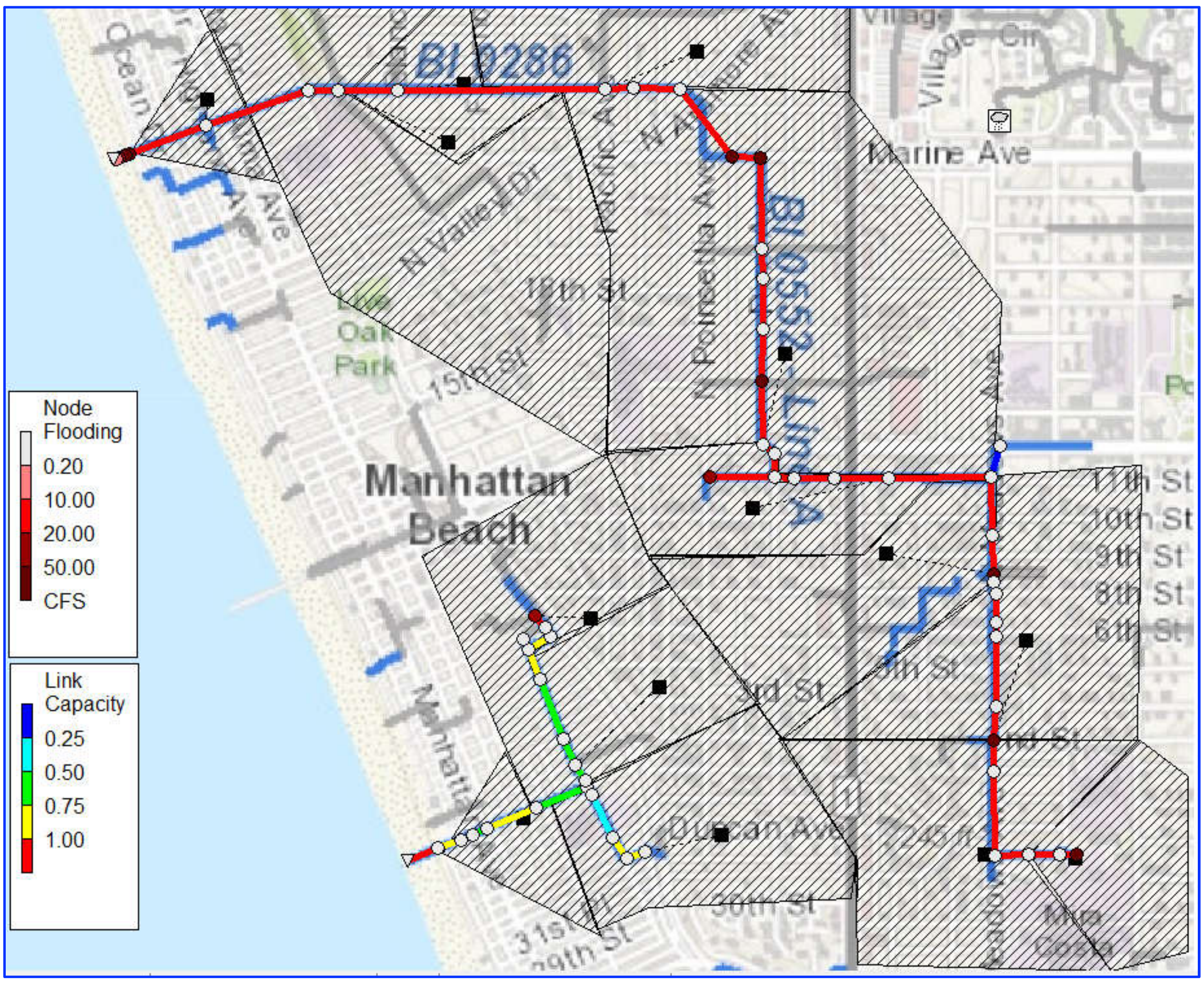


Figure 5: Map of the simulated status of the network under the most likely 25-yr compound flooding scenario + the 99.9th percentile of the projected mean sea levels in year 2100 (under RCP 8.5) at the 9th hour of simulation (the most extreme time-step during the simulation).

FLOOD DRIVERS AND CLIMATE CHANGE

Ocean Water Level and Sea Level Rise

In a warming climate, mean sea level (MSL) is projected to be significantly higher than the current level. Sea level rise (SLR) reduces the gap between coastal high water and flooding threshold and so increases the chance of flooding. MSL at the coast of Los Angeles has risen since 1920s at an average rate of 1.03 ± 0.23 mm/yr. This means the current MSL is approximately 4 inches higher than 1920s. Here, the coastal TWL estimates are analyzed using the Coastal Storm Modeling System (CoSMoS) by United States Geological Survey (USGS). CoSMoS 3.0 provides information about the severity (e.g., extent, depth) of flooding along the coasts of Southern California under scenarios combining SLR and possible coastal storm conditions (daily/background conditions, 1-year storm, 20-year storm, and 100-year storm). These coastal storm conditions include sea level anomalies, waves, storm surge and river discharge. Figure 6 shows SLR scenarios (in inches above MSL at year 2000) for the tide gauge at Los Angeles (NOAA # 9410660) for different future time horizons based on CoSMoS 3.0.

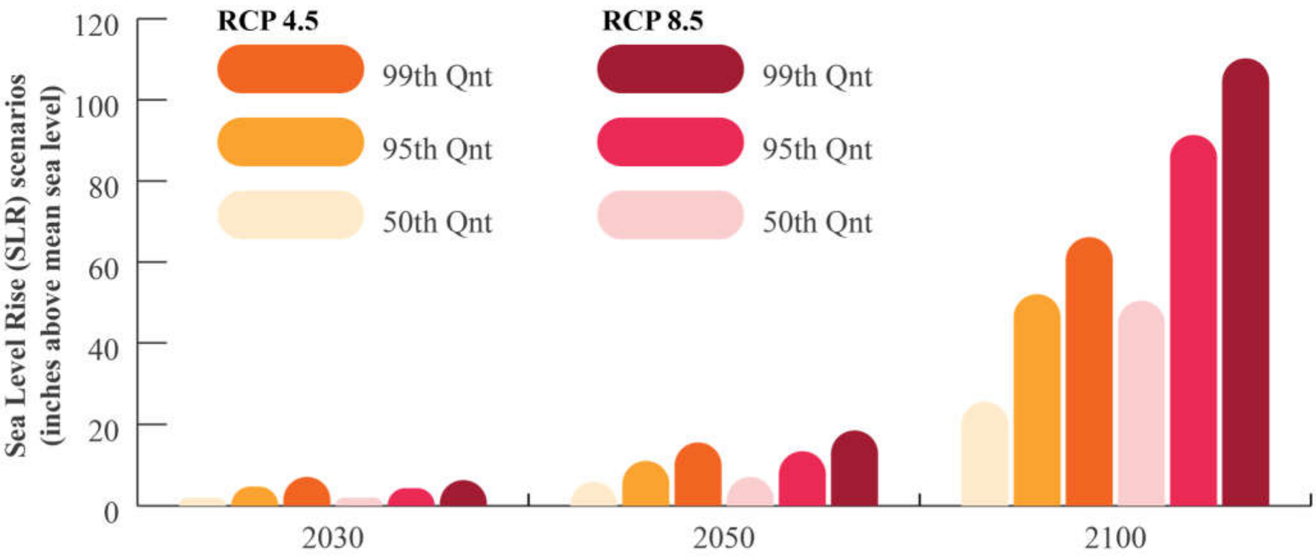


Figure 6: Sea Level Rise (SLR) scenarios (in inches above MSL at year 2000) for the tide gauge at Los Angeles (NOAA # 9410660) From CoSMoS 3.0.

The primary drivers of coastal flooding in Manhattan Beach are coastal ocean water level and pluvial flooding (resulting from direct rainfall). The risk stemming from oceanic drivers is changing continuously because of rising sea levels that also may interact with the pluvial driver.

The concurrence of heavy precipitation and storm surge can be considered a compound event in low-lying coastal regions Storm surges prevent water from discharging into the open sea, while heavy local precipitation results in excessive water levels in inland areas. The rising sea levels, also, will change the gradient of flow in storm drainage system towards ocean and impact the drainage capacity, making future coastal flooding more impactful even if rainfall intensity remain unchanged. Projections of tidal high water in Los Angeles, exceed historic flooding thresholds in the following decades. Bars in Figure 7 show the likelihood that an extreme coastal water level goes beyond these historic thresholds, based on coastal water-level projections from the Coastal Storm Modeling System (CoSMoS; Barnard et al. 2015). Figure 7 indicates that it is unlikely for the 10-year flooding threshold associated with tidal high waters to be exceeded in 2030; however, there is a 5% and 50% chance that this threshold will be surpassed by 2070 and 2100, respectively, under high emission scenarios. This highlights the importance of ocean water level as a potential flood driver.

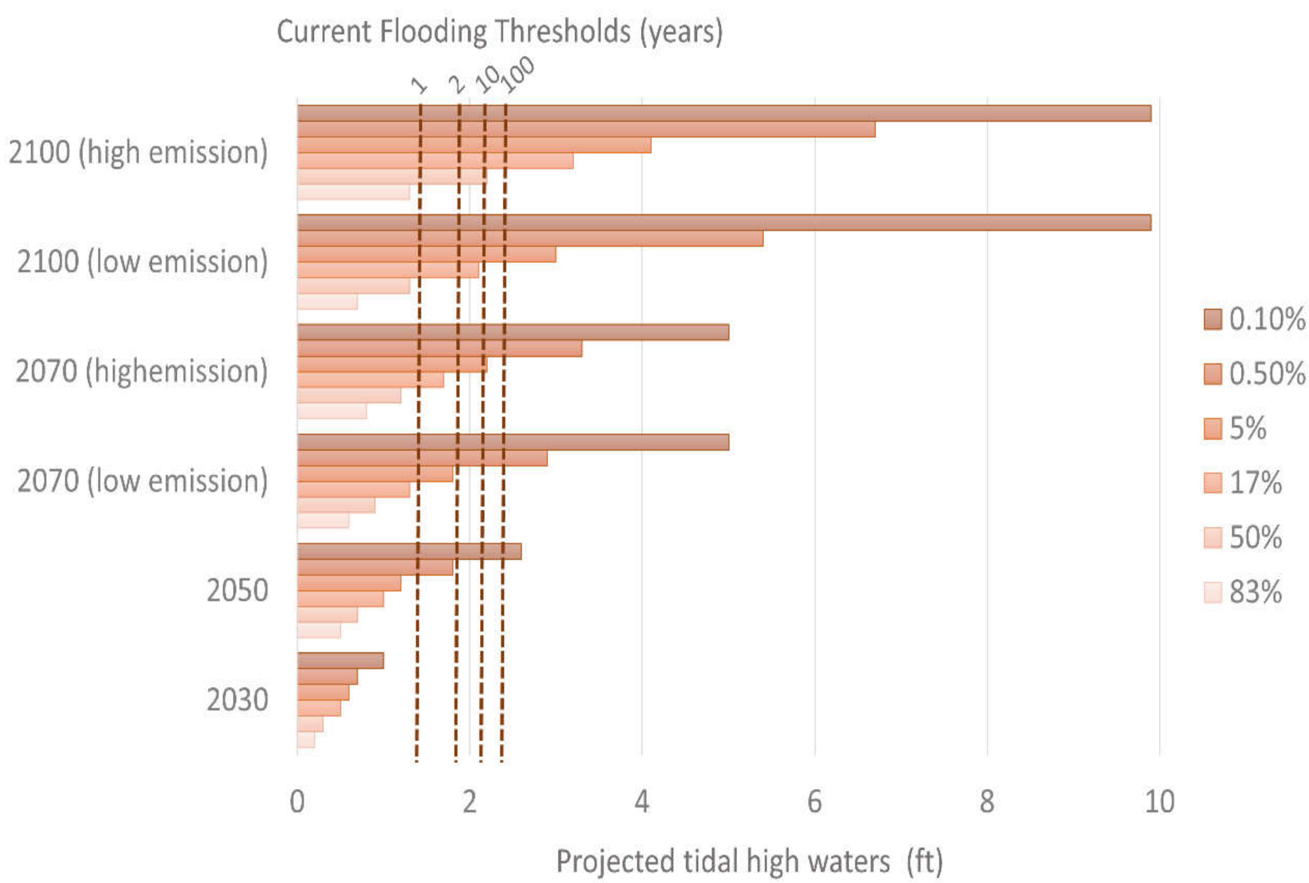


Figure 7: Probability of projected tidal high waters exceeding historic flooding thresholds in a warmer climate for Los Angeles, CA. Dashed vertical lines represent the historic flooding thresholds associated with 1-, 2-, 10-, and 100-year return periods.

Rainfall

Traditionally, infrastructure design and risk assessment rely on the notion of stationarity, which assumes that the statistics of hydroclimatic extremes (e.g., rainfall) do not change significantly over time. However, during the last century, we have observed a warming climate with more intense precipitation extremes in some regions, likely due to increases in the water holding capacity of the atmosphere. Consequently, infrastructure and natural slopes will likely face more severe climatic conditions, with potential human and socioeconomic consequences. In this project, a nonstationary model, used in California's Fourth Climate Change Assessment, to evaluate changes in rainfall intensity-duration-frequency (IDF) curves using historical and future climate model simulations. The inputs include bias-corrected multi-model simulations of historical and projected precipitation extremes from the Coupled Model Intercomparison Project Phase 5 (CMIP5) recommended for California. The approach evaluates changes in rainfall IDF curves and their uncertainty bounds using a non-stationary model based on Bayesian inference. Results show that precipitation extremes are projected to increase relative to the historical condition. This indicates that today's 50-yr rainfall will have a shorter return period in a warming climate. As an example, Figure 8 shows how today's 50-yr and 100-yr events are expected to change RCP 4.5 and RCP 8.5.

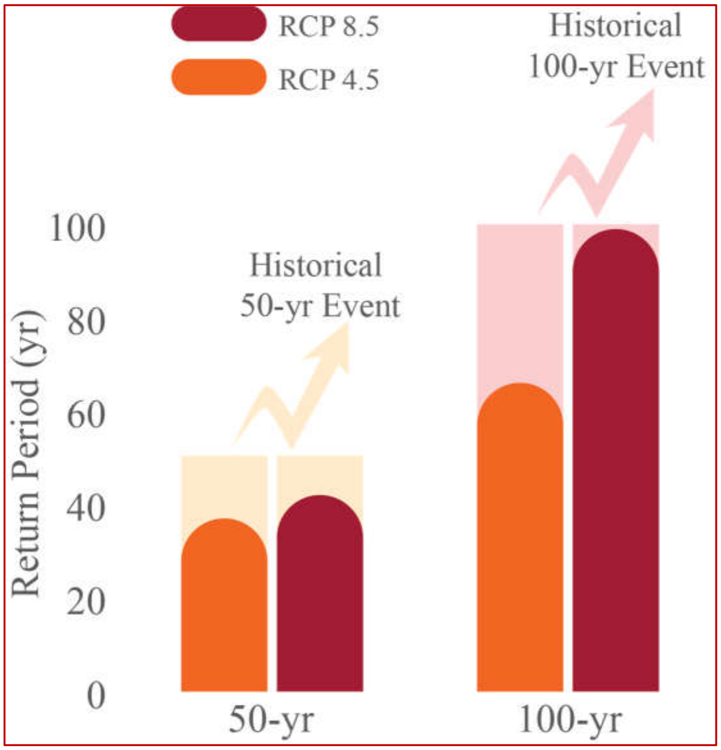


Figure 8: Expected changes to today's 50-yr and 100-yr events under RCP 4.5 and RCP 8.5.

COMPOUND FLOOD SCENARIOS

Compound events correspond to combination of two or more hazards (or climate variables) leading to an extreme impact. In Manhattan Beach, there are two main drivers for coastal flooding: rainfall (pluvial flooding) and ocean water level. As mentioned earlier, climate change can alter the flooding regime in coastal areas of Manhattan Beach through raising the mean water level and altering hydroclimate patterns (i.e., changes in precipitation extremes). For compound flood analysis, NOAA rainfall data and also climate model simulations of the future are used as discussed in the technical report. The historic records of coastal total water level (TWL) for the nearest tide gauge in Los Angeles, NOAA ID: 9410660, is obtained from NOAA's "Tides & Currents" portal for compound flood assessment. This gauge was established in November 1923 and the mean higher high water (MHHW) is 5.29 feet above NAVD88 (during tidal epoch 1983-2001). TWL (a.k.a still WL) measured at this gauge consists of three components: mean sea level (MSL), astronomic tides (AT) and nontidal residuals (NTR):

TWL = MSL + AT + NTR

Astronomic tides (AT) are highly predictable. Based on the calculated tidal constituents at this site, tides are mixed diurnal-semidiurnal with the greater diurnal tidal range of 5.5 ft. The estimates of change in MSL between the present and future time of interest, referred to as sea level rise (SLR), are taken from climate models. The non-tidal residual (NTR) is the part of the sea level that remains once the astronomical tidal component has been removed. This primarily contains the meteorological contribution to sea level, often called the surge.

As discussed in the technical report, there is a statistically significant relationship between NTR and rainfall in Manhattan Beach. In practice, a multivariate model can be constructed by fitting suitable univariate laws on the marginals, and an appropriate copula on the observed pairs. In this project, a recently developed model that comprehensively analyzes the dependence structure between flood drivers is used. The approach models the flood drivers using copula functions to estimate design return periods/levels. This model first fits the appropriate underlying marginal distribution for each of the drivers, from 17 univariate distributions, based on measures of goodness-of-fit including Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC). The copula model will then be selected from a plethora of 26 copula functions available in the literature. Parameters of these copula models are inferred through a Bayesian inference approach with Markov Chain Monte Carlo, to estimate the underlying uncertainties of the modeling framework. Then a hydrodynamic model is used to estimate the stormwater flooding across Manhattan Beach City under each of these compound scenarios. Compound statistical analysis of bivariate extreme samples show that an archimedean copula called Ali-Mikhail-Haq best characterizes the correlation structure between hourly precipitation and NTR (parameters and goodness-of-fit information is available in the technical report). The multivariate analysis leads to the joint relationship between NTR and precipitation (top right panel in Figure 9). For each return period, the model leads to a curve with different combinations of NTR and precipitation extremes. The most likely scenario is derived based on the density of the isoline. The two boundaries (here, extreme rainfall and extreme NTR) indicate rainfall dominated and coastal dominated scenarios. This figure can then be used to extract multi hazard flood water level scenarios under most likely, rainfall dominated and coastal dominated scenarios (see a sample output in lower left panel in Figure 9). Table 1 shows the TWL scenarios for 25-yr, 50-yr and 100-yr events. These bivariate hazard scenarios will be used to force the EPA-SWMM model for Manhattan Beach to characterize the flooding patterns under each of these scenarios.

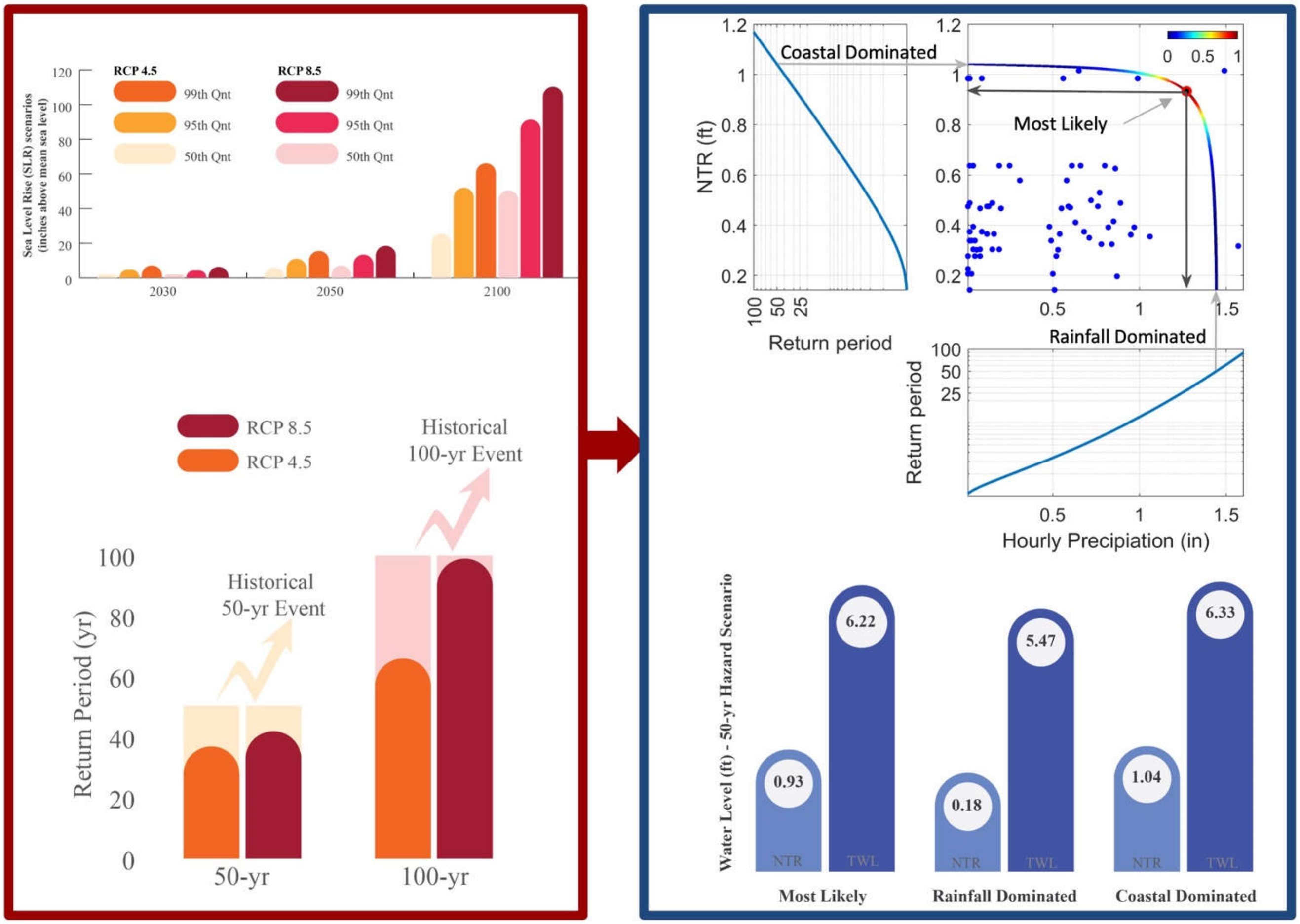


Figure 9: Expected changes to today's 50-yr and 100-yr events under RCP 4.5 and RCP 8.5.

RP (years)	Scenario	1hr rain. (in)	2hr rain. (in)	NTR (ft)	TWL = NTR + MHHW (ft above NAVD88)
25	Most likely	1.04	0.73	0.81	6.10
	Rainfall dominated	1.24	0.87	0.17	5.46
	Coastal TWL dominated	0.00	0.00	0.91	6.20
50	Most likely	1.27	0.89	0.93	6.22
	Rainfall dominated	1.44	1.01	0.18	5.47
	Coastal TWL dominated	0.00	0.00	1.04	6.33
100	Most likely	1.47	1.03	1.06	6.35
	Rainfall dominated	1.63	1.14	0.24	5.53
	Coastal TWL dominated	0.00	0.00	1.17	6.46

Table 1: Bivariate hazard scenarios for various return periods

HYBRID HYDROLOGIC-HYDRAULIC CONFLUENCE MODELING

Runoff Estimation

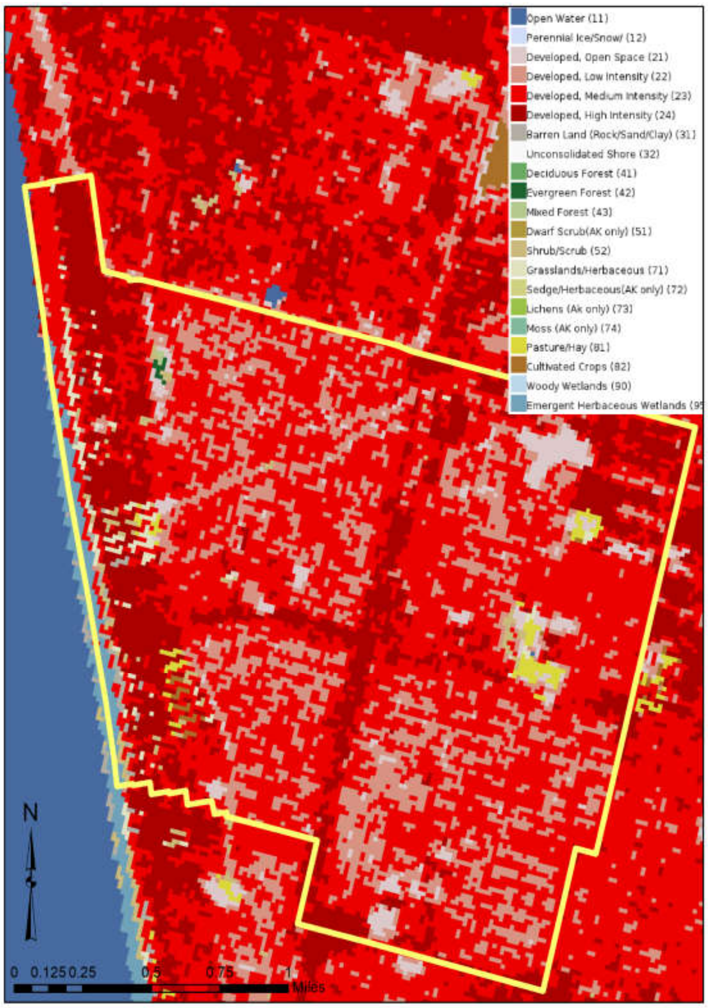


Figure 10: Distribution of land cover and land use in Manhattan Beach area (Data from NLCD 2016).

Manhattan Beach is a highly urbanized system. Figure 10 shows the distribution of land cover and land use types in Manhattan Beach. A large percentage of land in Manhattan Beach are characterized as "Developed" in National Land Cover Database 2016. This means the watershed mainly consists of impervious areas that turn a significant portion of received rainfall to excessive overland runoff. In this system, a man-made system of drainage channels facilitates the movement of runoff through the city and so time of concentration would be significantly less than an undeveloped watershed. For estimation of direct runoff from storm rainfall, the Natural Resources Conservation Service (NRCS) method was used that relates the depth of runoff (Q) to the depth of rainfall (P), and maximum potential retention (S), all in inches, as:

$$\{ P > I_a \rightarrow \quad Q = \frac{(P-0.2S)^2}{P+0.8S} \; P < I_a \rightarrow \qquad Q = 0$$

where, I_a is initial abstraction, which mainly consists of interception, infiltration during early parts of the storm, and surface depression storage. In this method, S is a function of curve number (CN) as:

$$S = \frac{1000}{CN} - 10$$

where, *CN* is a function of land cover, antecedent soil moisture and average slope of the catchment. Elevation contours (Figure 11) was used to generate a slope raster (Figure 12) in order to calculate the average slope of the watershed. The results of this geospatial analysis suggested an average 8.5% slope that was used for runoff coefficient calculation.

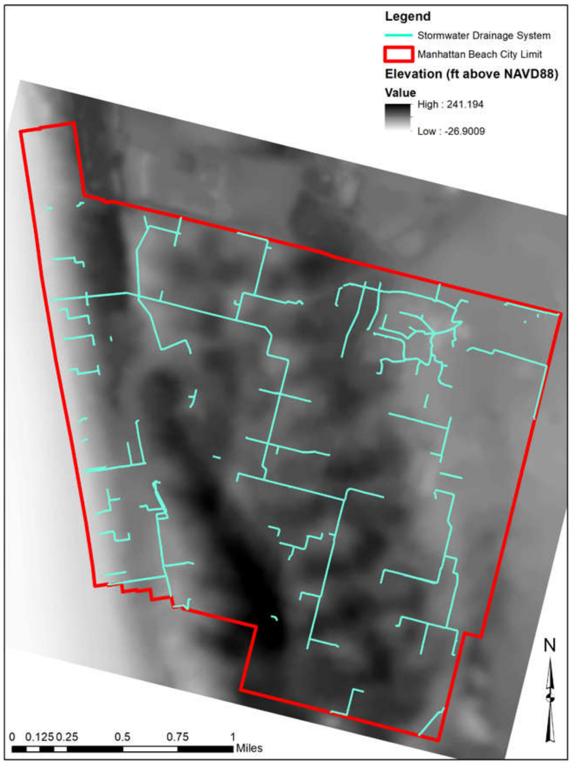


Figure 11: Elevation map of the City of Manhattan Beach.

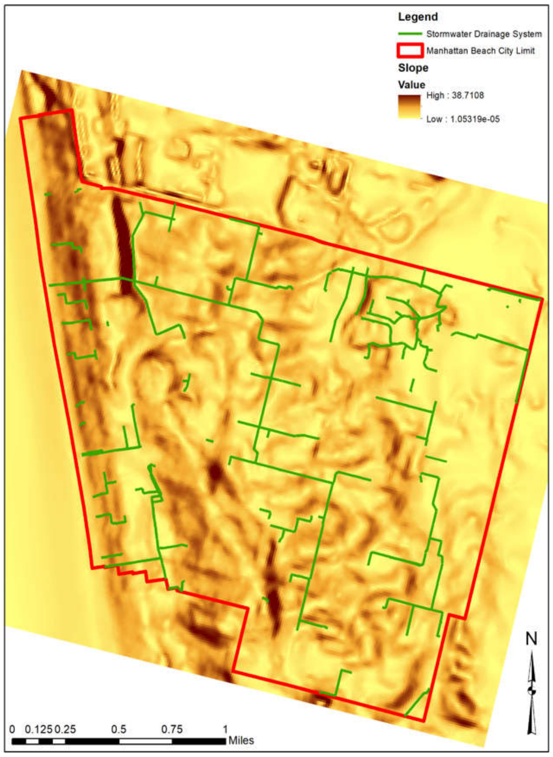


Figure 12: Slope map of the Manhattan Beach area.

Stormwater Modeling

The compounding effects of different flood drivers significantly contribute to the flood dynamics in urbanized coastal systems. Stormwater drainage systems are typically designed under the assumption of free outlet for delivering the inland fluvial/pluvial flooding to the ocean. With rising sea levels, the community may experience flooding from a design rainfall (or even smaller) events due to the blockage of outlet by a greater than normal coastal water level (i.e., a King tide), causing significant impacts. Numerical models have been developed to study the physical interaction of extreme fluvial/pluvial and coastal flooding drivers. Here, a hybrid hydrologic-hydraulic model was used for simulating compound coastal flooding based on the multi-hazard scenarios discussed earlier. The numerical model of the Manhattan Beach stormwater drainage system was developed in EPA-SWMM 5.0 to simulate the dynamical response of drainage system to under historical and future compound hazards. The outcome of such analysis will be fundamental to evaluating vulnerability of the current infrastructure to the projected extreme rainfall, sea level rise, extreme coastal water levels and their compounding effects.

Model setup

A coupled hydrologic and hydrodynamic (H&H) model of stormwater drainage system of Manhattan beach was developed to simulate the flow of excessive rainfall through the system and determine the flooding patterns under compound hazard scenarios of interest. Stormwater modeling of Manhattan Beach consists of a hydrologic model that simulates extreme rainfall event and the associated runoff generated overland. The generated runoff then will be dynamically routed through the drainage system and via outlet enter the coast of Pacific Ocean. How the model is developed, validated and applied is discussed in detail in the technical report. In the following, a brief summary is provided.

EPA-SWMM 5.0 offers a lumped hydrologic modeling module for generating synthetic storms over an urban watershed and tracking the generated runoff over each subcatchment to the inlets of the drainage system. Characteristics of the rainstorm event (i.e. intensity and duration) depends on the reginal hydroclimatic characteristics of the watershed and is highly variable across space. Characteristics of the generated runoff is a function of catchment features including land use land cover, slope and soil properties. For the same rainfall events, urbanization factors, such as large impervious areas (i.e. paved surfaces and roofs), intense channelization, and low overland flow roughness, can increase the flood risk through increased total volume of runoff and shorter time to flood peak.

The hydrologic model consists of fourteen subcatchments, from which two main subcatchments draining to the ocean. A dynamic wave model is used to rout the generated runoff throughout the system. Ponding is allowed over the subcatchments and routing time step is set to be 30 seconds. This time step yields in stable runs with acceptable model error (see the results section and Appendix 1 of the technical report for details).

Hydraulic modeling

As-Built drawings of the Manhattan Beach's storm drainage system available from the Los Angeles County Storm Drain System portal (https://pw.lacounty.gov/fcd/StormDrain/index.cfm) were used to build the model. These plots include detailed information about the hydraulic characteristics of the system, including length and cross-sectional dimensions (i.e. circular, box or horseshoe) elevations of manholes and conduit materials. As-Built drawings were used to set up the numerical model of the Manhattan Beach stormwater drainage system in EPA-SWMM 5.0. The hydraulics model consists of 60 nodes, including maintenance holes and outlets, and 58 links, including channels and culverts. All the modeled links are made of reinforced concrete and hence, the typical manning roughness coefficient of n = 0.014 was used in the model. Figure 13 shows a snapshot of information needed for detailed hydraulic modeling of the stormwater drainage system (see Figure 14 for the map of all hydraulic components).

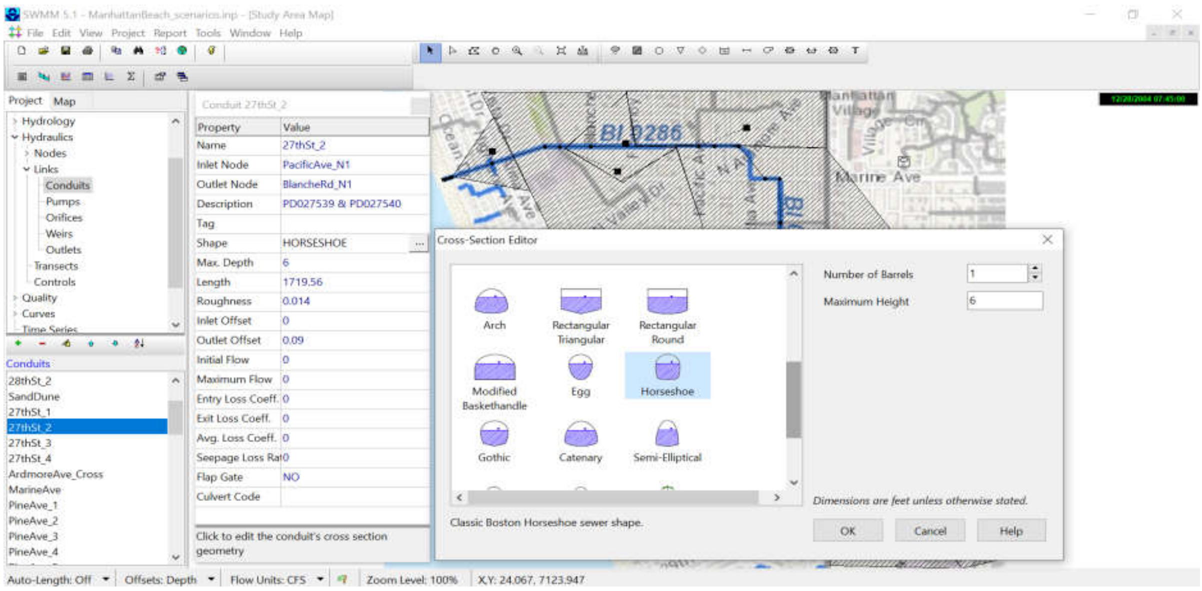


Figure 13: A sample snapshot of the hydraulic modeling module in EPA-SWMM 5.1. The code inside description box refers to the drawing file number on Los Angeles County Storm Drain System portal from which we obtained detailed information about the links.

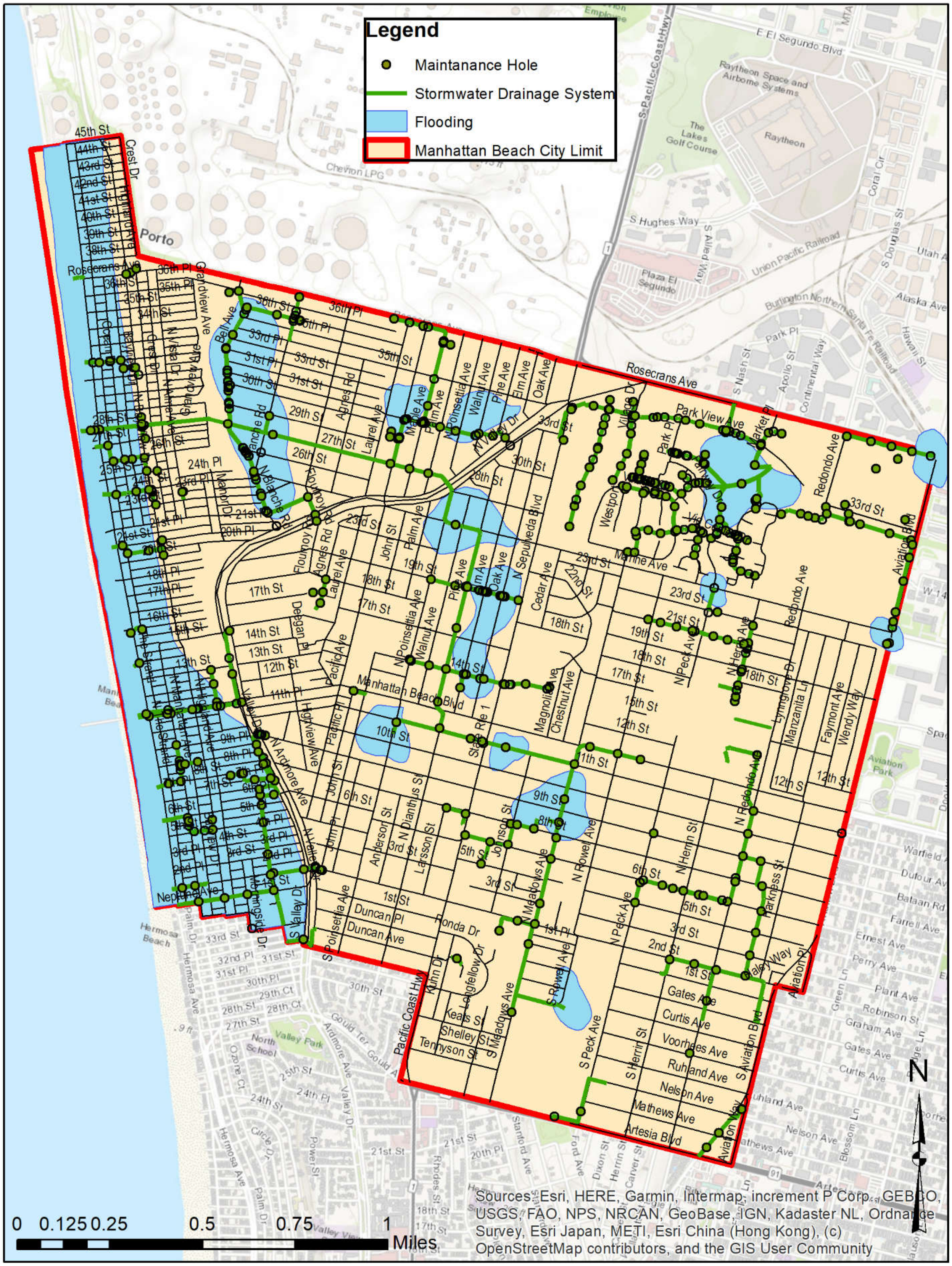


Figure 14: Map of Manhattan Beach's storm drainage system and observed/reported flooding during a storm in 2004 used for validation of the model.

Model Validation and Simulations

Local flood information from a historic event in Manhattan Beach, occurred in December 28, 2004, is used for validation and verification proposes. On that day, Manhattan Beach experienced two consecutive extreme floods one in the morning and one in the afternoon. The first storm with a larger volume and peak rainfall intensity, started at 2:00 AM, reached a peak intensity of 0.80 in/hr around 7:00 AM, and ended at 11:00 AM. The morning storm was followed by an afternoon storm with a peak intensity of 0.66 in/hr between 5:00 - 6:00 PM (see the time series in the technical report).

To appropriately force the model under compounding effects of rainfall and coastal sea level, the outlets were forced with the tidal record observed at the tide gauge in Los Angeles (NOAA ID: 9410660). On December 28, 2004, the coast of Manhattan Beach experienced a spring tide with the greater diurnal tidal range of 6.3 ft, and 0.75 ft of non-tidal residual at the time of higher high water. The verified total water level at the time of peak was 1.17 ft above MHHW.

The only available information for validation was the recorded calls about flooded locations. However, the information did not include the actual volume, depth and duration of flooding. For this reason, we were not able to quantitatively compare the model flow depth outputs with actual observations. However, comparing the outputs with the reported floods can be used to ensure the model generates floods consistent with observations. Model simulations showed at 6:00 AM, four hours after the storm started, even before reaching the storm’s peak intensity, a number of conduits reached their capacity around Voorhees Ave, along the S Meadows Ave, and some other conduits capacity (e.g., near the cross section of Valley Dr. and 27th St) reached close to their maximum. These are within close proximity of neighborhoods reported storm-related calls available from the City of Manhattan Beach.

Around 8:00 AM, extensive flooding occurred around the town and flow in majority of conduits along the larger network (draining to the northwest boundary outlet) exceeded the network capacity. The model simulations are again in line with spatial pattern of storm-related calls received between 7:00 and 8:00 AM on December 28, 2004 showing surcharge of runoff out of maintenance holes across the city including along the S Meadows Ave and Pine Ave (see Figure 15 and the technical report for more details about model validation). After validation, the model was used to run a wide range of (more than 100) univariate and compound hazard scenarios. All the simulations including water profiles are available the technical report, and hence are not included here for brevity.

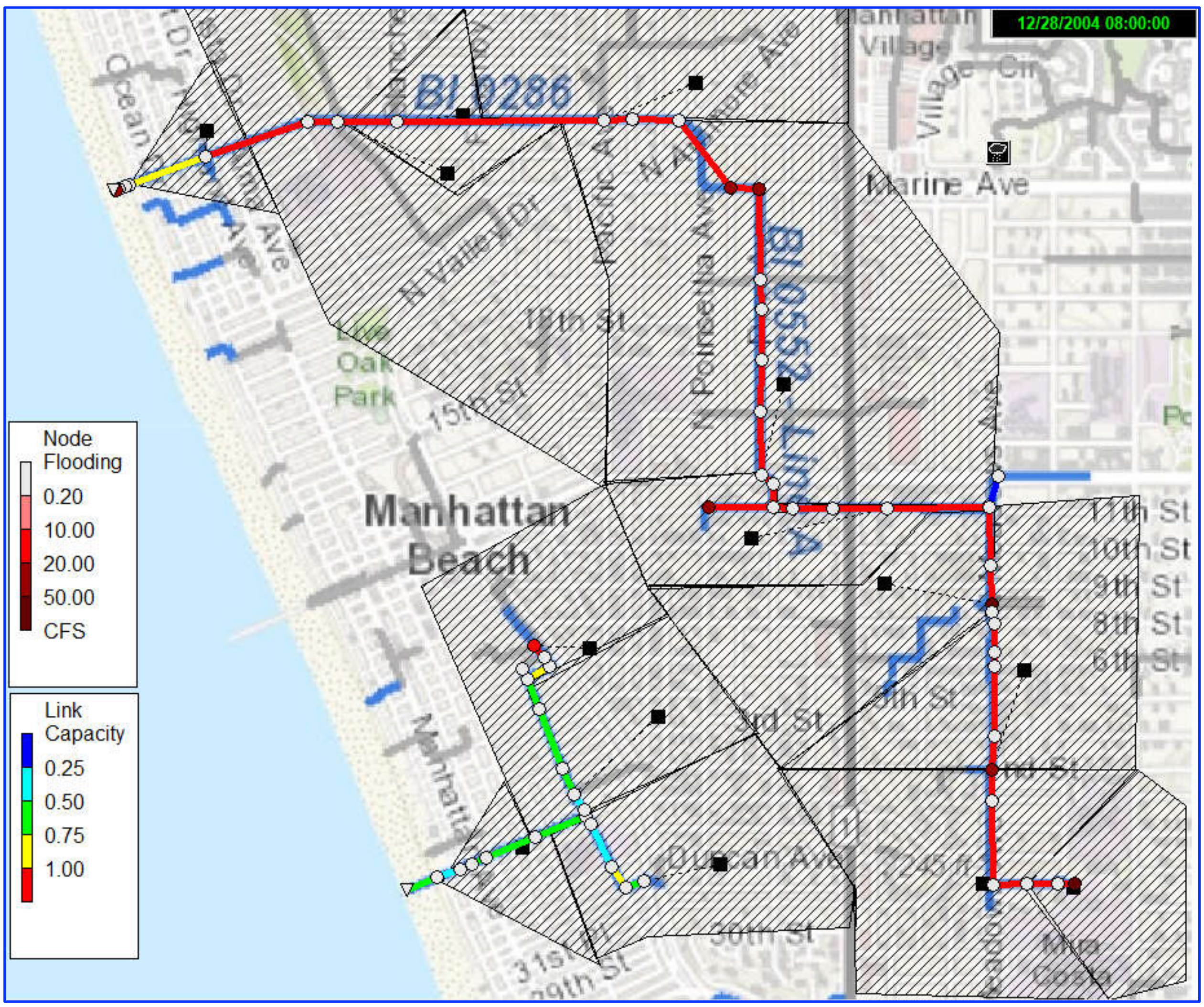


Figure 15: Simulated status of network at 8:00 AM, December 28, 2004.

Appendix B

Shoreline Evolution Model

Shoreline Evolution Model

In order to project beach widths through time, ESA applied its “two-line” shoreline evolution model that separately tracks shoreline and backshore erosion with beach width. The shoreline evolution model relies on historic shoreline and backshore erosion rates, shore geometry and sea-level rise amounts to calculate future erosion distances and beach width along the length of Manhattan Beach.

The City of Manhattan Beach has a uniform-width beach spanning about 400 feet on average between the Pacific Ocean and the edge of development. Historic erosion rates were taken from the CoSMoS beach erosion transects’ shoreline erosion rates. Sea-level rise predictions were taken from the medium-high risk aversion scenario from the State of California’s Sea-Level Rise Guidance document (OPC 2018). The CoSMoS historic erosion rates were applied to the beach edge and the backshore was assumed to be held in place (at the development line). Existing beach widths were determined for each transect using the CoSMoS transect profiles, the CoSMoS backshore line, and a shoreline based on mean high water (MHW)[1]. Shore geometry (foreshore slope and shoreface slope) was calculated using an estimated depth of closure point.

Beach Width

The beach width is the distance between the shoreline and the backshore. A starting beach width was estimated for each transect using the representative distance between the MHW line and the backshore location, as identified in CoSMoS. Subsequent beach widths are calculated based on the relative movement of the shoreline and backshore. If the shoreline erodes more quickly than the backshore, then the beach narrows, and vice versa.

Shoreline Movement

Three components contribute to shoreline movement in this quantified conceptual model: landward movement due to sea-level rise, shoreline erosion caused by other coastal processes (e.g., waves, wind, changes in sediment supply), and seaward movement of the shore due to sand placement activities:

$$Shoreline\ Movement = SLR\ transgression + Ongoing\ erosion + Beach\ nourishment$$

To evaluate how the shore may evolve if the City takes no action, beach nourishment was not included in the model. The other two components are explained in further detail below.

Sea-Level Rise Transgression

The impact of sea-level rise on shoreline movement is incorporated by assuming that the shoreline will move inland based on the shape of the beach profile and the amount of sea level rise:

$$Sea\text{-}Level\ Rise\ Transgression = \frac{increase\ in\ sea\ level}{shoreface\ slope}$$

The shoreface slope used in this equation generally depends on whether or not the backshore is eroding. Figure 1 shows how the sea-level rise erosion changes with beach width. When the backshore is not allowed to erode or

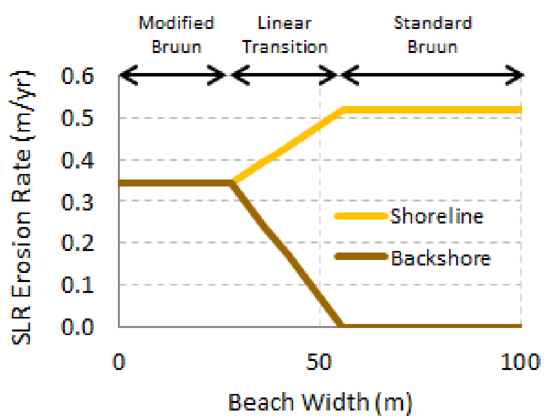
[1] MHW=4.55 ft NAVD88, from NOAA Santa Barbara tide gage.

the beach is so wide that backshore erosion is not occurring, both of which are true of this study, the shoreline erodes according to a standard Bruun[2] slope, which is the slope between the depth of closure and the backshore toe location (shoreface height/active profile length).

If the backshore was allowed to erode, it would release sand into the system that would slow future erosion. This case would require a modified Bruun slope, which accounts for the eroding dune height, and is calculated as below:

$$Modified\ Bruun\ slope = \frac{shoreface\ height + dune\ height}{active\ profile\ length}$$

The model assumes a linear transition between when a regular Bruun slope is used and when the modified Bruun slope is used (Figure 1**Error! Reference source not found.**). When the beach is more than 2x wider than the stable beach slope, the Bruun slope is used. When the beach is narrower than the stable beach slope and the backshore is allowed to erode, the modified Bruun slope is used. In between these two beach widths, the erosion is linearly interpolated between the two methods.



SOURCE: ESA

Figure 1
Example of empirical relationships between sea-level-rise-induced erosion rate and beach width

As the rate of sea-level rise increases towards the end of the century, the contribution of sea-level rise to shoreline movement will likely be greater than ongoing erosion.

Erosion

All beaches have an historic shoreline trend – either towards erosion or accretion. If no action is taken, and the beach is allowed to erode, this component of erosion will remain constant. However, if actions are taken that modify the beach's behavior (like beach nourishment or building a seawall), this component of erosion can increase or decrease. In general, historic erosion rates in Manhattan Beach show net accretion over time, so the

[2] Bruun, P., 1962. Sea-level rise as a cause of shoreline erosion. Proceedings of the American Society of Engineers. Journal of the Waterways and Harbors Division 88, 117-130.

baseline historic erosion rate was set to zero erosion in the two-line model to estimate conservatively high future erosion.

In this model, shoreline erosion is specified as a function of beach width. When the beach is nourished, the beach widens and the shoreline moves seaward. In this unusually wide beach configuration, the shoreline erosion rate is expected to increase (Dean 2002). If the beach narrows (either due to sea-level rise or background erosion combined with holding the line), shoreline erosion decreases. An exponential empirical relationship was established between shoreline erosion rate and beach width that reflects this conceptual model.

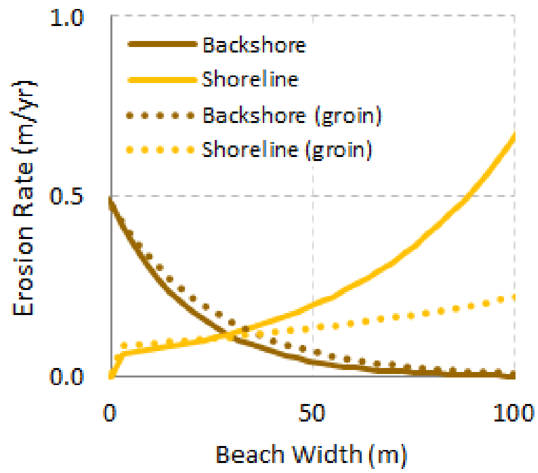
$$E_{shoreline}(t) = \min(E_{shoreline,historic} * e^{a\left(\frac{BW(t)}{BW_{stable}} - 1\right)}, E_{shoreline,max})$$

Where:

$E_{shoreline}$ (t)	= Shoreline erosion at time t
$E_{shoreline, historic}$	= Historic shoreline erosion rate
$E_{shoreline,max}$	= Maximum shoreline erosion rate
BW (t)	= Beach width at time t
$BW_{ambient}$	= "Ambient" beach width
a	= calibration parameter for erosion rate responsive to beach width

Similar exponential relationships have been proposed for existing sand placement projects (Dean 2002). One assumption is that sand placements are self-similar. Previous studies have shown that an exponential relationship may overestimate the erosion rates (Dette et al. 1994). Because very little data exist related to response of shoreline erosion to sand placement, the decay parameter was selected based on wave exposure. Then, the value of (a) is increased in areas with higher wave exposure and decreased in reaches with lower wave exposure. When a groin is implemented, the decay parameter is reduced by 50%, to account for the reduced potential sediment transport. In beach nourishment scenarios, the decay parameter can be increased over time to reflect decreasing availability of beach-sized sediments (finer sediments are removed from the system more quickly). See the discussions about beach nourishment below for more detail.

An example of this relationship is plotted in Figure 2. When the beach width is equal to the ambient beach width, the erosion rate is equal to the long-term historic erosion rate. The equation is capped with a maximum erosion rate to acknowledge that there is a limit to how quickly sand can be removed from the beach. A high value of the calibration parameter (a) leads to erosion rates being more responsive to beach width. A value of 0 would result in a constant erosion rate equal to the historic erosion rate, regardless of beach width.



SOURCE: ESA

Figure 2
Example of empirical relationships between erosion rate and beach width

Beach Nourishment

When implemented, beach nourishment widens the beach by shifting the shoreline seaward. The amount the shoreline is shifted seaward depends on the volume of sand placed on the beach, the beach profile, and sand quality. In this analysis, we assumed no beach nourishment.

Model Results

Under the medium-high risk aversion sea-level rise scenario, the average total beach width is expected to decrease to 310 feet by 2060 from its current width of 370 feet. By 2100, 200 feet of beach will remain.

Table 1
Total Beach Width Evolution by Decades

Year	Total beach width (ft)	Percentage Lost
2020	370	0%
2030	360	2%
2040	350	5%
2050	330	11%
2060	310	16%
2070	290	22%
2080	260	29%
2090	230	37%
2100	200	47%

Appendix C

Manhattan Beach Sea Level Rise Driven Groundwater Impacts on Infrastructure

Impact of Sea Level Rise on Manhattan Beach Coastal Aquifers and Groundwater Tables

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Introduction
Coastal communities throughout California are actively planning for coastal impacts from climate change. Many impacts, such as sea level rise, wave action, coastal storms, storm surges, shoreline change, and bluff erosion, have a comprehensive suite of scientific information that can help communities plan. Accordingly, many communities have either completed, or, as in the case of the City of Manhattan Beach, are in the course of conducting, sea level rise vulnerability assessments. This is an initial step generally followed by identification of appropriate climate adaptation strategies if those are warranted.

Emerging research indicates that sea level rise, in addition to its potential to increase overland flooding, can also lead to rising shallow groundwater tables and create flooding hazards where not previously or generally expected. Rising groundwater can:

- Emerge at the surface as ponded water or create areas of saturated soil that previously were dry
- Infiltrate underground wastewater and stormwater pipes, cause foundations to heave, and require extensive underground waterproofing;
- Increase the risk of soil liquefaction in a seismic event;
- Remobilize old soil contaminants, creating problems for public health and ecosystem health.

While this is an area of ongoing research, the USGS, in collaboration with Dr. Kevin Befus (U. of Arkansas), recently published model results that project the impact of rising sea levels on shallow coastal aquifers for the entire California coastline. The Coastal Storm Modeling System-Groundwater (CoSMoS-GW), builds on the CoSMoS model, which is being used by the City of Manhattan Beach in its assessment of the City's exposure to rising sea levels and coastal storms. The modeling was supported by a combination of CA Ocean Protection Council funds and internal funding from USGS.

The City of Manhattan Beach used CoSMoS-GW data to better understand its vulnerability to the potential impacts of rising seas on coastal water tables, and potentially on the City's coastal assets. Study methods and results are presented in this report, along with discussion of the findings. These findings are also summarized in the main body of this report: *Sea Level Rise Risk, Hazards, and Vulnerability Assessment, City of Manhattan Beach.*

Methods

Groundwater Modeling:

CoSMoS-GW uses high-resolution numerical modeling based on the U.S. Geological Survey (USGS) MODFLOW[1] program to calculate groundwater flow. Groundwater flow is modeled in three dimensions, driven by average annual recharge (water infiltrated through the ground surface), with the model allowed to stabilize to steady-state for each model run. The model uses a range of hydraulic conductivities (K; 0.1, 1 and 10 m/d) and coastal water level boundary conditions (MHHW (Mean Higher-High Water) and LMSL (Local Mean Sea Level)) to capture the range of likely conditions for coastal California. Steady-state groundwater tables are determined for 12 SLR conditions from present-day (0) to +5 meters (m). The full model includes a drain function that allows groundwater reaching the ground surface to be removed from the model via overland or stream channel flow. "Linear" runs also were performed with the drain feature disabled for comparison to other studies, but because the "Linear" results do not differ significantly from full model runs in Manhattan Beach, only the full model results were considered for this study.

In interpreting CoSMoS-GW model results, it is important to note that year-to-year variations in recharge are not considered in the model. Significant year-to-year fluctuations in groundwater table heights can be expected in response to natural fluctuations in annual recharge (e.g. associated with either extended drought conditions or years with unusually high rainfall). Similarly, effects due to seasonal and tidal fluctuations are not considered, although these should be relatively small due to the slow response of groundwater levels to external forcing in most areas. Impacts due to human activities (e.g. pumping, drains, augmentation) also are not considered but may be important in some areas. Model results discussed here provide the baseline long-term average water table heights that would be overprinted by seasonal, tidal, and other transient signals. For these results, areas with emergent groundwater (where the groundwater table rises above the surface of the ground) would be likely to experience chronic 'sunny day' surface flooding (i.e., surface flooding even in the absence of heavy precipitation), while areas of deeper groundwater might not produce visible impacts at the ground surface but might still impact buried assets. Full CoSMoS-GW modeling methodology is described in Befus et al., (2019).

Stormwater System Analysis:

Stormwater infrastructure vulnerability to SLR driven groundwater shoaling was assessed by determining the elevation of stormwater outfalls relative to predicted CoSMoS-GW groundwater tables for present and future sea-level rise conditions. Coastal stormwater systems generally are designed so that stormwater discharges at or above receiving water levels; receiving water levels that are higher than the outfall height (i.e. the discharge is partially or fully submerged) will impede stormwater discharge and potentially increase upstream flooding. Stormwater outfalls typically are at or slightly above the ground surface, so a first-order assessment of stormwater system vulnerability to SLR can be obtained simply by determining the depth to groundwater from the ground surface at the outfall location. For outfalls with known elevations relative to the ground surface, vulnerability can be determined more precisely.

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[1] MODFLOW: https://www.usgs.gov/mission-areas/water-resources/science/modflow-and-related-programs?qt-science_center_objects=0#qt-science_center_objects

Twenty-two coastal stormwater outfalls were identified in Manhattan Beach (Table 1, Figure 1). Outfall locations were estimated using a stormwater infrastructure shapefile provided by the City.[2] Stormwater line feature (pipe) endpoints were converted to points in ArcGIS, with the point at the seaward end of the system providing an estimate of the location of the outfall. Elevations were not available in the shapefile, so as-built drawings retrieved from an online library of Los Angeles County Storm Drain information[3] were used to obtain information on outfall elevations.

Of the 22 outfalls identified, online drawings were only available for six. Drawings did not typically specify the vertical datum for elevation measurements, but one stated that the vertical measurements were in “feet above the U.S.G.S. mean sea level datum”. That is not a current datum, but based on the time period (1960 – 1982) and annotated values for Maximum Mean High Water (MMHW) and Mean Higher-High Water (MHH) that are very close to superceded (1960-1978) values from the NOAA Los Angeles Tide Station, it appears that the drawing datum is very close to NOAA Mean Sea Level (MSL) for that period. Because CoSMoS-GW groundwater table elevations are relative to the NAVD88 vertical datum, stormwater discharge elevations were converted from NOAA MSL to NAVD88 using a vertical adjustment of 2.62’. For outfalls without elevation information, the ground elevation at the outfall location was extracted from the high-resolution digital elevation model (DEM) used for the groundwater model and used as an estimate of the minimum outfall elevation (as noted above, outfalls normally are built to discharge at or above the ground surface).

Depth to groundwater from the ground surface was extracted from appropriate model results at all outfall locations. Where possible, depths were then adjusted for outfall elevation relative to the ground surface. Because outfalls typically are at or above the ground surface, depth from the ground surface is expected to provide a conservative (greatest risk) estimate of hazard potential. Similarly, this analysis considered only models using the MHHW boundary condition (1.591m) because that produces the highest (most conservative with respect to risk) water tables. The lower Local Mean Sea Level boundary condition (0.792m) produced significantly lower and thus less hazardous groundwater tables. The actual boundary condition controlling the height of groundwater discharging at the coast in Manhattan Beach is likely to be somewhere between MHHW and LMSL but additional data would be needed to estimate it accurately.

Because geologic and hydraulic data were not available to directly estimate a specific hydraulic conductivity for Manhattan Beach, depths to groundwater were determined for all of the modeled hydraulic conductivities (K; 0.1, 1 and 10 m/d). Hydraulic conductivity is a measure of how easily water moves through the subsurface; dense, compact, clayey soils will have relatively low values, while looser substrates like sand and gravel will have higher values. For the entire State of California, water tables measured in shallow coastal wells generally fall between model results for the K 1 and K 10 cases. Well logs included with some of the as-built drawings show mostly sandy substrate in Manhattan Beach, suggesting that, like the State as a whole, a K of 0.1 likely is inappropriate for this area, but that a value between 1 and 10 probably is reasonable. Depths to groundwater were determined for this analysis for sea-level rise values of 0 (present day), 1, 2, and 3m.

[2] Shapefile (MB_StormPipes) was provided by the City of Manhattan Beach.
[3] pw.lacounty.gov/fcd/StormDrain/index.cfm, accessed 11/30/20

Study Asset ID	Outfall ID	Location
1	s9d100	44th St
2	s9d110	43rd St
3	s9d120	41st St
4	s9d130	39th St
5	s10d10	Rosecrans
6	s10d20	32nd St
7	s10d30	28th St
8	s10d40	27th St
9	s10d50	24th St
11	s10d60	21st St
10	s10d55	Marine Pl
12	s10d70	18th North
13	s10d75	18th South
14	s10d80	14th St
16	s11d2	Pier South
15	s11d1	Pier North
17	s11d5	9th St
18	s11d10	8th St
19	s11d15	7th St
20	s11d20	6th St
21	s11d23	2nd St
22	s11d25	1st St

Table 1. List of stormwater outfalls reviewed, including unique asset ID (column 1), City of MB outfall identification (column 2), and location (column 3).

Figure 1. Map of stormwater outfall location endpoints extracted from City shapefiles. Outfalls numbers correspond to labels in Table 1.

Unconfined coastal groundwater consists of relatively dense saline groundwater (infiltrated into the subsurface from the adjacent ocean) with fresh groundwater floating on the saline groundwater due to its lower density. As a result, even if fresh groundwater is only a small portion of the overall groundwater volume (e.g., in arid regions like Southern California) unconfined saline groundwater can be expected to rise with SLR and may create groundwater hazards. Saline groundwater levels can be expected to be similar to the adjacent sea level, but with little or no tidal fluctuation. To evaluate how much the <u>fresh</u> groundwater modeled in the study contributes to groundwater heads at the outfalls (compared to the underlying saline groundwater from marine intrusion), groundwater heads at the outfalls were compared to the MHHW boundary condition height. The difference in height was used to estimate the freshwater contribution to the groundwater table height. Results from this analysis show that, especially near the coast, the freshwater portion produces only a small (~1 to 7") increase in the overall water table height. Based on these results, it appears that most of the long-term steady-state risk associated with groundwater shoaling in Manhattan Beach can be assessed simply by considering SLR impacts on the saline groundwater table. However, it is important to note that increases in the fresh groundwater table will occur following unusually wet periods, potentially leading to temporary fresh groundwater shoaling issues in lower elevation areas.

Wastewater System

Wastewater system information was extracted from shapefiles provided by the City of Manhattan Beach. As with the stormwater system, x and y locations were determined for pipe segment endpoints in the most seaward portion of the wastewater system, which runs parallel to the shore, seaward of The Strand (Figure 2).

Figure 2. Map of sewer pipe segment endpoints extracted from City shapefiles.

For this study, no as-built drawings or plans were available to determine belowground sewer line depths. However, current code indicates that sewer lines generally should be located no deeper than ~2 m below ground level. Therefore, the depth to groundwater was estimated conservatively (maximum risk) by assuming that the bottom of the sewer line was located a full 2 m below the land surface, using ground elevations at the pipe segment endpoints from the model DEM.

Results and Discussion

Fresh groundwater abundance and associated impacts for the City of Manhattan Beach are likely to be minor due to low recharge (~2.5 cm, or 1" per year) and relatively permeable sandy substrate (boring logs for outfalls 7-10, 18, and 22 show that all are in areas of fine to medium-fine sand). Modeled water tables (WT) show relatively slow increases in elevation moving inland, even for K = 0.1, the lowest (and very unlikely) hydraulic conductivity case, while land surface elevations increase relatively rapidly, indicating that any SLR-driven GW shoaling impacts are likely to be confined to a narrow strip along the coast (Figures 3 and 4).

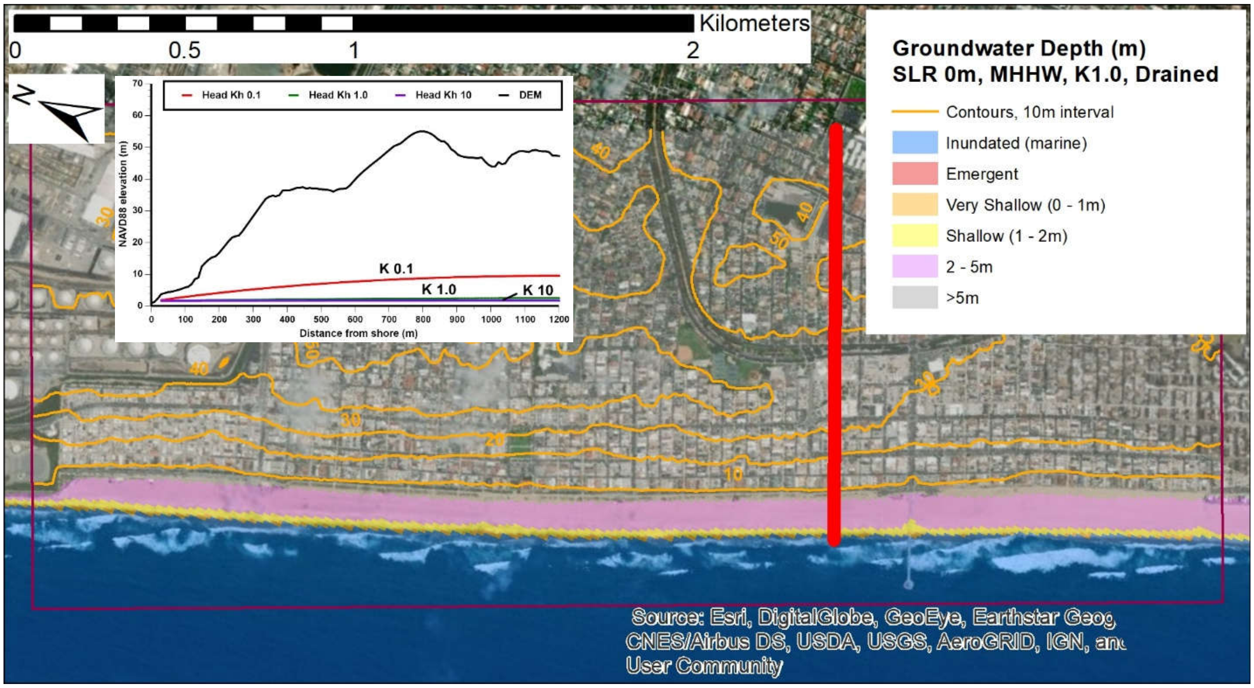

Figure 3. Modeled groundwater depth for SLR 0, K 1.0, and MHHW boundary condition. Inset shows the ground surface (DEM) and water table elevations along the red transect line for K = 0.1, 1 and 10 m/d. Groundwater depths for the case shown in the main figure (SLR 0, K 1.0, MHHW) are all > 5m at the Strand and increase rapidly moving inland, indicating that any groundwater impacts on buried infrastructure will be restricted to a narrow region along the coast.

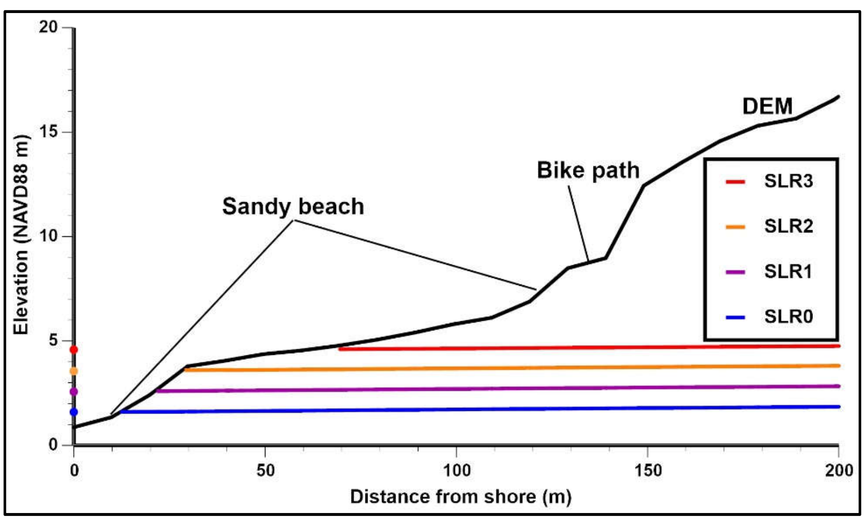

Figure 4. Groundwater table elevations for the MHHW K 1.0 model with SLR values of 0, 1, 2, and 3m along the red transect line in Figure 3. Water tables rise almost linearly with SLR, but the rapid increase in ground elevation at and just inland of the bike path limits potential groundwater shoaling impacts inshore of that region. MHHW boundary condition heights for each SLR case are shown by dots on the vertical axis. Note that the sandy beach portion of the DEM profile changes significantly from summer to winter as the beach erodes in the winter and accretes in the summer leading to burial of the 2 most seaward outfalls.

-500	Inundated (marine)
	Emergent
	Very Shallow (0 - 1m)
	Shallow (1 - 2m)
	Deeper than 2m

		Depth to groundwater (m)											
		K 0.1				K 1.0				K 10			
Label	Name	SLR 0	SLR 1	SLR 2	SLR 3	SLR 0	SLR 1	SLR 2	SLR 3	SLR 0	SLR 1	SLR 2	SLR 3
1	44th St	3.344	2.512	1.755	1.116	4.549	3.567	2.590	1.628	4.673	3.674	2.677	1.681
2	43rd St	3.028	2.194	1.446	0.831	4.173	3.190	2.213	1.254	4.289	3.291	2.293	1.298
3	41st St	3.075	2.240	1.460	0.825	4.332	3.348	2.369	1.407	4.460	3.461	2.464	1.467
4	39th St	3.290	2.455	1.674	1.043	4.634	3.650	2.671	1.709	4.771	3.772	2.774	1.778
5	Rosecrans	3.360	2.516	1.730	1.164	4.671	3.687	2.707	1.751	4.804	3.806	2.808	1.812
	32nd St	3.532	2.685	1.915	1.341	4.884	3.900	2.920	1.965	5.022	4.024	3.026	2.030
6	32nd St	3.532	2.685	1.915	1.341	4.884	3.900	2.920	1.965	5.022	4.024	3.026	2.030
7	28th St	1.228	0.393	-500	-500	1.571	0.589	-500	-500	1.607	0.609	-500	-500
8	27th St	2.657	1.810	1.067	0.510	3.898	2.914	1.935	0.983	4.025	3.026	2.028	1.033
9	24th St	4.641	3.797	3.005	2.386	6.047	5.063	4.083	3.122	6.190	5.192	4.194	3.198
10	Marine Pl	3.623	2.779	1.975	1.385	4.983	4.000	3.019	2.060	5.122	4.124	3.126	2.130
11	21st St	4.102	3.261	2.452	1.932	5.540	4.556	3.575	2.622	5.686	4.688	3.690	2.695
12	18th North	4.083	3.246	2.425	1.930	5.520	4.537	3.555	2.604	5.667	4.669	3.670	2.675
13	18th South	4.104	3.266	2.446	1.977	5.559	4.576	3.594	2.645	5.708	4.709	3.711	2.716
14	14th St	3.609	2.765	1.966	1.448	5.071	4.088	3.106	2.155	5.221	4.222	3.224	2.229
16	Pier South	3.040	2.207	1.577	1.513	4.590	3.607	2.629	1.733	4.748	3.750	2.752	1.762
15	Pier North	2.331	1.496	0.867	0.748	3.817	2.834	1.856	0.954	3.969	2.970	1.973	0.982
17	9th St	4.152	3.326	2.541	2.123	5.853	4.871	3.889	2.950	6.028	5.030	4.032	3.038
18	8th St	3.506	2.687	1.890	1.423	5.249	4.267	3.285	2.340	5.430	4.432	3.433	2.439
19	7th St	3.175	2.351	1.553	1.097	4.849	3.867	2.884	1.941	5.022	4.024	3.025	2.031
20	6th St	3.480	2.663	1.864	1.382	5.248	4.266	3.284	2.337	5.431	4.433	3.435	2.440
21	2nd St	3.885	3.073	2.300	1.841	5.643	4.661	3.680	2.737	5.827	4.829	3.831	2.837
22	1st St	1.492	0.641	0.044	-500	2.011	1.025	0.053	-500	2.066	1.068	0.070	-500

Table 2. Depth to groundwater for the MHHW boundary condition (worst/highest case), all K's and sea level rise rates of 0, 1, 2 and 3m.

For the 22 stormwater outfalls identified in this study, depths to groundwater from the ground surface (using the model DEM to extract ground surface points) were extracted (Table 2). The color-coding highlights results for various model cases using a series of management-relevant categorization bins. Blue (inundated) indicates that the asset is flooded by the ocean via overland inundation; any groundwater impact would be masked by the fact that the asset is now either permanently inundated by ocean water. Red (emergent) is not used in the table but would indicate that groundwater is emerging above the land surface; this would indicate sites where groundwater may already be observable (e.g. a river, pond, or ponded water following precipitation events) or where new groundwater will emerge due to the impacts of sea level rise on groundwater tables. Orange (very shallow) shows where groundwater is within 1 m of the land surface. At this depth, groundwater could impact shallow buried infrastructure as well as building foundations or other assets that were built requiring and assuming a dry subsurface. Yellow (shallow) delineates the 1 – 2 m zone where groundwater may interact with deeper assets (up to 6 feet below the ground surface). Stormwater system pipes, as well as wastewater pipes, are most often located in this depth range. White indicates depths to groundwater tables that are greater than 2m. Most stormwater and wastewater systems are not buried this deeply.

These results project where groundwater will shallow most quickly (depicted by the orange/"very shallow" shading). Pipes at 28th St and 1st are the most exposed to groundwater. This is not surprising as these are the outfalls closest to the ocean.

For the 6 outfalls with elevation data extracted from as-builts, depth to groundwater from the outfall was calculated. The 2 seaward outfalls (7 and 22) are well below the ground surface for the DEM used in the modeling and the outfalls are already underwater for the MHHW case. Except for outfall 8 (27th Ave), which is 1.5m below the ground surface, the other outfalls are very close to the ground surface and vulnerability is similar to that calculated above for groundwater depth from the ground surface (Table 3).

			Depth to groundwater from outfall (m)											
			K 0.1				K 1.0				K 10			
Lbl	Name	Eln	SLR 0	SLR 1	SLR 2	SLR 3	SLR 0	SLR 1	SLR 2	SLR 3	SLR 0	SLR 1	SLR 2	SLR 3
7	28th St	-1.88	-0.650	-1.485	-500	-500	-0.307	-1.289	-500	-500	-0.271	-1.269	-500	-500
8	27th St	-1.53	1.127	0.280	-0.463	-1.020	2.368	1.384	0.405	-0.547	2.495	1.496	0.498	-0.497
9	24th St	0.08	4.718	3.874	3.082	2.463	6.124	5.140	4.160	3.199	6.267	5.269	4.271	3.275
11	Marine Pl	-0.08	3.539	2.695	1.891	1.301	4.899	3.916	2.935	1.976	5.038	4.040	3.042	2.046
…														
18	8th St	0.12	3.621	2.802	2.005	1.538	5.364	4.382	3.400	2.455	5.545	4.547	3.548	2.554
…														
22	1st St	-1.80	-0.307	-1.158	-1.755	-500	0.212	-0.774	-1.746	-500	0.267	-0.731	-1.729	-500

Table 3. Depth to groundwater from outfall MHHW boundary condition (worst/highest case), all K's and sea level rise rates of 0, 1, 2 and 3m.

Table 4 provides estimates of the thickness of the freshwater layer floating on the underlying saline groundwater. For K = 1 and 10 (the most likely range), fresh groundwater adds very little to total groundwater heads; the increase is effectively zero for K = 10 and is only 2-18 cm (1 – 7") for K = 1. Fresh groundwater plays a much more significant role in the K = 0.1 case, increasing heads by 0.36 – 1.95 m (14 – 77"), but this K is likely to be much too low for

Manhattan Beach's sandy substrate. Thus, most of the groundwater hazard at Manhattan outfalls likely will be due to SLR impacts on saline groundwater.

		Estimated (head - MHHW) freshwater thickness (m)											
		K 0.1				K 1.0				K 10			
Label	Name	SLR 0	SLR 1	SLR 2	SLR 3	SLR 0	SLR 1	SLR 2	SLR 3	SLR 0	SLR 1	SLR 2	SLR 3
1	44th St	1.323	1.155	0.912	0.551	0.117	0.100	0.077	0.039	-0.006	-0.008	-0.010	-0.014
2	43rd St	1.255	1.089	0.837	0.451	0.110	0.093	0.070	0.029	-0.007	-0.008	-0.011	-0.015
3	41st St	1.380	1.215	0.994	0.630	0.123	0.106	0.085	0.047	-0.005	-0.007	-0.009	-0.013
4	39th St	1.476	1.311	1.092	0.723	0.133	0.116	0.095	0.057	-0.004	-0.006	-0.008	-0.012
5	Rosecrans	1.439	1.283	1.069	0.636	0.129	0.113	0.093	0.048	-0.005	-0.006	-0.008	-0.013
	32nd St												
6	32nd St	1.486	1.333	1.102	0.677	0.134	0.117	0.098	0.052	-0.005	-0.006	-0.008	-0.013
7	28th St	0.362	0.197	NaN	NaN	0.020	0.002	NaN	NaN	-0.016	-0.018	NaN	NaN
8	27th St	1.362	1.209	0.951	0.508	0.121	0.104	0.083	0.036	-0.006	-0.008	-0.010	-0.015
9	24th St	1.544	1.389	1.181	0.800	0.139	0.123	0.103	0.064	-0.004	-0.006	-0.008	-0.012
11	21st St	1.494	1.338	1.142	0.733	0.134	0.118	0.099	0.058	-0.005	-0.007	-0.008	-0.013
10	Marine Pl	1.580	1.421	1.231	0.750	0.143	0.126	0.107	0.061	-0.004	-0.006	-0.008	-0.012
12	18th North	1.580	1.417	1.238	0.733	0.142	0.126	0.108	0.059	-0.004	-0.006	-0.008	-0.013
13	18th South	1.600	1.437	1.257	0.726	0.144	0.128	0.110	0.059	-0.004	-0.006	-0.007	-0.013
14	14th St	1.608	1.451	1.251	0.768	0.146	0.129	0.111	0.062	-0.004	-0.006	-0.008	-0.012
16	Pier South	1.705	1.538	1.168	0.232	0.155	0.138	0.116	0.012	-0.003	-0.005	-0.007	-0.018
15	Pier North	1.634	1.469	1.098	0.217	0.148	0.131	0.108	0.011	-0.004	-0.006	-0.008	-0.018
17	9th St	1.874	1.700	1.485	0.904	0.173	0.156	0.137	0.077	-0.001	-0.003	-0.005	-0.011
18	8th St	1.845	1.669	1.467	0.923	0.171	0.154	0.136	0.079	-0.002	-0.004	-0.005	-0.011
19	7th St	1.923	1.741	1.539	1.006	0.179	0.162	0.144	0.089	-0.001	-0.003	-0.005	-0.010
20	6th St	1.950	1.767	1.566	1.048	0.183	0.165	0.147	0.094	-0.001	-0.002	-0.004	-0.010
21	2nd St	1.942	1.753	1.527	0.986	0.183	0.166	0.147	0.089	-0.001	-0.003	-0.004	-0.010
22	1st St	0.559	0.410	0.007	NaN	0.040	0.026	-0.002	NaN	-0.015	-0.017	-0.019	NaN

Table 4. Estimated freshwater thickness for the MHHW boundary condition (worst/highest case), all K's and sea level rise rates of 0, 1, 2 and 3m.

Wastewater System

Assuming that the maximum depth of a sewer pipe is 2m below the ground surface, a conservative depth-to-groundwater for the bottom of sewer pipes was determined by subtracting 2m from depths to groundwater determined for pipe endpoints (Table 5). For this case, points 18 and 20 may be ~0.5m underwater for K 0.1 and SLR 3m, but for a more reasonable K of 1 or 10, the sewer system will likely not be impacted by the shallowing of groundwater tables.

		Depth to groundwater assuming sewer is 2m below ground surface (m)											
		K 0.1				K 1.0				K 10			
Lbl	ID	SLR 0	SLR 1	SLR 2	SLR 3	SLR 0	SLR 1	SLR 2	SLR 3	SLR 0	SLR 1	SLR 2	SLR 3
1		6.514	5.691	4.939	4.311	8.238	7.257	6.280	5.320	8.415	7.417	6.419	5.423
2		2.288	1.456	0.702	0.074	3.647	2.665	1.688	0.727	3.786	2.788	1.790	0.794
3	P2997	2.583	1.752	0.993	0.363	3.976	2.994	2.016	1.055	4.118	3.120	2.122	1.126
4	P2997	2.468	1.636	0.860	0.231	3.904	2.922	1.943	0.982	4.051	3.053	2.055	1.059
5	P3018	2.801	1.969	1.190	0.563	4.289	3.306	2.327	1.366	4.441	3.443	2.445	1.449
6	P3017	4.218	3.377	2.591	2.013	5.730	4.747	3.767	2.811	5.884	4.886	3.888	2.892
7	P3016	3.508	2.667	1.878	1.287	5.012	4.028	3.048	2.091	5.165	4.167	3.169	2.173
8	P3015	2.345	1.500	0.702	0.100	3.703	2.719	1.738	0.780	3.842	2.843	1.845	0.849
9	P3014	2.737	1.892	1.107	0.531	4.110	3.127	2.146	1.191	4.251	3.252	2.254	1.259
10	P3013	3.304	2.458	1.684	1.126	4.737	3.753	2.773	1.820	4.883	3.885	2.887	1.892
11	P3012	2.546	1.700	0.925	0.343	3.905	2.921	1.941	0.986	4.044	3.046	2.048	1.052
12	P3012	3.888	3.048	2.297	1.741	5.312	4.329	3.351	2.399	5.458	4.460	3.462	2.467
13	P3021	4.042	3.199	2.449	1.935	5.552	4.569	3.590	2.641	5.706	4.708	3.710	2.715
14	P3022	4.042	3.199	2.449	1.935	5.552	4.569	3.590	2.641	5.706	4.708	3.710	2.715
15	P3022	2.986	2.138	1.360	0.771	4.349	3.365	2.386	1.428	4.489	3.490	2.492	1.496
16	P3023	2.641	1.797	1.005	0.386	4.047	3.063	2.083	1.122	4.190	3.192	2.194	1.198
17	P1586	2.543	1.700	0.897	0.304	3.945	2.961	1.980	1.021	4.088	3.089	2.091	1.095
18	P1586	1.602	0.758	-0.049	-0.589	2.952	1.968	0.987	0.032	3.089	2.091	1.093	0.097
19	P3025	2.163	1.321	0.506	-0.055	3.543	2.560	1.578	0.621	3.684	2.685	1.687	0.692
20	P3026	1.595	0.756	-0.065	-0.549	2.988	2.005	1.023	0.073	3.131	2.132	1.134	0.139
21	P3027	2.867	2.030	1.211	0.709	4.383	3.400	2.417	1.466	4.538	3.539	2.541	1.546
22	P3028	2.599	1.757	0.947	0.420	4.067	3.084	2.102	1.150	4.218	3.219	2.221	1.226
23	P3029	2.921	2.081	1.303	0.815	4.485	3.502	2.521	1.574	4.645	3.647	2.649	1.654
24	P3030	2.160	1.326	0.645	0.338	3.779	2.796	1.818	0.894	3.945	2.946	1.949	0.956
25	P1834	1.993	1.160	0.521	0.445	3.586	2.604	1.626	0.728	3.749	2.751	1.753	0.764
26	P1834	-1.047	-1.884	-2.496	-502	0.284	-0.699	-1.676	-502	0.420	-0.578	-1.576	-502
27	P2621	-1.105	-1.956	-502	-502	-0.581	-1.566	-502	-502	-0.528	-1.527	-502	-502
28	P2620	-502	-502	-502	-502	-502	-502	-502	-502	-502	-502	-502	-502
29	P2620	-502	-502	-502	-502	-502	-502	-502	-502	-502	-502	-502	-502

Table 5. Depth to groundwater for the MHHW boundary condition (worst/highest case), all K's and sea level rise rates of 0, 1, 2 and 3m.

Conclusions

The groundwater table in Manhattan Beach is between 5-20 feet below the beach, except at the edge of the water, where the groundwater table is closer to the surface. Based on the modeling used for this study (CoSMoS-GW), with 3.3 feet (1 meter) of sea-level rise, the model projects groundwater levels under the beach would increase 3.2 feet. With 6.6 feet (2 meters) of sea-level rise, the groundwater would increase 6.4 feet and with 9.8 feet (3 meters) of sea-level rise, it would increase 9.6 feet. Despite these significant increases in water table depth (which brings them closer to the land surface), because the land slopes up quickly from the beach, the groundwater under most of the city remains deep, yielding limited risk to inland flooding. As such, modeling results indicate that there is no expected emergence of groundwater leading to backshore ponding in Manhattan Beach.

The next potential impact to consider is if rising groundwater tables might rise enough to adversely impact underground infrastructure, such as stormwater and wastewater systems. Stormwater outfalls are the lowest points in the stormwater system and the closest to the ocean, and typically are located at or above ground level. As discussed above, several are close to the MHW line already and thus vulnerable to flooding from wave run-up today. These pipes were identified in the overland flooding analysis as ones that would require the most immediate attention by the City. Groundwater rising above the bottom of the outfall discharge opening would progressively reduce the efficiency of stormwater discharge, potentially increasing inland flooding. This study did not find that rising groundwater tables would cause impacts to the system above and beyond what would be expected from sea level rise-driven overland flooding. However, the combined impacts of changes in precipitation (to a flashier, more deluge-style rain events) in combination with sea level rise, may impact the City's stormwater system. For more detailed analysis, please see the accompanying study by Amir AghaKouchak and colleagues (Multi-Hazard Confluence Modeling of Manhattan Beach's Stormwater Infrastructure 2021).

Assuming sewer lines are buried no deeper than 2 m, this study showed limited potential impact to the City's wastewater system buried under the beach. With increasing sea level rise – 2m – 3m, there is potential for groundwater to rise to the depth where sewer lines are located. If the existing sewer lines have cracks or other permeable sections along the pipe, this rising groundwater could potentially permeate into the sewer line increasing the amount of water in the line. This potential impact could not be ascertained from this first study. To better understand the impact to the wastewater system, the City should verify actual depths of the sewer lines and to determine if the existing pipes are in a state of good repair. If the pipes are buried deeper than 2 m (the assumption in this study), and if they need repair, it is possible that there could be impacts to the pipe system with rising groundwater tables. Measures to address impacts could include slip-lining the pipe or utilizing a vacuum based sewer system.