Plan Morro Bay
Coastal Resources & Resiliency
H++ Update

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City of Morro Bay
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CALIFORNIA COASTAL COMMISSION

June 25, 2019

Table of Contents

TABLE OF TABLES

TABLE OF FIGURES

Acronyms and Abbreviations

CCC	California Coastal Commission
cm	centimeter
CoSMoS	Coastal Storm Modeling System
ft	feet
H++	Extreme SLR scenario due to rapid Antarctic ice sheet mass loss (Sweet et al, 2017)
HAPC	habitat areas of particular concern
in	inch
IP	Implementation Plan
LCP	Local Coastal Program
LUP	Land Use Plan
m	meter
M&N	Moffatt & Nichol
MHHW	mean higher high water
MLLW	mean lower low water
NAVD88	North American Vertical Datum of 1988
NOAA	National Oceanic and Atmospheric Administration
OPC	Ocean Protection Council
SLR	Sea Level Rise
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey
VA	Vulnerability Assessment
yr	year

Document Verification

Client	Michael Baker International; City of Morro Bay
Project Name	Morro Bay General Plan Amendment/Local Coastal Plan Project
Document Title	Coastal Resources & Resiliency
Document Sub-title	H++ Update
Status	Final Report
Date	25 June 2019
Project Number	9289
File Reference	\\mne.net\projects\LB\9289_MorroBaySLR\8 Deliverables\Reports\Task 11.6\Report

Revision	Description	Issued by	Date	Checked
00	Draft Report	Conor Ofsthun	September 2018	Aaron Holloway
01	Draft Report	Conor Ofsthun	March 2019	Aaron Holloway
02	Draft Report	Conor Ofsthun	April 2019	Russ Boudreau
03	Final Report	Conor Ofsthun	June 2019	Russ Boudreau

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Scope of Work

The scope of work described below is from Task 11.6 of the approved work program funded in part by LCP grant #78-140 awarded by the California Coastal Commission to the City of Morro Bay.

Task 11.6 Update Sea Level Rise Model

In the interest of presenting the most current and credible information when the Plan Morro Bay General Plan/LCP is adopted and investing resources into the best mitigation solutions identified in Task 11.3, this Task 11.6 incorporates the most up-to-date sea level rise projections into a summary report that can be appended to the previous studies prepared for Plan Morro Bay. This will benefit the City by enabling planning for risk reduction based on the best available science and will benefit the state by illustrating how LCPs can be dynamically updated to incorporate updates to climate change projections over time, creating a case study for numerous coastal communities. Recent studies have found that the observed rate of sea level rise exceeds the forecasted rate in some cases. The ability to frequently update LCPs to incorporate the newest sea level rise science and policy implications is important to protect and enhance coastal resources given this uncertainty. This task utilized sea level rise projections by the Ocean Protection Council's report, *State of California – Sea-Level Rise Guidance, 2018 Update* (OPC, 2018), as the best available science for the State. The Medium-High Risk Aversion projections are similar to the NRC 2012 projections which means the scenarios evaluated in Plan Morro Bay are still applicable. However, the OPC (2018) report presents a new Extreme Risk Aversion scenario, under which the projections increase significantly to 9.9 feet in 2100.

This task updated the sea level rise hazard assessment completed to date to incorporate the Extreme Risk Aversion projection for the year 2100, creating updated sea level rise hazard maps which were used to update the coastal asset vulnerability assessment for this scenario and provide greater understanding of potential sea level rise impacts when developing policies to protect these vital resources. The deliverable for this task also included a discussion of the modeling and mapping assumptions and limitations of evaluating hazards based on such a significant rise in sea levels. The resulting maps and vulnerability assessment are to be included in the Plan Morro Bay General Plan/LCP update.

Deliverable

The primary deliverable for this task includes an updated coastal hazard and vulnerability assessment with planning recommendations, as necessary and feasible.

1. Introduction

The City of Morro Bay (City) prepared a *Final Community Baseline Assessment* (CBA), also known as *Plan Morro Bay*, in September of 2016 (Michael Baker International, 2016). In support of the CBA, Moffatt & Nichol (M&N) prepared *Section 3.0 – Coastal Resources and Resilience* to analyze the existing and projected vulnerability of City assets to sea level rise (SLR). SLR has the potential to increase the frequency and severity of coastal hazards affecting coastal assets and resources in the City. The City is susceptible to coastal hazards such as inundation, flooding, and bluff/dune erosion associated with extreme waves and water levels.

The best available science at the time of CBA preparation (i.e. NRC, 2012) led to the assessment of SLR projections of 1 ft, 2 ft, and 5.5 ft scenarios for years 2030, 2050, and 2100, respectively. Since this time, the best available science advanced and recommends addressing a 9.9 ft SLR scenario by year 2100 for Extreme Risk Aversion assessment (OPC, 2018). The purpose of this report is to update the Coastal Resources and Resilience assessment for the City to provide consideration of the impacts from this extreme SLR scenario.

2. Coastal Setting

The City's coastal setting is described in this section in terms of waves, water levels, and littoral processes. Current and future coastal hazards in Morro Bay are a function of how these processes interact with the natural and built features along the coastline.

2.1 Wave Climate

Waves act to transport sand in both the cross-shore and longshore directions and can also cause short-duration flooding events by causing dynamic increases in water levels. Thus, the wave climate (or long-term exposure of a coastline to incoming waves) and extreme wave events are important in understanding future sea level rise vulnerabilities.

The largest percentage (>45%) of the waves approaching Morro Bay are from the west-northwest direction. Historically, the most frequent significant wave height is 8 to 10 feet and the most frequent wave periods were between 12 and 15 seconds. The largest waves occur in the winter when northern hemisphere cyclonic storms generate powerful, long period waves.

2.2 Water Levels

The tides in Morro Bay are mixed semidiurnal, with two high tides and two low tides of differing magnitude occurring each day. Astronomical tides make up the most significant amount of the total water level. Typical daily tides range from mean lower low water (MLLW) to mean higher high water (MHHW), a tidal range of about 5.3 feet based on the tidal station at Port San Luis (NOAA station 9412110). During spring tides, which occur twice per lunar month, the tide range increases to about 7 feet due to the additive gravitational forces of the sun and moon. During neap tides, which also occur twice per lunar month, the forces of the sun and moon partially cancel out resulting in a smaller tide range of about 4 feet. The largest spring tides of the year are sometimes referred to as "king tides" and result in high tides of 6.5 feet or more above MLLW and tidal ranges of more than 8 feet.

In addition to astronomical tide, factors such as sea level anomalies (El Niño events) and storm surge also contribute to the water levels along Morro Bay. An example of this occurred on November 25, 2015 when a king tide of about 6.63 feet above MLLW was predicted but a water level of 7.18 feet was measured at the Port San Luis station. The tide series from this event is shown in Figure 2-1. The predicted astronomical tide was elevated by 0.54 feet due to a sea level anomaly related to the strong El Niño and high ocean temperatures during the 2015-2016 winter season (Doherty, 2015). The historic observed extreme high water event occurred on January 18, 1973, with a water level of 7.65 feet above MLLW.

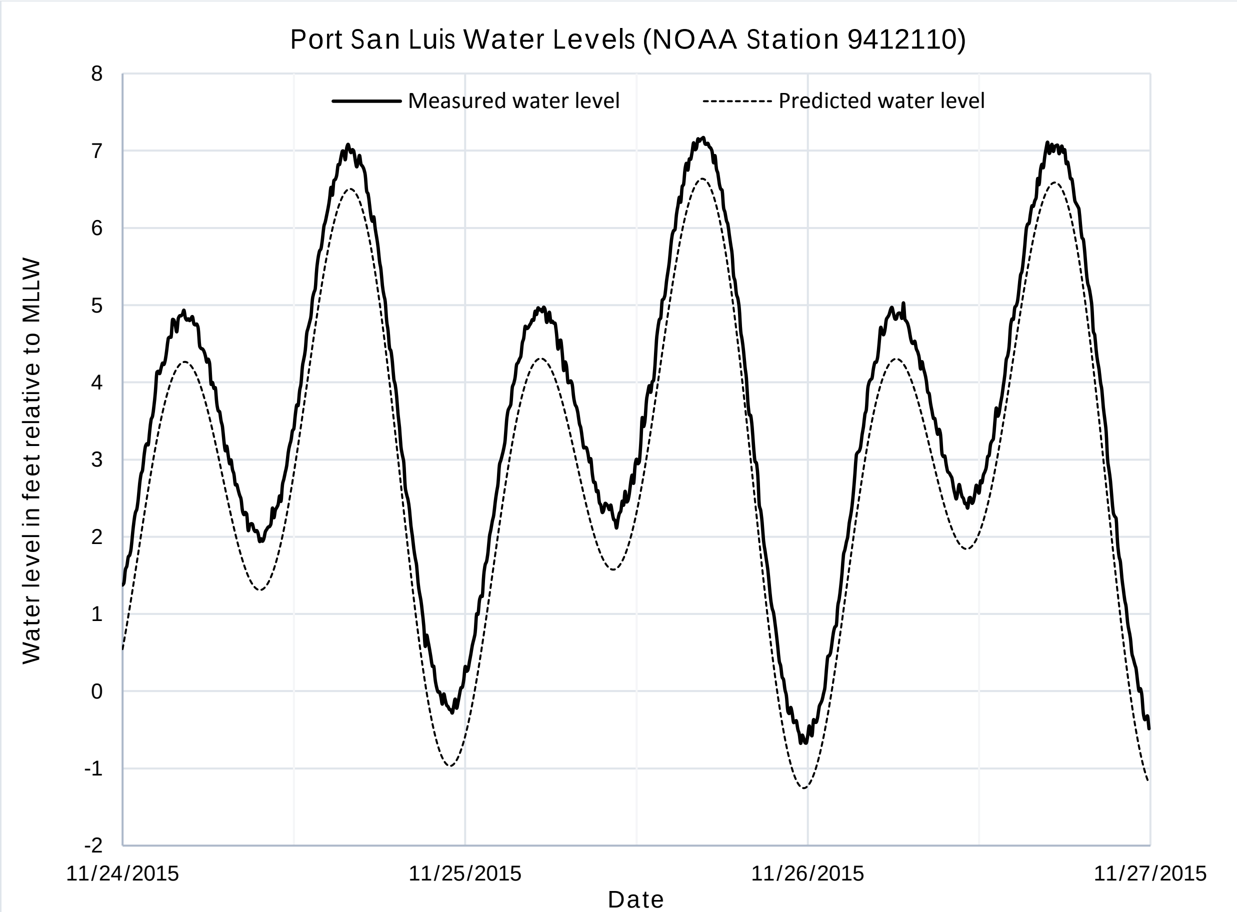


Figure 2-1. November 2015 Water Levels at Port San Luis

2.3 Littoral Processes and Shoreline Change

A littoral cell is a coastal compartment or physiographic unit that contains sediment sources, transport paths, and sediment sinks (Patsch and Griggs, 2007). The City of Morro Bay is within the Morro Bay littoral cell, which extends from about Piedras Blancas to Point Buchon in Los Osos. Sinks include aeolian losses to dunes and cross-shore transport to offshore. Some sinks, such as dunes, can later become sand sources as dunes erode during extreme wave events or as sea levels rise. Other sources of sand to the Morro Bay littoral cell include fluvial delivery of sand and bluff erosion.

Sediment transport in the City is shown in Figure 2-2, and described in this section. Beaches north of Morro Rock experience a net southward drift of 18,000 cy/yr while beaches south of Morro Rock experience a net northward drift of 32,000 cy/yr (Griggs et al. 2005). The Morro Bay entrance channel intercepts approximately 115,000 cy of sediment per year. Sediment is dredged annually by the Corps and placed in the nearshore and surfzone along Morro Strand State Beach. Placement at this site has resulted in wider beaches than might naturally occur (Griggs et al., 2005).

Wind-blown (aeolian) transport of sediment from the dunes into Morro Bay is estimated at 8,300 cy/yr (USACE, 2003). The barrier beach is estimated to be migrating landward at a rate of 1.1 to 1.7 ft/yr into the bay (USACE, 2003).

Analysis of shoreline position data from 1800 to 2002 found that beaches have accreted 4 inches per year, on average, during this period (Hapke et al., 2006). An analysis of shoreline change from 1970 to 2002 found that the beaches narrowed by 2.3 feet per year on average (Hapke et al., 2006). Thus, the findings of this study suggest that the beaches in the City have been accretional over the long-term and erosional in the short-term. Short-term erosion rates may be a result of decreased sediment supply or changes in the wave climate.

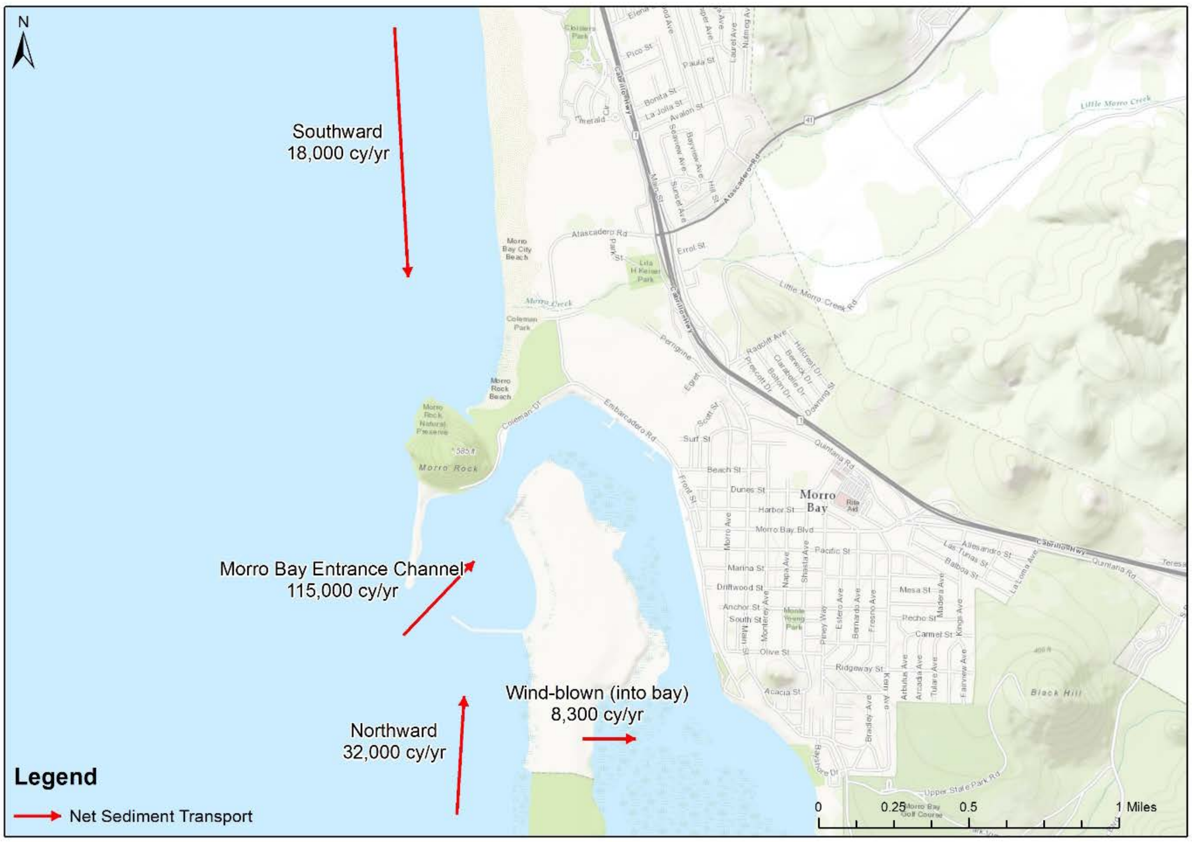


Figure 2-2. Sediment Budget in Morro Bay

3. Projected Conditions

Sea level rise has the potential to result in significant changes within the coastal zone. Current sea level rise projections and methods used to map how these increased water levels may impact the City are described in this section.

3.1 Sea Level Rise Science

There is broad agreement in the scientific community that the earth is predicted to warm and that sea levels will rise as a result of the thermal expansion of water and increased contributions from melting glaciers (Coastal and Ocean Working Group of the California Climate Action Team (CO-CAT), 2013; California Coastal Commission (CCC), 2015). Though there is consensus among the scientific community on these concepts, the timing and severity of sea level rise is relatively uncertain and is dependent on region-specific conditions. The uncertainty in the sea level rise projections is a result of future global emissions of carbon dioxide (a function of future social behavior) and the non-linear response of the ocean to warmer temperatures and contributions from land-based ice sources. Planning for potential future sea levels provides the City with the tools to make current and future planning decisions that allow the City's resources to adapt to changing conditions.

3.2 Best Available SLR Projections

At the time of preparation of the 2016 CBA, the 2012 National Research Council report titled, "Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future," was identified as the best available science for California. Furthermore, the California Coastal Commission (CCC) used the NRC (2012) report as the basis for its 2015 Sea Level Rise Policy Guidance. Following such guidance, the CBA analyzed three SLR scenarios: 1.0 ft (year 2030), 2.0 ft (year 2050), and 5.5 ft (year 2100).

Since this time, sea level rise science has progressed. Currently, the best available science most relevant to the City is the Ocean Protection Council (OPC), "State of California – Sea-Level Rise Guidance, 2018 Update." The OPC (2018) Guidance projects SLR for multiple emissions scenarios and uses a probabilistic approach based on Kopp et al. 2014 to generate a range of projections at a given time horizon. The guidance document has also suggested risk aversion Projected sea level rise values for a range of risk aversion applications are presented in Table 3-1. Except for the most extreme 2100 (H++) scenario, all other projections are covered by the range of SLR scenarios evaluated in the 2016 CBA.

For the 2030 time horizon the "likely range" of SLR is between 0.2 to 0.5 feet. Kopp et al. 2014 estimated there is a 66% probability that SLR will fall within this "likely range". The likely range of SLR at the 2050 time horizon is 0.5 - 1.0 feet for a high emissions scenario. The likely range of SLR at the 2100 time horizon is 1.5 – 3.3 feet for a high emissions scenario. The upper end of the "likely range" is recommended for low risk aversion situations where impacts from SLR greater than this amount would be insignificant, or easily mitigated.

For medium-high risk aversion situations more conservative (lower probability) projections for SLR are recommended by the OPC Guidance. These projections have a 1-in-200 chance (0.5% probability) of occurring at a given time horizon and would be appropriate for use on projects where damage from coastal hazards would carry a higher consequence and/or a lower ability to adapt such as residential and commercial structures. The results of the 2 foot SLR scenario, presented in the 2016 CBA, are applicable for the 2050 medium-high risk aversion projection. The results of the 5.5 foot SLR scenario, presented in the 2016 CBA, are applicable for the 2100 medium-high risk aversion projection.

The OPC guidance also includes a specific singular scenario (called H++), based on projections by Sweet et al 2017 which incorporates findings of DeConto and Pollard (2016) that predict Antarctic ice sheet instability could make extreme sea-level outcomes more likely than indicated by Kopp et al. 2014 (OPC, 2017). Because the H++ scenario is not a result of probabilistic modeling the likelihood of this scenario cannot be determined. Due to the extreme and uncertain nature of the H++ scenario, it is most appropriate to consider when planning for development that poses a high risk to public health and safety, natural resources and critical infrastructure (OPC 2018). The 2100 SLR projection under the H++ scenario (highlighted) is well above any scenario evaluated in the 2016 CBA and therefore is the focus of this vulnerability assessment update.

Table 3-1. Sea Level Rise Projections for Morro Bay

Year	**17% Probability SLR Scenario**	**5% Probability SLR Scenario**	**0.5% Probability SLR Scenario**	**H++ Scenario**
Risk Aversion	*Low Risk Aversion*		*Medium – High Risk Aversion*	*Extreme Risk Aversion*
2030	0.5 ft	0.5 ft	0.7 ft	1.0 ft
2050	1.0 ft	1.2 ft	1.8 ft	2.6 ft
2100	3.1 ft	4.1 ft	6.7 ft	9.9 ft

(Source: Ocean Protection Council 2018, Table 19 for Port San Luis)

3.3 Coastal Hazard Analysis and Mapping – H++ Update

Morro Bay's exposure to future rates of sea level rise was determined through modeling and analyses performed by Moffatt & Nichol (M&N) for this assessment using the projected 2100 H++ sea level rise scenario from the 2018 OPC SLR Guidance. The modeling efforts depict coastal flooding, shoreline change and bluff response to a composite, 100-year wave event in combination with sea level rise and baseline water levels (i.e., high tide, storm surge, and sea level anomaly).

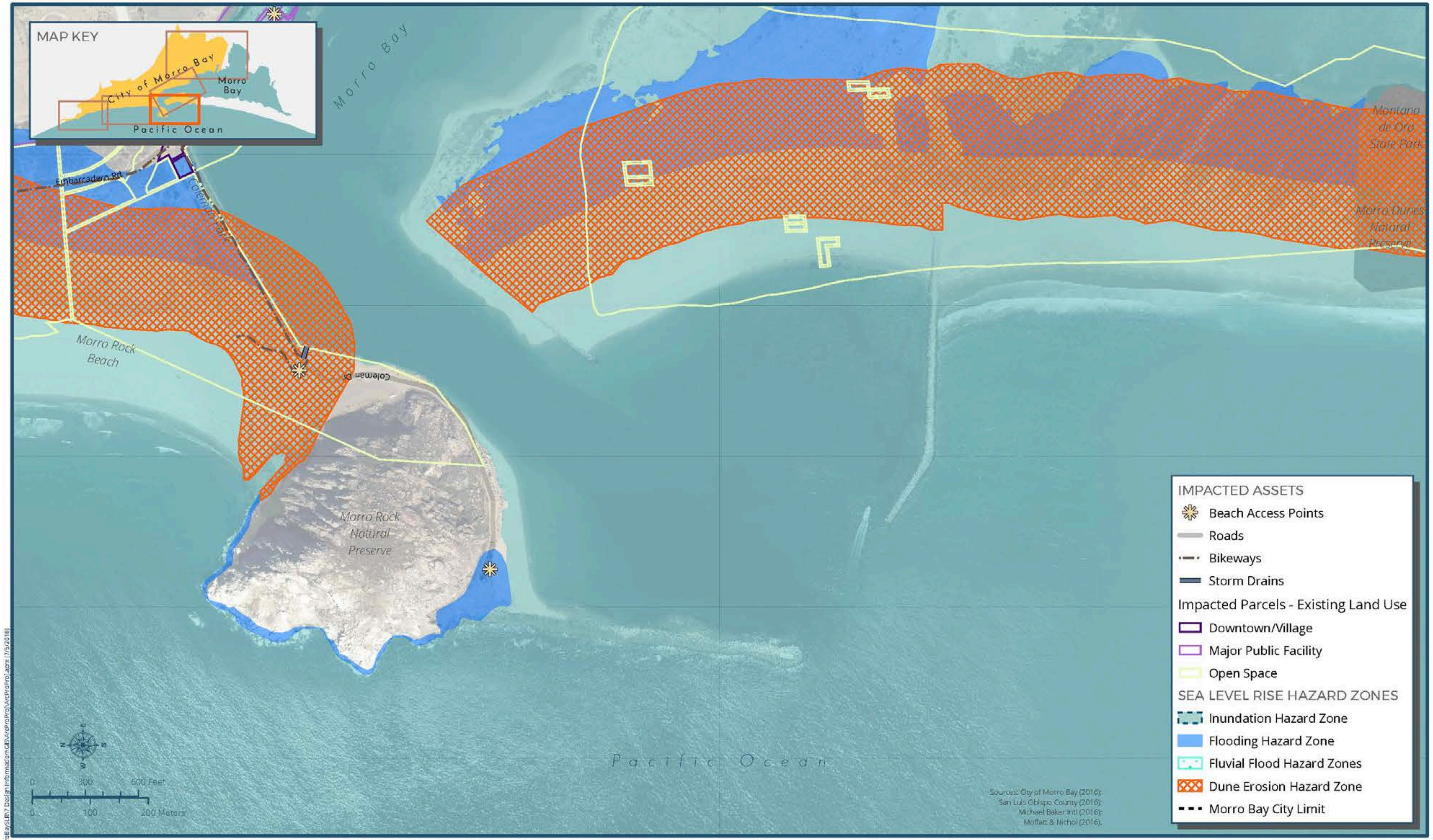
A baseline assessment included an evaluation of shoreline area vulnerabilities, as well as bay vulnerabilities. Vulnerabilities are discussed in terms of flooding (as a result of extreme coastal wave run-up and river discharge events), inundation (as a result of daily tides), and bluff and dune erosion resulting from a composite 100-Year wave event. These hazard zones are further described, as follows:

- Flood Hazard Zone – Flood events are typically short in duration (i.e., hours) and occur episodically in association with extreme waves and precipitation events (e.g., 100-year return period events). The flood hazard zone shows the limits of extreme water levels associated with a 100-year return event.
- Inundation Hazard Zone – Areas within the inundation hazard will be subject to daily wetting and drying associated with tides. A mean high water tide elevation was used as a proxy to represent future inundation hazard zones.

- Bluff Hazard Zone – Rising sea levels may result in the increased erosion of coastal bluffs due to more frequent exposure to wave attack. The bluff hazard zone is the area between the existing and future bluff edge.
- Dune Hazard Zone – Coastal dunes will respond to sea level rise by migrating landward. The Dune hazard zone represents the area between the current and future dune toe.

The vulnerability of City resources is evaluated with respect to sea level rise model results for the year 2100 H++ SLR scenario (9.9 ft). The assessment addresses inundation, flood, dune erosion, and bluff erosion hazards. Note, potential hazards from an extreme fluvial event combined with the H++ scenario were not evaluated for this task. Only inundation hazards were mapped for sheltered areas of Morro Bay to illustrate how the daily water levels could impact resources along the waterfront. See Figure 3-1 through Figure 3-5 for detailed maps of such hazards, followed by a discussion of asset risk and vulnerability.

It's important to emphasize the H++ scenario of 9.9 feet represents the most extreme projection for SLR this century. As such it is recommended for consideration on high stakes, long-term decisions with significant consequences to public health, safety, or the environment (OPC, 2018). In other words, if the Dynegy Power Plant was to be restored into service or replaced with a similar facility, the H++ SLR scenario and potential impacts would warrant careful consideration. However, the worst case SLR projection for the year 2100 is not appropriate for planning or design of lower consequence projects that could offer a benefit to the community over shorter time scales (~10-50 years). For example, the Morro Rock parking lot which provides valuable coastal access for the community today would not be designed for the H++ scenario because of the prohibitive cost and potential adverse impacts to coastal access and recreation.

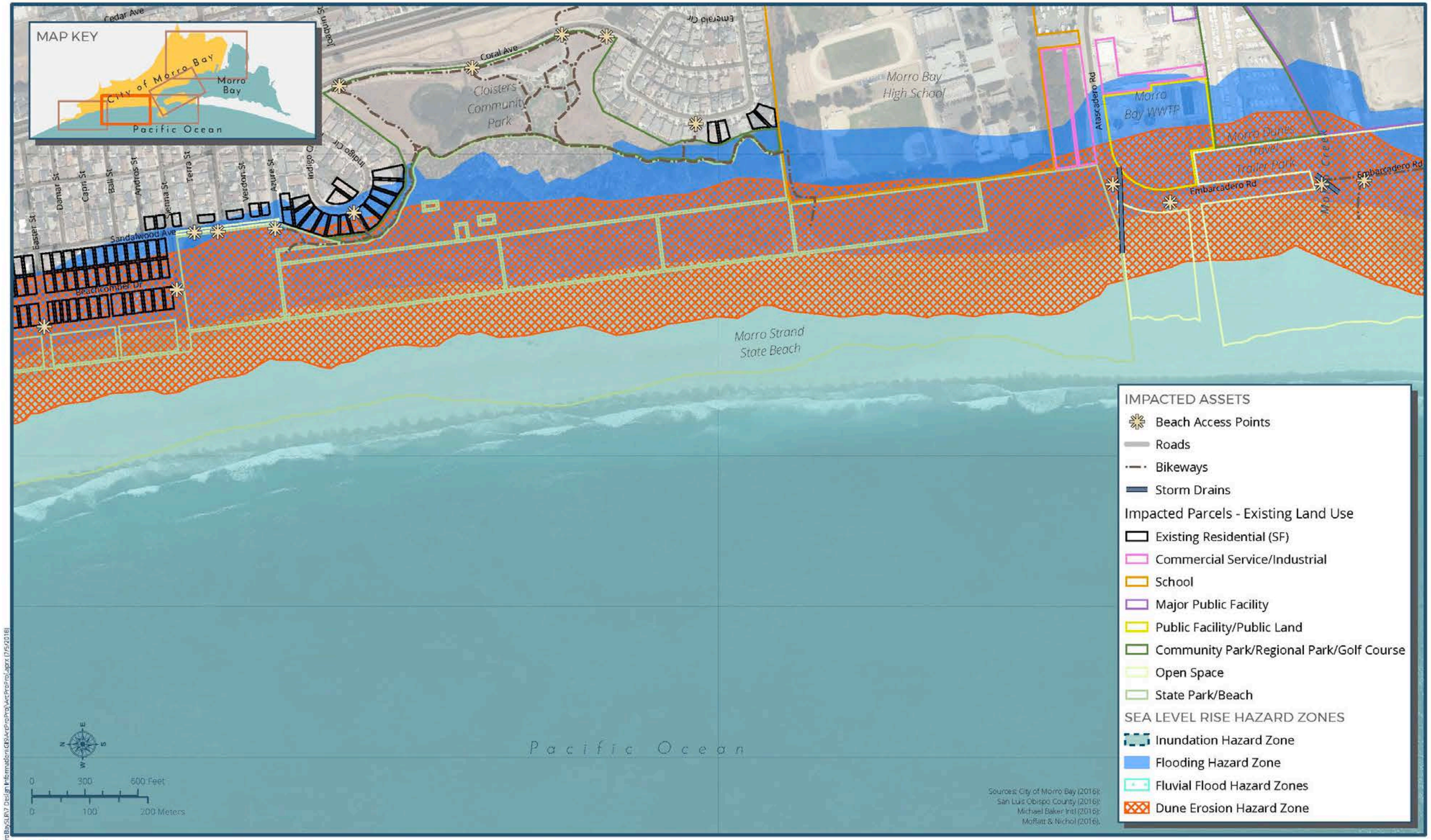


Plan MORRO BAY

YEAR 2100 H++ SEA LEVEL RISE HAZARDS

Plate 1 of 5

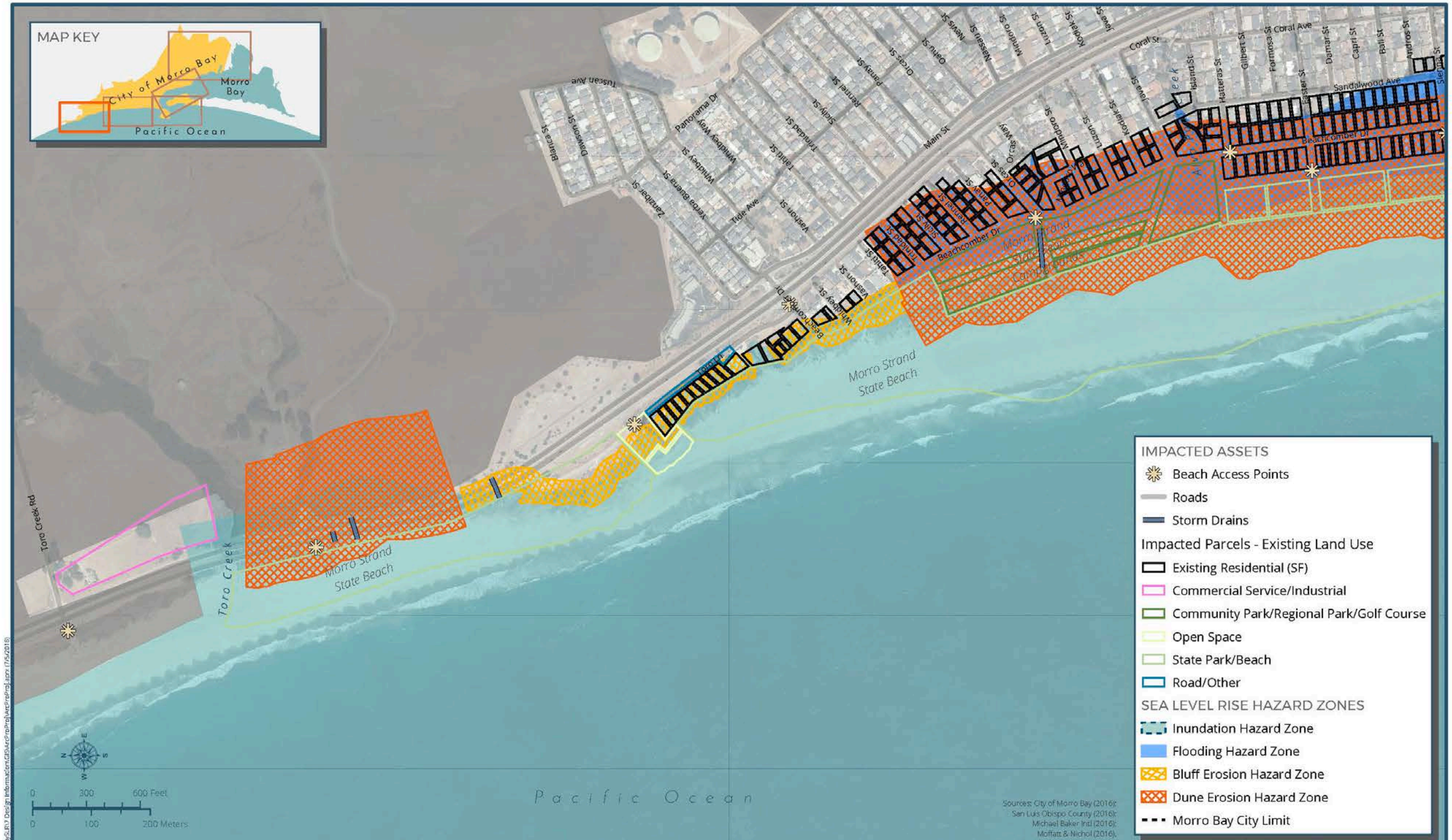
Figure 3-1. Year 2100 H++ Sea Level Rise Vulnerabilities (Plate 1)



YEAR 2100 H++ SEA LEVEL RISE HAZARDS

Plate 2 of 5

Figure 3-2. Year 2100 H++ Sea Level Rise Vulnerabilities (Plate 2)

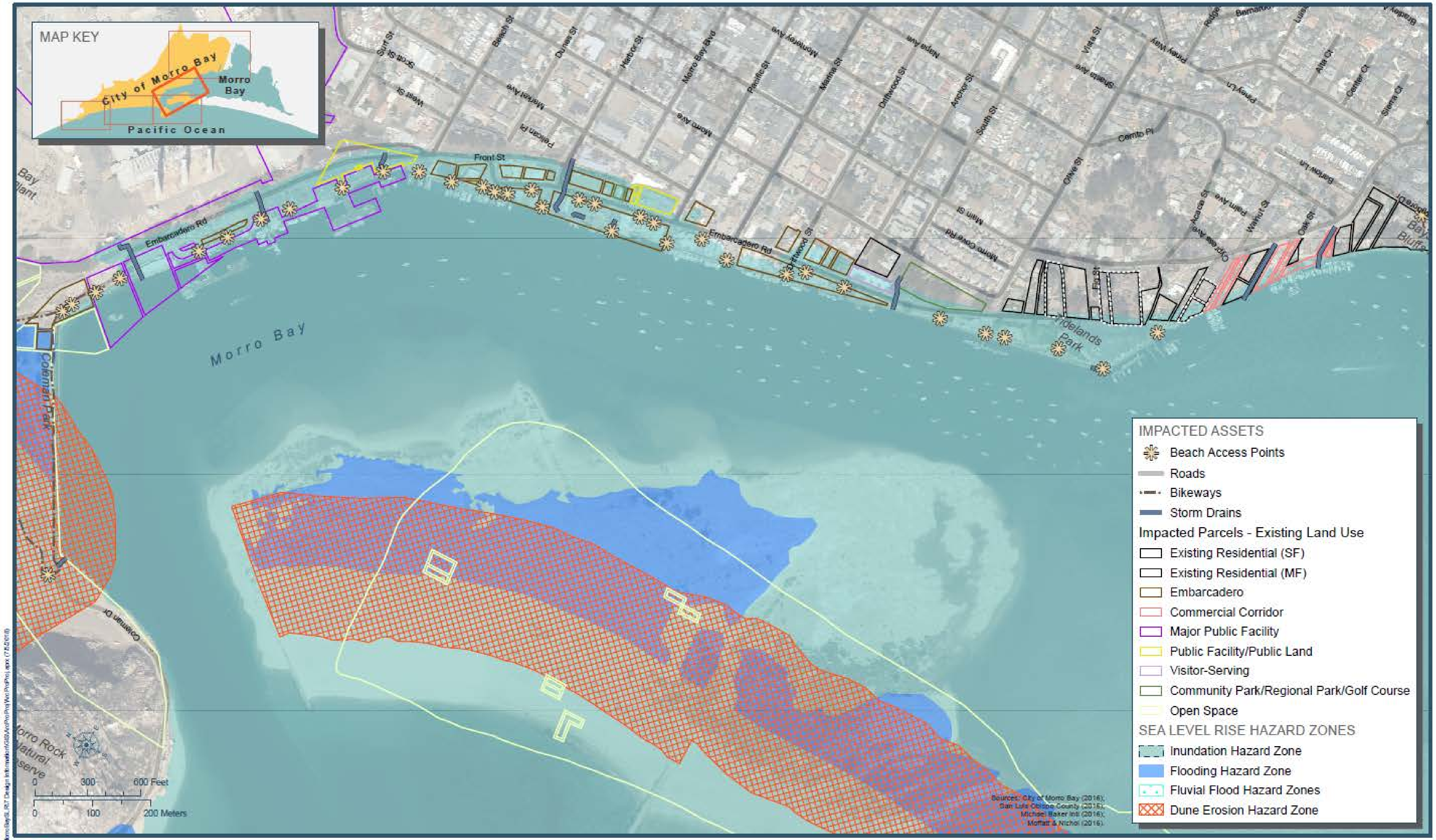


Plan MORRO BAY

YEAR 2100 H++ SEA LEVEL RISE HAZARDS

Plate 3 of 5

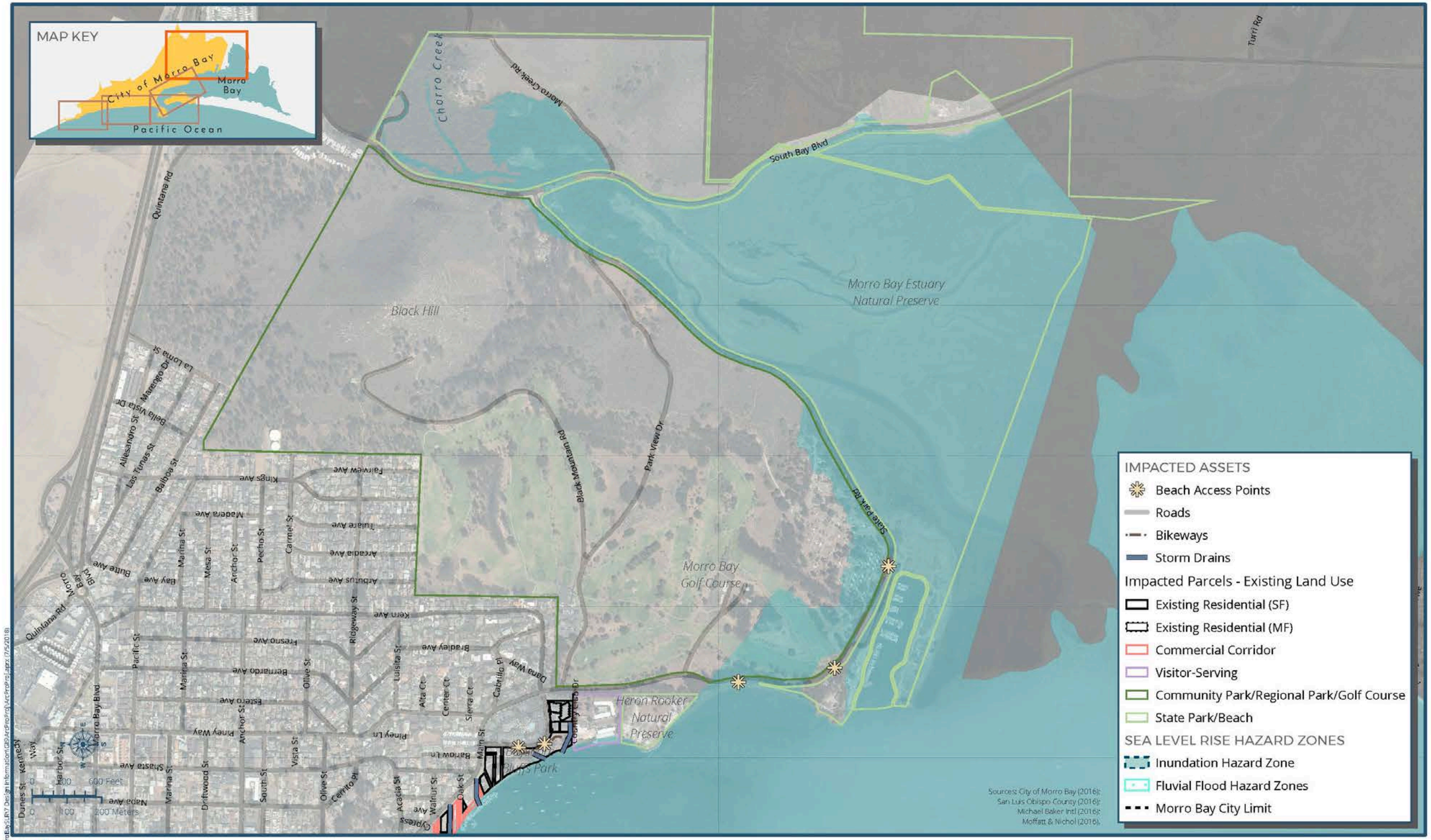
Figure 3-3. Year 2100 H++ Sea Level Rise Vulnerabilities (Plate 3)



YEAR 2100 H++ SEA LEVEL RISE HAZARDS

Plate 4 of 5

Figure 3-4. Year 2100 H++ Sea Level Rise Vulnerabilities (Plate 4)



MORRO BAY

YEAR 2100 H++ SEA LEVEL RISE HAZARDS

Plate 5 of 5

Figure 3-5. Year 2100 H++ Sea Level Rise Vulnerabilities (Plate 5)

3.4 Model Assumptions and Limitations

Both the CBA Coastal Resources & Resiliency and this H++ Update applied the same technical approach. However, the extreme water levels in the H++ Update necessitated a few assumptions and limitations in order to analyze and map coastal hazards:

1. Mapping of each hazard zone was reassessed with regard to the H++ SLR scenario:
    - Dune Erosion Hazard Zone – Under the H++ scenario, roadway and building infrastructure was assumed to erode, allowing for dunes to migrate landward.
    - Bluff Erosion Hazard Zone – Due to the limited data and research available to reliably predict bluff response to accelerated sea level rise, this report put forth a bluff erosion hazard zone equal to that of the 2100 SLR scenario presented in the CBA.
    - Inundation Hazard Zone – No new assumptions were made.
    - Flood Hazard Zone – Waves overtopping of the Morro Rock causeway and Morro Dunes Nature Preserve were not modelled to propagate to Morro Bay harbor and therefore the Embarcadero waterfront could experience a stronger wave climate under such an extreme SLR scenario. Toro Creek and the northern section of Highway 1 does not include a flood hazard zone as inundation extends across the roadway, and flooding beyond this point would occur outside the City boundary.
2. Shore protection features, including the Morro Bay harbor entrance channel jetties, revetment, and the Chevron bulkhead wall, were assumed to not maintain their protective functions and effectiveness, as these features were not designed with the H++ scenario in mind.
3. The impacts of an H++ scenario on riverine flooding from Morro Creek, Chorro Creek, Toro Creek and other local drainage facilities was not evaluated as part of this analysis and mapping effort. An H++ sea level rise scenario in 2100 would significantly increase downstream boundary water levels resulting in backwater affects and increased flooding from creeks and local drainage systems beyond what is shown on the maps in this report.
4. The empirical methods applied in the CBA are not developed for such an extreme rise in sea level. It is possible that some processes like shoreline/dune erosion may not respond as predicted by these empirical methods under such an extreme SLR case.
5. Potential adaptation strategies are not reflected in the H++ coastal hazard maps. An H++ scenario would likely overwhelm most existing coastal infrastructure such as the harbor entrance, Morro Rock causeway & parking lot and Hwy 1 revetment. How this infrastructure is adapted to SLR will have a major impact on the potential hazard zones.
6. The analysis performed is transect based and requires interpolation between transects to delineate potential flood zones. M&N used their best judgement to map a flood hazard zones beyond the anticipated dune erosion that factored in topography, land use and type of development.

See Appendix A of the Plan Morro Bay CBA for more detailed information on model data inputs, assumptions and limitations.

4. Vulnerability and Risk Assessment – H++ Update

This section presents the methods for and results of evaluating the vulnerability and risk of assets with respect to the preceding sea level rise hazard maps for the H++ scenario.

4.1 Methods

Vulnerability is assessed as a function of an asset's exposure, sensitivity, and adaptive capacity (Table 4-1). While the vulnerability assessment is performed to identify impacts from sea level rise, a risk assessment was performed to evaluate the magnitude of these impacts and likelihood of occurrence. The risk assessment is performed qualitatively to help the City manage risk related to sea level rise in their planning and decision-making process.

The following H++ Update Vulnerability and Risk Assessment is intended to address high level vulnerabilities within the City for the purposes of long-term planning. This approach is a departure from the format presented in the CBA, which quantified assets impacted and assigned a vulnerability rating score. The modeling and mapping associated with the H++ SLR scenario required a number of assumptions in order to capture the full potential impact of such an extreme SLR scenario (as described in Section 3.4). Such assumptions reduced the accuracy of quantifying hazard impacts, thus a high-level approach is instead taken.

This vulnerability assessment evaluates sea level rise impacts to various City assets. Coastal resources in the City are diverse and include natural resources such as Morro Rock, Morro Bay estuary, and sandy beaches backed by dunes and bluffs. Resources of the built environment include the harbor infrastructure, commercial fishing industry, visitor-serving commercial waterfront, and numerous recreational opportunities along the coastline and bay. Such resources are divided into the following asset categories:

- Beaches,
- Public access ways,
- State Parks,
- Parcels,
- Critical infrastructure, and
- Transportation.

Table 4-1. Vulnerability Assessment System

Exposure is the degree to which an asset or resource is susceptible to coastal hazards such as flooding, inundation and bluff erosion for a given sea level rise scenario. The mapped hazard zones were used to rate the level of exposure to a given asset or category.		
Category	**Rating**	**Explanation**
Exposure	Low	Asset or resource partially exposed to flooding, inundation or bluff/dune erosion.
	Moderate	Asset or resource moderately exposed to flooding, inundation or bluff/dune erosion.
	High	The majority of the asset or resource is exposed to flooding, inundation or bluff/dune erosion.
Sensitivity is the degree to which the function of an asset or resource would be impaired (i.e., weakened, compromised or damaged) by the impacts of sea level rise. *Example: State Park Road/Main Street in the vicinity of the campground has a high sensitivity to sea level rise because even minor flooding can cause significant disruption in service.*		
Category	**Rating**	**Explanation**
Sensitivity	Low	Asset or resource is not affected or minimally affected by coastal hazards at a given sea level rise scenario.
	Moderate	A moderately sensitive asset or resource may experience minor damage or temporary service interruption due to coastal hazard impacts, but can recover relatively easily.
	High	A highly sensitive asset or resource would experience major damage or long-term service interruptions due to coastal hazard impacts, requiring significant effort to restore/rebuild to original condition.
Adaptive capacity is the inherent ability of an asset or resource to adjust to sea level rise impacts without the need for significant intervention or modification. *Example: Some wetland habitats have a high adaptive capacity due to their ability to naturally migrate landward and upward with rising water levels; provided adequate space exists.*		
Category	**Rating**	**Explanation**
Adaptive Capacity	High	Asset or resource can easily be adapted or has the ability and conditions to adapt naturally.
	Moderate	Asset or resource can be adapted with minor additional effort.
	Low	Asset or resource has limited ability to adapt without significant changes.

4.2 Results

The following section presents vulnerability assessment results identifying impacts that sea level rise and coastal hazards may have on existing resources and assets within the City.

4.2.1 Beaches

The exposure of sandy beaches to sea level rise impacts is high with anticipated erosional impacts under any sea level rise scenario. In a natural setting, beaches can be thought to have a high adaptive capacity because they will naturally adjust to a rising sea level if adequate sand exists in the system. However, the adaptive capacity of beaches can be low in areas where beaches are backed by coastal structures, development or where insufficient sand exists in the system.

Under the year 2100 H++ SLR scenario, beaches are significantly impacted by coastal hazards compared to the current horizon and beaches become squeezed between rising sea level and dunes/bluffs/coastal development. This vulnerability poses a high risk to the City as increased beach erosion will reduce the natural barrier to storm waves and reduce opportunity for beach access and recreation. There are also economic costs associated with such impacts; beach visitation from both in-town and out-of-town guests results in economic benefits to City businesses (e.g., retail, restaurants, hotel).

South of Morro Rock, the Morro Dunes Natural Preserve is entirely vulnerable to inundation, flooding, and dune erosion. It is anticipated that the beach and dune system will retreat inland as erosion progresses and will be overtopped by storm waves and even high tide at particularly low points. This erosion is expected to significantly alter the current sediment transport regime as the sand spit is reworked by changing oceanographic conditions. The protective value that the Natural Preserve provides to Morro Bay harbor will be threatened and potentially lost, thus allowing increased wave energy to reach the Embarcadero waterfront and marina. All intertidal and upland habitat would be altered by erosion, inland migration, and increased water levels: threatening to transform dry beach and dune areas to intertidal and subtidal zones, and transforming estuarine zones on the bay side into dry beach and dune areas.

North of Morro Rock, Morro Rock Beach and Morro Strand State Beach will experience inundation, flooding, and dune erosion hazards. Sand dunes are anticipated to erode inland greater than the length of a football field. If coastal development management elects to hold the line and maintain in place through the use of hard armoring and raised structures, sandy beaches and dune in Morro Bay would potentially be entirely eliminated. This would coincide with an almost complete loss of intertidal and upland coastal habitat, almost complete loss of a soft protective buffer between ocean and development, and almost complete loss of public access to one of the City's most prominent assets.

4.2.2 Public Access Ways

Public access ways consist of vertical beach access points and lateral access ways (trails) that run along the beach and bay. Coastal flooding and erosion has the potential to impact beach access points and access trails in the City. For example, erosion of the beach may create a large scarp (or drop off) at the end of a beach access trail. Generally, public access ways have a relatively high exposure due to their location at sandy beaches and waterfronts. In beach areas where access ways are exposed to inundation, flooding, and erosion there is a low to moderate sensitivity as they are already located in a dynamic environment. Access ways can often naturally adapt to increased water levels and erosion, some minor repair and adaptation measures may be needed. Waterfront access ways on fixed or floating structures continue to provide access as long as they are located at an elevation above predicted water levels or able to accommodate increased water levels.

Public beach access ways will be very vulnerable in the 2100 H++ scenario. Dune and bluff erosion are anticipated to encroach upon most vertical beach access points, causing damage and requiring repairs and adaptations such as clearing, grading, and fill. Access points that become inundated will naturally migrate inland where open space is available, some adaptation may be needed to maintain safety and ease of access at these locations. Additionally, lateral access ways approaching beach access points are vulnerable to inundation, dune and bluff erosion, and flooding. Although public access ways are generally adaptable features, due to the considerable beach loss anticipated under the H++ SLR Scenario, vertical beach access points may be rendered relatively useless with no beach to access.

Along the Embarcadero, public access ways which allow for dock, boat, and harbor access will nearly all be compromised by daily inundation. Of greater concern, however, is the threat that infrastructure such as docks, piles, and piers will become dysfunctional under the H++ SLR scenario unless action is taken to raise and retreat such infrastructure with respect to sea level rise. This is discussed below in Coastal Development.

4.2.3 State Parks

State park facilities exist along the City's shoreline and consist of parking lots, campgrounds, and a marina. Dunes and dune habitats represent a significant natural resource in the state parks as they are actively restored and preserved. State park facilities are recognized as important assets to the City in terms of economic and recreation value. The state park facilities also provide an important low cost visitor-serving amenity with prime access to coastal resources. Though economic impacts to the physical structures (i.e., asphalt paving, restrooms, some utilities and marina facilities) within the affected state parks would be relatively low, loss of these amenities would be significant since these features may not be easily or realistically moved inland.

State Parks throughout Morro Bay would be extremely vulnerable in the H++ SLR scenario. Coastal access and recreation opportunities may be impeded by temporary to permanent disruptions due to flooding and dune erosion. Morro Strand State Beach Campgrounds are overwhelmed by dune erosion, inundation, and flooding. The Morro Strand Campground may require significant adaptation to remain functional prior to and following flooding and erosion events. However, by the 2100 H++ SLR scenario, it is unlikely that the campgrounds could continue to function unless major revitalization was constructed to protect and raise the campgrounds. Dune losses and associated habitat losses will increase and may be completely lost as erosion carries inland to the line of development. Dune habitats are of intrinsic value to the state parks; providing ecological, recreational, and storm protection values; and their loss would be significant. State Park Road will be threatened by inundation on many sides impacting access to the marina and leaving the Museum of Natural History isolated from the City. Lands surrounding the state park marina will be inundated and floating docks, gangways, and fixed access ways may require significant adaptation to accommodate increased water levels. Access to the marina via State Park Road will be impacted as portions of the road become inundated.

4.2.4 Coastal Development

Coastal development evaluated for sea level rise impacts include privately held parcels of various land uses or zoning. Current City land use data was used to categorize the parcels. Parcels generally have a low adaptive capacity and high sensitivity. However, the adaptive capacity of buildings could potentially be moderate for some parcels with finished floors on an elevated building pad. Note that impacts to parcels may not necessarily represent impacts to the physical buildings located on the parcel.

Coastal development within the City is severely threatened by the year 2100 H++ SLR scenario due to the increased exposure and sensitivity of parcels to flooding, erosion and inundation during an extreme storm event. Bayfront parcels will experience increased water levels impacting uses but structures are expected to be moderately sensitive as only the bayside edge of many parcels are below predicted water levels. Lower lying parcels along the Bayfront, such as the golf course, will be particularly sensitive to inundation. The Embarcadero waterfront and marina would be significantly threatened by the H++ SLR scenario. Inundation would likely overwhelm Embarcadero Rd and Front St, disrupting all commercial, private, and public parcels seaward of these roadways. The function of the Embarcadero business district would be permanently disabled unless action is taken to protect, raise, or retreat the vulnerable development. Additionally, waterfront infrastructure such as docks and piers will be overwhelmed by tidal inundation, jeopardizing the public recreation and commercial uses of Morro Bay harbor. Many parcels with coastal access ways and docks will need modification to accommodate the water levels predicted for this time horizon. Protective development features including the jetties at the mouth of Morro Bay will diminish in effectiveness, further threatening the function of Morro Bay harbor and the Embarcadero waterfront.

North of Morro Bay harbor, the Morro Dunes Travel Trailer Park and Morro Bay High School are threatened by dune erosion and flooding. The encroachment of erosion and intensified flooding will require preventative action to maintain development in place. In the northern region of the City, flooding and dune erosion threaten coastal parcels, with floods extending approximately the width of three parcels inland. Beachcomber Drive, its offshoots, and Toro Lane are especially exposed to flooding, dune and bluff erosion hazards. These parcels are highly sensitive to flooding and erosion events. Furthermore, the adaptive capacity of these parcels is low requiring significant changes to maintain current use. Major protective measures would be required to maintain usability, otherwise managed retreat will be necessary.

4.2.5 Utilities: Water, Wastewater, Gas, Electricity and Telecommunications

Utility assets includes facilities necessary to run the City effectively and efficiently since loss of water, sewer or power would significantly disrupt quality of life for residents. When exposed to flooding, inundation or erosion, this infrastructure typically has a high sensitivity and low adaptive capacity. Wastewater was determined to be the most vulnerable utility to sea level rise. The Morro Bay Waste Water Treatment Plant site would be vulnerable to coastal flooding and erosion in the 2100 H++ SLR scenario. Impacts to the existing waste water treatment plant site are not expected in the 2030 and 2050 time horizons.

Vulnerability of the waste water treatment plant is rated as high due to the high sensitivity and low adaptive capacity of this asset in its current state. The waste water treatment plant is exposed to flooding and erosion hazards that could lead to a disruption of service, especially during a large surf event. Service disruption can result in overflow conditions where untreated and partially treated wastewater is released onsite and through outfall facilities.

Since the wastewater treatment plant is planned for relocation, the vulnerability of proposed future property uses to sea level rise and associated coastal hazards should be considered.

4.2.6 Transportation: Roads, Bike, and Pedestrian Assets

Transportation related assets are generally highly sensitive to coastal hazards as even minor amounts of flooding can cause significant traffic delays, potentially disrupting emergency service vehicles and evacuation routes. Maintenance and repair requirements may also increase after significant flooding and erosion events. Roadways typically have a low adaptive capacity because significant costs are associated with relocating or raising these structures. Many of the roadways include bike and pedestrian facilities or have separate bike and pedestrian facilities running parallel to roads.

Vulnerability is considered high for the 2100 H++ SLR scenario as major transportation corridors, roadways, bikeways, and pedestrian assets become exposed to inundation, flood, and erosion hazards. South Bay Boulevard and State Park Road may become impassable due to projected inundation. Front Street and Embarcadero Road are also anticipated to experience inundation, requiring major adaptive measures or relocation.

The Morro Rock Beach parking lot is anticipated to experience significant erosion and inundation, threatening to breach the ocean to bay causeway on the northeast side of Morro Rock. Overtopping and erosion, potentially to the point of breaching, of this connection will threaten the oceanographic conditions of Morro Bay harbor, potentially allowing for an intensified wave climate at the Embarcadero and sediment accretion in the boat channel. Such conditions threaten to disrupt and disable the function of harbor recreation and commercial activities, as well as Embarcadero waterfront activity. Additionally, Coleman Drive is anticipated to experience flooding and erosion at Morro Rock Beach, ultimately isolating Morro Rock Natural Preserve from the City.

Local ocean fronting roads such as Indigo Circle, Sandalwood Avenue, Mindoro Way, Beachcomber Drive and its offshoots, and Toro Lane are vulnerable to inundation, flood, and erosion hazards. Highway 1 is especially vulnerable to undermining at the northern edge of the City where bluff erosion, dune erosion, and Chevron bulkhead overtopping are anticipated. Major corridors will be highly sensitive to flooding in this time horizon and due to the low adaptive capacity. Improvements will be needed to maintain continuous access. Highway 1 will require relocation or bridge construction.

4.2.7 Environmentally Sensitive Lands

Environmentally sensitive lands include wetlands, rivers, riparian areas, dunes, and other natural resources in the coastal zone. These lands generally have some adaptive capacity in areas where adequate space exists for them to naturally shift landward to a rising sea level.

Environmentally sensitive lands will experience significantly increased tidal inundation with rising sea level. Wetland hydrology may be altered by the rising freshwater-saltwater interface (CNRA, 2014) and intertidal and subtidal ecosystems will be affected by changes in water depth and sunlight penetration. Some flora and fauna may be able to adapt by migrating vertically and/or horizontally, however, such exposure may adversely impact density and diversity of these resources. Many flora and fauna may not be able to adapt due to lack of suitable upland areas or failure to keep pace with the rate of sea level rise. Particularly, the Morro Bay Estuary Natural Preserve will experience significant inundation creating greater open water habitat and forced habitat transition. Coastal squeeze of the wetlands between ocean and roadway (State Park Rd and South Bay Boulevard) will limit the ability for habitat to transition.

Furthermore, as discussed previously, the many dune systems of Morro Bay, including Morro Dunes Natural Preserve, are predicted to undergo severe erosion and inland migration unless action is taken.

Restoration efforts may be needed, where possible, to adapt certain species to predicted water levels and many areas where steep slopes and urban development constrain the space available for landward migration. Risk of this vulnerability is high as the consequences to density and diversity of environmental resources are significant.

4.2.8 Visual Resources

Visual resources in the City of Morro Bay include views of the beaches, bluffs, dunes, Morro Bay, Pacific Ocean, and Morro Rock. As sea level rises, sandy beaches will narrow and eventually disappear in front of existing coastal developments due to erosion and inundation. Erosion will also alter the size and appearance of bluffs and dunes fronting the beach. Views may also be impacted by coastal structures built to protect assets or to accommodate sea level rise. Waterfront views may be impacted if structures increase in height in order to accommodate increased water levels. Major construction to adapt Highway 1 and the Embarcadero waterfront will likely alter visual conditions as well.

4.2.9 Cultural Resources

Historic sites existing within the coastal hazard zones will be vulnerable. In addition to physical impacts, exposure of historic sites can lead to irreplaceable loss of cultural heritage. Any Archaeological resources that exist in these coastal areas will also be vulnerable. Erosion, inundation, and flooding of these areas could result in loss of these resources.

4.2.10 Saltwater Intrusion

As sea levels rise, saltwater has the ability to migrate inland through manmade and natural channels, drainage structures, soils and underground pathways. The migration of saltwater results in salinity changes that can lead to a variety of ecological and agricultural resource impacts. Additionally, saltwater intrusion can impact freshwater resources including surface waters and groundwater.

5. Priority Findings

The exposure of existing coastal resources to coastal hazards such as inundation, flooding and erosion associated with extreme waves and water levels was established to provide a baseline condition for evaluating the vulnerability of these resources to sea level rise and a changing coastal environment. For completeness sake, a summary of the coastal resource vulnerabilities for each time horizon are summarized below, including existing vulnerabilities, years 2030, 2050, 2100, and the year 2100 H++ Update. Hazard maps and greater vulnerability discussion of the 2030, 2050, and 2100 time horizon vulnerabilities can be found in the Plan Morro Bay, CBA.

5.1.1 Existing Coastal Resource Vulnerabilities

Under existing (baseline) conditions beaches and dunes are among the most exposed resources along the open coastline. Erosion and flooding associated with extreme storm events can result in significant loss of beach area and dune habitat. The sandy beaches are more resilient than dunes and typically regain width during calm wave conditions. Once eroded the dune system takes a longer time to re-establish and is less resilient to impacts from extreme storms.

Despite being one of the least disturbed estuaries in Southern and Central California, the environmentally sensitive habitats of the Morro Bay estuary face many stressors including saltwater intrusion, accelerated sedimentation, water quality concerns due to pollutant loading, increasing demand for freshwater resources, and threats to existing biodiversity (MBNEP, 2016).

Much of the coastal development faces limited exposure to inundation, erosion and flooding from coastal storm events under the baseline conditions. Coastal development north of Morro Rock is setback from the active shoreline and protected by the beach and dune system. Along the bay front, most development is elevated above extreme high water levels and protected by a revetment or bulkhead structure.

5.1.2 Projected Coastal Resource Vulnerabilities

Projected vulnerabilities were evaluated for three sea level rise scenarios representing the upper range of projections for years 2030, 2050, 2100 in the CBA, and reevaluated as a fourth assessment to include the 2100 H++ sea level rise scenario in this report. Coastal hazards were mapped for each scenario to estimate flooding, inundation, dune erosion, and bluff erosion hazard areas.

Flooding is generally short in duration (hours), however can present significant disruptions to parcels, critical infrastructure, and transportation corridors. Parcels may be highly sensitive to flooding, especially if the finished floor elevation of a structure is below flood depths. Flooding of residential parcels may displace homeowners, result in property damage, and decrease value, commercial parcels may experience operation interruptions, displacement, and property/equipment damage. Critical infrastructure, specifically the waste water treatment plant would be highly sensitive to flooding due to the consequences of service interruptions and potential for the release of untreated sewage. Transportation corridors may remain viable after flooding, however any amount of flooding can temporarily disrupt traffic and choke vital transportation and evacuation routes.

Erosion may be gradual or episodic and consequential to many assets based on their exposure and sensitivity. Beaches, state parks, parcels, and transportation corridors are exposed to dune and bluff erosion hazards. Erosion at beaches and state parks may impact recreational opportunities as sand and dune areas become squeezed between rising seas and upland development. Storm protection provided by beaches, dunes, and bluffs will be degraded as erosion progresses inland which can result in damage to roadways, residential parcels, and commercial parcels currently fronted by these features.

Inundated areas will be subject to daily wetting from tidal waters impacting beaches, state parks, parcels, and transportation corridors. Inundation will reduce recreation space and opportunities in state parks and beaches. Transportation corridors subject to inundation will no longer be viable. Parcel inundation may result in damage and displacement with impacts to structures, use and value. Environmentally sensitive lands may decrease in density and diversity as significant habitat areas are lost and species are unable to keep pace with rising seas or become constrained by development or geographic features.

A summary of coastal resources vulnerable to sea level rise is provided in Table 5-1.

Table 5-1. Priority Findings Summary table

Asset Category	Potential Impacts	Consequences
Transportation	HWY-1, south of Toro Creek, vulnerable to flooding and erosion in 2030. Coleman Drive and the Morro Rock parking lot are vulnerable to flooding in 2050. Main Street/State Park Road vulnerable to flooding in 2100. Under the H++ scenario, nearly all ocean fronting roadways, from South Bay Boulevard through the Embarcadero Waterfront and up to northern local roads/HWY-1, are vulnerable to flooding, inundation, and/or erosion. Morro Rock parking lot vulnerable to overtopping and breaching, threatening the function of Morro Bay harbor.	Interruption of a major North-South transportation and evacuation route (Hwy 1). Traffic delays, road closures, debris and damage. Isolated land masses and an inundated, inoperable waterfront under H++ scenario
Environmentally Sensitive Lands	Wetlands, intertidal & subtidal habitats impacted by increased tidal inundation in 2030. Impacts more significant in 2050 and beyond as steep topography and development limit the ability of habitats to adapt. Morro Bay Estuary Natural Preserve significantly vulnerable to coastal squeeze and open water habitat transition under 2100 H++ scenario.	Loss of habitat area and species diversity. Loss of soft protective buffer for coastal development and transportation.
State Parks	Dune system and Morro Strand campground vulnerable to flooding and erosion in 2030, more so in 2050 and 2100. 2100 H++ scenario threatens complete loss of dune system and state parks.	Loss of sensitive dune habitat and loss of recreational beach/camping area.
Beaches	Flooding, erosion, and inundation of sandy beaches, dunes, and bluffs. Significant loss of beach area expected for 2050 and 2100. 2100 H++ scenario threatens total beach loss if coastal development	Loss of recreation opportunities and storm protection provided by beaches.

	holds the line. Overtopping of the Morro Dunes Natural Preserve threatens to alter sediment dynamics and wave climate in Morro Bay harbor.	
Coastal Development	Moderate vulnerability to coastal development in 2050 due to storm related flooding. High vulnerability in 2100 as flooding, dune erosion and bluff erosion impact oceanfront parcels. 2100 H++ scenario amplifies such vulnerabilities and introduces inundation and the potential for an inoperable Embarcadero waterfront.	Impacts to uses and value of residential and commercial parcels.
Utilities	The existing waste water treatment plant site was found to be vulnerable to coastal flooding by the 2100 time horizon and beyond.	Disruption of water treatment service, damage to infrastructure, potential overflow, if it were not relocated. (The existing waste water treatment plant is currently planned for relocation.)

6. References

California Coastal Commission, 2015. California Coastal Commission Sea Level Rise Policy Guidance. Adopted August 12, 2015.

Coastal and Ocean Working Group of the California Climate Action Team (CO-CAT). 2013. State of California Sea-Level Rise Guidance Document, March 2013 Update.

City of Morro Bay, 1982. Proposed Land Use Plan of the Local Coastal Program. City of Morro Bay Community Development Department.

California Natural Resources Agency (CNRA). 2014. Safeguarding California: Reducing Climate Risk.

Doherty, 2015. Elevated Sea Levels During 2015-2016 Strong El Nino. December 2105.

Griggs, et al. 2005. Living with the changing California Coast. Gary Griggs, Kiki Patsch, and Lauret Savoy, et al. University of California Press, 2005.

Hapke, C.J., Reid, D., Richmond, B.M., Ruggiero, P., and List, J., 2006. National Assessment of Shoreline Change Part 3: Historical Shoreline Change and Associated Coastal Land Loss Along Sandy Shorelines of the California Coast. Part of the U.S. Geological Survey National Assessment of Shoreline Change http://pubs.usgs.

MBNEP, 2016. Climate Vulnerability Assessment Report, Prepared by the Morro Bay National Estuary Program for submittal to the US EPA. February 2016.

Michael Baker International, 2016. City of Morro Bay – Community Baseline Assessment. Prepared for City of Morro Bay. Prepared by Michael Baker International. September 2016.

National Research Council of the National Academies. 2012. Sea Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future.

Ocean Protection Council (OPC), 2018. State of California – Sea-Level Rise Guidance, 2018 Update.

Patsch, Kiki and Gary Griggs. 2007. Development of Sand Budgets for California's Major Littoral Cells. Institute of Marine Sciences. University of California, Santa Cruz.

USACE, 2003. Morro Bay Estuary City of Morro Bay, San Luis Obispo County, CA Ecosystem Restoration Feasibility Study Draft F3 Conference Report Without-Project Conditions Analysis. US Army Corps of Engineers, Los Angeles District. July 15, 2003.

USACE, 2016. San Luis Obispo County Coastal Regional Sediment Management Plan. Prepared by US Army Corps of Engineers Los Angeles District, San Luis Obispo Council of Governments, Everest International Consultants, Inc., Merkel & Associates, Inc., and Philip King, Ph.D. Final Draft.

Appendix A. Coastal Hazard Modeling and Mapping

Table of Contents

List of Figures

List of Tables

1. BACKGROUND

This appendix presents technical information on the numerical modeling approach used to estimate and map future sea level rise hazard zones. These hazard zones were used as the basis of the vulnerability assessment.

2. INTRODUCTION

Morro Bay's exposure to coastal hazards due to sea level rise was estimated using modeling tools and coastal datasets. The coastal hazards that were modeled as part of the Community Baseline Assessment include inundation, flooding (both coastal and fluvial) and dune/bluff erosion. Flooding and inundation terms are used explicitly in this report. Flooding is used to describe episodic events that result in relatively short-duration periods of standing water. Wave run-up limits are used as a proxy for flooded areas since these areas would only become exposed during extreme wave conditions (i.e., 50- or 100-year events). Inundation represents a condition of nearly continuous periods of standing water. The mean high water (MHW) shoreline position was used as a proxy for the inundation limit for this study.

The modeling variables, approaches, and equations used to define the study's coastal hazards are shown in Table 1. Figure 1 illustrates the response of dune-backed beach to an extreme wave event and resultant inundation, flood and dune hazard zones.

TABLE 1: MODELING APPROACHES

Hazard	Metric	Input Variables	Modeling Approach	Modeling Equations
Inundation	Mean High Water	Slope, Depth of Closure, Sea Level Rise	Empirical	Modified Bruun Rule (Rosati, Dean, Walton 2013)
Dune Erosion	Dune Toe	2% Run-up Elevation, Dune Toe, Beach Slope	Empirical +Monte Carlo	Stockdon, 2006 - Komar, 1999
Coastal Flooding	2% Run-up Elevation	Surge, Sea Level Anomalies, Tide, Significant Wave Height, Peak Wave Period, Beach Slope	Empirical +Monte Carlo	Stockdon, 2006
Fluvial Flooding	100-year Flood Limit	100-year River Discharge	Empirical	1-D HEC-RAS Steady State
Bluff Erosion	Top of Bluff	Historic Erosion Rate, Sea Level Rise	Empirical	Revell et al. 2011

The general modeling approach was to collect and analyze available coastal topographic / bathymetric data, model existing and future hazards, and then map the hazards. Experiment-based (empirical) equations and a data simulation model were used to quantify the future hazards. The data simulation was conducted using a Monte Carlo method, which is a probabilistic computational tool where the governing equations are well known, but the independent variables of the input (demand) and the resulting design components (capacity) may not be completely known. The Monte Carlo approach uses a distribution of each variable, then uses that random variable within the described parameters to generate a single computation. The process repeats hundreds or thousands of times to generate a statistical output of design parameters, which accounts for the uncertainty of the input parameters. For instance, tides, waves and beach characteristics all influence coastal flooding and have their own statistics and likelihoods. These variables were randomly combined thousands of times in order to simulate the statistics and likelihood of a given coastal hazard.

Details on model inputs, such as local water levels, waves and sea level rise scenarios, as well as how the respective coastal hazards were mapped are described in this section.

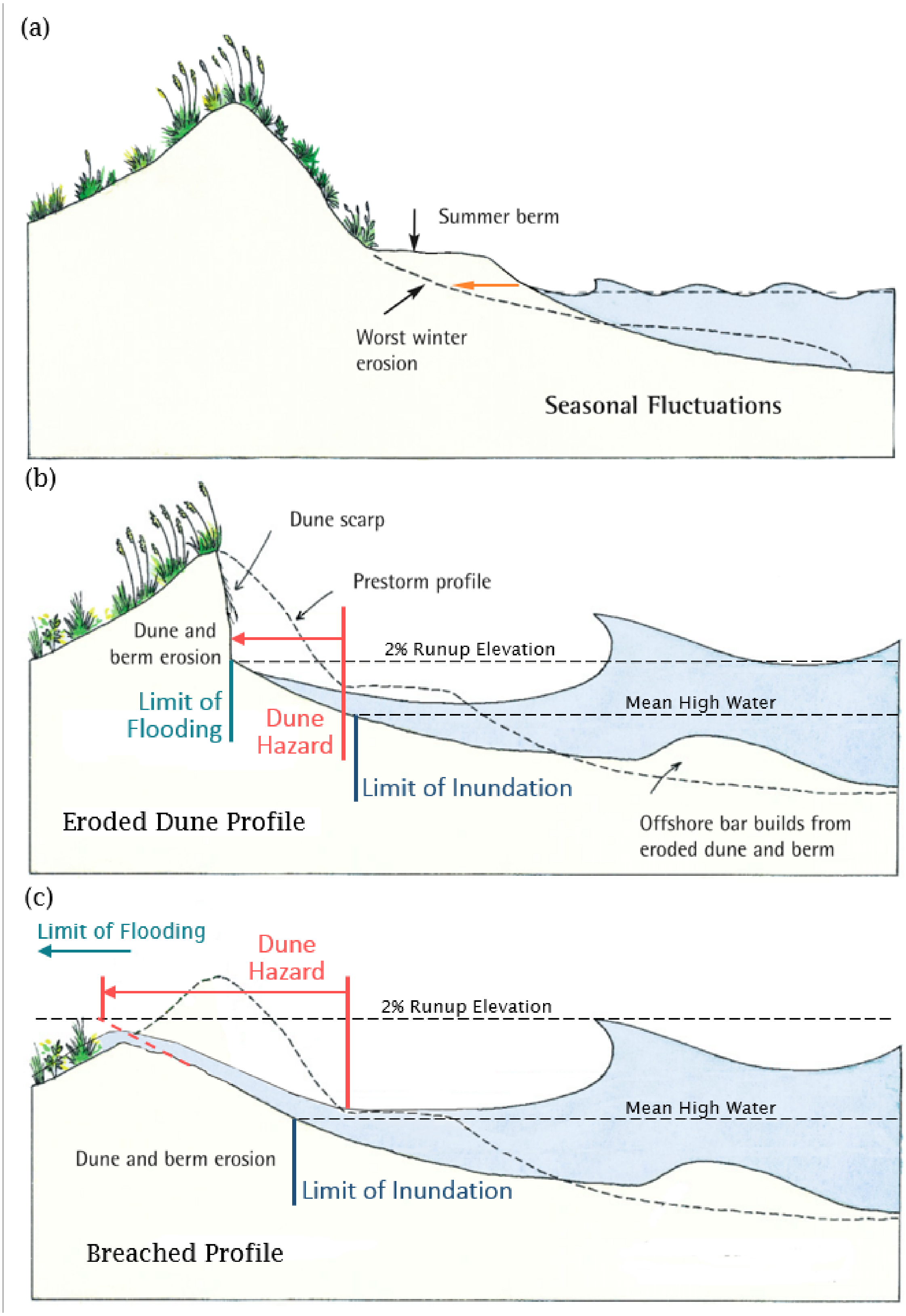


FIGURE 1: DETERMINATION OF COASTAL FLOODING AND INUNDATION ZONES
(Modified Illustrations. Originals by D Williams, in Rogers & Nash 2003)

3. Coastal Site Conditions

3.1. Water Levels

3.1.1. Historical Statistics

The nearest, long-term sea level record in proximity to the study area is the Port San Luis tide gage (Station 9412110) operated by the National Oceanic and Atmospheric Administration (NOAA). The gage is located on the Harford Pier, which has been collecting data since 1948. These data are applicable to the open-ocean coastline in Central California and are summarized in Table 2.

Table 2: Water Levels in Port San Luis (1983-2001 Tidal Epoch)

Description	Datum	Elevation (feet MLLW)
Highest Observed Water Level (1/18/1973)	Maximum	7.65
Highest Astronomical Tide	HAT	7.10
Mean Higher-High Water	MHHW	5.32
Mean High Water	MHW	4.62
Mean Sea Level	MSL	2.80
Mean Low Water	MLW	1.04
Mean Lower-Low Water	MLLW	0.00
North American Vertical Datum of 1988	NAVD88	0.08
Lowest Astronomical Tide	LAT	-1.99
Lowest Observed Water Level (01/07/1951)	Minimum	-2.40

(Source: NOAA 2016)

Tidal data obtained from the Port San Luis tide gage was used to estimate probability distributions for tidal levels, surge, and sea-level anomalies (e.g., higher water levels due to warm water temperatures or low atmospheric pressure). The parameterized water levels used in the Monte Carlo analysis are described below:

- Tides – Tides in Morro Bay are semi-diurnal, which refers to two highs and two lows occurring per day. A mean of 0 ft (MSL) with a standard deviation of 1.6 ft was used. These probabilistic parameters were calculated by analyzing the astronomical tide record. Astronomical tides result solely from gravitational effects of the moon and sun, without any atmospheric influences.

- Sea-Level Anomaly (SLA) – Anomalous water levels as a result of unusual water temperatures (El Niño), salinities, average monthly winds, atmospheric pressures, and/or coastal currents. These effect occur on a time scale of weeks and months. A mean SLA of 0 ft (MSL) with a standard deviation of 0.2 ft was used. These parameters were calculated using 14-day moving average of tidal residual. The tidal residual is the difference between the recorded tide and the predicted astronomical tide.

- Storm Surge – Storm surge is the abnormal rise of sea levels in response to wind associated with a short-term event. Return period storm surge values of 2.4 ft (10 yr), 2.9 ft (25 yr), 3.2 ft (50y r) and 3.5 t (100 yr) were used in the analysis. These return periods were calculated by running an extreme value analysis on tidal residual. Storm surge events were limited to tidal residuals spikes less than a day in length.

3.1.2. Sea Level Rise Scenarios

The California Coastal Commission Sea Level Rise Policy Guidance (CCC 2015) document considers "Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past Present, and Future" (NRC 2012) the best available science on relative sea level rise for the state of California. Therefore, the Coastal

Commission recommends that the sea level rise projections in this study be used for coastal planning and sea level rise policy. Sea level rise projections for the various planning horizons being considered (i.e., 2030, 2050, and 2100) were derived from this study. The NRC 2012 study's high range sea level rise projections for the area south of Cape Mendocino were used as the basis of the vulnerability assessment (Table 3). The high range projections for sea level rise coincide with an upper estimate of a "business as usual" greenhouse gas emissions scenario. This climate scenario assumes that emissions continue to increase until the end of the 21st Century without a significant decrease in fossil fuel use (Snover et al. 2013).

TABLE 3: SEA LEVEL RISE PROJECTIONS FOR THE STUDY AREA

Year	Projected Sea Level Rise (ft)	Projection Uncertainty (ft, +/-)	Low Range (ft)	High Range (ft)
2030	0.5	0.2	0.2	1.0
2050	0.9	0.3	0.4	2.0
2100	3.1	0.8	1.5	5.5

(Source: National Research Council 2012)

3.2. WAVES

Waves act to carry sand in both the cross-shore and longshore directions and can also cause short-duration flooding events by causing dynamic increases in water levels. Thus, the wave climate (or long-term exposure of a coastline to incoming waves) and extreme wave events are important in understanding future sea level rise vulnerabilities.

Offshore wave data was analyzed by combining NOAA measurements and a USGS wave forecast data set. Data for both sources were obtained 60 miles west-northwest of Morro Bay at NOAA buoy 46028 (Figure 2).

The USGS wave forecast information was derived using four separate global circulation models (GCM) to force a numerical wave model (WaveWatch III) to create future wave information (Erikson et al. 2015). The four GCMs were forced using a future climate scenario called RCP 8.5, as defined by the fifth phase of the Coupled Model Inter-comparison Project (CMIP5). CMIP5 RCP 8.5 corresponds to the upper end of climate emission scenarios; thus, correlates with the high projected rates of sea level rise used throughout the analysis. The four forecasted wave data records and the historic NOAA buoy wave data were combined to create four, 117-year datasets.

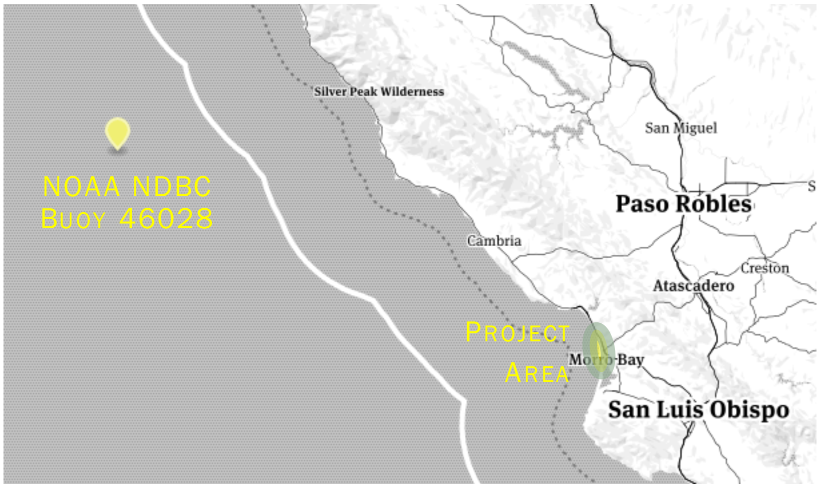


Figure 2: Location of NOAA NDBC Buoy 46028

3.2.1. Wave Climate

The largest percentage (>45%) of the waves approaching Morro Bay are from the west-northwest (293 degrees). Historically, the most frequent significant wave height is 8.2 to 9.8 feet (2.5 to 3 meters) and the most frequent wave periods were between 12 to 13 seconds and 14 to 15 seconds (Figure 3 and Figure 4). The largest waves occur in the winter when northern hemisphere cyclonic storms generate powerful, long period waves.

For the sheltered beach within the Morro Bay jetties, the wave heights were reduced 75%. This wave reduction value was calculated by estimating breaking wave characteristics from aerials and bathymetry. The wave heights within the jetties were typically 75% less than those outside the jetties.

3.2.2. Extreme Waves

An extreme value analysis was used for each of the four 117-year hybrid datasets and averaged to produce extreme wave return periods. The results of the analysis on the four hybrid datasets is shown in Figure 5. The 50- and 100-year return period significant wave heights are 28.8 and 30.0 feet, respectively. A relationship between wave height and period was fitted to the historic buoy data and used to estimate peak wave periods corresponding with extreme waves (Erikson et al. 2015). The peak period for 50- and 100-year waves is approximately 18 seconds.

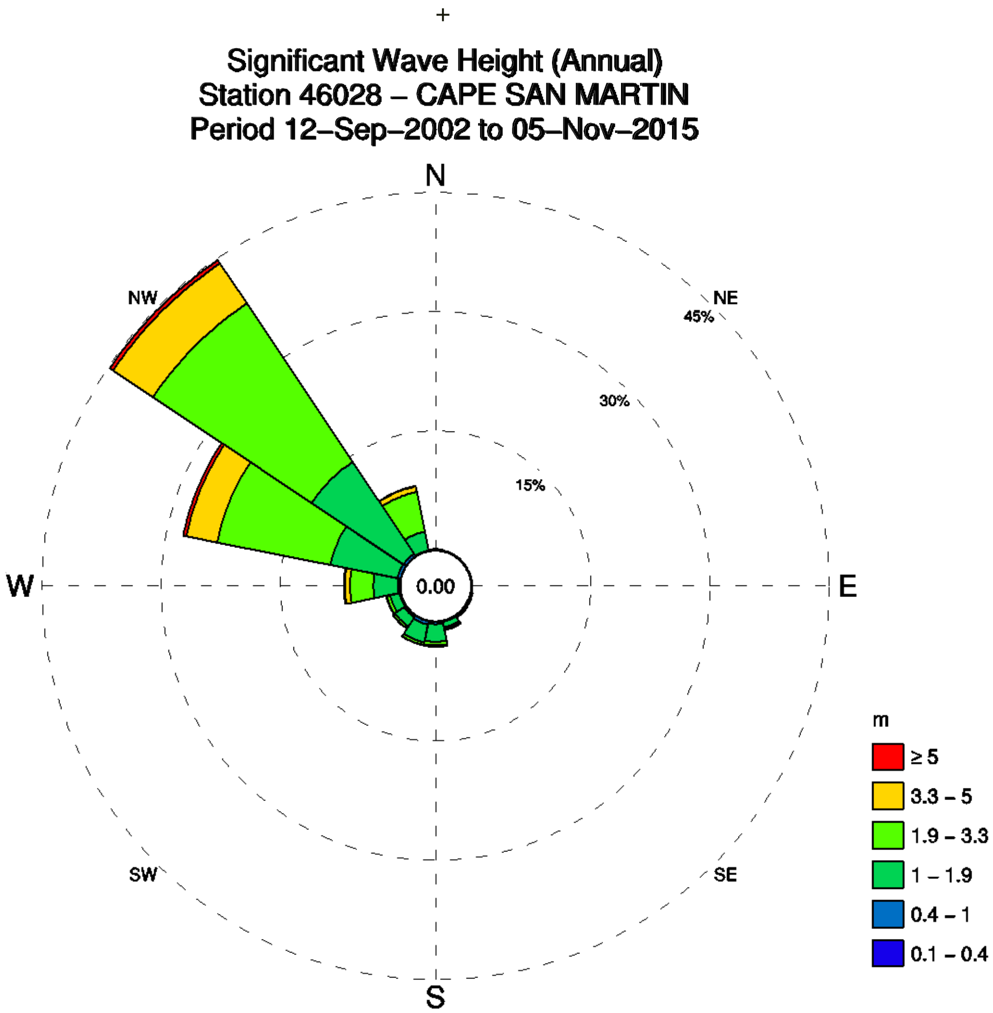


FIGURE 3: HISTORIC ANNUAL SIGNIFICANT WAVE HEIGHT AND DIRECTION (NOAA NDBC BUOY 46028)

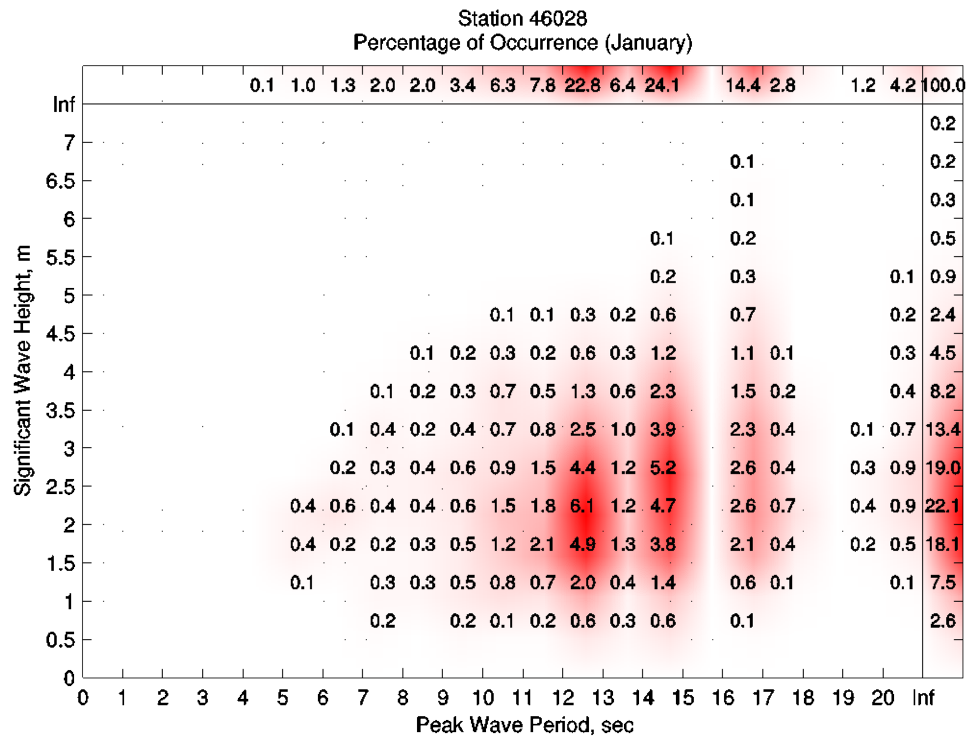


FIGURE 4: HISTORIC SIGNIFICANT WAVE HEIGHT AND PEAK WAVE PERIOD JOINT HISTOGRAM

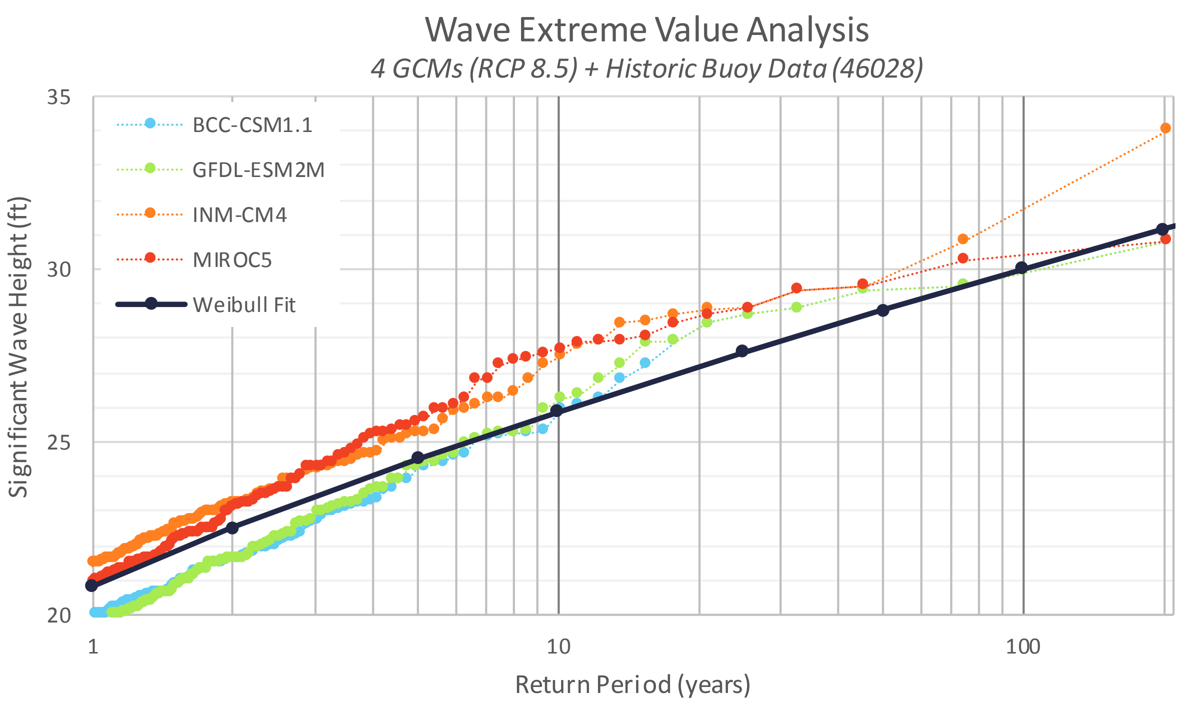


FIGURE 5: EXTREME WAVE RETURN PERIODS (WEIBULL FIT LINE USED FOR ANALSIS)

3.3. COASTAL TOPOGRAPHY / BATHYMETRY

The beach characteristics of the Morro Bay coastline were parameterized using five, bare-earth, light detection and ranging (LiDAR) data collected between 1997 and 2013. The flight date, source and coverage of the individual flights is shown in Table 4.

TABLE 4: LIDAR DATASETS

Survey Name	Flight Date	Source	Coverage
1997 Pre-El Nino	October 1997	NOAA/USGS/NASA	Entire Study Area
1998 Post-El Nino	April 1998	NOAA/USGS/NASA	Entire Study Area
2010 USACE NCMP Lidar	August 2010	JALBTCX, USACE	Entire Study Area
2011 PG&E: Los Osos, CA	March 2011	PG&E	Only south of Morro Rock
2013 PG&E: San Simeon, CA	February 2013	PG&E	Only north of Morro Rock
2013 California Topobathy Merge	February 2014	Hybrid Sources (published by NOAA)	Entire Study Area

Topographic data was used to create representative beach profiles for eight reaches within the City, as shown in Figure 6. The reaches were delineated based on similar characteristics such as foreshore slope and dune toe. An example of beach profile change between the topographic data sources used for this study is shown in Figure 7.

The XX DEM was used for mapping inundation hazards within the bay. The

The XX

FIGURE 6: STUDY SHORELINE REACHS (BOUNDED BY ORANGE LINES)

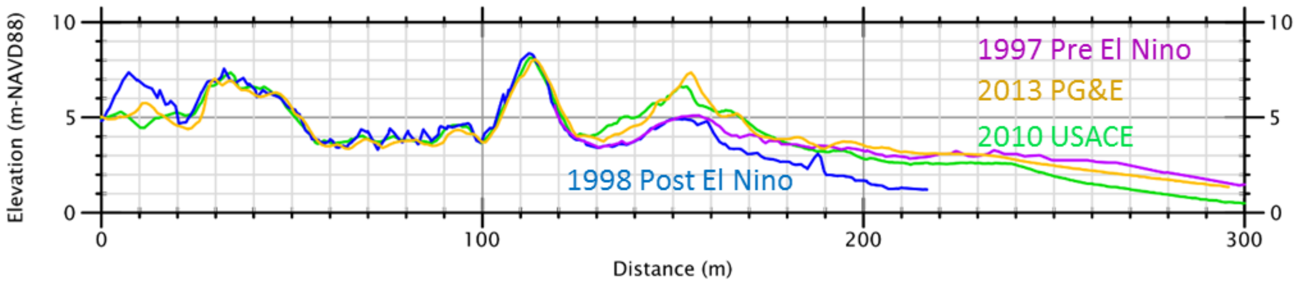


FIGURE 7: BEACH TRANSECT WITHIN MORRO BAY HIGH SCHOOL REACH

3.4. COASTAL STRUCTURES

Coastal structures in the City includes three coastal protection structures (i.e., seawalls and revetment), a harbor entrance channel jetty system and numerous shoreline protection structures (i.e., bulkhead walls and rip rap) along the bay waterfront. The location of these structures is shown in Figure 8. The modeling assumed that coastal structures were not present as a worst-case scenario. A "hold the line" scenario would result in modeled hazards stopping at these structures. It is anticipated that these coastal structures would be overwhelmed at some point in the future. The potential overwhelming of these structures are discussed qualitatively elsewhere.

Bay waterfront structures crest elevations (as determined by the topobathy merge LiDAR dataset) were analyzed relative to projected water levels to determine if overtopping would occur. No structural evaluation of the structures was conducted relative to these projected water levels.

FIGURE 8: SHORE PROTECTION IN MORRO BAY

4. Coastal Sea Level Rise Hazard Analysis

4.1. Inundation Hazard Zones

Methods used to determine coastal and bay inundation zones are described in this section.

4.1.1. Coastal Inundation Hazard Zone

A widely accepted method for quantifying shoreline response associated with sea level rise is referred to as the modified Bruun Rule (Rosati, Dean, Walton 2013). The method, or rule, assumes that as mean sea level rises, the beach profile and the foredune is able to adjust upwards and landward as sediment is conserved across the profile (Figure 9).

The modified Bruun Rule does not explicitly account for local sediment sources or sinks. Some approaches for quantifying future erosion incorporate short-term shoreline change rates. However, due to the sparsity of data and the influence of harbor dredging and nourishment practices on those surveys, the short-term shoreline change rates could not reliably be calculated.

The current and projected future coastal inundation hazard zone was mapped using the mean high water (MHW) line as a proxy. Using the offshore slope of approximately 20:1 (horizontal to vertical) for Morro Bay, the beach face and foredune shifts up and back 20 ft for every foot of sea level rise. Inundation due to seasonal erosion is accounted for through use of a winter profile beach slope.

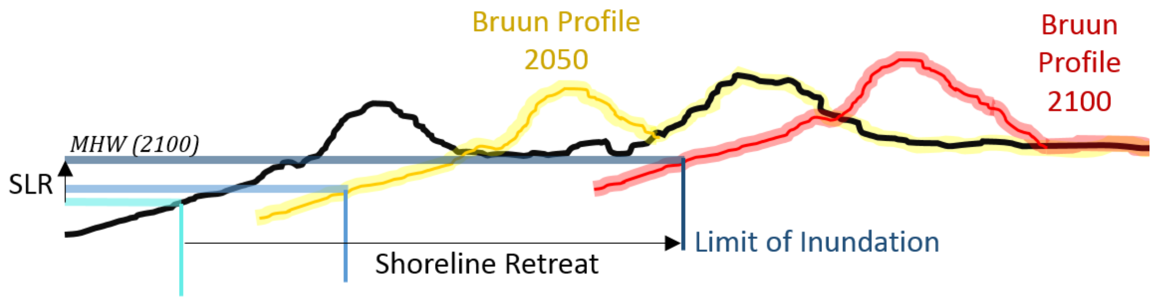


Figure 9: Beach Profile and Inundation Hazard Zone Adjustment According to the Bruun Rule

4.1.2. Bay Inundation Hazard Zone

Mapping of the inundation hazard zone within the bay was determined using a "bathtub" model approach. The bathtub approach compares the elevation of future tidal water levels to existing grades. For this analysis, the 2009-2011 TopoBathy merge LiDAR dataset was compared to a tidal elevation of mean higher high water (MHHW) in combination with sea level rise. The combined water levels within the bay for the inundation hazard zone were as follows:

- Year 2030 – 6.25 ft NAVD88
- Year 2050 – 7.25 ft NAVD88
- Year 2100 – 10.75 ft NAVD88

Note that the accuracy of these hazard zones are contingent on the quality of the topographic data in these areas.

4.2. Dune Erosion Hazard Zone

The dune erosion hazard zone was mapped using simple geometric model referred to as the Komar method (Komar 1999). This model is a commonly used tool for estimating dune erosion on the swell-dominated U.S. West Coast and is recommend by FEMA (Heberger et al. 2009, Revell et al 2011, FEMA 2015). The method assumes that the dune toe elevation erodes following the upper beach slope until it reaches the wave run-up elevation (Figure 10). The method requires the use of a "most likely winter profile". In general, a winter profile is one in which the flat sandy berm (towel space) has migrated offshore to form sand bars. Winter profiles for this study were constructed using the dune features of the PG&E LiDAR datasets and upper-beach slopes measured from the post-El Niño LiDAR surveys. For the dune-backed beaches in Morro Bay, the dune toe is typically found at elevations of 11 to 12 ft NAVD88 with a typical winter beach slope of 3.5% to 4.5%.

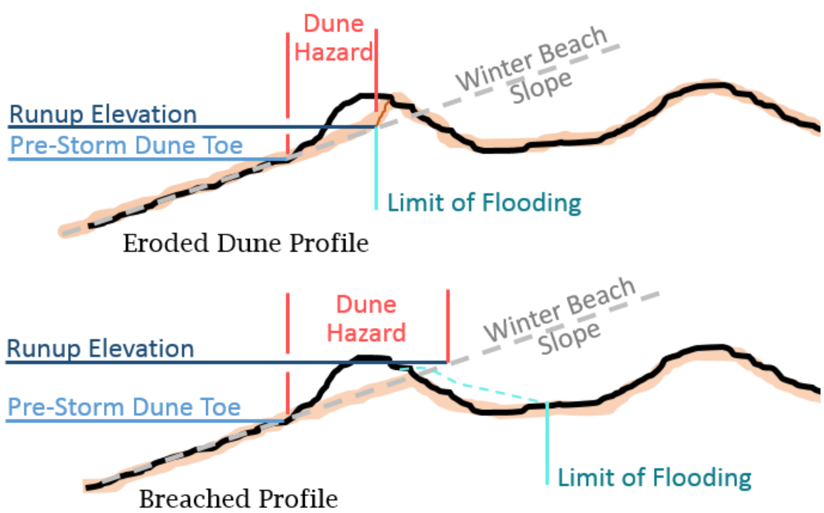


Figure 10: Schematic Showing the Mechanics of Komar Dune Erosion Method

4.3. Coastal Flood Hazard Zone

The coastal flood hazard zone was estimated to be the limits of wave run-up on the eroded beach profile. Wave run-up is the condition of waves breaking on the beach and water "running up" the beach face and/or beachfront structure. Wave run-up extends farther landward than the "still water" level. Wave run-up is a function of wave conditions, which, in turn, are based on storm events, shoreline geometry and still water levels. The landward extents of the still water and run-up elevations (i.e., the intersection of these elevations onto the beach) are based on the profile of the beach face. Wave run-up was calculated using an empirical run-up equation (Stockdon et al. 2006) for this study. The equation was forced with an extreme wave event, as discussed above.

The wave run-up elevation is the combination of tide, SLA, storm surge, and the 2% wave run-up height (Figure 11). On the open-water Western U.S., wave run-up is often the largest of these components. The run-up height for the study area was estimated using a Monte Carlo methodology where the water level, wave constituents, and beach slope are input into the Stockton, et al. (2006) empirical run-up equation. This equation is commonly used to estimate run-up on sandy beaches along the Western U.S. shorelines. The equation is defined as follows:

$$R_{2\%} = 1.1\left(0.35\,\beta_f\,(H_0L_0)^{1/2} + \frac{\left[H_0L_0\,\left(0.563\,\beta_f^2 + 0.004\right)\right]^{1/2}}{2}\right)$$

Where $R_{2\%}$ is the run-up point reached or exceeded by only 2% of all waves, H_0 is offshore significant wave height, L_0 is offshore significant wavelength and β_f is beach slope. The $R_{2\%}$ run-up level is a common metric for quantifying the maximum elevation inundated during a storm event.

The limit of coastal flooding is tied to the results of the dune erosion analysis and depends on whether the foredune is large enough to withhold the storm or breaches (Figure 1 and Figure 10). A breach is identified if the calculated dune erosion distance was located at an elevation less than the wave run-up elevation. For breaching conditions, the overwash distance was limited to a couple hundred feet for natural surfaces but allowed to expand further for paved and declined overflow pathways. Mapping of the overwash flood hazard required engineering judgement and is highly dependent on the conditions of the back beach.

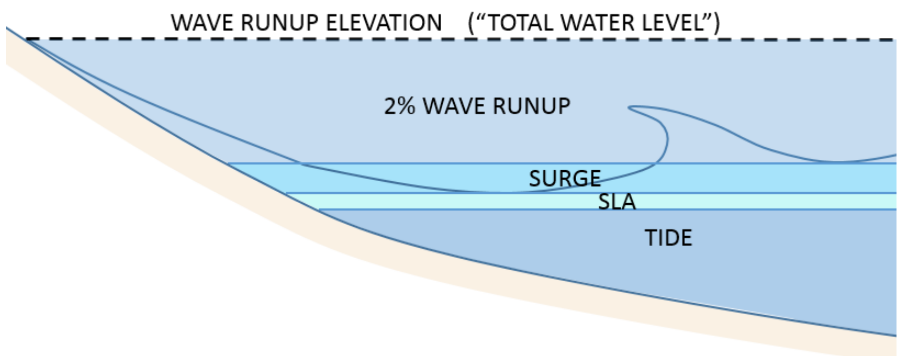


FIGURE 11: COMPONENTS OF WAVE RUN-UP ELEVATION

4.4. BLUFF EROSION HAZARD ZONE

A segment of coastline near the northern city limits consists of a sand and rocky beach backed by coastal bluffs. The shoreline response and dune erosion estimates indicate these bluffs will experience more frequent wave action at the bluff toe as sea levels rise. The increased intensity and extent of wave action at the bluff toe will result in episodic bluff erosion when large waves coincide with high water levels.

Revell et al. (2011) provides a method for predicting future bluff erosion hazards that increases historic erosion rates based on the relative increase in time that the total water level (TWL) exceeds the bluff toe elevation. The study provided state-wide average and maximum bluff erosion rates for a 4.6 ft (1.4 m) sea level rise scenario. In San Luis Obispo County the average cliff erosion was about 50 ft (15 m) with a maximum of 640 ft (195 m). For the region near our study location the bluff retreat for this sea level rise scenario was about 130 ft (40 m). Estimates for the bluff erosion hazard zones for each sea level rise scenario are depicted as a distance landward from the approximate top of bluff. There is a large uncertainty in these estimates due to unknowns associated with geologic make up of these bluffs and the alongshore variability around the adjacent headland. More detailed geological investigation and run-up analysis would be required to develop parcel-specific estimates of bluff erosion and how the hazard will change with sea level rise.

4.5. FLUVIAL FLOOD HAZARD ZONE

Sea level rise can influence flooding along rivers that discharge into tidal waters. 1-D HEC-RAS steady state modeling and analyses were performed to assess the influence of sea level rise during a 100-year fluvial flood at the most significant rivers that discharge to tidal waters in the City (i.e., Chorro Creek and Morro Creek). These creeks were selected for modeling based on the size of their 100-year flood flow discharge and location. Model results were used to assess the extent of sea level rise influence on upstream water surface elevations in the river.

4.5.1. Model Setup

1-D HEC-RAS models were created for Chorro Creek and Morro Creek. Geographic data from the 2013 NOAA Coastal California TopoBathy Merge Project was compiled in ArcMap 10.1 using the HEC-GeoRAS extension. The data was then exported to HEC-RAS to create the model. The river centerlines were drawn using contour data and aerial imagery. Cross-sections were drawn balancing span length and a perpendicular alignment with the main channel and geographic features. Flow centerlines were also drawn for the left and right floodplain to provide downstream cross-section distance.

Roughness factors (Manning's "n") used in the model were obtained from a range of values specified in the FEMA Flood Insurance Study (FEMA FIS 2012). Roughness factors for Chorro Creek ranged from a channel "n" of 0.015-0.040 and an overbank "n" of 0.045-0.100. Roughness factors for Morro Creek ranged from a channel "n" of 0.015-0.080 and an overbank "n" of 0.045-0.100.

The model developed for Chorro Creek had 36 cross-sections, covering approximately 2 miles of the river extending upstream of the South Bay Boulevard Bridge and downstream to the river outlet into Morro Bay, the model layout is shown in Figure 12. The model developed for Morro Creek has 24 cross-sections, covering approximately 0.5 miles of the river with the upstream end just east of Cabrillo Highway and extending downstream to the river outlet into the Pacific Ocean. The model layout for Morro Creek is shown in Figure 13.

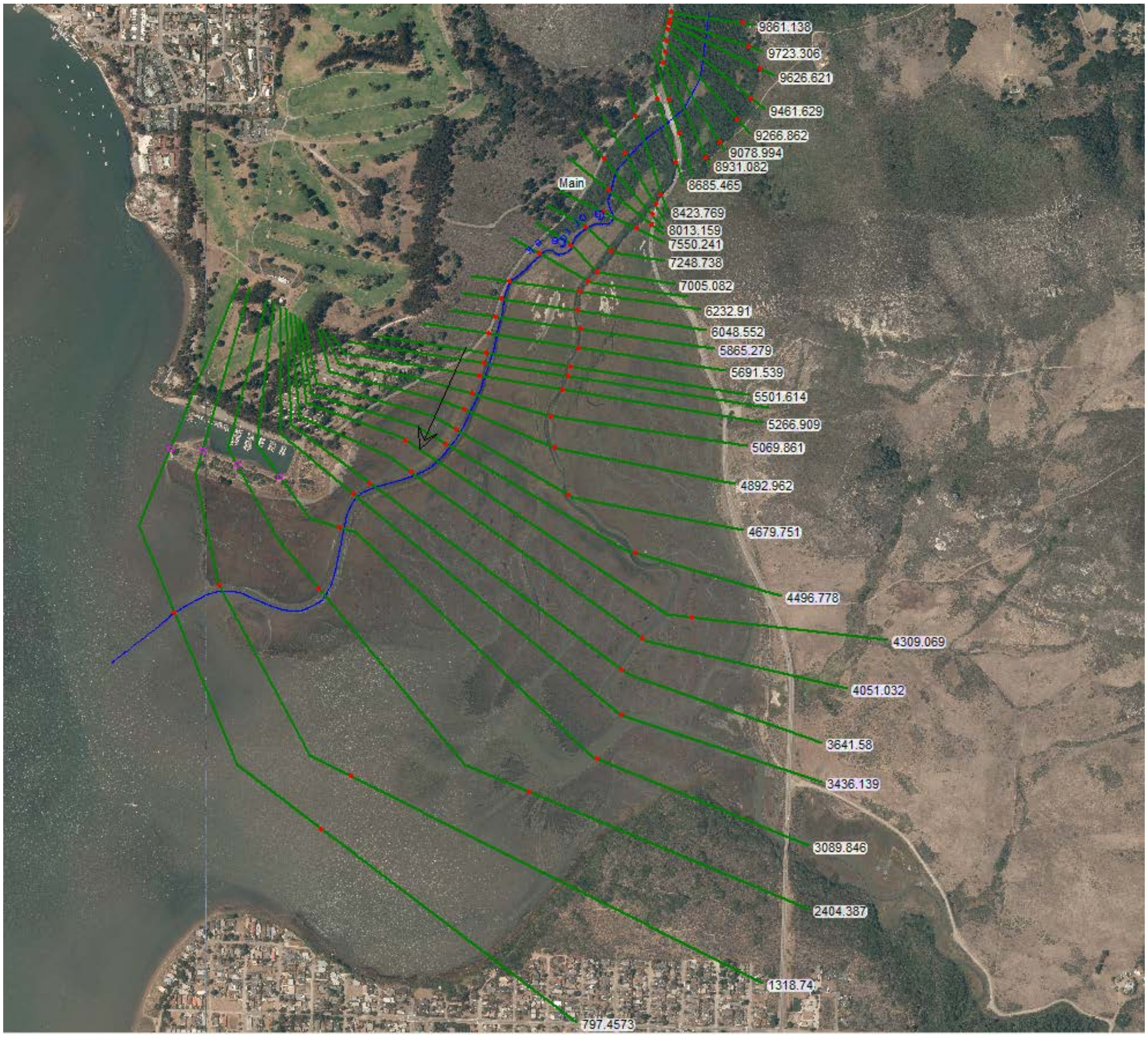


FIGURE 12: HEC-RAS MODEL LAYOUT FOR CHORRO CREEK

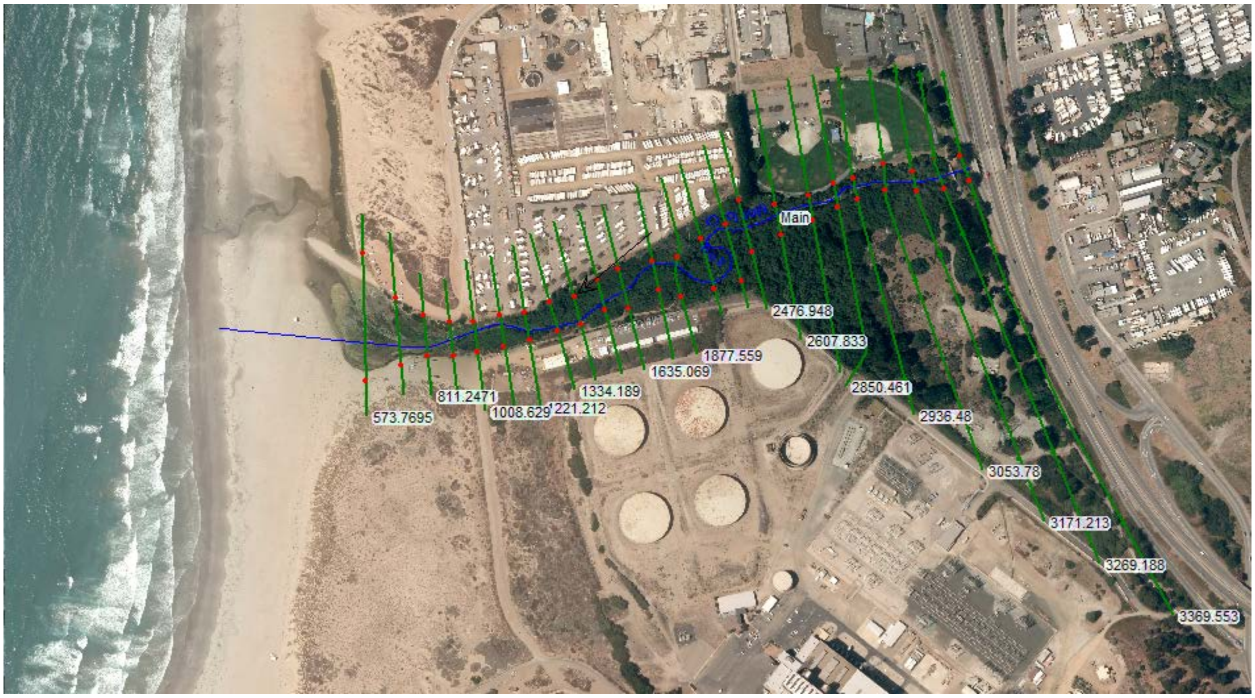


FIGURE 13: HEC-RAS MODEL LAYOUT FOR MORRO CREEK

4.5.2. Model Boundary Conditions

The upstream boundary for each model is controlled by the 100-year flood peak discharge. A 100-year flood has a one percent change of occurring in any given year. The 100-year flood peak discharge was obtained from the FEMA FIS (2012) and is 18,900 cfs for Chorro Creek and 11,800 cfs for Morro Creek.

The downstream boundary for both models is controlled by the tidal water surface elevation. The NOAA tidal gage closest to Morro Bay is located at Port San Luis, California (NOAA Station No.: 9412110). Mean higher high water (MHHW) was selected as the baseline tidal datum for the sea level rise modeling effort. The downstream model boundary assumes still water conditions where sea level rise scenarios were added to MHHW (i.e., 5.24 ft), as summarized in Table 5 below.

TABLE 5: DOWNSTREAM MODEL BOUNDARY CONDITIONS

Time Horizon	SLR Projection (ft)	Still Water Surface Elevation (ft, NAVD 88)
Current MHHW	0	5.24
2030	1.0	6.24
2050	2.0	7.24
2100	5.5	10.74

4.5.3. Chorro Creek

Steady state model runs were performed for Chorro Creek with current and projected sea level conditions during a 100-year flood. Model results under the 100-year flood and MHHW sea level condition were agreeable with water surface elevations shown on the FEMA FIRM map number 06079C1027G, panel 1027 of 2050 (2012). Additional model runs were performed for the projected sea level rise scenarios and results are summarized in Table 6 below.

TABLE 6: CHORRO CREEK MODELING SUMMARY

Time Horizon	Upper Range SLR (ft)	100-year Fluvial Flood (cfs)	Limit of Upstream Influence (HEC-RAS X-Section No.)
Current MHHW	0	18,900	N/A
2030	1.0	18,900	4496
2050	2.0	18,900	5501
2100	5.5	18,900	7808

These results show the water surface elevation migrating upstream with increased sea level rise, this is to be expected for a wide and flat wetland area with subcritical flow during a flood event. As shown in Figure 14, a modest increase is seen in the water surface elevation in the immediate vicinity of the downstream boundary and the flood flow profile interface. The increase in water surface elevation is localized and does not extend upstream of the downstream boundary and flood flow profile interface (where the tidal water surface elevation meets the flood water surface elevation); therefore, the influence of sea level rise was not found to result in the backup of flood waters in Chorro Creek. The influence of sea level rise on Chorro Creek is limited to the extent of tidal inundation and is not expected to increase the limits of fluvial flooding during an extreme event. Thus, no additional fluvial flood hazards as a result of sea level rise are anticipated at Chorro Creek.

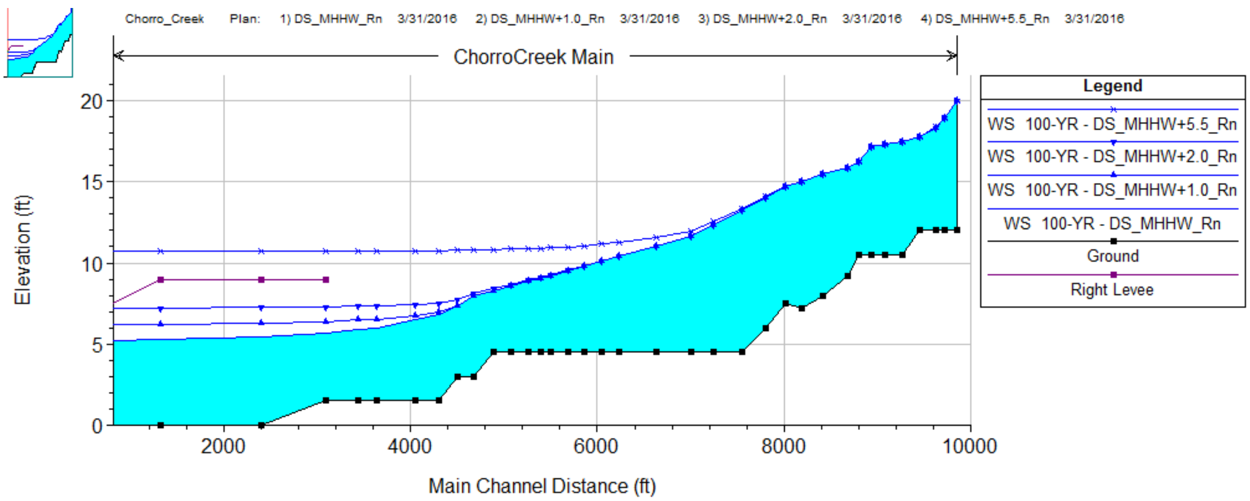


FIGURE 14: CHORRO CREEK WATER SURFACE PROFILE.

4.5.4. Morro Creek

Steady state model runs were performed for Morro Creek using the same downstream boundary as Chorro Creek during a 100-year flood. Model results under the 100-year flood and MHHW sea level condition were agreeable with water surface elevations shown on the FEMA FIRM map number 06079C0813G, panel 813 of 2050 (2012). Additional model runs were performed for the projected sea level rise scenarios.

Model results indicate that a supercritical flow regime develops during the 100-year fluvial flood in the downstream reach of Morro Creek. Supercritical flow develops as a result of the contraction created by Morro Dunes RV Park to the north and the berm to the south, this flow regime continues until the flood flow passes through the dunes and onto the beach. Sea level rise does not increase fluvial flooding in Morro Creek; due to the supercritical flow regime, tidal velocities are not able to overcome the fluvial flood velocity. As shown in Figure 15 below, sea level rise does not result in floodwater backup and does not increase upstream water surface elevations in Morro Creek.

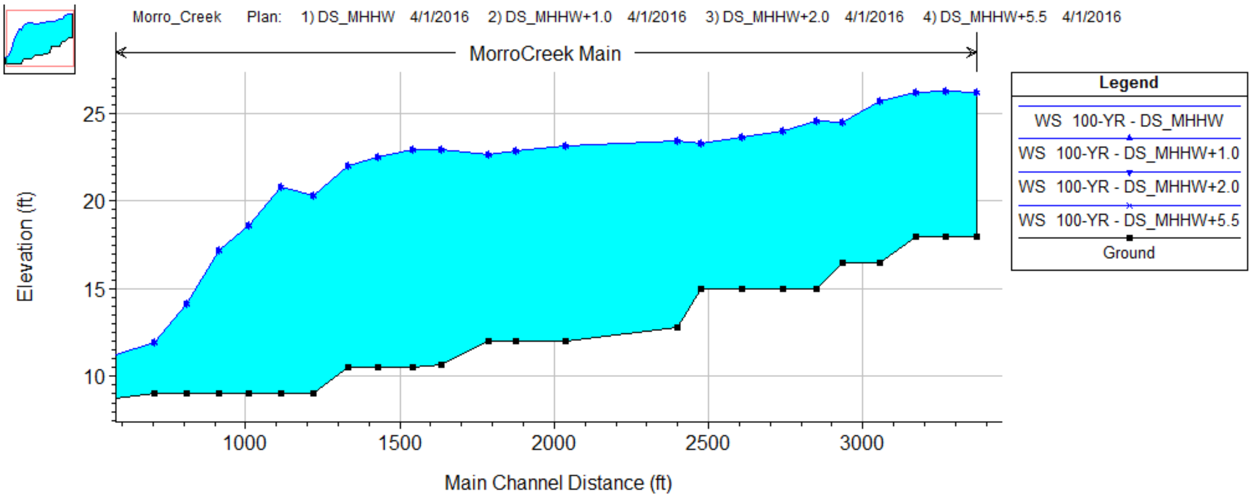


FIGURE 15: MORRO CREEK WATER SURFACE PROFILE

Water surface elevations listed on the FEMA FIRM (2012) should be used for planning purposes upstream of the Beach. No additional fluvial flood hazards as a result of sea level rise are anticipated at Morro Creek.

4.5.5. Other Creeks

Three additional creeks in the city of Morro Bay outlet into the ocean: Toro Creek, Unnamed Creek (Alva Paul Creek), and Noname Creek. The influence of sea level rise in these creeks is expected to be similar to that at Chorro Creek and Morro Creek. Sea level rise is not expected to backup floodwaters and increase fluvial flooding resulting from these creeks. The creeks outlet onto the beach and are subject to tidal inundation and wave run-up. Thus, no additional fluvial flood hazards as a result of sea level rise are anticipated.

5. References

California Climate Change Center, May 2009. The Impacts of Sea-Level Rise on the California Coast.

California Coastal Commission (CCC). 2015. Sea-Level Rise Policy Guidance, August 2015.

L.H. Erikson, C.A. Hegermiller, P.L. Barnard, P. Ruggiero, M. van Ormondt, Projected wave conditions in the Eastern North Pacific under the influence of two CMIP5 climate scenarios, Ocean Modelling, Volume 96, Part 1, December 2015.

Federal Emergency Management Agency (FEMA), November 16, 2012. Flood Insurance Study (FIS) San Luis Obispo County, California and Incorporated Areas.

Federal Emergency Management Agency (FEMA), November 16, 2012. Flood Insurance Rate Map (FIRM) Map Nos. 06079C1027G and 06079C0813G.

Federal Emergency Management Agency (FEMA), November 2015. Guidance for Flood Risk Analysis and Mapping – Coastal Erosion.

Heberger, M., Cooley, H., Herrera, P., Gleick, P.H., Moore, E., 2009. The Impacts of Sea-Level Rise on the California Coast. Pacific Institute. Prepared for California Climate Change Center.

Komar PD, McDougall WG, Marra JJ, Ruggiero P (1999) The rational analysis of setback distances: applications to the Oregon coast. Shore & Beach 67(1):41–49

National Research Council of the National Academies (NRC). 2012. Sea Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future.

NOAA Tides & Currents. 2016. Observed Water Levels at 9411110 Port San Luis, California. http://tidesandcurrents.noaa.gov/waterlevels/.

NOAA. 2013. Coastal California TopoBathy Merge Project: Lidar data (NAVD 88, ft; NAD83 NSRS2007 California zone 5, ft)

Revell, D.L., Battalio, R., Spear, B., Ruggiero, P. and Vandever, J., 2011. A methodology for predicting future coastal hazards due to sea-level rise on the California Coast. Climatic Change, 109(1), pp.251-276.

Rogers S, Nash D (2003) The Dune Book. Illus. D Williams. North Carolina Sea Grant, Raleigh, NC

Rosati, J.D., Dean, R.G. and Walton, T.L., 2013. The modified Bruun Rule extended for landward transport. Marine Geology, 340, pp.71-81.

Snover, A.K, G.S. Mauger, L.C. Whitely Binder, M. Krosby, and I. Tohver. 2013. Climate Change Impacts and Adaptation in Washington State: Technical Summaries for Decision Makers. State of Knowledge Report prepared for the Washington State Department of Ecology. Climate Impacts Group, University of Washington, Seattle

Stockdon, H.F., R.A. Holman, P.A. Howd, and A.H. Sallenger. 2006. Empirical Parameterization of Setup, Swash, and Run-up. Coastal Engineering 53: 573–88.