FEMA Region IX

California Coastal Analysis and Mapping Project / Open Pacific Coast Study

Sea Level Rise Pilot Study

Future Conditions Analysis and Mapping
San Francisco County, California

CONTRACT NUMBER: HSFEHQ-09-D-0368 / TASK ORDER HSFE09-10-J-0002

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BakerAECOM
An Integrated Production Team

FEMA

Executive Summary

The Department of Homeland Security's Federal Emergency Management Agency (FEMA) is developing updated flood hazard data for the populated coast of the U.S. under the Risk Mapping, Assessment and Planning (Risk MAP) program. FEMA launched the California Coastal Analysis and Mapping Project (CCAMP) Open Pacific Coast (OPC) Study in Region IX to analyze the existing coastal high hazard areas for the entire coast of California, update Flood Insurance Rate Maps for 15 coastal counties, and provide resources for communities to increase public awareness and encourage mitigation actions that reduce coastal flood risk. FEMA's nationwide coastal floodplain mapping efforts depict hazards associated with existing conditions and do not consider anticipated future sea levels or climate change[1].

The purpose of this study, *Sea Level Rise Pilot Study Future Conditions Analysis and Mapping, San Francisco County, California* (SLR pilot study), was to evaluate the feasibility of incorporating sea level rise (SLR) and shoreline change into the analysis and mapping methodology developed as part of the CCAMP OPC Study. The pilot study leveraged preliminary coastal analysis and mapping results from the CCAMP OPC Study to analyze future coastal flood risks in a wave runup-dominated Pacific coast environment. Mid-range and high-range SLR projections from the 2012 National Research Council report on west coast SLR were incorporated into the coastal analysis methodology. The eight mile segment of the open Pacific coast of the City and County of San Francisco (CCSF) west of the Golden Gate Bridge was selected as the study area for the pilot study.

Collaboration with Federal, state, and local agencies and stakeholders was a key element of the pilot study. FEMA coordinated with partnering agencies and stakeholders through a focus group to formulate the initial criteria for the pilot study. Subsequent workshops focused on the future conditions technical analysis, communicating the results, and application of the study on the west coast. FEMA also organized a peer review panel of national experts to provide support to the focus group. The Peer Review Panel included members from FEMA Headquarters, U.S. Geological Survey (USGS), National Oceanic and Atmospheric Administration, U.S. Army Corps of Engineers, United States Global Change Research Program, and the RAMPP Production and Technical Services contractor.

The deliverables of the pilot study include this report, which documents methods and results, geospatial data layers depicting the projected limits of the future conditions Special Flood Hazard Areas (SFHA), and a Flood Risk (non-regulatory) Product showing future conditions coastal flood hazard information. The SLR data were also compared to other California studies that analyzed future conditions coastal flooding scenarios. The pilot study report concludes with methodology recommendations for studying future conditions coastal flood risks that can be applied to future Pacific coast studies.

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[1] In accordance with the Biggert-Waters Flood Insurance Reform Act of 2012, FEMA established a Technical Mapping Advisory Council (TMAC) that will provide recommendations to FEMA on flood hazard guidelines, including recommendations for future mapping conditions and the impacts of sea level rise.

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BakerAECOM identified the following key findings as a result of the analysis and mapping conducted as part of the pilot study:

- Water level, wave, and topographic datasets compiled as part of the CCAMP OPC study provide a solid foundation upon which to conduct future conditions analysis, not only in the pilot study area but throughout California.
- The direct analysis approach to incorporate SLR into the determination of wave runup elevations for coastal floodplain mapping was found to capture wave runup feedback processes that would not have otherwise been captured by a linear superposition approach for certain shoretypes. This finding was particularly applicable to steep and erosion-resistant shorelines such as rocky cliffs and coastal structures.
- Future changes to the coastal SFHA will result from both the vertical increase in BFEs due to SLR and the horizontal increase in the landward extent of the SFHA due to future shoreline change.
- Implementation of a GIS-based buffering technique was found to be a viable method to efficiently map future SFHA limits and produce geospatial datasets.

BakerAECOM developed the following recommendations based on the findings of the SLR pilot study that could be considered to refine the current study or to expand the methodology to other wave runup-dominated areas along the Pacific coast:

- Future studies should consider adoption of a direct analysis methodology to estimate future conditions TWLs for certain shoretypes and shoreline characteristics; however, the direct analysis methodology may not be required at all locations. Implementation of the direct analysis methodology is most applicable to steep, erosion-resistant shorelines (such as coastal bluffs and cliffs) and coastal structures (such as revetments and seawalls).

- Future studies may benefit from application of the linear superposition methodology to estimate future conditions TWLs for certain shoretypes and shoreline characteristics. Implementation of the linear superposition methodology may produce results very similar to those based on direct analysis methods for some shoretypes, such as sandy beaches and dunes and highly erodible bluffs.

- Future studies should explore the potential to develop a modified linear superposition approach or look-up table to facilitate rapid first-order approximation of future conditions TWLs in wave-runup dominated environments. The modified linear superposition approach could develop TWL amplification factors applicable to each shoretype based on the findings of this pilot study and further research. The study team recommends conducting additional testing of the methods developed for this pilot study across a larger suite of locations and environmental conditions to inform the development and application of the modified linear superposition approach.

- Future studies should evaluate other aspects of climate change such as changes in storminess, storm tracks, and frequency and intensity of future El Niño events. The pilot study methodology could be expanded to address these factors, many of which were of interest to the stakeholder group.

- Future studies in other communities should convene a local stakeholder group (similar to the stakeholder group assembled for the pilot study) to advise the study team on local conditions and assumptions, such as planned coastal protection projects (e.g., bluff armoring, sea walls, dunes, beach nourishment, etc.) and expected life span of existing coastal structures so appropriate treatments can be incorporated into the TWL and shoreline change analysis and mapping.

- Future studies may wish to refine the shoreline change methods developed for the pilot study and use local shoreline change data, where available, to provide more site-specific shoreline retreat projections. The pilot study relied on regional shoreline change rates developed from publically available USGS shoreline change datasets.

- By identifying existing structures in areas of increased future SFHAs, communities can use a risk analysis program such as FEMA's Hazus methodology to estimate the incremental monetary impacts of future vs. existing coastal flooding. Such an analysis could be used to develop a benefit-cost ratio for potential flood and/or coastal erosion mitigation projects.

- Communities with coastal areas vulnerable to future conditions flooding in response to the 1-percent-annual-chance event due to a combination of shoreline retreat and wave overtopping may wish to analyze future impacts due to a less severe flood event (such as a 10-, 2-, etc., percent-annual-chance event). This could further inform planning and development of benefit-cost analyses for potential mitigation strategies.

It is anticipated that CCSF will use the SLR data and Flood Risk Products to increase public awareness, encourage mitigation actions that reduce coastal flood risk, and/or adopt higher floodplain management standards for protecting lives and property along the open coast through incorporation of these datasets into the Local Coastal Program Update and Sea Level Rise Action Plan.

Document History - FINAL

Revision History

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1.0	January 25, 2015	Final Report	BakerAECOM/Justin Vandever, PE

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Version 1.0 of this document has been reviewed by the following persons:

Role	Organization/Name	Title	Review Date
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Client Distribution

Name	Title/Organization	Location
Ed Curtis, PE, CFM	Study Manager/FEMA	Region IX (Oakland, CA)

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List of Acronyms

BFE	Base Flood Elevation
CA	California
CCAMP OPC	CA Coastal Analysis and Mapping Project for the Open Pacific Coast
CCC	California Coastal Commission
CCSF	City and County of San Francisco
DEM	Digital Elevation Model
DIM	Direct Integration Method
DWL	Dynamic Water Level
EPA	Environmental Protection Agency
EPR	End Point Rate
FEDI	Fugro EarthData, Inc.
FEMA	Federal Emergency Management Agency
FIRM	Flood Insurance Rate Map
FIS	Flood Insurance Study
GFNMS	Gulf of the Farallones National Marine Sanctuary
GGNRA	Golden Gate National Recreation Area
GHG	Greenhouse Gas
GPD	Generalized Pareto Distribution
GROW	Global Reanalysis of Ocean Waves (model)
IDS	Intermediate Data Submittal
IPCC	Intergovernmental Panel on Climate Change
LRR	Linear Regression Rate
MHHW	Mean Higher High Water
MLLW	Mean Lower Low Water
MSL	Mean Sea Level
NAVD88	North American Vertical Datum of 1988
NFIP	National Flood Insurance Program
NGDC	National Geophysical Data Center

NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
OCOF	Our Coast Our Future
OWI	Oceanweather Inc.
Pacific Guidelines	Final Draft Guidelines for Coastal Flood Hazard Analysis and Mapping for the Pacific Coast of the United States
PFD	Primary Frontal Dunes
RAMPP	Risk Assessment, Mapping, and Planning Partners
Risk MAP	Risk Mapping, Assessment and Planning
SFHA	Special Flood Hazard Area
SFPUC	San Francisco Public Utilities Commission
SHELF	Scripps Institution of Oceanography Coastal Data Information Program Nearshore Wave Transformation Model
SIO	Scripps Institution of Oceanography
SLR	Sea Level Rise
TAW	Technical Advisory Committee for Water Retaining Structures
TWL	Total Water Level
USACE	United States Army Corps of Engineers
USGCRP	United States Global Change Research Program
USGS	United States Geological Survey

1. Introduction

1.1. Background and Purpose

BakerAECOM, LLC is providing engineering and mapping services to the Federal Emergency Management Agency (FEMA) Region IX in support of the Risk Mapping, Assessment and Planning (Risk MAP) program, which aims to deliver quality data that increase public awareness and lead to actions that reduce risk to life and property. FEMA initiated the California Coastal Analysis and Mapping Project (CCAMP) Open Pacific Coast (OPC) Study in 2009 as part of the Risk MAP program. The CCAMP OPC Study will establish and/or revise the effective Special Flood Hazard Areas (SFHA) and Base Flood Elevations (BFE) for the entire open Pacific coast of California (Figure 1). The new flood data and mapping will be used to update and revise the Flood Insurance Study (FIS) and Flood Insurance Rate Map (FIRM) for each of the 15 coastal counties in California.

FEMA’s Risk MAP efforts in California will provide useable flood risk information to communities with respect to existing flood hazards; however, consideration of the impacts of sea level rise (SLR) and shoreline change on coastal flood hazards has not historically been a component of FEMA’s regulatory mapping. As scientific consensus on the likelihood of accelerated SLR in response to climate change continues to build, local communities seek guidance and tools to facilitate responsible planning along their shorelines. Given FEMA’s prominent position as one of the Federal agencies conducting comprehensive nationwide coastal flood hazard mapping, local communities are increasingly looking to FEMA to provide the necessary tools for effective planning in the coastal zone in light of future climate change.

FEMA’s OPC Study provides a unique opportunity to investigate the feasibility of developing a non-regulatory SLR layer to compliment the traditional regulatory products as part of the Risk MAP program. To accomplish this goal, FEMA initiated this pilot study to leverage the data products of the OPC Study. The purpose of this pilot study is to assess potential changes to the SFHA due to SLR in a wave runup-dominated Pacific coast environment. Similar pilot studies are underway or have been conducted along the Atlantic and Gulf coasts (see Section 3.3). Specific objectives of this study include:

- Develop a framework for incorporating SLR into the detailed coastal flood hazard analysis and mapping in a wave runup-dominated Pacific coast environment
- Develop a non-regulatory SLR Risk MAP product and database depicting an estimate of the future SFHA incorporating the effects of SLR
- Compare results of the future conditions coastal flood hazard determinations (e.g. flooding and erosion) with ongoing or completed studies in this region
- Collaborate with local stakeholders to provide input into the approach and products to ensure utility for local planning and mitigation efforts
- Develop recommendations and lessons learned for future SLR studies in California and along the Pacific coast

Figure 1. CCAMP OPC Study Area

Note: The CCAMP OPC Study was divided into Phase 1 and Phase 2 focusing on northern/central California and southern California, respectively.

1.2. Study Area Selection and Overview

FEMA selected the open Pacific coast shoreline of the City and County of San Francisco (CCSF) for the SLR pilot study. The San Francisco open coast includes approximately 8 miles of shoreline, comprising beaches, rocky outcrops, and bluffs extending from the Golden Gate Bridge south to the San Mateo County line at Fort Funston (Figure 2). The northern section of the study area, from the Golden Gate Bridge to Point Lobos, consists mostly of Federal lands that are part of the Golden Gate National Recreation Area (GGNRA). This segment has several stretches of wave-cut rocky cliffs as well as two stretches of sandy shoreline at Baker Beach and China Beach. The backing cliffs are generally resistant to wave attack and exhibit relatively low rates of retreat (Griggs et al. 2005). South of Point Lobos, the shoreline transitions to Ocean Beach – a relatively wide sandy beach backed by seawalls and dunes. The northern portion of the beach is relatively stable due to dredging of the San Francisco Bar navigation channel which passively nourishes the beach; however, the southern portion of the study area between Sloat Boulevard and Fort Funston is particularly vulnerable to erosion. In this reach, the broad sandy beaches of Ocean Beach transition into steep, high, unconsolidated sandy bluffs which are highly erodible. The area immediately south of Sloat Boulevard has a history of erosion control measures, including sand, rubble, and rock placement at the base of the eroding bluff.

The San Francisco shoreline was selected for the pilot study for a number of reasons, including: availability of completed detailed existing conditions coastal flood hazard analysis as part of the CCAMP OPC Study; diversity of backshore features, including bluffs, dunes, and coastal structures; availability of recent well-accepted SLR projections and climate change data; presence of a well-informed engaged local stakeholder group with interest and willingness to participate in the study; and existence of other ongoing SLR planning studies by Federal, state, and local agencies.

1.3. Report Organization

This report summarizes the approach and findings of the SLR pilot study for the open Pacific coast of the City and County of San Francisco. The sections that follow present the peer review panel and local stakeholder coordination (Section 2); prior reporting and study references (Section 3); climate science data and SLR scenario selection (Section 4); methodologies for existing and future conditions analysis and mapping (Section 5) and results (Sections 6 and 7); and conclusions and recommendations (Section 8).

Figure 2. Open Pacific Coast Study Area for City and County of San Francisco

2. Technical Coordination

FEMA, with support from BakerAECOM, conducted extensive technical coordination as part of the SLR pilot study. The technical coordination included engagement with the CCAMP OPC Stakeholder Group (Section 2.1) and review and input from a Peer Review Panel of national experts (Section 2.2).

2.1. Stakeholder Participation

The CCAMP Stakeholder Group was established in 2012. The Stakeholder Group members are Federal and California state agencies that have a vested interest, share funding sources, and/or provide products and data that compliment and support FEMA‘s CCAMP Study. Collaboration with these key stakeholders helped FEMA manage study risks through partnerships and aligned messaging.

A Local Working Group was formed from the CCAMP Stakeholder Group. The Local Working Group consisted of San Francisco Bay Area Federal agencies, including the U.S. Army Corps of Engineers (USACE), National Oceanic and Atmospheric Administration (NOAA), and United States Geological Survey (USGS), state agency members, including the California Coastal Commission (CCC), California Ocean Science Trust, and State Coastal Conservancy, and the local sponsor, the CCSF.

The Local Working Group held workshops with the study team on multiple occasions over the course of the project. The workshops served as a vehicle for inter-agency coordination with agencies involved in west coast SLR Studies. The Local Working Group helped formulate the initial criteria, collaborated on programmatic decisions, and solicited critical feedback that informed the development of the SLR Pilot study. Through this collaboration the study team gained a more in-depth understanding of future flood risk identification along the Pacific Ocean.

FEMA collaborated exclusively with CCSF to initiate a strategic alliance and partnership to understand how the study could be value-added to best support the local community. The study team presented to the SLR Committee of SF Adapt, a collaboration of CCSF Departments evaluating the effects of SLR on their community. The SLR Committee led by David Behar, San Francisco Public Utilities Commission (SFPUC), helped the study team understand the needs of the end-users. Overall the CCSF input led to a more robust study and useful modeling results for CCSF’s long-term local coastal planning process.

The study team will continue to work closely with the all members of the CCAMP Stakeholder Group, including the CCSF, beyond the scope of this SLR pilot study. Future collaboration with these stakeholder agencies and CCSF will inform future study activities beyond this pilot study, test the implementation of non-regulatory Risk MAP Products, and align communications and outreach to "at risk" property owners.

2.2. Peer Review Panel

FEMA designated a Peer Review Panel led by Mark Crowell, Physical Scientist, FEMA Headquarters. The Peer Review Panel is a consortium of national experts from Federal agencies including: United States Global Change Research Program (USGCRP), Environmental Protection Agency (EPA) NOAA, USGS, the USACE, and the RAMPP Production and Technical Services contractor. Members of the Peer Review Group were recognized with a GreenGov Presidential Award for developing the Sea Level Rise Tool for Sandy Recovery, which is now being used in New York and New Jersey where planning and rebuilding is underway (http://www.globalchange.gov/browse/sea-level-rise-tool-sandy-recovery).

Peer Review Panel

Lead: Mark Crowell – Physical Scientist, FEMA Headquarters

Patrick Barnard, Ph.D. – Coastal Geologist, USGS, Coastal and Marine Science Center

Brian Batten, Ph.D. – Senior Coastal Scientist, Dewberry (RAMPP Production and Technical Services contractor)

Doug Marcy – Coastal Hazards Specialist, NOAA, Office for Coastal Management

Adam Parris – Executive Director, Science and Resilience Institute at Jamaica Bay (formerly Climate Assessment and Services Division Chief & Regional Integrated Sciences and Assessments (RISA) Program Manager at NOAA)

Chris Weaver, Ph.D. – U.S. Global Change Research Program and Environmental Protection Agency

Kathleen White, Ph.D., P.E. – U.S. Army Corps of Engineers, Institute for Water Resources, Global and Climate Change Team

The Peer Review Panel held conference calls with the study team at specific milestones in the SLR pilot study process. The Peer Review Panel offered: (1) expertise in national SLR studies; (2) technical guidance; (3) coastal resources and data; and (4) input on tools that communicate future condition flood risk. The contributions of the Peer Review Panel provided assurance that this SLR pilot study was instrumental in the path to understanding how future conditions SLR Studies might be conducted on the west coast. The Peer Review Panel leadership will ultimately lead to a more consistent effort nationally to align future conditions analysis and mapping that can lead to actions that reduce the risk of coastal flooding and reduce risk to life and property.

3. Prior Reporting and Study References

The SLR pilot study builds upon a number of prior reports and references related to climate change and SLR impacts to coastal flood and erosion hazards. The sections that follow summarize the relevant documentation from FEMA's CCAMP OPC Study in San Francisco (Section 3.1), ongoing work in the study area (Section 3.2), and other technical references that relate to the pilot study (Section 3.3).

3.1. California Coastal Analysis and Mapping Project

As discussed in Section 1.1, the CCAMP OPC Study will establish new or revised effective SFHAs and BFEs for the entire California coastline. The SLR pilot study leveraged the results of the existing conditions coastal flood hazard analysis and mapping completed for CCSF. The CCAMP OPC Study methods, results, and mapping are documented in four Intermediate Data Submittal (IDS) reports:

- **Intermediate Data Submittal #1 – Scoping and Data Review.** IDS #1 provided background information on the study setting (including a description of the San Francisco shoreline) and data availability relevant to the study area and proposed methodologies, including topographic and bathymetric data, environmental data, site reconnaissance, and an overview of the technical approach (BakerAECOM 2012).
- **Intermediate Data Submittal #2 – Offshore Waves and Water Levels.** IDS #2 documented the offshore wave and water level analysis tasks that were performed on a regional scale for the Phase 1 counties, including results from the deepwater wave model hindcast, nearshore wave transformation, stillwater level reconstruction, and regional tide frequency analysis (BakerAECOM 2013).
- **Intermediate Data Submittal #3 – Nearshore Hydraulics.** IDS #3 documented the detailed methodology and results of the 1-D transect-based wave hazard analyses. The results presented in the IDS #3 submittal defined the base flood conditions at the shoreline that provided the basis for the coastal flood data used in the coastal floodplain mapping (BakerAECOM 2014a).
- **Intermediate Data Submittal #4 – Draft Flood Hazard Mapping.** IDS #4 summarized the methods used to map coastal flood hazard zone for the open Pacific coast shoreline of San Francisco. Coastal analyses results presented in IDS #3 were used to determine the BFEs, delineate floodplain boundaries, and establish flood hazard zone designations. Workmaps depicting the draft flood hazard zone mapping were included in this submittal (BakerAECOM 2014b).

The existing conditions coastal flood hazard analysis and mapping documented in the abovementioned reports served as the foundation for the future conditions analysis and mapping documented in this SLR pilot study report. The SLR pilot study builds upon the existing conditions methods developed as part of the CCAMP OPC Study (summarized in Section 5.1) to incorporate SLR into the future conditions analysis and mapping framework.

3.2. Ongoing Work in Pilot Study Area

There is considerable interest in understanding climate change impacts to shorelines along the central California coast, including several studies that overlap geographically with FEMA's SLR pilot study in San Francisco. Federal, state, and local agencies are conducting work in the pilot study area. Table 1 summarizes the studies that have been completed or are ongoing within the San Francisco pilot study area.

Table 1. Summary of Ongoing Work in Sea Level Rise Pilot Study Area

Project	Lead Agencies	Description
Our Coast Our Future (OCOF)	Gulf of the Farallones National Marine Sanctuary (GFNMS); Point Blue Conservation Science; U.S. Geological Survey (USGS) Pacific Coastal & Marine Science Center; National Oceanic and Atmospheric Administration (NOAA)	The OCOF project is a collaborative project focused on providing San Francisco Bay Area coastal resource and land use managers local, online maps and tools to help understand, visualize, and anticipate vulnerabilities to SLR and storms within San Francisco Bay and along the open coast from Half Moon Bay to Bodega Bay. Data products include SLR inundation maps and user-generated reports obtained from an online data portal. http://data.prbo.org/apps/ocof
Sea Level Rise and Coastal Flooding Impacts Viewer	NOAA Coastal Services Center	The NOAA SLR Viewer is a visualization tool released in 2012 for coastal communities that shows potential impacts from SLR and coastal flooding. The tool shows inundation by the Mean Higher High Water tide in one foot increments up to six feet of SLR. http://www.csc.noaa.gov/digitalcoast/tools/slrviewer
The Impacts of Sea Level Rise on the California Coast	Pacific Institute	In 2009 the Pacific Institute examined the impacts of SLR on the California coast. Data products include estimates of future flood and erosion hazard zones along the open Pacific coast shoreline. http://pacinst.org/publication/the-impacts-of-sea-level-rise-on-the-california-coast
Climate Change Analysis and Adaptation for the Sewer System Improvement Program (SSIP)	San Francisco Public Utilities Commission (SFPUC)	The SFPUC SSIP is a 20-year multi-billion dollar citywide investment to upgrade aging sewer infrastructure to ensure a reliable sewer system into the future. As part of the SSIP, the SFPUC is conducting climate change analyses and examining adaptation options along San Francisco's open coast and Bay shorelines.

Project	Lead Agencies	Description
		http://www.sfwater.org/index.aspx?page=116
Ocean Beach Master Plan	San Francisco Planning and Urban Research (SPUR) Association and CCSF	The Ocean Beach Master Plan is a long-term planning vision which presented recommendations for the management and protection of San Francisco's Ocean Beach. The Plan was the result of an 18-month-long public process developed with the input of Federal, state, and local stakeholders and the public. http://www.spur.org/featured-project/ocean-beach-master-plan
Climate Adaptation Working Group	City and County of San Francisco	The Climate Adaptation Working Group is coordinating across City of San Francisco agencies to understand impacts of climate change and potential adaptation options. The interagency working group includes the Department of the Environment, Public Utilities Commission, City Administrators Office, San Francisco International Airport, Department of Public Works, Municipal Transportation Agency, Department of Public Health, and Department of Recreation and Parks. http://www.sfenvironment.org/article/climate-change/adaptation
Climate Central Program on Sea Level Rise	Climate Central	Climate Central is an independent organization of scientists and journalists researching and reporting on the changing climate change and its impacts. The group's Program on sea level rise focuses on providing SLR science, coastal flood information, and visualization tools at a local level to assist communities and stakeholders in understanding potential impacts of the hazard. http://sealevel.climatecentral.org/ssrf/california

3.3. Other Technical References

Numerous other technical references related to coastal flood and erosion hazard assessments and climate change-related impacts to the National Flood Insurance Program (NFIP) provide a strong foundation upon which to develop this SLR pilot study. FEMA has been investigating potential impacts of SLR to the NFIP since 1991 (FEMA 1991) and its understanding of those impacts has continued to evolve since then. Several key studies and findings are summarized below:

- **Evaluation of Erosion Hazards (Heinz Center 2000).** In 2000, The Heinz Center for Science, Economics, and the Environment evaluated the impacts of coastal erosion to the NFIP. The study noted that the NFIP does not inform homeowners of the risk to property from coastal erosion through the FIRM process. The report presented a range of policy options and evaluated the effectiveness of each option to reduce erosion losses. The study made two key recommendations: (1) FEMA should develop erosion hazard maps that display the location and extent of coastal areas subject to erosion and (2) FEMA should include the cost of expected erosion losses when setting flood insurance rates along the coast. Another important concept presented in the study was the use of dedicated erosion maps to convey risk to the public. The study recommended that erosion maps be used to convey areas of "high risk" rather than displaying exact predictions of future shoreline position, as shoreline positions can be highly episodic and the processes are not well understood.

- **The Impact of Climate Change and Population Growth on the National Flood Insurance Program through 2100 (AECOM et al. 2013).** This FEMA-funded study provided an estimate of the potential financial impact of climate change and population growth on the NFIP through the year 2100. The study was based upon regional methods and engineering inference, relying upon existing and readily available science and modeling data. The tools created by the project were developed so as to allow updates to be made with relative ease as climate change projections evolve. The study found that under a fixed shoreline scenario, the coastal SFHA would on average increase by 55% by the year 2100, with wide regional variability. The typical increase ranged from less than 50% along the Pacific coast to greater than 100% for portions of the Gulf and Atlantic coasts. Under a receding shoreline scenario, SLR would cause the SFHA to migrate landward without significant change in size, although the landward extent of the SFHA would increase.

- **FEMA SLR Advisory Map Proof of Concept Study (RAMPP 2010).** This FEMA-funded study evaluated methods for developing SLR advisory geospatial layers that could be used as supplemental products to the FIS. Rather than serving as additional regulatory products, the outcome of this work was intended as guidance to help communities identify and adapt to potential hazards posed by SLR. The relative accuracy and cost-effectiveness associated with data and methodologies used as input to the advisory products were also evaluated. The study made several recommendations, including: (1) FEMA should leverage local FIS storm surge modeling studies for comparison with linear superposition methodologies on a variety of shoretypes to evaluate its effectiveness in approximating future changes in floodplains; (2) Considering wave height can increase the total water level (TWL) by more than half the SLR component;

assessment of potential increases in freeboard due to SLR should consider both potential changes in storm surge elevation and wave height; (3) Simple calculations such as linear superposition are an effective means of capturing the potential spread of BFE increases in the study area and, when combined with simplified mapping approaches, can rapidly produce SLR guidance with an overall low production cost. 1-percent-annual-chance storm event elevations determined through the computationally intensive ADCIRC SLR simulations were found to be very similar to those calculated through linear superposition with a median difference of 0.1 ft and spread of 0.7 ft. The study noted that although sensitivity testing supports use of linear superposition as a means of incorporating SLR into flood hazard maps in a storm surge dominated environment such as Puerto Rico, it is a site-specific finding that may not be applicable in all coastal settings.

- **Gulf Coast SLR Pilot Study.** This FEMA-funded study was initiated to examine the feasibility of producing SLR advisory layers in Hillsborough and Pinellas Counties, Florida. The study area contains both an open coast shoreline area as well as a sheltered shoreline area in Tampa Bay and is subject to strong storm surge associated with Gulf Coast hurricanes. The study will incorporate SLR into the storm surge model to assess the nature of the change in BFEs in response to future SLR. The mapping product will be an advisory product showing future flood hazard zones and the goal of the study is to increase community and organizational resilience.

4. Climate Science Data Inventory and Review

This section provides a brief overview of the current SLR science that was adopted for application to the San Francisco SLR pilot study (Section 4.1) and a description of the approach used to select SLR scenarios for incorporation to the future conditions coastal flood hazard analysis (Section 4.2).

4.1. Sea Level Rise Science

The science associated with global SLR is continually being updated, revised, and strengthened. Although there is no doubt that sea levels have risen in the previous century and will continue to rise at an accelerated rate over the remainder of this century, it is difficult to predict with certainty how much SLR will occur over any given time frame. The uncertainties increase over time (e.g. the uncertainties associated with 2100 projections are greater than with 2050 projections) because of uncertainties in future greenhouse gas (GHG) emissions trends, the sensitivity of climate conditions to GHG concentrations, and the overall capabilities of climate models. The SLR projections presented in this document draw on the best available science on the potential effects of SLR in California as of May 2014.

In March 2013, the California Ocean Protection Council adopted the 2012 National Research Council (NRC) Report *Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future* as the best available science on SLR for the state (California Ocean Protection Council 2013). The CCC also supported the use of the NRC 2012 report as best available current science, noting that the science of SLR is continually advancing and future research may enhance the scientific understanding of how the climate is changing, resulting in the need to regularly update SLR projections (California Coastal Commission 2015). The NRC report includes discussions of historical SLR observations, three SLR projections of likely SLR for the coming century, high and low extremes for SLR, and insight into the potential impacts of a rising sea for the west coast of the United States.

Table 2 presents the NRC SLR projections for San Francisco relative to the year 2000 (mean ± 1 standard deviation). These projections (for example, 6 ± 2 inches at 2030) represent the mid-range SLR values based on a moderate level of greenhouse gas emissions and extrapolation of continued accelerating land ice melt patterns, plus or minus one standard deviation. The extreme upper limits of the ranges (for example, 12 inches at 2030) represent unlikely but possible levels of SLR using high emissions scenarios and, at the high end, including significant land ice melt that is not anticipated at this time but could occur. The NRC report is also notable for providing regional estimates of net SLR for the Oregon, Washington, and California coastlines that include the sum of contributions from the local thermal expansion of seawater, wind driven components, land ice melting, and vertical land motion. The chief differentiator among net SLR projections along the west coast derives from vertical land motion estimates, which show uplift (reducing net SLR) of lands north of Cape Mendocino and subsidence (increasing net SLR) of lands south of Cape Mendocino.

Table 2. SLR Estimates for San Francisco Relative to the Year 2000

Year	Projections (inches)	Ranges (inches)
2030	6 ± 2	2 to 12
2050	11* ± 4	5 to 24
2100	36 ± 10	17 to 66

Source: NRC (2012).

*As a simplifying assumption, the 2050 mid-range value selected for this study is 12 inches rather than the 11 inch value noted in the table.

After the release of the NRC report and the development of the draft California Coastal Commission guidance, the International Panel on Climate Change (IPCC) released the Fifth Assessment Report, Climate Change 2013: The Physical Science Basis, which provides updated consensus estimates of global SLR (IPCC 2013). Additionally, the U.S. Global Change Research Program (USGCRP) recently released the Third National Climate Assessment (Melillo et al. 2014). This report draws from a large body of scientific, peer-reviewed research to describe current and future impacts of climate change downscaled from global projections to eight U.S. regional levels. NOAA was charged by the USGCRP's Federal advisory committee with synthesizing the scientific literature on global SLR for the latest assessment. Details of this task are described in the Global SLR Scenarios for the United States National Climate Assessment (Parris et al. 2012). These studies provide additional information pertaining to sea level science at the national and state level; however, current California state guidance recommends the use of the NRC projections as best available science.

4.2. Sea Level Rise Scenario Selection

The abovementioned references were reviewed by the SLR pilot study team and it was determined that use of the mid-range and high-range NRC projections were most appropriate for the SLR pilot study for each of the two planning horizons (2050 and 2100) (Figure 3). The 12-inch and 36-inch NRC mid-range projections and 24-inch and 66-inch high-range projections were selected because they encompass the best available science, they have been derived considering local and regional processes and conditions, and their use is consistent with current California state guidance[2]. The use of the 12-inch, 24-inch, 36-

[2] It should be noted that rates of SLR vary regionally along the California coast. The primary driver of spatial variability in rates of relative SLR within California is local vertical land motion, which is not directly considered in this pilot study. According to NRC projections, the portion of the California coast north of Cape Mendocino is experiencing uplift. As a result, projected rates of future relative SLR are generally lower in northern California than in central and southern California – with the exception of Humboldt Bay, which is subsiding. As a result, the SLR projections adopted for the San Francisco SLR Pilot Study should be re-evaluated if the pilot study methodology is expanded to other portions of the California coastline.

inch, and 66-inch SLR amounts was also supported by the Peer Review Panel and Local Working Group. As recommended in the CCC's SLR Guidance (CCC 2015), BakerAECOM developed quadratic SLR curve fits to the mid-range (12- and 36-inch) and high-range (24- and 66-inch) SLR projections as shown in Figure 3. The quadratic curve fits will be used in subsequent shoreline change analysis to pro-rate historical rates of shoreline change to project future shoreline retreat. For consistency of units with subsequent reporting of BFEs, SLR scenarios will be reported in feet for the remainder of the report with 12-inch, 24-inch, 36-inch, and 66-inch corresponding to the 1-ft, 2-ft, 3-ft, and 5.5-ft SLR scenarios, respectively.

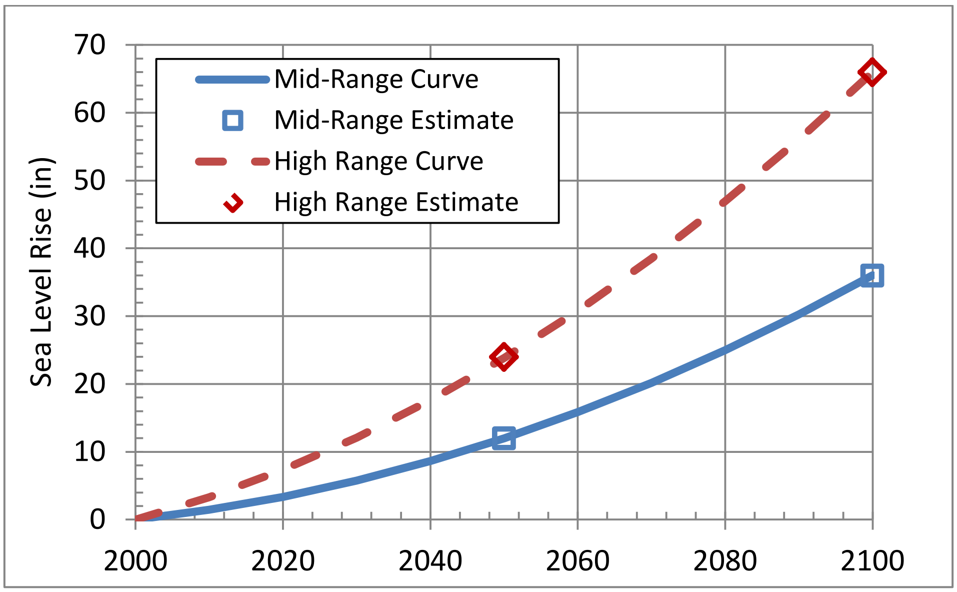

Figure 3. Quadratic Best-Fit SLR Curves for 12 and 36-inch and 24 and 66-inch SLR Scenarios

Notes: Quadratic curve fits were calculated for the mid-range and high-range NRC SLR values shown above.
Mid-Range curve fit: $SLR\ (in) = 0.0024t^2 + 0.12t,\ \ t = yrs\ from\ 2000$
High-Range curve fit: $SLR\ (in) = 0.00366t^2 + 0.2936t,\ \ t = yrs\ from\ 2000$

5. Methodology

5.1. Existing Conditions Coastal Analysis

As part of the CCAMP OPC Study, existing conditions coastal flood hazards were evaluated for the San Francisco open Pacific coast shoreline. The existing conditions coastal analysis included determining total water levels (TWL = stillwater level (SWL) + wave setup + wave runup), overtopping extent, event-based dune erosion, and impacts to coastal structures. The analysis was conducted on a one-dimensional (1-D) transect basis and the TWLs were determined at shore-perpendicular transects placed to capture alongshore variations in shoretype, nearshore bathymetry, wave exposure, and degree of development. The sections below provide a summary of the coastal analysis methods (Figure 4). For a complete description, see IDS #3 – Nearshore Hydraulics, San Francisco County (BakerAECOM 2014a).

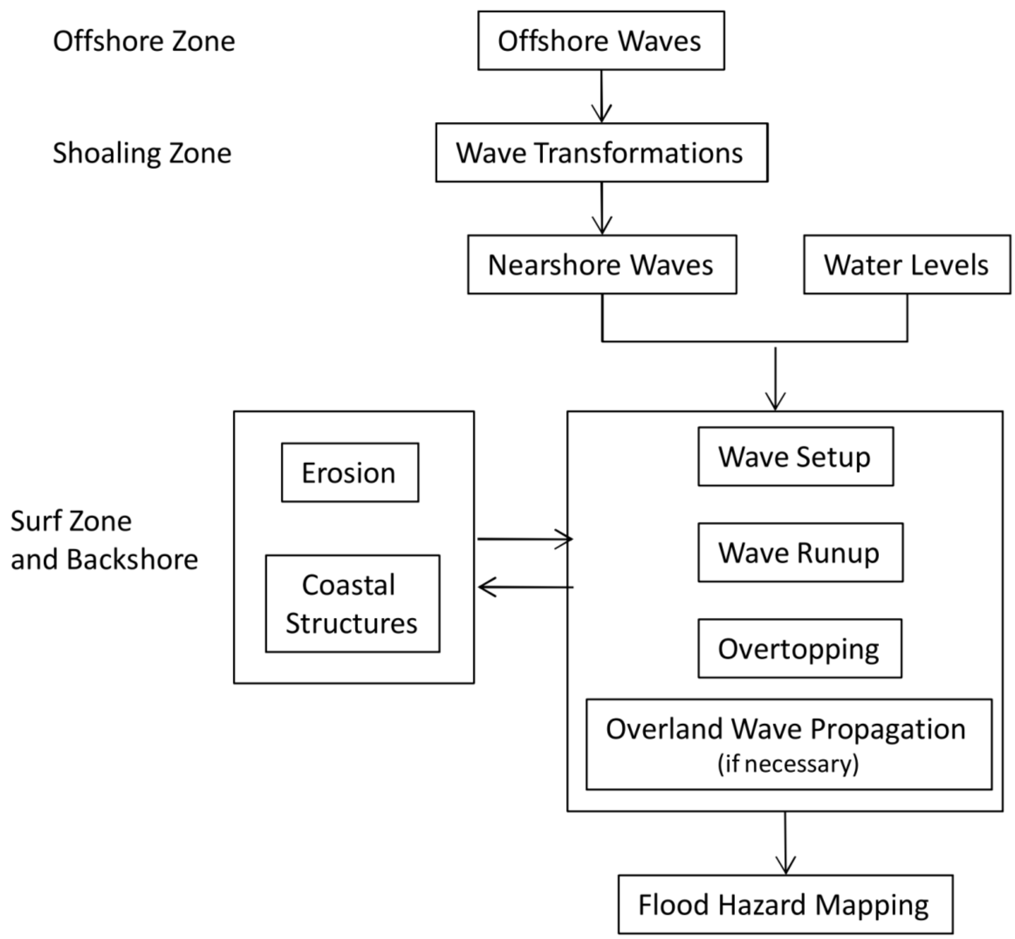

Figure 4. Summary of Technical Approach Adapted from FEMA *Pacific Guidelines*

5.1.1. Water Levels and Waves

As part of the detailed coastal analysis for San Francisco County, a 50-year hindcast (January 1, 1960 to December 31, 2009) of water level and wave conditions was constructed. Nearshore wave data were paired with a coincident time series of SWL to obtain estimates of the TWL at each analysis transect. A 50-year SWL record was reconstructed using water level records obtained from NOAA tide stations along the California coast. Temporal gaps in the record were filled using empirically-derived statistical relationships to infer estimates of the non-tidal residual at each station based on observations at neighboring tide stations.

A 50-year deepwater and nearshore wave hindcast was developed as part of the CCAMP OPC Study in San Francisco County. The deepwater wave hindcast fed into the nearshore wave model to estimate nearshore wave conditions at the seaward edge of the surf zone. The deepwater wave modeling was conducted by Oceanweather, Inc. (OWI) under a subcontract to BakerAECOM. The modeling effort consisted of three nested numerical modeling grids of sequentially higher resolution to resolve the wave conditions at varying spatial scales, using the Global Reanalysis of Ocean Waves (GROW) model. The nearshore wave modeling, which accounts for shallow water wave transformations, was conducted by the Scripps Institution of Oceanography (SIO) under a subcontract to BakerAECOM. The nearshore wave transformation utilized SIO's existing SHELF model, which was refined to include recent bathymetry data and configured to accept deepwater wave spectra from OWI's model output. Nearshore wave data were extracted from the model output at an alongshore spacing of 200 meters for input to the 1-D wave analysis transects.

5.1.2. Terrain Dataset

A merged topographic/bathymetric (i.e., terrain) dataset was developed from topographic and bathymetric source datasets for San Francisco County. BakerAECOM utilized airborne topographic LiDAR data collected and processed by Fugro EarthData, Inc. (FEDI) between 2009 and 2011 for a project funded by the California Ocean Protection Council and the U.S. Army Corps of Engineers. The topographic LiDAR data were collected at the California State Standard[3] and the data coverage extends from the mean lower low water (MLLW) line to approximately the 10 m elevation contour or 500 m inland, whichever is farther onshore. For San Francisco County, these data are maintained and distributed by the USGS in southern San Francisco and NOAA in northern San Francisco. BakerAECOM utilized bathymetric data from a variety of sources. Most data consisted of hydrographic survey data primarily collected and processed by FEDI for the California Seafloor Mapping Project (CSMP; http://seafloor.csumb.edu/csmp/csmp.html) between 2005 and 2011. The data generally extend from 3 nautical miles offshore to the -10 m NAVD contour and are available as Digital Elevation Models (DEM) at 2 m horizontal spacing in shallow water and 10 m spacing in deeper water. Shallow water voids in the dataset were filled with the National Geophysical Data Center (NGDC[4]) NOAA Tsunami Inundation

[3] http://www.opc.ca.gov/webmaster/ftp/pdf/opc_cclp_report_final.pdf

[4] NGDC is now part of the National Centers for Environmental Information (NCEI)

DEMs at 10 m and 30 m horizontal spacing (http://www.ngdc.noaa.gov/mgg/inundation/tsunami/inundation.html).

5.1.3. Wave Analysis Transects

One-dimensional (1-D) wave analysis transects were oriented along the San Francisco County open Pacific coast shoreline to conduct detailed coastal analysis (see Appendix A for transect layout). Each transect was selected to be representative of a specific homogeneous reach of the coastline. Homogeneity is dependent on a variety of factors, including hydrodynamic and geomorphic parameters, and was assessed quantitatively and with engineering judgment. For each transect, an elevation profile was extracted from the terrain surface and physical attributes such as shoretype, slope, toe elevation, and crest elevation were determined.

5.1.4. Wave Setup and Runup

A combination of approaches was employed to determine the wave setup and runup at the shoreline depending on beach slope and shoretype. In general, for sandy beaches, either the Stockdon (Stockdon et al. 2006) or the parametric Direct Integration Method (DIM) (FEMA 2005) was used. Both methods provide estimates of the static and dynamic wave setup components and incident wave runup based on deepwater equivalent significant wave height and period and profile slope. For other shoretypes, such as bluff-backed shoreline or coastal structures, the Technical Advisory Committee for Water Retaining Structures (TAW) (van der Meer 2002) method was used.

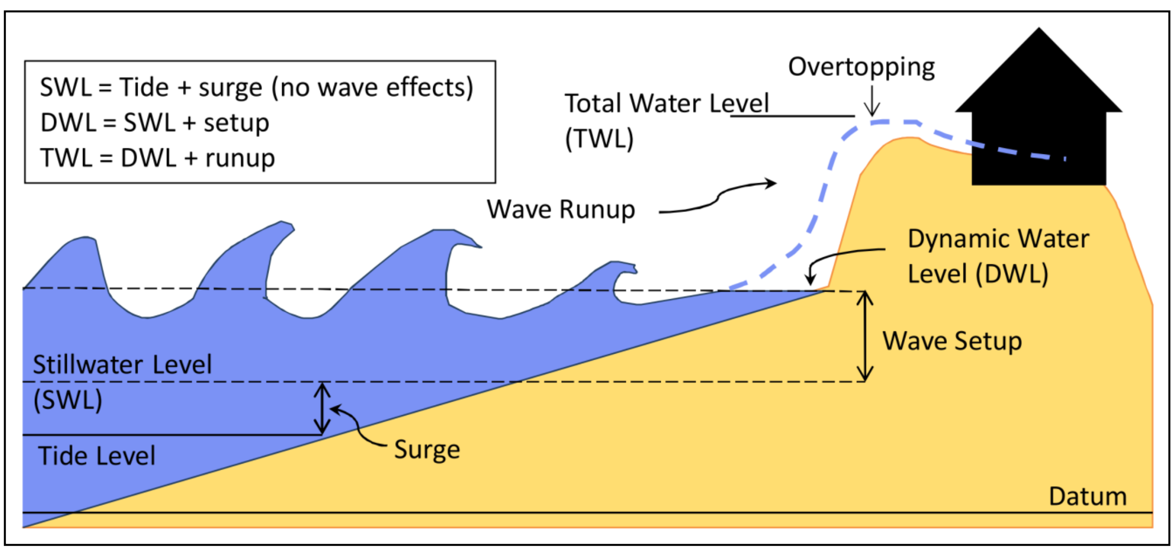

Figure 5. Definition Sketch of SWL, DWL, and TWL

Note: SWL = Stillwater Level; DWL = Dynamic Water Level; and TWL = Total Water Level

Estimates of wave setup and runup were combined with the SWL to estimate the TWL at the shoreline for each hourly time step of the 50-year hindcast. The TWL is the combination of SWL, wave setup, and wave runup (Figure 5).

5.1.5. Statistical Analysis of TWL

Once the hourly 50-year time series of TWL was obtained at each wave analysis transect, an extreme value analysis (EVA) was performed on the TWL data to obtain estimates of extreme TWL elevations. For the CCAMP OPC Study, the 50-, 20-, 10-, 4-, 2-, 1-, and 0.2-percent-annual-chance TWLs were estimated for each transect. The Generalized Pareto Distribution in combination with the peaks-over-threshold method was implemented to determine extreme TWL estimates. The 1-percent-annual-chance TWLs are used for FEMA regulatory floodplain mapping purposes.

5.1.6. Event-based Dune Erosion

Unarmored dune backshores are anticipated to retreat in response to extreme storm conditions. As waves impinge upon the dune, sand is eroded from the toe, thereby destabilizing the dune face which then adjusts to a stable slope through landward retreat. The dune retreat in response to the 1- and 0.2-percent-annual-chance TWL was evaluated using the MK&A geometric dune erosion model (Komar et al. 1999; Komar et al. 2002) with the K&D (Kriebel and Dean 1993) time convolution component.

5.1.7. Treatment of Coastal Structures

A variety of coastal structures such as revetments, retaining walls, and seawalls are present within the SLR pilot study area. IDS #3 for San Francisco documented the coastal structure treatments applied at transect as part of the existing conditions analysis of the 1-percent-annual-chance coastal storm event. In general, existing conditions TWL analyses assumed that large, publically maintained concrete seawalls would remain intact during the 1-percent-annual-chance storm. At these locations, intact-only TWL analyses were conducted. For engineered and non-engineered revetments, both intact and failed TWL analyses were conducted because structure performance during the 1-percent-annual-chance coastal storm event was uncertain. A partial failure or removed structure geometry was applied at each transect where a failed scenario was evaluated. For the purposes of the coastal floodplain mapping for the existing conditions FIRM, the worst-case TWL was mapped at each transect where intact and failed analyses were conducted.

5.1.8. Wave Overtopping Hazard Zones

Wave overtopping occurs when the potential limit of the TWL exceeds the crest elevation of the controlling topographic feature, such as a dune, bluff, or coastal structure. After profiles were adjusted to reflect event-based erosion or failure of coastal structures, overtopping of the profile was determined and evaluated. Two types of overtopping were considered: bore overtopping, where waves break onto or over the barrier, and splash overtopping, where waves break seaward of the barrier face and a jet of water rushes up and over the barrier crest. For each overtopped transect, the landward limit of influence of the overtopping was determined for input to the SFHA mapping.

5.2. Existing Conditions Floodplain Mapping

The results of the existing conditions coastal analyses were used to determine the BFEs and designate flood hazard zones for each transect. The flood hazard zones are categorized according FEMA's SFHA designations. These variables were in turn used to produce a series of work maps as the basis for updating the FIS and FIRM for CCSF. All mapping was performed in accordance with guidance in FEMA's 2005 update of the *Guidelines and Specifications for Flood Hazard Mapping Partners*. Refer to IDS #4 for full details on mapping methodology and results (BakerAECOM 2014b). A summary of the floodplain mapping process is provided below.

5.2.1. Flood Hazard Zone Delineations

Each wave analysis transect (Section 5.1.3) was used as the basis for mapping the existing conditions SFHAs. In accordance with FEMA's regulatory floodplain mapping guidelines, BFEs represent the mapped water elevation during a 1-percent-annual-chance flood event. The FIRM also displays and ties-in the riverine SFHAs from adjacent effective riverine flood studies where they intersect with the coastal SFHA (note that no riverine SFHAs are mapped in CCSF). Coastal SFHAs in CCSF were identified using the criteria in FEMA's *Pacific Guidelines*. These criteria included wave runup, wave overtopping, high-velocity flow, breaking wave height, and presence of primary frontal dunes (PFD). Five SFHA zones were applicable to the flood hazard mapping, as documented in IDS#4: Zone VE, Zone AE, Zone AO, Zone X, and Zone X (shaded). Due to map scale limitations, SFHA zones are only shown when visible at map scale. A summary of the most common coastal SFHA designations is provided below:

- **Zone VE** represents an area of coastal high hazard where wave action and/or high-velocity water can cause structural damage during the 1-percent-annual-chance flood.
- **Zone AE** represents an area of inundation during the 1-percent-annual-chance flood with lower velocity water and wave energy and thus a lower coastal hazard area than the VE Zone. The majority of the CCAMP OPC Study AE Zone areas are confined to sheltered waters and embayments.
- **Zone AO** represents an area of sheet-flow shallow flooding (<3 ft water depth) landward of an overtopped barrier crest. The sheet flow in these areas will either flow into another flooding source, result in ponding, or deteriorate because of ground friction and energy losses.
- **Zone X (unshaded and shaded)** represents an area with ground elevation higher than the 1-percent-annual-chance flood level. On a FIRM, a shaded Zone X represents inundation by the

0.2-percent-annual-chance flood hazard or inundation by the 1-percent-annual-chance flood hazard with average depths of one foot or less. An unshaded Zone X area is determined to be outside the 0.2-percent-annual-chance floodplain.

5.2.2. Mapping Interpretation

Shorelines are composed of various natural formations (sandy beaches, bluffs, cliffs, etc.), man-made coastal structures (revetments, seawalls, levees, etc.), areas of development, and river outlets. Together, these create a complex array of influences on coastal flooding that are accounted for in the detailed coastal analyses which then need to be translated and depicted on the flood hazard maps. Mapping components include the representative transects and shoreline reaches, transition zone mapping, limited detail study area mapping, overtopping, overland wave propagation, inundation, event-based dune erosion, coastal structures, and PFDs. A summary of key mapping considerations is provided below:

- **Representative transects and shoreline reaches** include shoreline reaches with similar beach slope and orientation and a representative transect was used for the runup analyses to generate the BFE for each reach. In cases where two neighboring reaches share the same BFE, the dividing Zone Break Line was removed to create a single reach; however, all transects used for runup analyses are shown on the flood hazard map. The representative transect is not necessarily located in the precise center of the reach it represents.

- **Transition zone mapping** describes areas where flood boundaries were smoothed or an intermediate transition zone was placed in between adjacent reaches due to large differences between adjacent BFEs.

- **Limited detail study area mapping** is used in unpopulated areas, such as parklands and nature preserves, which are not subject to future development, to provide reasonable estimates of coastal flood hazards while avoiding extensive data collection and analysis. Limited detail study area mapping may also be applied along developed high bluff and cliff shorelines where development is located well above the limit of coastal flood processes. In these areas, the results from nearby, similar reaches were applied to determine coastal BFEs.

- **Overtopping** occurs when the potential limit of TWL exceeds the crest elevation of the controlling topographic feature, such as a dune, bluff, or coastal structure. In areas with overtopping, the inland extents of flood hazard areas due to overtopping were determined. There are two types:
  a) Bore Overtopping - where waves break onto or over the barrier and propagate landward.
  b) Splash Overtopping - where waves break seaward of or on the barrier face, and a jet of water flows over the top of the crest.

- **Overland wave propagation** occurs when the SWL plus static wave setup exceeds the crest elevation of the controlling backshore feature, such as a dune or sandy barrier, or in low lying coastal floodplains, inland bays, and sheltered waters. This is not applicable along the coast of San Francisco County due to a steep shoreline and backshore features.

- **Inundation** mapping for areas of minimal wave hazard effects that are inundated by the SWEL alone are mapped as Zone AE. Since the San Francisco County OPC Study area does not include any tidally-influenced backwater areas, the extreme SWELs are not directly used for any portion of the flood hazard mapping.

- **Event-based dune erosion** assesses dune recession distances in response to the 1-percent-annual-chance flood event for the most likely winter profile. The dunes within the San Francisco County study area are relatively tall and wide. They undergo minimal event-based erosion during the 1-percent-annual-chance event.

- **Coastal structures** are taken into consideration particularly when they either partially or fully impede the flood water levels. Results from the intact and failed structure analysis (if applicable) were evaluated and the worst-case flood condition was mapped.

- **Primary Frontal Dune VE Zone Mapping** incorporates the PFD, up to the dune heel location (where the dune slope on the landward side changes from relatively steep to relatively mild) within the VE zone in accordance with NFIP regulations.

The future conditions flood hazard mapping is described in Section 5.4.

5.3. Future Conditions Coastal Analysis

5.3.1. Total Water Level Analysis

5.3.1.1 Approach

The future conditions coastal analysis framework adopted for the SLR pilot study closely followed the existing conditions coastal analysis developed as part of the CCAMP OPC Study (Section 5.1). TWL analysis was conducted at the same set of transects evaluated for the existing conditions coastal flood hazard analysis (see Appendix A for transect layout). BFEs were determined at each wave analysis transect from an extreme value analysis of the 50-year hourly hindcast of wave runup elevations at the shoreline. The primary modification to the existing conditions analysis was the inclusion of SLR and long-term shoreline change in the analysis framework. The SLR pilot study evaluated two approaches to incorporate the effect of SLR on future condition TWLs: 1) Linear Superposition and 2) Direct Analysis. The two approaches are summarized below and shown schematically in Figure 6.

- **Linear Superposition.** In the linear superposition approach, the future condition TWL is estimated by adding SLR to the existing condition TWL (TWL_{SLR} = TWL + SLR). The future condition TWL is greater than the existing condition TWL by an amount exactly equal to the amount of SLR. Due to the proportional increase in the TWL with respect to the amount of SLR, the linear superposition result is referred to as a 1:1 (or "linear") response in this study. The addition of SLR into the methodology framework is denoted as "Linear" in Figure 6.

- **Direct Analysis.** In the direct analysis approach, the future condition TWL is estimated by incorporating the effect of SLR directly into the 50-year hourly SWL time series. The SWL time series is adjusted by adding the constant SLR value corresponding to the scenario under consideration. The future condition SWL is then carried through the analysis and a future condition TWL is computed at each time step. The direct analysis approach captures known feedbacks[5] in the wave runup process due to increased depth of inundation at the toe of barriers (e.g., bluffs, revetments, etc.) as a result of higher SWLs with SLR. The addition of SLR into the methodology framework is shown as "Direct" in Figure 6.

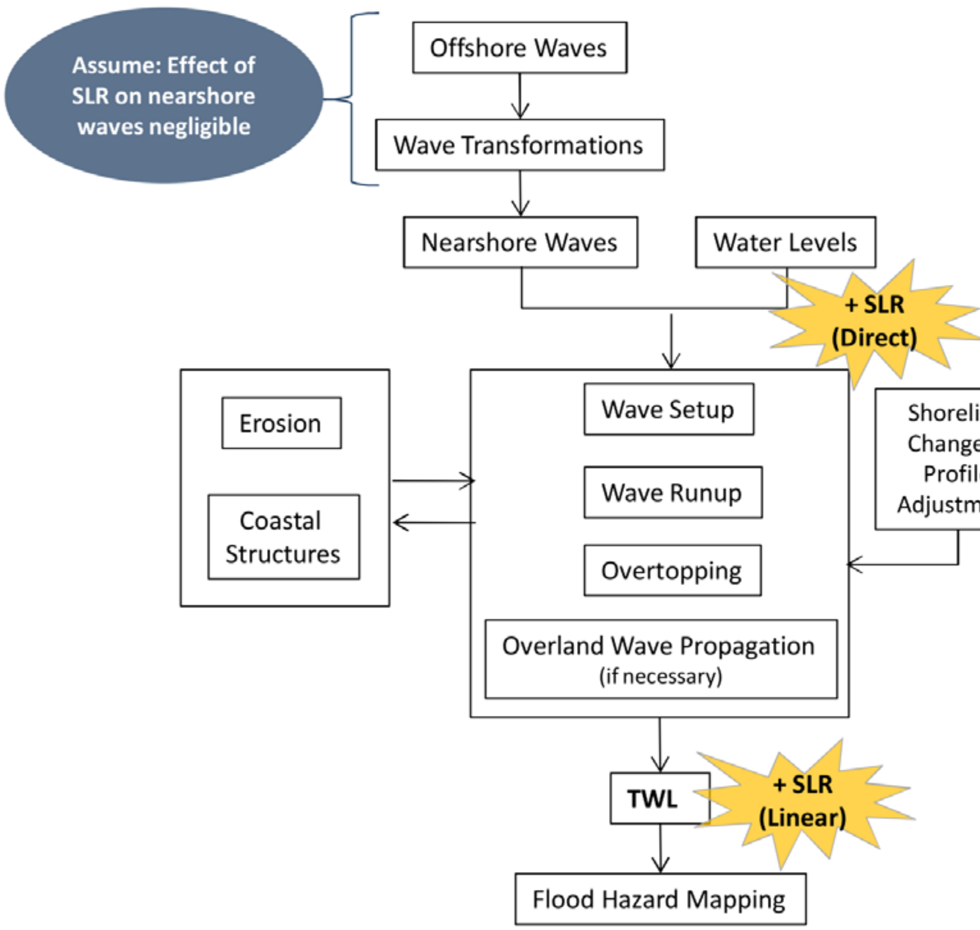

Figure 6. TWL Analysis Flowchart with Addition of SLR for Linear Superposition and Direct Analysis Methods

[5] In this report, the concept of a *feedback process* is introduced and used to describe the amplification of wave runup that occurs at certain shoretypes as a result of SLR. This amplification of wave runup is due to the increase in water depth at the toe of a barrier (such as a bluff or structure), which allows a larger depth-limited wave to impact the steep face of the barrier and produce a larger wave runup. As a result, the increase in the wave runup elevation may exceed the base increase in mean sea level because of this feedback process.

For both approaches, it was assumed that the impact of SLR on the offshore wave climatology or nearshore wave transformation is negligible and that the 50-year hourly hindcast of nearshore wave conditions developed for existing conditions as part of the CCAMP OPC Study could be applied to the future conditions analysis without further modification. The focus of the SLR pilot study was therefore the direct influence of SLR and shoreline change on the calculation of TWLs at the shoreline. Future studies may wish to examine how climate change and SLR will influence deepwater wave climatology and nearshore wave transformation processes.

5.3.1.2 Sensitivity Testing and Method Selection

BakerAECOM conducted sensitivity testing to evaluate the performance of the linear superposition and direct analysis methods for a variety of shoretypes. A range of SLR amounts (1-foot, 2-feet, 3-feet, 4-feet, and 5.5-feet) was tested to determine trends in TWL response due to varying amounts of SLR at different shoretypes. Since it was not necessary to conduct the TWL analysis for all SLR amounts at all transects, a few representative transects were selected for evaluation. For the purposes of the sensitivity testing, the effects of shoreline change in modifying the profile were neglected and TWL analyses were conducted using the static profile extracted from the existing conditions terrain (see Section 5.3.3 for a description of coupled shoreline change and TWL analysis). The results of the sensitivity testing at a representative structure-backed transect (i.e., the armored bluff near Sloat Boulevard) are shown in Figure 7 and Table 3.

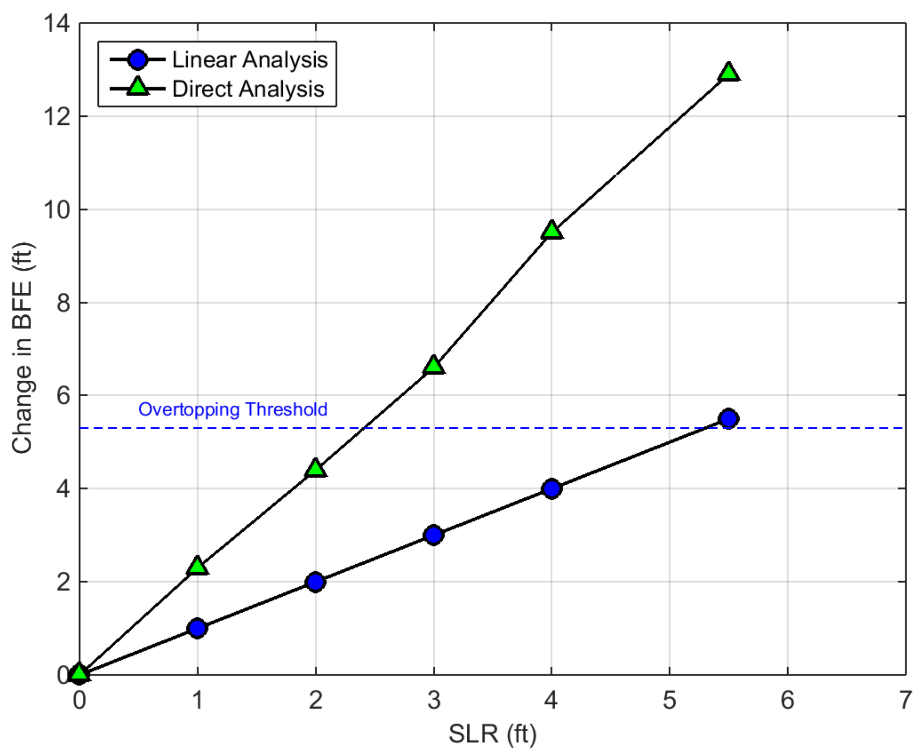

Figure 7. Results of TWL Sensitivity Testing at a Representative Structure-backed Transect

Table 3. Results of TWL Sensitivity Testing at a Representative Structure-backed Transect

SLR (ft)	1-percent-annual-chance TWL (ft NAVD88)		Change Relative to Existing Conditions (ft)		Factor Increase
	Linear Superposition	Direct Analysis	Linear Superposition	Direct Analysis	
Existing	25.6	25.6	-	-	-
+ 1.0	26.6	27.8	+ 1.0	+ 2.2	2.2
+ 2.0	27.6	29.9	+ 2.0	+ 4.3	2.2
+ 3.0	28.6	31.9	+ 3.0	+ 6.3	2.1
+ 4.0	29.6	35.2	+ 4.0	+ 9.6	2.4
+ 5.5	31.1	38.5	+ 5.5	+12.9	2.3

The results show the change in the 1-percent-annual-chance TWL as a result of different amounts of SLR. At this transect, the TWL increase (as determined using the direct analysis method) exceeds the linear superposition increase by approximately a factor of two. Additionally, overtopping at this location would be predicted under a much lower SLR scenario (3 feet) using the direct analysis method than by the linear superposition method (5.5 feet). The sensitivity testing at this transect and others confirmed the feedback mechanism discussed in Section 5.3.1.1, whereby the increase in the future condition TWL exceeds the amount of SLR (TWL_{SLR} > TWL + SLR) by a factor of two or more (up to a factor of three at some locations). The primary reason for the relatively large increase in future conditions TWL under the direct analysis approach is that the increased inundation of the structure toe due to SLR allows larger wave heights to impact the structure, thereby producing higher values of wave runup. This feedback process can only be captured by modeling the SLR effect with the direct analysis method.

It should be noted that future conditions TWL analysis on static (non-eroded) profiles will produce a higher TWL amplification than TWL analysis on more dynamic, erodible shorelines, so the findings discussed above may highlight a relatively extreme example. Based on the results of the sensitivity testing and additional analysis conducted by the study team (Vandever et al. 2015), it appears that a TWL amplification factor of 2.5 to 3.5 times the amount of SLR likely represents an upper bound on the TWL response for static shorelines; however further testing in other areas would be required to better estimate this limit.

Based on the results of the sensitivity testing, the direct analysis method was selected as the preferred method of analysis for the SLR pilot study. Results of both the linear superposition and direct analysis methods are presented in Section 6 for comparison purposes. Section 8 presents a summary of key findings and recommendations for application of the direct analysis and linear superposition methods in future studies.

5.3.2. Shoreline Change Analysis

Shoreline change is a complex process that can occur on a variety of time scales, ranging from event-based to multi-decadal, and can result in either retreating or prograding shorelines. Short-term shoreline change generally consists of episodic, storm-induced erosion or human alterations (e.g., beach nourishments or placement of coastal protection or sand retention structures). Long-term shoreline change is typically facilitated by natural or human-induced changes in sediment budget, longshore and cross-shore sediment transport, wave climate, SLR, and other processes such as river mouth migration, surface runoff, and groundwater processes (Hapke et al. 2006).

For the purposes of this study, SLR and shoreline change were assumed to exert both an influence on the vertical change in the TWL as well as the horizontal extent of the SFHA. The "vertical" response is due to two primary factors: (1) SLR, which increases the base water level upon which wave runup processes are occurring and (2) non-linear feedback processes at the toe of the backshore feature which further increase future TWLs. The "horizontal" influence is due to overall profile response to SLR, which results in a landward and upward shift of the shoreline in response to SLR (Figure 8).

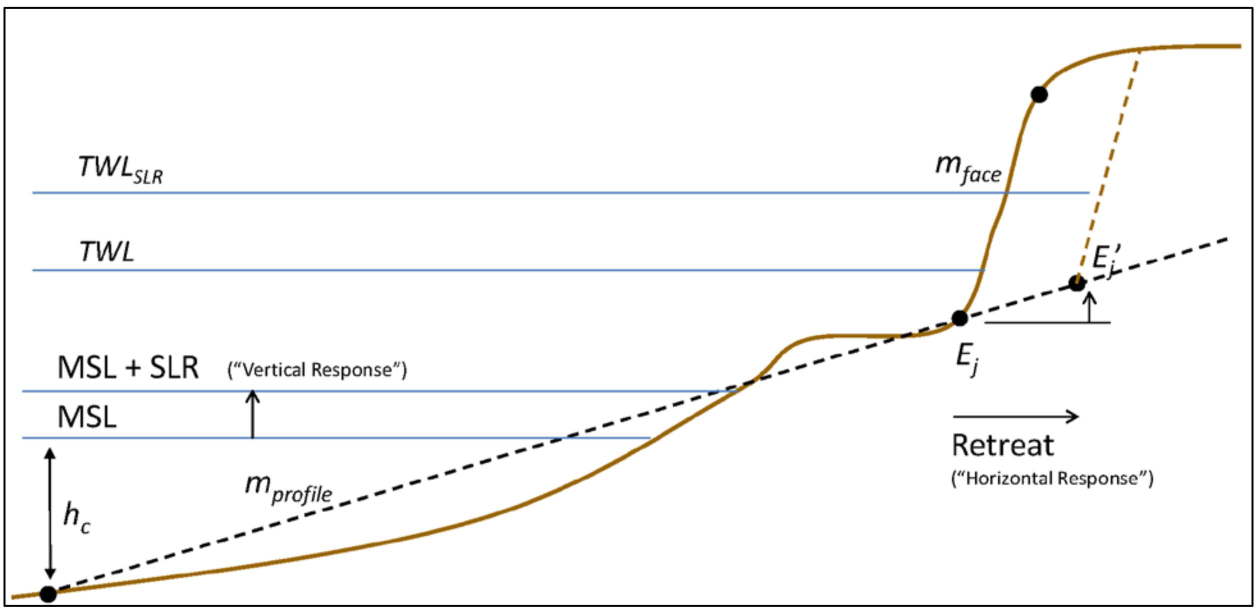

Figure 8. SLR and Shoreline Change Effects on Profile

While the primary objective of this study was to examine the influence of SLR on future conditions TWLs, the influence of long-term shoreline change on the landward extent of the SFHA was also evaluated.

Three components of shoreline change were considered in this study[6]:

- **Episodic storm-induced erosion for dunes.** Similar to the event-based dune erosion calculations performed for FEMA's CCAMP OPC Study (for existing conditions), profile response to a 1-percent-annual-chance storm event was evaluated ($R_{1\%}$). Event-based erosion at bluff-backed transects was not evaluated.

- **Continuation of long-term historical shoreline change trends.** Long-term coastal processes have resulted in observed historical rates of shoreline retreat or accretion over the past century along California's shorelines. These shoreline change trends were identified at each transect using published data from the U.S. Geological Survey (Section 5.3.2.2) and assumed to continue unchanged into the future ($R_{coastal}$). The pilot study does not account for future changes in coastal processes such as sediment supply, wave climate, alongshore sediment transport, or beach nourishments, which may alter future $R_{coastal}$ rates

- **Increased shoreline retreat due to profile adjustment to SLR.** A portion of the observed long-term historical shoreline change is due to ongoing profile adjustments to historical rates of SLR (on the order of 2 mm/yr of SLR along the San Francisco coastline; or approximately 8 inches of SLR over the 20th century). For the purposes of this study, it was assumed that increased rates of SLR in the future will produce increased rates of shoreline retreat as profiles adjust to new, higher sea levels (R_{SLR}). The calculation of future rates of shoreline retreat in response to SLR (E_{SLR}) is discussed in Section 5.3.2.3 (sandy shorelines) and Section 5.3.2.4 (bluff shorelines).

The evaluation of each of these three components as part of the SLR pilot study is discussed in more detail in the sections that follow.

5.3.2.1 Background and Approach

There are several different methods to incorporate the effects of SLR on future rates of shoreline change. The simplest approach is to project historical rates of shoreline change unchanged into the future; however, there is broad consensus that SLR will increase rates of shoreline retreat so a simple projection of historical rates would likely underestimate retreat distances. Various investigators have applied different methods to link future shoreline change and SLR. Previous methods include applying a linear factor of increase to historical shoreline change rates based on the relative increase in the rate of SLR (Bray and Hooke 1997; PWA 2008). For example, doubling the rate of SLR from 2 mm/yr to 4 mm/yr would increase the rate of shoreline retreat by a factor of two. The so-called Bruun Rule is another method commonly applied by coastal engineers to project future shoreline positions in response to SLR by assuming the profile adjusts to the new equilibrium sea level by shifting landward and upward (Bruun 1962; Bruun 1983). The amount of horizontal retreat is proportional to the amount of SLR and the overall

[6] In the discussion that follows, the variables *R* and *E* are used to define retreat distances and rates of shoreline change, respectively.

slope of the profile. A study by the Pacific Institute applied a TWL exceedance methodology that pro-rated future rates of shoreline retreat by the relative increase in the duration of time in which the TWL exceeded the bluff toe (PWA 2009; Revell et al. 2011).

For the purposes of this study, a simplified, hybrid approach was adopted for sandy beaches and bluffs within the SLR pilot study area. Shoreline change projections for sandy beach, dune, and bluff shoretypes relied on an approach which pro-rated a portion of the historical shoreline change rate (the portion assumed to have been caused by ongoing SLR over the past century) by a “SLR Factor”, which was assumed to be proportional to the ratio of the future and historical rates of SLR (S_f/S_h) (Ashton et al. 2011):

$$SLR\ Factor = \left(\frac{S_f}{S_h}\right)^m \qquad \text{(Eq. 1)}$$

where Sh and Sf are the historical and future projected rates of SLR (in mm/yr), respectively, and m is a coefficient dependent on the response behavior of the shoreline (values of m range from 0 to 1). SLR Factors were calculated for the mid-range and high-range SLR curves (see Figure 3) in decadal blocks (e.g., 2000-2010, 2010-2020, etc.) using the quadratic curve fits presented in Section 4.2). The SLR Factors for the mid-range and high-range SLR curves are shown in Table 4 and Table 5 from 2000 to 2100 (assuming a value of m equal to 1.0; see Sections 5.3.2.3 and 5.3.2.4 for additional discussion of selection of values for m). For each decade, the SLR Factor was calculated relative to the observed historical rate of SLR at the San Francisco tide station (NOAA #9414290), assumed to be equal to 2.01 mm/yr7. Table 4 and Table 5 show that the rate of SLR is projected to increase by a factor of 4 to 8 by 2050 and by 7 to 12 by 2100. An average SLR Factor was computed for the time periods of 2000 to 2050 and 2050 to 2100 for the mid-range and high-range SLR curves to simplify the future shoreline change pro-rating calculations for each planning horizon (2050 and 2100)[8].

[7] Note that NOAA’s estimate of the observed historical rate of SLR at the San Francisco tide station (NOAA #9414290) was updated after completion of the coastal analysis for this project. The current published average rate of historical SLR is 1.92 mm/yr. Use of this revised value would have a negligible effect on the computed future rates of shoreline retreat for this study.

[8] This simplification is mathematically valid because the rate of SLR at any point in time is equal to the slope of the SLR curve. Since the SLR curve is a quadratic fit to the published NRC values for 2050 and 2100, the slope is defined as a linear curve and use of an average factor over each planning horizon produces an equivalent result to using the decadal values and calculating intermediate amounts of shoreline retreat for each decade.

Table 4. SLR Factors for Mid-Range SLR Projection (1- and 3-ft)

Year	SLR Rate (mm/yr)	SLR Factor	Average SLR Factor (2000-2050)	Year	SLR Rate (mm/yr)	SLR Factor	Average SLR Factor (2050-2100)
Historical	2.01	-	-	-	-	-	-
2010	3.7	1.8		2060	9.8	4.9	
2020	4.9	2.4		2070	11.0	5.5	
2030	6.1	3.0	**3.0**	2080	12.2	6.1	**6.0**
2040	7.3	3.6		2090	13.4	6.7	
2050	8.5	4.2		2100	14.6	7.3	

Note: SLR Factor calculated as the ratio of future SLR rate to historical SLR rate (S_f /S_h). Average SLR Factors reported in table are rounded for ease of application. A value of the coefficient, *m*, equal to 1.0 was assumed to calculate the factors shown.

Table 5. SLR Factors for High-Range SLR Projection (2- and 5.5-ft)

Year	SLR Rate (mm/yr)	SLR Factor	Average SLR Factor (2000-2050)	Year	SLR Rate (mm/yr)	SLR Factor	Average SLR Factor (2050-2100)
Historical	2.01	-	-	-	-	-	-
2010	8.4	4.2		2060	17.7	8.8	
2020	10.2	5.1		2070	19.5	9.7	
2030	12.1	6.0	**6.0**	2080	21.4	10.7	**10.5**
2040	14.0	6.9		2090	23.3	11.6	
2050	15.8	7.9		2100	25.1	12.5	

Note: SLR Factor calculated as the ratio of future SLR rate to historical SLR rate (S_f /S_h). Average SLR Factors reported in table are rounded for ease of application. A value of the coefficient, *m*, equal to 1.0 was assumed to calculate the factors shown.

The sections that follow describe the methods implemented to determine historical shoreline change rates at each transect (E_h), partition the observed historical rates into a coastal processes component ($E_{coastal}$) and a SLR component (E_{SLR}), pro-rate the SLR component of shoreline change accounting for future changes in the rate of SLR, and compute potential shoreline retreat distances at each transect for each SLR scenario and planning horizon. Section 5.3.2.2 presents the data sources leveraged to determine historical shoreline change rates. Section 5.3.2.3 presents the shoreline change data and pro-rating methods at sandy beach and dune shorelines. Section 5.3.2.4 presents the shoreline change data and pro-rating methods at bluff shorelines.

5.3.2.2 Data Sources

In 2006-2007, the USGS completed a comprehensive analysis of historical shoreline change rates for beaches and cliffs along the California coast (Hapke et al. 2006; Hapke and Reid 2007). The study calculated long-term linear regression rates (LRR; four points spanning approximately 120 years) and short-term endpoint rates (EPR) for sandy beaches (two most recent points spanning approximately 25 years) and cliffs (two data points spanning approximately 70 years). EPRs of cliff and sandy beach shorelines were extracted for all USGS transects from the digital transect shapefiles obtained from the USGS website. The short-term EPRs were selected for sandy beaches to characterize shoreline change trends over recent time, using shorelines derived from imagery and topography datasets dating from approximately 1945-1976 to 1998-2002. Table 6 summarizes the USGS datasets evaluated for this study from each region (northern, central, and southern) for sandy beaches and cliffs.

Table 6. USGS Shoreline Change Data for California Coast

Shoreline Type	Section	Number of Transects	Date Ranges for End Points	Average EPR (ft/yr)*	Transect Spacing (m)
Cliffs	Northern CA	2,325	1928-1935 to 2002	-1.33 ± 0.66	20
	Central CA	10,389	1929-1935 to 1998-2002	-0.85 ± 0.66	
	Southern CA	4,939	1932-1934 to 1998	-0.67 ± 0.66	
	State	17,653	1928-1935 to 1998-2002	-0.86 ± 0.66	
Beaches	Northern CA	3,382	1952-1971 to 2002	+1.12 ± 1.31	50
	Central CA	6,506	1945-1976 to 1998-2002	-1.71 ± 1.31	
	Southern CA	6,334	1971-1976 to 1998	-0.47 ± 1.31	
	State	16,222	1945-1976, 1998-2002	-0.64 ± 1.31	

Note: Northern CA = Del Norte County to Tomales Point (Marin County); Central CA = Tomales Point (Marin County) to El Capitan Beach (Santa Barbara County); and Southern CA = El Capitan Beach (Santa Barbara) to San Diego County.

* End-point rate (EPR) for beaches and cliffs is based on a time period of 25 and 70 years, respectively.

Figure 9 shows the USGS data availability for the San Francisco study area (full statewide data coverage is shown in Appendix B). As can be seen in the figure, there are no cliff retreat data available in the study area; sandy beach shoreline change data only cover the central and southern portion of the San Francisco open Pacific coast shoreline. As a result, an approach was developed to categorize each FEMA coastal analysis transect into shoreline change categories determined from the regional central CA USGS dataset (application of this methodology to another region within the state would require evaluation and determination of appropriate shoreline change categories for that region). Application of the available datasets within the San Francisco study area for sandy beach/dune and bluff shorelines is discussed in Section 5.3.2.3 and Section 5.3.2.4, respectively.

Figure 9. USGS Shoreline Change Data Inventory - San Francisco Study Area

Note: There were no published cliff retreat data in the USGS dataset for the San Francisco County pilot study area.

5.3.2.3 Sandy Shorelines

Shoreline change data for sandy beaches were extracted from the USGS California dataset (Hapke et al. 2006). The San Francisco study area falls within the central California region of the USGS dataset and includes 137 out of 6,506 central California transects. The USGS shoreline change transects are typically spaced 50 meters apart and span the shoreline from the Cliff House in San Francisco southward to the San Mateo County line (Table 6 and Figure 9).

Because historical shoreline change rates are extremely variable at the 50 meter transect spacing and because historical shoreline change data were not available for the entire study area, BakerAECOM developed a binning approach to categorize the historical shoreline change rates at each coastal analysis transect in San Francisco. For sandy shorelines, seven shoreline change categories ranging from accretionary to stable to erosional were defined to estimate median historical shoreline change rates within each category. The USGS data were analyzed to inform the definition of categories and their corresponding median shoreline change rate. The goal of the binning approach was to simplify shoreline change estimates to accurately represent trends at the individual transect locations within the limitations of the available data while also remaining true to what are typically considered “high,” “moderate,” or “low” accretion or erosion rates for the central California coastline. BakerAECOM assigned each CCAMP OPC transect a shoreline change category based on available USGS shoreline change data, local knowledge of the study area, anecdotal and documented evidence of historical shoreline change trends and storm damage, published shoreline change rates from other sources, and qualitative examination of oblique aerial photos.

Table 7 shows the seven shoreline change categories developed for sandy shorelines in central CA. The inherent error[9] of the USGS short-term EPR for sandy shorelines is estimated to be ± 0.4 m/yr and the data range from +7.3 m/yr to -6.7 m/yr (negative rates denote erosion and positive rates denote accretion) with approximately 73% of the data falling between +1 m/yr and -1 m/yr. Unlike cliffs, sandy shorelines can either erode, be stable, or accrete over time. The “stable” category was selected to include approximately half of the error (+/- 0.15 m/yr) above and below zero and is assigned an effective historical EPR of 0 ft/yr. Each accretion category captures approximately one third of the remaining accretion data (EPR > 0 m/yr) and each erosion category captures approximately one third of the remaining erosion data (EPR < 0 m/yr) within central CA. Median values (± one standard deviation) within each accretion and erosion category were calculated and are used as the effective historical EPR ($E_{h,Dune}$). The median value was used as opposed to the mean value to minimize the bias of extreme values at highly accretionary or erosional transects.

[9] Short-term EPR error was calculated by USGS using estimates of error associated with all input datasets used to determine shoreline positions, including errors due to geo-referencing, digitizing, and T-sheet accuracy. The total EPR error was annualized and reported to be ± 0.4 m/yr for sandy shorelines and ± 0.2 m/yr for cliff shorelines (Hapke et al. 2006; 2007).

Table 7. Historical Shoreline Change Rate Categories for Sandy Beaches and Dunes in Central CA

Shoreline Change Category	Shoreline Change Index	Shoreline Change Category Range		Median Shoreline Change Rate, $E_{h,Dune}$ (ft/yr)
		(m/yr)	(ft/yr)	
High Accretion	+3	> +0.91	> +3.0	+5.5 ± 3.6
Moderate Accretion	+2	+0.46 to +0.91	+1.5 to +3.0	+2.1 ± 0.4
Low Accretion	+1	+0.15 to +0.46	+0.5 to +1.5	+0.9 ± 0.3
Stable	0	-0.15 to +0.15	-0.5 to +0.5	0.0 ± 0.1
Low Erosion	-1	-0.15 to -0.46	-0.5 to -1.5	-1.0 ± 0.3
Moderate Erosion	-2	-0.46 to -0.91	-1.5 to -3.0	-2.1 ± 0.4
High Erosion	-3	< -0.91	< -3.0	-4.4 ± 2.3

Note: The shoreline change index was developed as a numerical indicator for use in the coastal analysis calculations and GIS/mapping databases. The shoreline change categories shown in Table 7 are specific to central California. Application of this methodology to another region would require evaluation and determination of region-specific shoreline change categories and rates. Source data: Hapke et al. (2006).

The observed historical USGS shoreline change rate ($E_{h,Dune}$) at sandy beach and dune transects was assumed to be comprised of two components: a coastal processes component ($E_{coastal}$) and a historical SLR component ($E_{h,SLR}$):

$$E_{h,Dune} = E_{coastal} + E_{h,SLR} \qquad \text{(Eq. 2)}$$

Similarly, the future shoreline change rate at sandy beach and dune transects was taken to be:

$$E_{f,Dune} = E_{coastal} + E_{f,SLR} \qquad \text{(Eq. 3)}$$

$$\text{where } E_{f,SLR} = E_{h,SLR}(SLR\ Factor) \qquad \text{(Eq. 4)}$$

$E_{h,SLR}$ is the historical rate of retreat in response to SLR over the 20th century and $E_{f,SLR}$ is the projected future rate of retreat in response to future SLR, as discussed below. The total future shoreline change distance (R_{Dune}) was calculated as the sum of the shoreline change distance due to ongoing coastal processes ($R_{coastal}$), SLR retreat ($R_{f,SLR}$), and event-based dune erosion ($R_{1\%}$) (Eq. 5). The coastal processes retreat rate ($E_{coastal}$) was held constant for future conditions while the SLR retreat rate ($E_{h,SLR}$) was pro-rated using the average SLR Factors from Table 4 and Table 5 to obtain the future SLR retreat rate ($E_{f,SLR}$). Equations 5 to 8 show the combination of each retreat component to calculate the total retreat distance at each planning horizon. It is important to note that $E_{coastal}$ can be either positive (accretion) or negative (erosion), depending on the historical shoreline change trends at each transect. The erosion distances for $R_{1\%}$ are taken from the existing conditions analysis conducted as part of the CCAMP OPC Study at each dune-backed transect (BakerAECOM 2014a). The dune retreat in response to a future 1-percent-annual-chance coastal storm event was assumed to be equal to that determined for existing conditions because the dune will retreat to maintain an equilibrium position relative to SLR.

The summation of the three components to estimate future shoreline retreat distances at dunes is shown below:

$$R_{Dune} = R_{coastal} + R_{f,SLR} + R_{1\%} \quad \text{(Eq. 5)}$$

$$R_{coastal} = E_{coastal}\Delta t \quad \text{(Eq. 6)}$$

$$R_{f,SLR} = E_{f,SLR}\Delta t = E_{h,SLR}(SLR\ Factor)\Delta t = \left(E_{h,SLR}\right)\left(\frac{S_f}{S_h}\right)^m \Delta t \quad \text{(Eq. 7)}$$

$R_{1\%}$ = event-based dune erosion as determined from existing conditions analysis (Eq. 8)

where Δt is the time duration of the planning horizon (either 39 years for 2011-2050 or 50 years for 2050 to 2100)[10] and m=1.0 for dune-backed shoretypes. The assumption of the exponent m=1.0 is consistent with the "instantaneous response" behavior described by Ashton et al. (2011), where the sandy profile is assumed to follow a Bruun-type response (i.e., the increase in the future rate of shoreline retreat is directly proportional to the relative increase in the rate of SLR).

The historical SLR recession ($R_{h,SLR}$) was estimated using the Bruun Rule[11]:

$$R_{h,SLR} = SLR\frac{L}{h_c+B} = \frac{SLR}{\tan\theta} = SLR\cot\theta \quad \text{(Eq. 9)}$$

where $R_{h,SLR}$ = historical landward recession of the profile in response to SLR; SLR = historical increase in mean sea level, h_c = closure depth, B = berm height, L = cross-shore distance to depth h_c, and θ = overall profile slope over the active length of the profile (from the shoreline to a depth of 10 m). From the form of the equation, it can be seen that the recession is equal to the product of the increase in sea level and the overall profile slope. For typical profile slopes of 1:50 to 1:100 (cot θ = 50-100), a typical rule of thumb is that the horizontal recession is on the order of 50 to 100 times the amount of SLR. Typical nearshore profile slopes were examined in the San Francisco study area and it was determined that a slope of 1:50 was representative of profiles along the San Francisco open Pacific coast study area. Using a historical SLR amount of approximately 8 inches over the past 100 years (from the NOAA published SLR trend of 2.01 mm/yr at the San Francisco tide station) resulted in a R_{SLR} of approximately -33 ft. Converting this

[10] 2011 was selected as the starting year for shoreline change calculations since this corresponded to the date of the coastal LiDAR data collection for the CCAMP OPC Study.

[11] Various researchers have noted issues with application of the Bruun Rule to predict future response of shorelines to SLR (e.g., Cooper and Pilkey 2006); however, there is general consensus within the coastal engineering community that the general conceptual model of the Bruun Rule – that a sandy beach profile will respond to SLR by migrating landward and upward – appears to be a valid assumption. The approach developed as part of this pilot study relies on the Bruun Rule for projection of a portion of the shoreline response to SLR but acknowledges that other coastal processes play an important role in determining future rates of shoreline change in addition to the SLR-induced retreat. These other coastal processes are accounted for by inclusion of the coastal processes shoreline change rate, $E_{coastal}$. This hybrid approach segregates the Bruun-type retreat and the ongoing coastal processes shoreline change into two components and treats them independently to develop estimates of future shoreline position for sandy shorelines.

retreat distance to an equivalent shoreline change rate resulted in a historical SLR retreat rate, $E_{h,SLR}$, of -0.33 ft/yr.

Once the historical SLR retreat rate ($E_{h,SLR}$) was determined, $E_{coastal}$ was estimated for each shoreline change category using Eq. 2. Table 8 through Table 11 show the historical $E_{coastal}$ and $E_{h,SLR}$, projected future E_{SLR}, and sandy beach and dune shoreline change distances (R_{SLR} and $R_{coastal}$) for each SLR amount. It should be noted that the values of shoreline change shown in the tables do not include the event-based dune retreat in response to the 1-percent-annual-chance coastal storm ($R_{1\%}$). All components of shoreline change ($R_{coastal}$, $R_{f,SLR}$, and $R_{1\%}$) will be combined to compute the full shoreline change distances in Section 5.4.

The following example for a moderate erosion sandy beach and the 3-ft SLR scenario (2050-2100) is provided below to illustrate the methodology. From Table 4, the average SLR Factor for this SLR scenario is 6.0. The results corresponding to this example are shown in Table 10.

$E_{h,Dune}$ = -2.1 ft/yr (from Table 7)

$E_{h,SLR}$ = -0.33 ft/yr (from Bruun Rule)

$E_{coastal} = E_{h,Dune} - E_{h,SLR} = -2.1 - (-0.33) = -1.8$ ft/yr

$E_{f,SLR} = E_{h,SLR}\ (SLR\ Factor) = (-0.33)(6.0) = -2.0$ ft/yr

$E_{f,Dune} = E_{f,SLR} + E_{coastal} = -2.0 + (-1.8) = -3.8$ ft/yr

$R_{coastal} + R_{SLR} = (E_{coastal} + E_{f,SLR})\ \Delta t = (-2.0 - 1.8)(50) = -188$ ft

Table 8. Projected Sandy Beach and Dune Shoreline Change Distances for 2050 with 1-ft SLR

	Historical			2011-2050 (1-ft SLR)			
Shoreline Change Category	$E_{h,Dune}$ (ft/yr)	$E_{h,SLR}$ (ft/yr)	$E_{coastal}$ (ft/yr)	$E_{f,SLR}$ (ft/yr)	$E_{coastal}$ (ft/yr)	$E_{f,Dune}$ (ft/yr)	Shoreline Change, $R_{f,SLR} + R_{coastal}$ (ft)*
High Accretion	+5.5	-0.3	+5.8	-1.0	+5.8	+4.8	+188 ± 50
Moderate Accretion	+2.1	-0.3	+2.5	-1.0	+2.5	+1.5	+57 ± 50
Low Accretion	+0.9	-0.3	+1.3	-1.0	+1.3	+0.3	+10 ± 50
Stable	0.0	-0.3	+0.3	-1.0	+0.3	-0.7	-26 ± 50
Low Erosion	-1.0	-0.3	-0.7	-1.0	-0.7	-1.6	-64 ± 50
Moderate Erosion	-2.1	-0.3	-1.8	-1.0	-1.8	-2.8	-109 ± 50
High Erosion	-4.4	-0.3	-4.1	-1.0	-4.1	-5.1	-197 ± 50

Note: SLR factor of 3.0 applied to historical SLR retreat rate ($E_{h,SLR}$) from 2011-2050 for the 1-ft SLR scenario.
*Shoreline change distances shown in table do not include event-based dune retreat ($R_{1\%}$).

Table 9. Projected Sandy Beach and Dune Shoreline Change Distances for 2050 with 2-ft SLR

	Historical			2011-2050 (2-ft SLR)			
Shoreline Change Category	$E_{h,Dune}$ (ft/yr)	$E_{h,SLR}$ (ft/yr)	$E_{coastal}$ (ft/yr)	$E_{f,SLR}$ (ft/yr)	$E_{coastal}$ (ft/yr)	$E_{f,Dune}$ (ft/yr)	Shoreline Change, $R_{f,SLR} + R_{coastal}$ (ft)*
High Accretion	+5.5	-0.3	+5.8	-2.0	+5.8	+3.8	+149 ± 50
Moderate Accretion	+2.1	-0.3	+2.5	-2.0	+2.5	+0.5	+19 ± 50
Low Accretion	+0.9	-0.3	+1.3	-2.0	+1.3	-0.7	-28 ± 50
Stable	0.0	-0.3	+0.3	-2.0	+0.3	-1.7	-64 ± 50
Low Erosion	-1.0	-0.3	-0.7	-2.0	-0.7	-2.6	-103 ± 50
Moderate Erosion	-2.1	-0.3	-1.8	-2.0	-1.8	-3.8	-147 ± 50
High Erosion	-4.4	-0.3	-4.1	-2.0	-4.1	-6.1	-236 ± 50

Note: SLR factor of 6.0 applied to historical SLR retreat rate ($E_{h,SLR}$) from 2011-2050 for the 2-ft SLR scenario.
*Shoreline change distances shown in table do not include event-based dune retreat ($R_{1\%}$).

Table 10. Projected Sandy Beach and Dune Shoreline Change Distances for 2100 with 3-ft SLR

	Historical			2050-2100 (3-ft SLR)			
Shoreline Change Category	$E_{h,Dune}$ (ft/yr)	$E_{h,SLR}$ (ft/yr)	$E_{coastal}$ (ft/yr)	$E_{f,SLR}$ (ft/yr)	$E_{coastal}$ (ft/yr)	$E_{f,Dune}$ (ft/yr)	Shoreline Change, $R_{f,SLR} + R_{coastal}$ (ft)*
High Accretion	+5.5	-0.3	+5.8	-2.0	+5.8	+3.8	+192 ± 65
Moderate Accretion	+2.1	-0.3	+2.5	-2.0	+2.5	+0.5	+24 ± 65
Low Accretion	+0.9	-0.3	+1.3	-2.0	+1.3	-0.7	-37 ± 65
Stable	0.0	-0.3	+0.3	-2.0	+0.3	-1.7	-83 ± 65
Low Erosion	-1.0	-0.3	-0.7	-2.0	-0.7	-2.6	-132 ± 65
Moderate Erosion	-2.1	-0.3	-1.8	-2.0	-1.8	-3.8	-189 ± 65
High Erosion	-4.4	-0.3	-4.1	-2.0	-4.1	-6.1	-303 ± 65

Note: SLR factor of 6.0 applied to historical SLR retreat rate ($E_{h,SLR}$) from 2050-2100 for the 3-ft SLR scenario.
*Shoreline change distances shown in table do not include event-based dune retreat ($R_{1\%}$).

Table 11. Projected Sandy Beach and Dune Shoreline Change Distances for 2100 with 5.5-ft SLR

Shoreline Change Category	Historical			2050-2100 (5.5-ft SLR)			
	$E_{h,Dune}$ (ft/yr)	$E_{h,SLR}$ (ft/yr)	$E_{coastal}$ (ft/yr)	$E_{f,SLR}$ (ft/yr)	$E_{coastal}$ (ft/yr)	$E_{f,Dune}$ (ft/yr)	Shoreline Change, $R_{f,SLR} + R_{coastal}$ (ft)*
High Accretion	+5.5	-0.3	+5.8	-3.5	+5.8	+2.3	+117 ± 65
Moderate Accretion	+2.1	-0.3	+2.5	-3.5	+2.5	-1.0	-50 ± 65
Low Accretion	+0.9	-0.3	+1.3	-3.5	+1.3	-2.2	-111 ± 65
Stable	0.0	-0.3	+0.3	-3.5	+0.3	-3.1	-157 ± 65
Low Erosion	-1.0	-0.3	-0.7	-3.5	-0.7	-4.1	-206 ± 65
Moderate Erosion	-2.1	-0.3	-1.8	-3.5	-1.8	-5.3	-263 ± 65
High Erosion	-4.4	-0.3	-4.1	-3.5	-4.1	-7.5	-377 ± 65

Note: SLR factor of 10.5 applied to historical SLR retreat rate ($E_{h,SLR}$) from 2050-2100 for the 5.5-ft SLR scenario.
*Shoreline change distances shown in table do not include event-based dune retreat ($R_{1\%}$).

Following determination of the shoreline change distances for R_{SLR} and $R_{coastal}$ for each SLR scenario, the shoreline change distances for 2050 and 2100 were combined to produce projected sandy beach and dune shoreline change distances for the mid-range and high-range SLR projections. Table 12 presents the combined results for the mid-range SLR projection (1-ft at 2050 and 3-ft at 2100) and the high-range SLR projection (2-ft at 2050 and 5.5-ft at 2100). Based on the USGS annualized error for EPRs of +/- 1.3 ft/yr, there is considerable uncertainty in the future shoreline change projections. Projecting this annualized error out to 2050 (39 years) and 2100 (89 years) yields approximate uncertainties in the future shoreline positions of ± 50 ft at 2050 and ± 115 ft at 2100.

The predicted dune erosion distances in response to the 1-percent-annual-chance event ($R_{1\%}$) from the existing CCAMP OPC Study were added to the total retreat distances for the dune-backed transects: 17, 101, 26, and 29 (No dune erosion was predicted to occur at Transects 59 and 60 from the 1-percent-annual-chance event due to their sheltered location). See Section 5.4 for total retreat distances applied for future conditions SFHA mapping.

Table 12. Projected Sandy Beach and Dune Shoreline Change Distances for 2050 and 2100 Planning Horizons

	Mid-Range SLR Projection, $R_{SLR} + R_{coastal}$			High-Range SLR Projection, $R_{SLR} + R_{coastal}$		
	1-ft (a)	3-ft (b)	Total (a) + (b)	2-ft (c)	5.5-ft (d)	Total (c) + (d)
Category	**2011-2050**	**2050-2100**	**2011-2100**	**2011-2050**	**2050-2100**	**2011-2100**
High Accretion	+188	+192	+379	+149	117	+267
Moderate Accretion	+57	+24	+81	+19	-50	-32
Low Accretion	+10	-37	-26	-28	-111	-139
Stable	-26	-83	-108	-64	-157	-221
Low Erosion	-64	-132	-195	-103	-206	-308
Moderate Erosion	-109	-189	-298	-147	-263	-411
High Erosion	-197	-303	-500	-236	-377	-613
Projected Shoreline Change Uncertainty	± 50	± 65	± 115	± 50	± 65	± 115

Note: Projected shoreline change distances include projection of historical coastal processes shoreline change component ($E_{coastal}$) unchanged into the future. The historical SLR component of shoreline change ($E_{h,SLR}$) was pro-rated using the average SLR Factors shown in Table 4 and Table 5 to obtain a future SLR retreat rate ($E_{f,SLR}$). Shoreline change distances shown in table do not include event-based dune retreat ($R_{1\%}$).

5.3.2.4 Bluff Shorelines

Shoreline change data for bluffs were extracted from the USGS California dataset (Hapke and Reid 2007). The San Francisco study area falls within the Central California section of the USGS data. Although 10,389 transects were analyzed for central California segment, none of the transects is located within the study area.

Similar to the approach adopted for sandy shorelines, BakerAECOM developed a binning approach to categorize the historical shoreline change rates at each CCAMP OPC Study analysis transect. For bluff shorelines, three categories ranging from low to high erodibility were selected to model historical shoreline change rates. BakerAECOM evaluated the USGS data to inform the selection of each category and its corresponding shoreline change rate. The goal of the shoreline change rate categorization approach was to simplify shoreline change estimates to accurately represent trends at the individual transect locations within the limitations of the available data while also remaining true to what are typically considered “high,” “moderate,” or “low” rates for the California coastline. Since no USGS data are available for the pilot study area, shoreline change categories were assigned to each transect based on a combination of sandy beach shoreline change rates, local knowledge, cliff rock and sediment characteristics, and inspection of aerial photographs (Google Earth and California Coastal Records Project).

The error of the USGS EPR shoreline change data is estimated to be ± 0.2 m/yr and the data range from 0 m/yr to -3.05 m/yr (negative rates denote erosion) with approximately 87% of the data between 0 m/yr and -0.5 m/yr. Cliff erosion occurs episodically and is controlled by various factors both natural and anthropogenic. Cliff EPRs are assumed to be always negative so a stable (0 ft/yr) category was not included. Each erosion category captures approximately one third of the data. Median values within each category are used as the effective historical EPR. The median value was used as opposed to the mean value to minimize the bias of extreme values at highly erosional transects. Shoreline change categories and median shoreline change rates (± one standard deviation) for bluffs are shown in Table 13.

There is no fully-accepted methodology for estimating future bluff erosion in response to SLR (CCC 2015). For the purposes of this study, it was assumed that future rates of shoreline retreat are directly proportional to historical rates, with an amplification due to increased rates of SLR. To develop this relationship, the observed historical rate of shoreline change at bluff-backed transects was directly related to the historical rate of SLR. Contributions to bluff retreat rates from other coastal ($E_{coastal}$) or terrestrial ($E_{terrestrial}$) processes were neglected[12]. Event-based bluff retreat in response to a 1-percent-annual-chance coastal storm event ($R_{1\%}$) was also neglected. As a result, the observed historical shoreline change rate ($E_{h,Bluff}$) was assumed to be driven-only by the historical SLR component ($E_{h,SLR}$), with an amplification for the effects of SLR:

$$E_{h,Bluff} = E_{coastal} + E_{terrestrial} + E_{h,SLR}, \text{ where } E_{coastal} = E_{terrestrial} = 0$$

$$\text{therefore, } E_{h,Bluff} = E_{h,SLR} \qquad \text{(Eq. 10)}$$

$$R_{Bluff} = R_{coastal} + R_{terrestrial} + R_{f,SLR} + R_{100-yr}, \text{ where } R_{coastal} = R_{terrestrial} = R_{1\%} = 0$$

$$\text{therefore, } R_{Bluff} = R_{f,SLR} \qquad \text{(Eq. 11)}$$

$$R_{Bluff} = E_{f,Bluff}\Delta t = E_{h,SLR}(SLR\ Factor)\Delta t = \left(E_{h,SLR}\right)\left(\frac{S_f}{S_h}\right)^m \Delta t \qquad \text{(Eq. 12)}$$

where Δt is the time duration of the planning horizon (either 39 years for 2011-2050 or 50 years for 2050 to 2100) and m=0.5 for bluff-backed shoretypes. The assumption of the exponent m=0.5 is consistent with the “damped response” behavior described by Ashton et al. (2011), where bluff retreat is assumed to be proportional to the relative increase in the rate of SLR, but to a lesser extent than the linear Bruun-type approach applied for sandy beach and dune shorelines. The SLR Factors for each SLR scenario and

[12] Wave action plays a dominant role in coastal bluff retreat by eroding the toe of the bluff and destabilizing the bluff face; however, it is not the only driver of coastal bluff retreat. Coastal bluff retreat is a complex process that occurs due to a combination of terrestrial and coastal processes. Coastal bluff retreat in California can occur by a variety of mechanisms including terrestrial processes such as weathering by rain and wind, groundwater seepage, seismic shaking, animal burrowing, landslide, and human development. For the purposes of the pilot study in San Francisco County, coastal processes were assumed to be the dominant mechanism driving coastal bluff retreat; however, this assumption should be re-evaluated if the pilot study methodology is expanded to other portions of the California coastline where other processes may govern.

planning horizon are shown in Table 13 assuming a value of *m*=0.5. Projected shoreline change distances for 2050 and 2100 are included in Table 14 for each shoreline change category and SLR scenario.

Table 13. Shoreline Change Categories and Projected Future Shoreline Change Rates for Bluffs

Shoreline Change Category	Shoreline Change Range		Median Shoreline Change Rate, $E_{h,bluff}$ (ft/yr)	Projected Future Shoreline Change Rate, $E_{f,Bluff}$ (ft)			
	(m/yr)	(ft/yr)		2011-2050 (1-ft)	2011-2050 (2-ft)	2050-2100 (3-ft)	2050-2100 (5.5-ft)
Average SLR Factor = $(S_f/S_h)^{0.5}$				1.7	2.4	2.4	3.2
Low Erosion	> -0.09	> -0.30	-0.16 ± 0.1	-0.3	-0.4	-0.4	-0.5
Moderate Erosion	-0.09 to -0.24	-0.3 to -0.8	-0.49 ± 0.1	-0.8	-1.2	-1.2	-1.6
High Erosion	< -0.24	< -0.8	-1.35 ± 1.2	-2.3	-3.3	-3.3	-4.4

Table 14. Projected Bluff Shoreline Change Distances for 2050 and 2100 Planning Horizons

Shoreline Change Category	Shoreline Change Index	Median Shoreline Change Rate, E_h (ft/yr)	Projected Future Shoreline Change, R_{Bluff} (ft)					
			2011-2050 (1-ft) (a)	2011-2050 (2-ft) (b)	2050-2100 (3-ft) (c)	2050-2100 (5.5-ft) (d)	2011-2100 Total (Mid-Range) (a) + (c)	2011-2100 Total (High-Range) (b) + (d)
Low Erosion	-1	-0.16	-11	-15	-20	-26	-30	-41
Moderate Erosion	-2	-0.49	-33	-47	-60	-79	-93	-126
High Erosion	-3	-1.35	-91	-129	-165	-219	-257	-348
Projected Shoreline Change Uncertainty			± 25		± 35		± 60	

Note: The mid-range total shoreline change distance was calculated by adding together the 2011-2050 distance for 1-foot SLR and the 2050-2100 distance for 3-feet SLR. The high-range total shoreline change distance was calculated by adding together the 2011-2050 distance for 2-feet SLR and the 2050-2100 distance for 5.5-feet SLR.

Based on the USGS annualized error for EPRs of +/- 0.66 ft/yr, there is considerable uncertainty in the future shoreline change projections. Projecting this annualized error out to the 2050 (39 years) and 2100 (89 years) planning horizons yields approximate uncertainties in the future shoreline positions of ± 25 ft at 2050 and ± 60 ft at 2100.

5.3.3. Coupled TWL and Shoreline Change Analysis

A primary goal of the pilot study was to conduct a coupled TWL and shoreline change analysis. This means that the future conditions TWL calculations were performed on profiles that were adjusted to account for projected shoreline change. It is widely acknowledged that SLR and ongoing coastal erosion will act to modify sandy beach, dune, and bluff profiles in the future. The applied methodology to compute shoreline change distances for each shoretype was presented in Section 5.3.2. The next step in the coastal analysis procedure was to modify each profile to account for shoreline retreat prior to conducting the future conditions TWL analysis. Once each profile was adjusted to account for profile geometry changes due to shoreline retreat, the future conditions TWL analysis was conducted. The sections that follow present the assumptions and methods applied to adjust sandy beach and dune profiles (Section 5.3.3.1) and bluff profiles (Section 5.3.3.2) to account for shoreline change.

5.3.3.1 Sandy Shorelines

Sandy beach and dune shorelines were assumed to respond rapidly to SLR such that the profile achieves a dynamic equilibrium with future sea levels. According to the Bruun Rule of shoreline change, a sandy shoreline will respond to an increase in mean sea level by shifting landward and upward, maintaining the same profile shape as it migrates landward. As a result, the overall geometry of the profile is assumed to remain constant between existing and future conditions and it is only its position and elevation relative to sea level that changes. This is the same process that has allowed sandy beaches and dunes to migrate for thousands of years in response to historical sea level change. Since TWL calculations at sandy beach and dune shorelines were performed using the Stockdon et al. (2006) formula, the only profile variable that controls TWL response is the foreshore beach slope (since changes in wave climatology are not considered in the pilot study). For the purposes of this study, it was assumed that the foreshore beach slope would remain constant and unchanged in the future. As a result, the wave setup and runup calculations at these transects were performed using the existing conditions profile. Under these assumptions, the sandy beach and dune shoretype will display a linear TWL response due to SLR. One exception to the linear response at these shoretypes is sandy beaches backed by coastal structures. Similar to the existing conditions analysis, if the structure toe becomes inundated at a future SLR scenario, the TAW wave runup methodology is initiated. In that case, it is possible that the TWL response could shift from a linear (1:1) response to an amplified response at some intermediate SLR scenario. No profile modifications were performed on sandy beach and dune shoretypes for the TWL calculations performed as part of the pilot study. Note that shoreline change at these shoretypes is still considered in the mapping phase (see Section 5.4).

5.3.3.2 Bluff Shorelines

The shoreline change distances determined for each bluff transect (Section 5.3.2.4) were applied to the bluff toe to estimate the profile geometry for the future conditions TWL analysis for each SLR scenario (Figure 10). The depth of closure (approximated at h_c = -10 m NAVD88) was first identified on the existing cross-shore profile. The average profile slope was then calculated between the depth of closure and the existing bluff toe (E_j). This slope was projected landward by the specific shoreline change distance determined for each SLR scenario (the "Horizontal Response" in Figure 10). The bluff toe position was projected upwards along this slope to its retreated position (E_j'). To determine the eroded bluff face, the average slope (m_{face}) between the existing bluff toe and bluff edge (E_j to E_{edge}) was calculated. This slope was projected landward and upward from the eroded toe. The point where the projected slope intersected the existing profile was taken as the eroded bluff edge (E_{edge}'). Figure 10 shows a conceptual diagram of the slope projection and future conditions profile geometry for hypothetical 1 foot and 2 feet SLR scenarios.

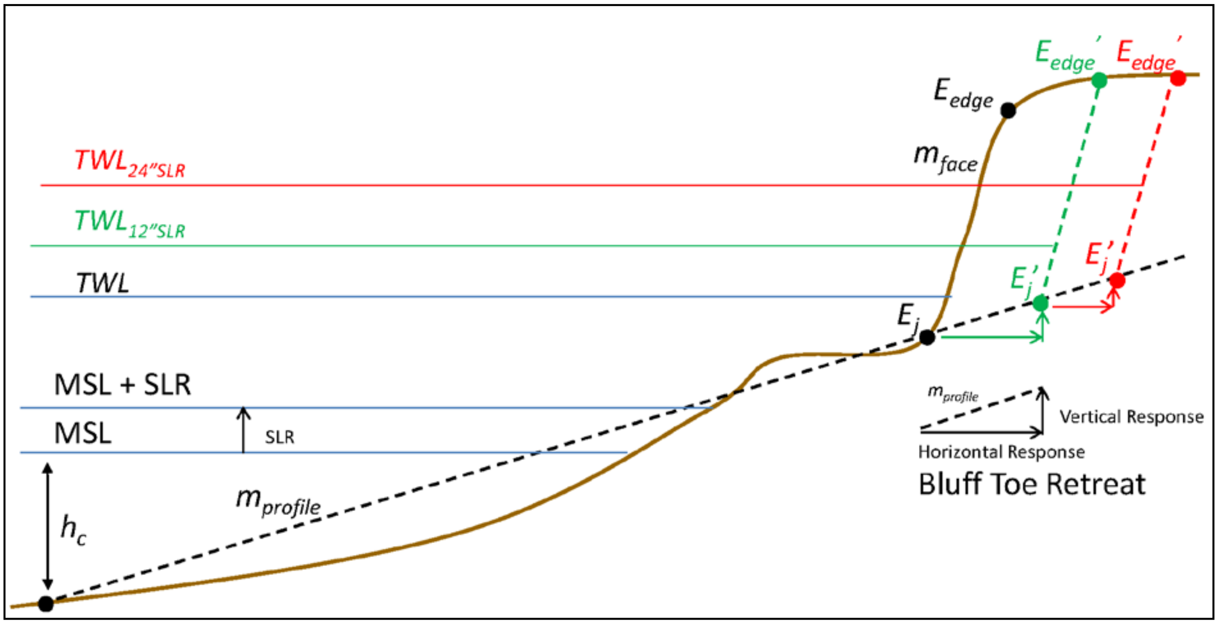

Figure 10. Profile Modifications in Response to Shoreline Retreat at Bluff Shorelines

Figure 10 shows that as the bluff retreats inland, the toe moves both landward and upward[13]. This vertical response has a direct impact on calculations of the TWL, because the water depth at the toe of the bluff is an important parameter in wave runup calculations. A higher toe decreases the water depth at the toe during storms and reduces the depth-limited waves that impact the bluff face. This ultimately decreases

[13] The conceptual response that the bluff toe moves landward and upward is a fundamental assumption of the applied methodology. The adjustment of the toe elevation with respect to rising sea level depends on multiple factors, including the amount of SLR, the overall profile geometry, and the bluff erodibility. The exact landward migration of a given profile may follow an unknown response – some bluff toes may retreat horizontally and maintain their toe elevation whereas some may experience larger vertical increases in toe elevation; however, making this distinction among transects is beyond the scope of this pilot study. This is an area of active research and the approach adopted is within the standard of coastal engineering practice for this type of analysis.

wave runup on the bluff face and the TWL compared to a profile geometry where bluff retreat does not occur, such as an armored slope or highly erosion resistant bluff. When profile retreat is included in the TWL calculations, the vertical migration of the bluff toe mitigates the TWL increase so the increase in the vertical hazard is less than for a static profile. This is an important feedback mechanism that is captured using the direct analysis method coupled with profile modifications due to SLR. If bluff retreat were not considered, water levels and depth-limited waves at the toe would increase to an even greater extent.

5.3.4. Coastal Structures

Coupled TWL and shoreline change analysis at coastal structure was handled as follows. TWL calculations at coastal structure transects were performed using the existing conditions profiles for intact and failed conditions. At these locations (Transects 100, 14, 22, 24, 32, 37, 41, and 55), no profile modifications to account for shoreline change were performed. As discussed in Section 5.4, potential shoreline change is shown in the future conditions SFHA maps at these locations, but is symbolized differently (using a dashed line instead of solid shading) to indicate the presence of a coastal structure.

5.4. Future Conditions Floodplain Mapping

5.4.1. Approach

The purpose of the future conditions floodplain mapping is to produce digital geospatial data for communities to visualize and understand the potential future impacts of SLR on flood and erosion hazards in their communities. The final mapping product is FIRM-like in nature, in the sense that it depicts flood hazard areas, but is a non-regulatory product for informational purposes only. The future conditions maps include the existing conditions SFHAs from IDS #4 alongside the future conditions SFHAs for each SLR scenario. Future conditions scenario mapping provides approximate representations using the best available data at the time of this study.

Results from the SLR pilot study were used to delineate future conditions SFHA boundaries. Future conditions floodplain mapping was conducted incorporating both the vertical change in BFE due to SLR and the horizontal change in the landward limit of the SFHA due to shoreline retreat (see Section 5.3). Shoreline change was incorporated into the future conditions SFHA maps using a buffering technique in ArcGIS, as described below.

5.4.2. TWL and Shoreline Change Mapping

Future conditions TWLs were incorporated into the SFHA mapping by first projecting the 1-percent-annual-chance TWL elevations landward onto the terrain to determine the future conditions TWL shoreline. Once the future conditions TWL shoreline layer was created for each SLR scenario, the shoreline change distances (Section 5.3.2), overtopping extents, and event-based dune erosion were incorporated to estimate the maximum potential landward extent of the future SFHA using a buffering technique in ArcGIS. The SFHA buffer is comprised of projected future shoreline change, landward extent of overtopping, and storm-induced dune erosion, and is added to the TWL shoreline extent for each SLR scenario:

SFHA Buffer = Future Shoreline Change + Overtopping Distance + Storm-induced Dune Erosion

The SFHA buffering method is shown schematically in Figure 11 and Figure 12 for sandy beach/dune and bluff shorelines, respectively. Overtopping distances are not shown in the figures but are added in a similar manner. For the purposes of the pilot study, the combined overtopping zone width (VE and AO) were included in the overtopping buffer distance.

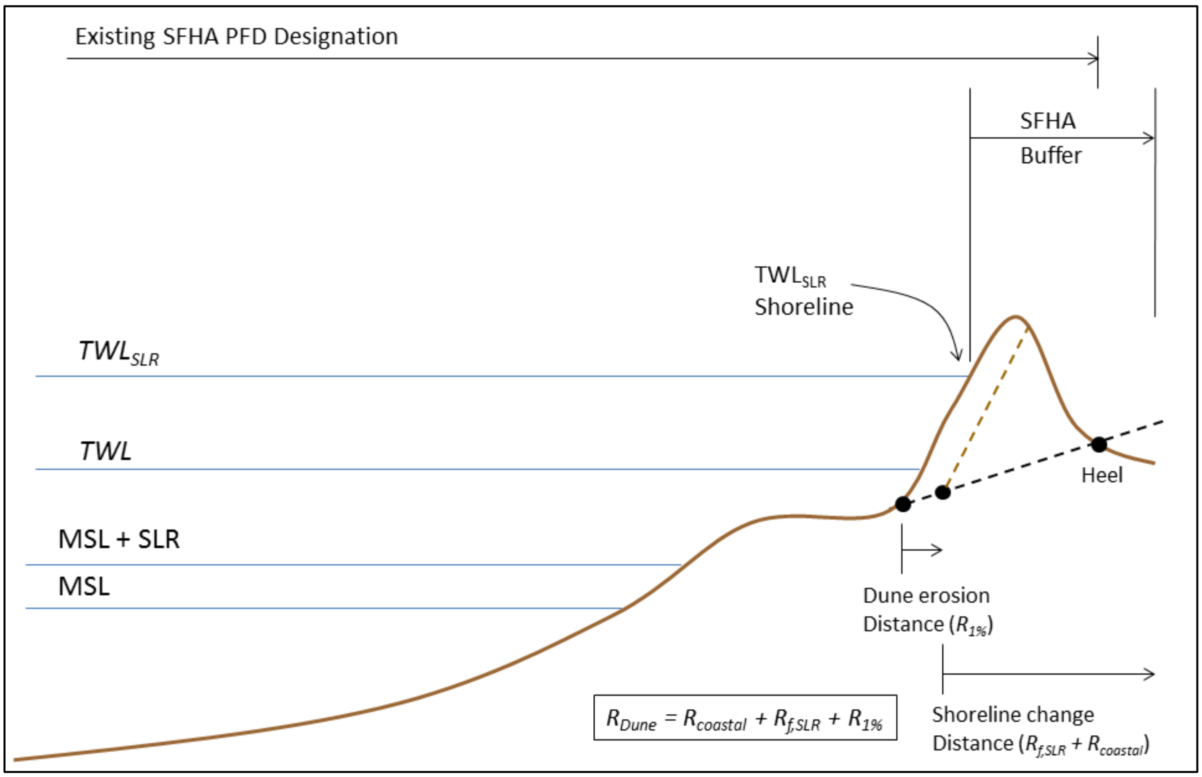

Figure 11. Shoreline Change Buffering at Sandy Beach and Dune Shoretypes

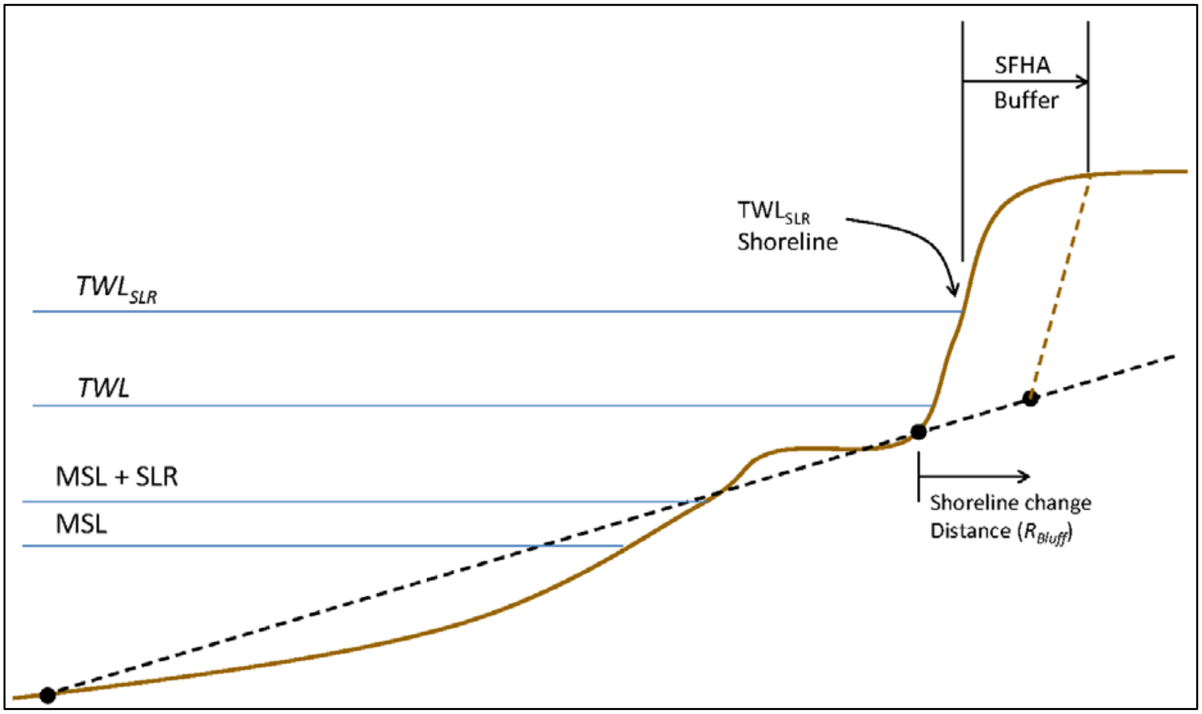

Figure 12. Shoreline Change Buffering at Bluff Shoretypes

Although a static DEM was used to estimate the landward extent of the future conditions BFE, the GIS buffering approach provided a means of translating 1-D hazard information onto a 2-D spatial interface. Local results of the 1-D coastal analyses for overtopping distances and storm-induced dune erosion were combined with future shoreline change projections for each reach to extend SFHAs landward for each SLR scenario.

As previously discussed, reaches containing coastal structures were analyzed using methods consistent with non-armored reaches. To account for the possibility that the structure may or may not be maintained, future estimated shoreline change distances were incorporated into the SFHA buffer zone but symbolized by a dashed boundary (instead of a solid boundary) and identified as "potential inundation."

Overtopping was restricted only to the individual reach where overtopping occurred. Lateral flooding from adjacent reaches was not permitted, although this flooding mechanism may occur in the future.

Figure 13 shows an example application of the buffering technique in plan and profile view. The upper panel shows the landward extent of the SFHA pre- and post- buffering as solid and dashed lines, respectively. The pre-buffering limits are based on the landward extent of the existing and future conditions TWL. The post-buffering limits include the effects of future shoreline change in increasing the landward extent of the SFHA. The bottom panel is aligned with the landward limits shown in the top panel and shows how the landward buffering was applied from the TWL intersection with the existing conditions TWL shoreline.

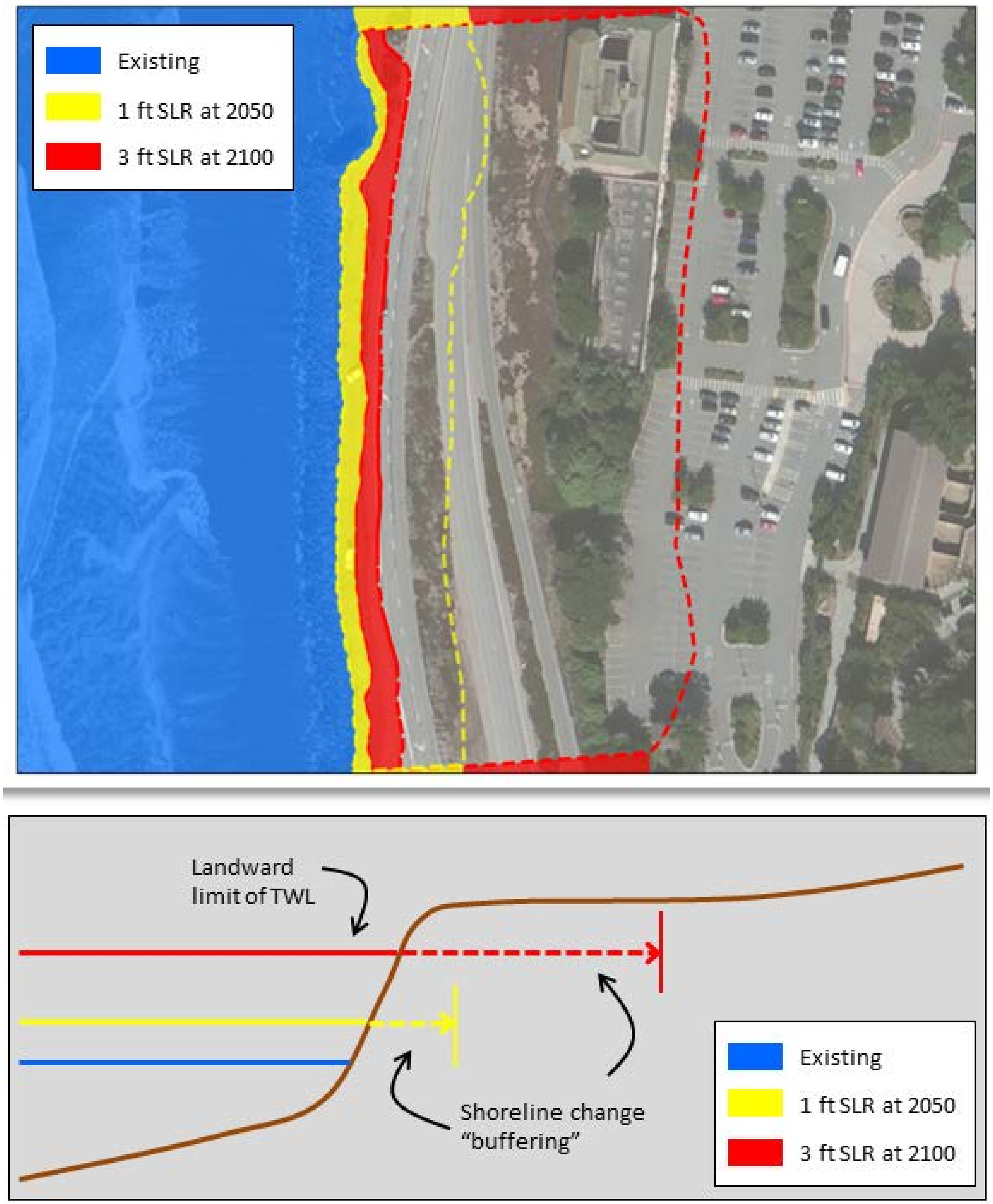

Figure 13. Example Application of the Shoreline Change Buffer in Plan and Profile View

An example of the future conditions SFHA mapping is shown in Figure 14 for a segment of the pilot study shoreline characterized by highly erodible coastal bluffs. The increased landward extent of the future SFHA for each SLR scenario as a result of higher BFEs and shoreline retreat can be seen in the figure.

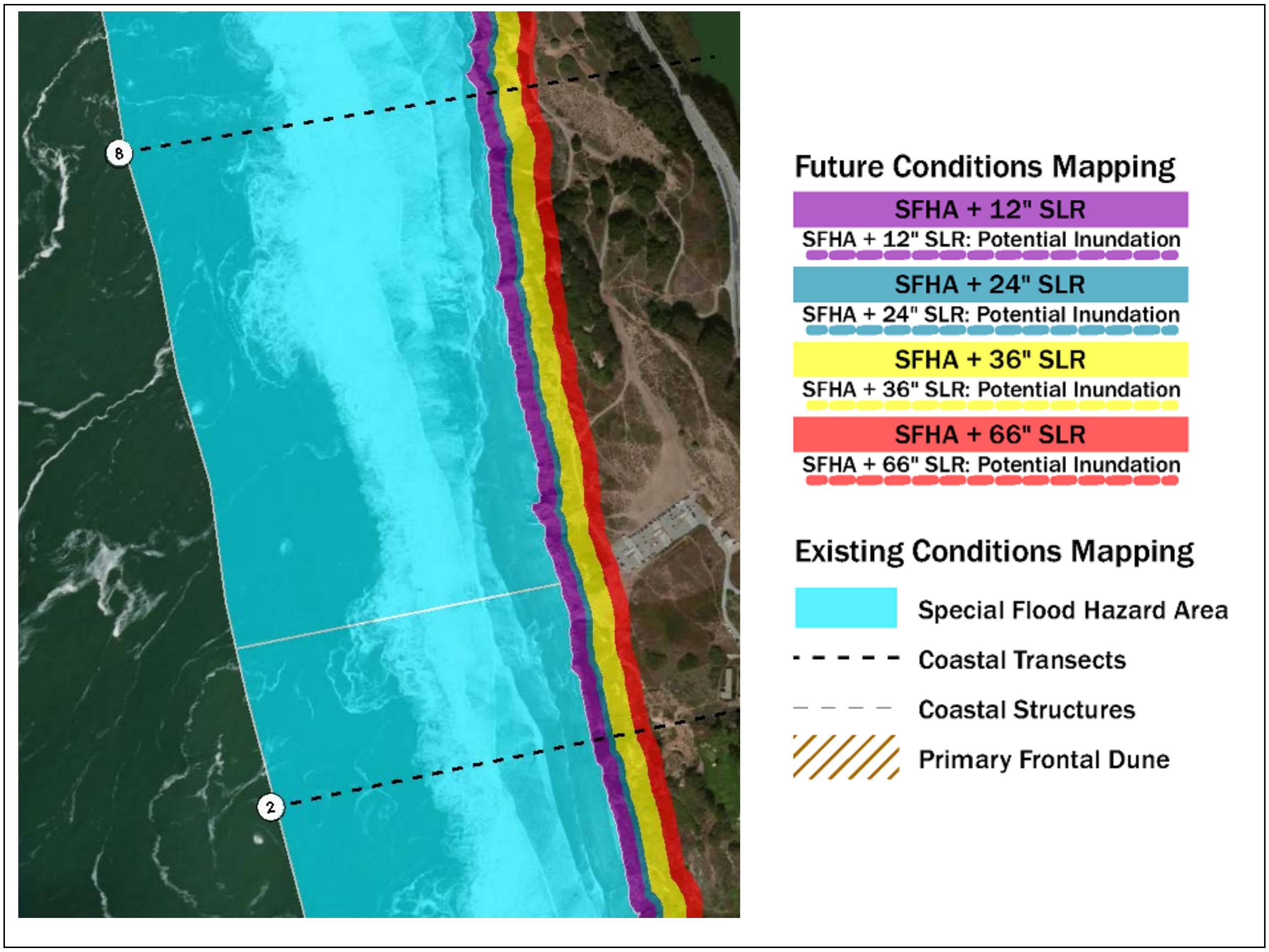

Figure 14. Example Future Conditions SFHA Mapping in San Francisco Pilot Study

Note: Dashed "Potential Inundation" lines shown in legend above indicate the potential landward limit of the SFHA along reaches protected by existing coastal armoring structures such as seawalls and revetments. Future estimated shoreline change distances were incorporated into the SFHA buffer zone for these reaches but symbolized by a dashed boundary (instead of a solid boundary). Note that there are no coastal protection structures in the geographic region shown above so there are no potential inundation zones visible in this map extent.

Table 15 through Table 18 provide summaries of the SFHA buffer distances for each SLR scenario used to map the future conditions floodplain areas. The final column, SFHA Buffer, represents the total landward extent of the SFHA calculated as a summation of the Shoreline Change Distance, Overtopping Distance, and Dune Erosion Distance columns. It should be noted that although the Shoreline Change Distance column lists distance values as negative numbers (to indicate erosion and not accretion), they were treated as positive numbers when adding all the shoreline change distance values together to create a positive SFHA buffer value.

5.4.3. Future Conditions SFHA Mapping at Primary Frontal Dunes

Mapping of future conditions SFHAs at locations of PFDs was given special attention. Because the delineation of the existing SFHA extends landward to the heel of the PFD, the future SFHA will only extend landward beyond the existing SFHA when the buffer distance exceeds the dune heel. This can be seen in Figure 11, which shows the landward extent of the existing SFHA based on the PFD designation. If the SFHA buffer distance does not exceed the existing dune heel, then the PFD designation will govern the landward limit of the SFHA and the future SFHA will be equal to the existing SFHA. Only once the buffer distance exceeds the existing dune heel will the future SFHA extend landward farther than the existing SFHA.

Table 15. SFHA Buffer Distances for 1-ft SLR at 2050 Future Conditions Mapping

Analysis Transect	Mapping Transect	Shoretype	Shoreline Change Category	Shoreline Change Distance (ft)	Overtopping Distance (ft)	Dune Erosion Distance (ft)	SFHA Buffer (ft)
2	26	Bluff	-3	-91	0	0	91
8	25	Bluff	-3	-91	0	0	91
100*	24	Revetment + Bluff	-3	-91	0	0	91
12	23	Bluff	-3	-91	0	0	91
13	22	Bluff	-3	-91	0	0	91
14*	21	Revetment + Bluff	-3	-91	0	0	91
15	20	Bluff	-3	-91	0	0	91
17	19	Dune	-2	-109	0	8	117
101	18	Dune	-2	-109	0	27	136
22*	17	Beach + Seawall	-2	-109	0	0	109
24*	16	Beach + Seawall	-3	-197	0	0	197
26	15	Dune	-2	-109	0	8	117
29	14	Dune	-2	-109	0	12	121
32*	13	Beach + Seawall	-1	-64	0	0	64
37*	12	Beach + Seawall	0	-26	0	0	26
Transition*	Transition	Retaining Wall + Bluff	-1	-11	0	0	11
40	11	Bluff	-1	-11	0	0	11
41*	10	Revetment + Seawall + Bluff	N/A	N/A	33	0	N/A
45	9	Bluff	-1	-11	0	0	11
50	8	Bluff	-1	-11	0	0	11
52	7	Bluff	-1	-11	0	0	11
55*	6	Beach + Seawall + Bluff	-1	-11	0	0	11
Transition	Transition	Bluff	-1	-11	0	0	11
102	5	Bluff	-1	-11	0	0	11
59	4	Dune	-1	-64	0	0	64
60	3	Dune	-1	-64	0	0	64
62	2	Bluff	-1	-11	0	0	11
66	1	Bluff	-1	-11	0	0	11

Note: SFHA Buffer is the sum of the shoreline change distance, overtopping distance, and dune erosion distance. Due to rounding of each value, the SFHA Buffer reported in the table may not be exactly equal to the sum of the columns. *Denotes transects with coastal structures for which no profile change was included in the coupled TWL calculations; however, potential inundation is still indicated on the future conditions SFHA maps at these locations.

Table 16. SFHA Buffer Distances for 2-ft SLR at 2050 Future Conditions Mapping

Analysis Transect	Mapping Transect	Shoretype	Shoreline Change Category	Shoreline Change Distance (ft)	Overtopping Distance (ft)	Dune Erosion Distance (ft)	SFHA Buffer (ft)
2	26	Bluff	-3	-129	0	0	129
8	25	Bluff	-3	-129	0	0	129
100*	24	Revetment + Bluff	-3	-129	0	0	129
12	23	Bluff	-3	-129	0	0	129
13	22	Bluff	-3	-129	0	0	129
14*	21	Revetment + Bluff	-3	-129	7	0	136
15	20	Bluff	-3	-129	0	0	129
17	19	Dune	-2	-147	0	8	155
101	18	Dune	-2	-147	0	27	174
22*	17	Beach + Seawall	-2	-147	0	0	147
24*	16	Beach + Seawall	-3	-236	0	0	236
26	15	Dune	-2	-147	0	8	155
29	14	Dune	-2	-147	0	12	159
32*	13	Beach + Seawall	-1	-103	0	0	103
37*	12	Beach + Seawall	0	-64	0	0	64
Transition*	Transition	Retaining Wall + Bluff	-1	-15	0	0	15
40	11	Bluff	-1	-15	0	0	15
41*	10	Revetment + Seawall +Bluff	N/A	N/A	36	0	N/A
45	9	Bluff	-1	-15	0	0	15
50	8	Bluff	-1	-15	0	0	15
52	7	Bluff	-1	-15	0	0	15
55*	6	Beach + Seawall + Bluff	-1	-15	0	0	15
Transition	Transition	Bluff	-1	-15	0	0	15
102	5	Bluff	-1	-15	0	0	15
59	4	Dune	-1	-103	0	0	103
60	3	Dune	-1	-103	0	0	103
62	2	Bluff	-1	-15	0	0	15
66	1	Bluff	-1	-15	0	0	15

Note: SFHA Buffer is the sum of the shoreline change distance, overtopping distance, and dune erosion distance. Due to rounding of each value, the SFHA Buffer reported in the table may not be exactly equal to the sum of the columns. *Denotes transects with coastal structures for which no profile change was included in the coupled TWL calculations; however, potential inundation is still indicated on the future conditions SFHA maps at these locations.

Table 17. SFHA Buffer Distances for 3-ft SLR at 2100 Future Conditions Mapping

Analysis Transect	Mapping Transect	Shoretype	Shoreline Change Category	Shoreline Change Distance (ft)	Overtopping Distance (ft)	Dune Erosion Distance (ft)	SFHA Buffer (ft)
2	26	Bluff	-3	-257	0	0	257
8	25	Bluff	-3	-257	0	0	257
100*	24	Revetment + Bluff	-3	-257	0	0	257
12	23	Bluff	-3	-257	0	0	257
13	22	Bluff	-3	-257	0	0	257
14*	21	Revetment + Bluff	-3	-257	20	0	277
15	20	Bluff	-3	-257	0	0	257
17	19	Dune	-2	-298	0	8	306
101	18	Dune	-2	-298	0	27	325
22*	17	Beach + Seawall	-2	-298	0	0	298
24*	16	Beach + Seawall	-3	-500	0	0	500
26	15	Dune	-2	-298	0	8	306
29	14	Dune	-2	-298	0	12	310
32*	13	Beach + Seawall	-1	-195	0	0	195
37*	12	Beach + Seawall	0	-108	0	0	108
Transition*	Transition	Retaining Wall + Bluff	-1	-30	0	0	30
40	11	Bluff	-1	-30	0	0	30
41*	10	Revetment + Seawall +Bluff	N/A	N/A	38	0	N/A
45	9	Bluff	-1	-30	0	0	30
50	8	Bluff	-1	-30	0	0	30
52	7	Bluff	-1	-30	0	0	30
55*	6	Beach + Seawall + Bluff	-1	-30	0	0	30
Transition	Transition	Bluff	-1	-30	0	0	30
102	5	Bluff	-1	-30	0	0	30
59	4	Dune	-1	-195	0	0	195
60	3	Dune	-1	-195	0	0	195
62	2	Bluff	-1	-30	0	0	30
66	1	Bluff	-1	-30	0	0	30

Note: SFHA Buffer is the sum of the shoreline change distance, overtopping distance, and dune erosion distance. Due to rounding of each value, the SFHA Buffer reported in the table may not be exactly equal to the sum of the columns. *Denotes transects with coastal structures for which no profile change was included in the coupled TWL calculations; however, potential inundation is still indicated on the future conditions SFHA maps at these locations.

Table 18. SFHA Buffer Distances for 5.5-ft SLR at 2100 Future Conditions Mapping

Analysis Transect	Mapping Transect	Shoretype	Shoreline Change Category	Shoreline Change Distance (ft)	Overtopping Distance (ft)	Dune Erosion Distance (ft)	SFHA Buffer (ft)
2	26	Bluff	-3	-348	0	0	348
8	25	Bluff	-3	-348	0	0	348
100*	24	Revetment + Bluff	-3	-348	0	0	348
12	23	Bluff	-3	-348	0	0	348
13	22	Bluff	-3	-348	0	0	348
14*	21	Revetment + Bluff	-3	-348	38	0	386
15	20	Bluff	-3	-348	0	0	348
17	19	Dune	-2	-411	0	8	419
101	18	Dune	-2	-411	0	27	438
22*	17	Beach + Seawall	-2	-411	23	0	434
24*	16	Beach + Seawall	-3	-613	27	0	640
26	15	Dune	-2	-411	0	8	419
29	14	Dune	-2	-411	0	12	423
32*	13	Beach + Seawall	-1	-308	0	0	308
37*	12	Beach + Seawall	0	-221	0	0	221
Transition*	Transition	Retaining Wall + Bluff	-1	-41	0	0	41
40	11	Bluff	-1	-41	0	0	41
41*	10	Revetment + Seawall	N/A	N/A	46	0	N/A
45	9	Bluff	-1	-41	0	0	41
50	8	Bluff	-1	-41	0	0	41
52	7	Bluff	-1	-41	0	0	41
55*	6	Beach + Seawall + Bluff	-1	-41	28	0	69
Transition	Transition	Bluff	-1	-41	0	0	41
102	5	Bluff	-1	-41	0	0	41
59	4	Dune	-1	-308	0	0	308
60	3	Dune	-1	-308	0	0	308
62	2	Bluff	-1	-41	0	0	41
66	1	Bluff	-1	-41	0	0	41

Note: SFHA Buffer is the sum of the shoreline change distance, overtopping distance, and dune erosion distance. Due to rounding of each value, the SFHA Buffer reported in the table may not be exactly equal to the sum of the columns. *Denotes transects with coastal structures for which no profile change was included in the coupled TWL calculations; however, potential inundation is still indicated on the future conditions SFHA maps at these locations.

6. Results

6.1. Total Water Levels

A comparison of the existing and future conditions BFE estimates and shoreline change distances at each San Francisco CCAMP OPC coastal analysis transect is shown in Table 19 and Appendix C for each SLR scenario. The difference between the existing and future BFEs is also tabulated to show the relative increase in BFE due to SLR. At all transects, the BFE increase is, at a minimum, equal to the amount of SLR for each scenario. At some transects, relatively large increases in the BFE are projected and the number of overtopped transects increases at higher SLR scenarios. A summary of the SLR impacts is shown in Table 20. The table identifies locations of largest BFE increases and shows the progression of overtopping from the 1-ft to 5.5-ft SLR scenario. In general, the highest BFE increases are at locations of steep backshores with either coastal armoring or low erodibility shorelines – for example, the revetments south of Sloat Blvd and the erosion-resistant bluffs at the Cliff House. Natural sandy beach and dune shoretypes typically show linear increases in BFEs. The highest BFE increases for the 1-ft, 2-ft, 3-ft, and 5.5-ft SLR scenarios were +5 ft, +9 ft, +13 ft, and +23 ft, respectively, as determined using the direct analysis approach.

Table 19. Future Conditions Base Flood Elevation Estimates at San Francisco County Transects

Transect ID	Mapping ID	Shoretype	Existing BFE (ft NAVD88)	Future BFE 1-ft SLR at 2050 (ft NAVD)	Difference (ft)	Shoreline Change (ft)	Future BFE 2-ft SLR at 2050 (ft NAVD)	Difference (ft)	Shoreline Change (ft)	Future BFE 3-ft SLR at 2100 (ft NAVD)	Difference (ft)	Shoreline Change (ft)	Future BFE 5.5-ft SLR at 2100 (ft NAVD)	Difference (ft)	Shoreline Change (ft)
2	26	Bluff	19.0	20.0	1.0	-91	21.0	2.0	-129	22.0	3.0	-257	24.5	5.5	-348
8	25	Bluff	18.6	19.6	1.0	-91	20.6	2.0	-129	21.6	3.0	-257	24.1	5.5	-348
100†	24	Revetment + Bluff	17.3	19.6	2.3	-91	22.8	5.5	-129	25.9	8.6	-257	31.5	14.2	-348
100_F†		Bluff	17.0	19.5	2.5	-91	25.7	8.7	-129	30.5	13.5	-257	39.3	22.3	-348
12	23	Bluff	17.2	18.2	1.0	-91	19.2	2.0	-129	20.2	3.0	-257	22.7	5.5	-348
13	22	Bluff	22.6	23.6	1.0	-91	24.6	2.0	-129	25.6	3.0	-257	28.1	5.5	-348
14†	21	Revetment + Bluff	25.7	28.0	2.3	-91	30.1	4.4	-129	32.4 (OT)	6.7	-257	38.8 (OT)	13.1	-348
14_F†		Bluff	22.0	26.7	4.7	-91	30.8 (OT)	8.8	-129	34.9 (OT)	12.9	-257	44.8 (OT)	22.8	-348
15	20	Bluff	20.1	21.1	1.0	-91	22.1	2.0	-129	23.1	3.0	-257	25.6	5.5	-348
17	19	Dune	21.7	22.7	1.0	-109	23.7	2.0	-147	24.7	3.0	-298	27.2	5.5	-411
101	18	Dune	22.5	23.5	1.0	-109	24.5	2.0	-147	25.5	3.0	-298	28.0	5.5	-411
22†	17	Beach + Seawall	22.0	23.0	1.0	-109	24.0	2.0	-147	25.0	3.0	-298	27.5 (OT)	5.5	-411
24†	16	Beach + Seawall	23.3	24.3	1.0	-197	25.3	2.0	-236	26.3	3.0	-500	28.8 (OT)	5.5	-613
26	15	Dune	16.7	17.7	1.0	-109	18.7	2.0	-147	19.7	3.0	-298	22.2	5.5	-411
29	14	Dune	20.9	21.9	1.0	-109	22.9	2.0	-147	23.9	3.0	-298	26.4	5.5	-411
32†	13	Beach + Seawall	16.5	17.5	1.0	-64	18.5	2.0	-103	19.5	3.0	-195	22.8	6.3	-308
37†	12	Beach + Seawall	16.3	17.3	1.0	-26	18.3	2.0	-64	19.3	3.0	-108	22.2	5.9	-221
Transition	Transition	Retaining Wall + Bluff	20.0	21.0	1.0	-11	22.0	2.0	-15	23.0	3.0	-30	25.5	5.5	-41
40	11	Bluff	25.3	28.3	3.0	-11	30.7	5.4	-15	32.6	7.3	-30	39.6	14.3	-41
41†	10	Revetment + Seawall + Bluff	28.0 (OT)	30.2 (OT)	2.2	N/A	32.3 (OT)	4.3	N/A	34.4 (OT)	6.4	N/A	41.9 (OT)	13.9	N/A
41_F†		Seawall + Bluff	24.8 (OT)	27.4 (OT)	2.6	N/A	29.6 (OT)	4.8	N/A	32.0 (OT)	7.2	N/A	40.1 (OT)	15.3	N/A
45	9	Bluff	17.8	19.0	1.2	-11	20.1	2.3	-15	21.3	3.5	-30	24.1	6.3	-41
50	8	Bluff	18.9	20.0	1.1	-11	21.3	2.4	-15	22.5	3.6	-30	25.4	6.5	-41
52	7	Bluff	15.7	16.8	1.1	-11	17.8	2.1	-15	18.6	2.9	-30	22.9	7.2	-41
55†	6	Beach + Seawall + Bluff	15.5	17.0	1.5	-11	18.6	3.1	-103	20.7	5.2	-195	33.1 (OT)	17.6	-308
Transition	Transition	Bluff	18.9	19.9	1.0	-11	20.9	2.0	-15	21.9	3.0	-30	24.4	5.5	-41
102	5	Bluff	15.8	16.8	1.0	-11	17.8	2.0	-15	18.9	3.1	-30	22.3	6.5	-41
59	4	Dune	19.9	20.9	1.0	-64	21.9	2.0	-103	22.9	3.0	-195	25.4	5.5	-308
60	3	Dune	15.5	16.5	1.0	-64	17.5	2.0	-103	18.5	3.0	-195	21.0	5.5	-308
62	2	Bluff	15.1	16.1	1.0	-11	17.1	2.0	-15	18.1	3.0	-30	20.6	5.5	-41
66	1	Bluff	17.1	18.4	1.3	-11	19.5	2.4	-15	20.5	3.4	-30	24.9	7.8	-41

Note: Analysis transects 39 and 56 were treated as transition zones in the existing conditions mapping, as discussed in IDS #4. At these transects, future conditions BFEs were determined using the linear superposition method. OT denotes transects subject to overtopping during the 1-percent-annual-chance event. † Denotes structure transects where TWL analysis was conducted with no shoreline change profile modifications (potential shoreline change is still shown on the future conditions SFHA maps at these locations).

Table 20. San Francisco County Pilot Study Areas of Significant Impacts

	1-percent-annual-chance TWL Response to SLR Areas with Highest TWL Increase			Overtopping Assessment	
SLR Scenario	**Analysis Transect**	**1% TWL Increase (ft)**	**Location**	**Analysis Transect**	**Location**
1-ft (at 2050)	100 14 40 41	+2.5 ft +4.7 ft +3.0 ft +2.6 ft	WWTP EQR Sloat Blvd EQR Cliff House Sutro Baths	41	Sutro Baths
2-ft (at 2050)	100 14 40 41	+8.7 ft +8.8 ft +5.4 ft +4.8 ft	WWTP EQR Sloat Blvd EQR Cliff House Sutro Baths	14 41	Sloat Blvd EQR Sutro Baths
3-ft (at 2100)	100 14 40 41 55	+13.5 ft +12.9 ft +7.3 ft +7.2 ft +5.2 ft	WWTP EQR Sloat Blvd EQR Cliff House Sutro Baths China Beach	14 41	Sloat Blvd EQR Sutro Baths
5.5-ft (at 2100)	100 14 40 41 55	+22.3 ft +22.8 ft +14.3 ft +15.3 ft +17.6 ft	WWTP EQR Sloat Blvd EQR Cliff House Sutro Baths China Beach	14 22 and 24 41 55	Sloat Blvd EQR Great Highway Seawall from Noriega St to Santiago St Sutro Baths China Beach Seawall

Note: EQR = emergency quarrystone revetment; WWTP = wastewater treatment plan

6.2. Shoreline Change

The methodology to estimate future shoreline change distances for sandy beach and bluff shorelines in response to SLR was presented in Section 5.3.2. In general, the southern portion of the study area from Fort Funston to Sloat Blvd (Analysis Transects 2 through 15) historically showed the highest rates of shoreline retreat. As a result, the projected future shoreline retreat distances are highest in this area. The northern portion of the study area showed historically low to moderate rates of shoreline retreat and the projected retreat distances are less in this area. Projected shoreline retreat distances for the 1-foot SLR scenario ranged from 10 to 90 ft for bluffs and from 25 to 200 ft for sandy beach and dune transects. Projected shoreline change distances for the 2-feet SLR scenario ranged from 15 to 130 ft for bluffs and from 65 to 235 ft for sandy beach and dune transects. Projected shoreline change distances for the 3-feet SLR scenario ranged from 30 to 260 ft for bluffs and from 110 to 500 ft for sandy beach and dune transects. Projected shoreline change distances for the 5.5-feet SLR scenario ranged from 40 to 350 ft for bluffs and from 220 to 610 ft for sandy beach and dune transects. The wide variability in the shoreline retreat distances is due to the spatial variability in historical shoreline change rates throughout the study area. The projected future shoreline change distances were combined with the overtopping and event-based dune erosion distances to estimate the full SFHA buffer distances applied in the mapping phase, as described in Section 5.4.

6.3. Future Conditions Mapping Products

A primary goal of the SLR pilot study was to evaluate the feasibility of developing a set of non-regulatory Risk MAP products to convey future flood and erosion risk. After considering the nature and inherent uncertainty of the future conditions coastal analysis data products (i.e., future conditions BFEs, overtopping areas, and projected shoreline change distances) and the anticipated use of the data layers by local stakeholders, BakerAECOM produced the following mapping deliverables:

- **Future Conditions SFHA Mapping –** As discussed in Section 5.4, the mapping product that was derived from the future conditions coastal analysis represents an estimate of the future extent of the SFHA, considering the effects of SLR and projected shoreline change. This approach captures both the “vertical” change in flood hazards through the increase in BFEs as a result of SLR and the “horizontal” change in flood hazards through the continuation and amplification of ongoing shoreline change. The future conditions SFHA maps are presented in Appendix D and show the projected future extents of the SFHA for each SLR scenario. For the purposes of the SLR pilot study, the future conditions SFHA maps combine all SFHA zones (e.g., VE, AE, AO, etc.) associated with the 1-percent-annual-chance coastal flood event into a single hazard zone. Flood hazards associated with the 0.2-percent-annual-chance coastal flood event are not presented in the future conditions SFHA maps.

- **Future Conditions Flood Risk Database –** All geospatial data layers produced through the SLR pilot study were compiled in a future conditions Flood Risk Database. The database conforms to ESRI’s geodatabase format. The contents of the geodatabase are described in a data dictionary, presented in Appendix E.

- **Online Geospatial User Interface –** BakerAECOM will upload the future conditions Flood Risk Database to FEMA’s GeoPlatform (http://fema.maps.arcgis.com/home) for web-based hosting and display of the future conditions SFHA data layers.

7. Discussion of Results

7.1. Mapping Comparisons with Other Federal and State Studies

As discussed in Section 3.2, there are several completed or ongoing Federal and state studies in the San Francisco pilot study area, including SLR hazard mapping by the USGS, NOAA, and Pacific Institute. As part of the pilot study, BakerAECOM conducted a mapping comparison using methods and data layers produced by those studies. Appendix F presents the results of the mapping comparison. Appendix F presents comparisons along San Francisco's open Pacific coast to highlight the differences between the various studies. For example, NOAA's SLR viewer maps SLR using the Mean Higher High Water (MHHW) tidal datum as the base water level whereas FEMA uses the 1-percent-annual-chance TWL. USGS's Coastal Storm Modeling System (CoSMoS) model inundation mapping models many of the same physical processes as FEMA's analysis (some of which are modeled in more detail); however, the inundation mapping is based on a different reference water level, uses different SLR scenarios, uses a future projection of wave climate instead of a hindcast, and does not include erosion or long-term shoreline change in the inundation mapping (see additional discussion in Section 7.2 and Appendix G). The Pacific Institute's inundation mapping also relied on a reference water level of MHHW and used different SLR scenarios than NOAA, USGS, and FEMA. It is important to note that no single study is necessarily "better" than the others; however, it is important to understand key differences between the maps so that mapping results can be correctly interpreted.

7.2. Detailed Comparison with Our Coast Our Future

Similar to FEMA's CCAMP OPC SLR pilot study, the Our Coast Our Future project recently developed an approach for modeling and mapping future coastal vulnerability to SLR and storm conditions in central California, including the San Francisco pilot study area (see Section 3.2 for a summary of ongoing work in the pilot study area). Although both approaches rely on the combination of local stillwater levels and waves to develop their hazard analysis, they diverge in the technical details and implementation of the methodologies. The discussion below summarizes the two approaches and results. A detailed quantitative comparison of the TWL results is presented in Appendix G.

The OCOF approach relies on the USGS CoSMoS model to derive water level estimates for regional inundation mapping (Barnard et al. 2014). Surf zone processes including wave setup, runup, cross-shore profile evolution, and maximum TWLs were calculated by applying a 1-D XBeach simulation. Coastal flood elevations and landward extent were estimated based on a future conditions storm scenario. Flood extents were mapped on an interactive web interface where the user can visualize flooding depth, extent, and uncertainty associated with each SLR and storm surge scenario. Maximum wave runup elevations were extracted from the XBeach model runs at each transect.

Due to methodology differences with the SLR pilot study, a direct evaluation between of the approaches was not possible without manipulation of at least one of the datasets. BakerAECOM coordinated with USGS scientists to obtain the detailed CoSMoS output within the pilot study area. The key difference between the FEMA and USGS data is that the FEMA wave runup elevations are 1-percent-annual-chance

TWLs based on a 2% exceedance wave runup formulation (as determined from a 50-year water level and wave hindcast from 1960-2009) whereas the USGS data are maximum wave runup elevations associated with a 1-percent-annual-chance offshore wave height (as determined from a Global Circulation Model-derived projection of 21st century wave climatology). To facilitate comparison of the wave runup outputs from the two models, BakerAECOM converted FEMA's 1% TWLs to maximum TWL values. Appendix G shows comparisons of FEMA and OCOF TWL results for existing conditions and the 3-ft (36-inch) at 2100 SLR scenarios.

Despite differences in data input, model selection, and conceptual design, the two approaches showed general agreement for maximum calculated TWLs, considering the significant differences in methodology and modeling framework. There are large differences, however, at steep bluff and armored shorelines, where the FEMA methodology relies on the TAW equation to estimate wave runup on barriers. Further investigation into the additional factors responsible for the differences between the two studies was beyond the scope of this pilot study.

7.3. Extrapolation of Results to Higher SLR Scenarios

The study team evaluated the potential to extrapolate the results of the future conditions TWL analysis to higher SLR scenarios, based on feedback received from the Peer Review Panel. NOAA's Global Sea Level Rise Scenarios for the United States National Climate Assessment (Parris et al. 2012) proposed a high global SLR scenario of approximately 2.0 m (6.6 ft), which exceeds the high-range estimate (5.5 ft) evaluated as part of this pilot study. Figure 15 shows a linear (1:1) and amplified TWL response at an example transect. As can be seen in the figure, both TWL curves are roughly linear, although the amplified response displays a steeper slope indicating that the increase in future TWL is greater than the amount of SLR. The study team observed similar behavior at other transects as well, which suggests that simple linear extrapolation of the TWL results may provide reasonable first-order approximations of future TWLs at higher SLR scenarios not evaluated as part of this pilot study. Further testing and application of the methodologies developed as part of this pilot study to other locations and environmental settings may help confirm this proposed methodology.

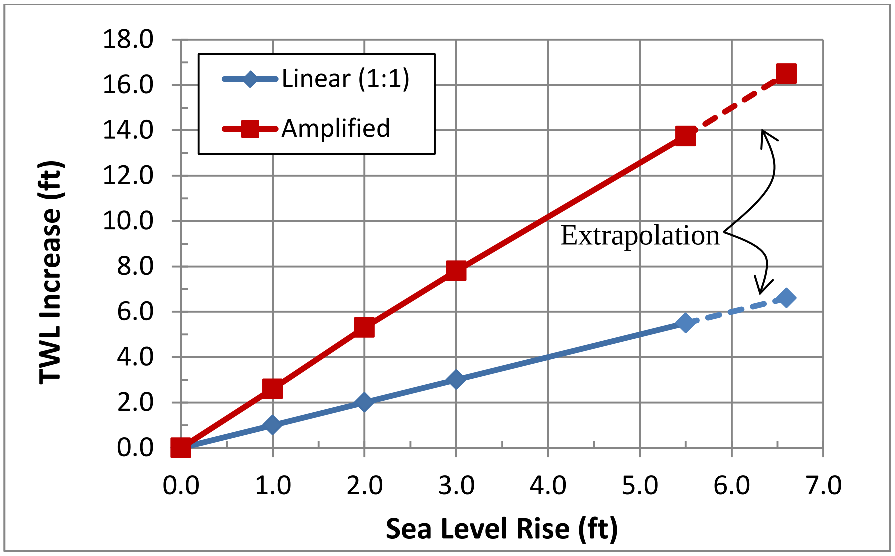

Figure 15. Example Extrapolation of Future Conditions TWL Results to Higher SLR Scenarios

7.4. Study Assumptions and Limitations

A number of simplifying assumptions were made in the development and application of the SLR pilot study. The study assumptions and limitations are summarized below:

Shoreline Change

- The shoreline change methods applied in this pilot study provide a general representation of the potential magnitude of future shoreline change, but the results have much intrinsic uncertainty due to the assumptions.
- The SLR pilot study relied on median values of regional shoreline change rates for the central California coastline, applied to San Francisco using limited data and engineering judgment. Future studies may wish to refine the shoreline change methods developed for the SLR pilot study and use local shoreline change data, where available, to provide more site-specific shoreline change projections.
- There is no fully-accepted methodology for estimating future bluff retreat in response to SLR. The SLR pilot study assumed that future rates of bluff shoreline retreat would be directly proportional to historical rates, with an amplification due to increased rates of SLR.
- The SLR pilot study assumed that wave action plays a dominant role in coastal bluff retreat by eroding the toe of the bluff and destabilizing the bluff face; however, this process is not the only driver of coastal bluff retreat. This assumption should be revisited if the pilot study methodology is expanded to other portions of the California coastline.
- There is considerable uncertainty in the estimated historical shoreline change rates. This uncertainty in historical rates is transferred to the estimates of future shoreline change distances

as well. Uncertainty in future shoreline positions for sandy beaches and dunes was estimated to be ± 50 ft at 2050 and ± 115 ft at 2100. Uncertainty in future shoreline positions for bluff transects was estimated to be ± 25 ft at 2050 and ± 60 ft at 2100. These uncertainty estimates only account for uncertainties in historical shoreline change rate estimates as reported in the USGS study.

- The SLR pilot study did not take into account future potential changes in coastal processes such as sediment supply, wave climate, alongshore sediment transport, beach nourishment, or other anthropogenic alterations to the shoreline.
- Future shoreline change projections within the San Francisco pilot study area were based on limited historical shoreline change data. There were no cliff retreat data available within the pilot study area and sandy beach shoreline change data covered only a portion of the pilot study area. An approach was developed to categorize each coastal analysis transect into shoreline change categories based on regional shoreline change data to address this data gap.

Storm Erosion

- Contributions to shoreline change from event-based bluff erosion were not considered in the study due to data gaps and methodology limitations. For the purposes of the pilot study, only long-term shoreline change was considered at bluffs. For example, slumping and block failure as mechanisms of bluff retreat are not explicitly addressed in the methodology, although these mechanisms are implicitly included in the historical and future projected retreat rates.
- Event-based dune retreat distances were not computed for future conditions at dune-backed transects. Instead, the event-based dune retreat results from the existing conditions analysis were assumed to be representative of the response to a future coastal storm event.
- The SLR pilot study methodology for calculating future TWLs at sandy beach and dune transects assumed that the foreshore beach slope would remain constant and unchanged in the future. Further, no profile modifications were performed on sandy beach and dune profiles for the future conditions TWL calculations. This assumption should be revisited as additional research into this topic (i.e., geomorphic response of shorelines to SLR) is completed in the future.

Other Impacts of Climate Change

- The SLR pilot study did not evaluate other aspects of climate change such as changes to storminess, storm tracks, wave heights, and frequency and intensity of future El Niño events.
- The impact of climate change and SLR on the offshore wave climatology and nearshore wave transformation was assumed to be negligible and not accounted for in the pilot study methodology. Future studies may wish to examine how climate change will influence these processes and their effect on coastal flood processes at the shoreline.

Mapping

- The SLR pilot study developed projections of the future landward extent of the SFHA corresponding to the 1-percent-annual-chance storm event. The pilot study did not attempt to differentiate between the future landward extent of V and A Zones and future conditions mapping depicts the total SFHA (V and A Zone combined). Hazard zones associated with more severe events, such as the 0.2-percent-annual-chance storm event, were not evaluated.
- The SLR pilot study projected future TWLs landward within the limits of each individual reach. Overtopping was restricted only to the individual reach where overtopping occurred. Lateral flooding from adjacent reaches was not evaluated in the analysis or mapping.
- Reach zone breaks established during the existing conditions mapping were carried over to the future conditions analysis and mapping without modification to ensure consistency with the FIRM mapping. As a result, reach break locations may not necessarily be placed in the optimal locations for future conditions mapping considering changes in TWL extent, overtopping, and shoreline change. This issue could be a topic for further consideration in future studies.
- Future conditions SFHA buffers were applied in GIS as raw buffer distances relative to the existing conditions SFHA limit and were not smoothed or tied-in across reach breaks to create smooth transitions between reaches.

Sea Level Rise

- SLR projections corresponding to the San Francisco tide station were applied along the SLR pilot study area coastline. Expansion of the pilot study to other areas will require evaluation of local SLR projections, which take into account regional SLR projections as well as local vertical land motion.

Other Considerations

- For the purposes of the SLR pilot study, it was generally assumed that existing coastal structures would be maintained into the future. This assumption was made based on discussions with CCSF staff; however, this assumption should be confirmed if the pilot study approach is expanded to other areas of the California coastline through engagement with a local stakeholder group.

8. Conclusions and Recommendations

8.1. Summary and Key Findings

A SLR pilot study was conducted along the open Pacific coastline of San Francisco County, California as part of FEMA Region IX's ongoing CCAMP OPC Study. The purpose of the pilot study was to investigate methods to incorporate SLR and long-term shoreline change into FEMA's analysis framework and mapping of coastal hazards along a wave runup-dominated coastline. Coastal communities throughout California require information on future coastal flood and erosion hazard zones to make informed planning decisions along their coastlines and the data layers produced as part of this study will help the City and County of San Francisco better prepare for future coastal hazards.

The pilot study area included a variety of shoretypes, including erodible and non-erodible bluffs, sandy beaches, dunes, and coastal structures. As part of the study, BakerAECOM developed methods of TWL analysis and profile adjustment in response to shoreline change for each shoretype. The wave, water level, and topographic datasets developed as part of the CCAMP OPC Study provided a strong foundation upon which to base the future conditions analysis. The availability of these datasets enabled the study team to efficiently develop future conditions estimates of BFEs and SFHAs within the pilot study area.

The results from a direct analysis and linear superposition approach were compared and it was determined that the direct analysis approach better captured the physical processes of wave runup in response to SLR for certain shoretypes and shoreline characteristics. This finding was especially true at steep shorelines such as rocky, resistant cliffs and areas of coastal armoring (such as revetments), where the increase in TWL was found to exceed the amount of SLR by a factor of two to four in some instances. At natural sandy beach and dune transects, the TWL increase was found to be linear and equal to the amount of SLR, due to the methodology assumptions for these shoretypes. The TWL analysis conducted as part of the pilot study is the first known quantitative comparisons of TWL response to SLR for natural vs. armored shorelines and highlights the potentially large TWL increases that may occur for certain shoretypes in the future.

Shoreline change was found to exert a strong influence on the landward extent of future SFHAs and was also found to be a potentially significant data gap. The results of the shoreline change analysis demonstrated that at natural sandy beach and dune shoretypes, SLR may increase the rate of shoreline retreat by a factor of 3.0 to 6.0 through 2050 and by a factor of 6.0 to 10.5 from 2050 to 2100, based on the methods applied in this study. At bluff shoretypes SLR may increase the rate of shoreline retreat by a factor of 1.7 to 2.4 through 2050 and by a factor of 2.4 to 3.2 from 2050 to 2100, based on the methods applied in this study. As a result, future SFHAs will increase not only due to the vertical increase in BFEs due to SLR but also due to the horizontal increase in landward extent due to shoreline retreat. As part of the pilot study, BakerAECOM developed a GIS-based buffering procedure to project future BFEs landward to account for shoreline change. The buffering technique was found to produce physically reasonable delineations of future SFHAs due to SLR and avoided potentially time-intensive topographic DEM modifications.

8.2. Recommendations

BakerAECOM developed the following recommendations based on the findings of the SLR pilot study that could be considered to refine the current study or to expand the methodology to other wave runup-dominated areas along the Pacific coast:

- Future studies should consider adoption of a direct analysis methodology to estimate future conditions TWLs for certain shoretypes and shoreline characteristics; however, the direct analysis methodology may not be required at all locations. Implementation of the direct analysis methodology is most applicable to steep, erosion-resistant shorelines (such as coastal bluffs and cliffs) and coastal structures (such as revetments and seawalls).

- Future studies may benefit from application of the linear superposition methodology to estimate future conditions TWLs for certain shoretypes and shoreline characteristics. Implementation of the linear superposition methodology may produce results very similar to those based on direct analysis methods for some shoretypes, such as sandy beaches and dunes and highly erodible bluffs.

- Future studies should explore the potential to develop a modified linear superposition approach or look-up table to facilitate rapid first-order approximation of future conditions TWLs in wave-runup dominated environments. The modified linear superposition approach could develop TWL amplification factors applicable to each shoretype based on the findings of this pilot study and further research. The study team recommends conducting additional testing of the methods developed for this pilot study across a larger suite of locations and environmental conditions to inform the development and application of the modified linear superposition approach.

- Future studies should evaluate other aspects of climate change such as changes in storminess, storm tracks, and frequency and intensity of future El Niño events. The pilot study methodology could be expanded to address these factors, many of which were of interest to the stakeholder group.

- Future studies in other communities should convene a local stakeholder group (similar to the stakeholder group assembled for the pilot study) to advise the study team on local conditions and assumptions, such as planned coastal protection projects (e.g., bluff armoring, sea walls, dunes, beach nourishment, etc.) and expected life span of existing coastal structures so appropriate treatments can be incorporated into the TWL and shoreline change analysis and mapping.

- Future studies may wish to refine the shoreline change methods developed for the pilot study and use local shoreline change data, where available, to provide more site-specific shoreline retreat projections. The pilot study relied on regional shoreline change rates developed from publically available USGS shoreline change datasets.

- By identifying existing structures in areas of increased future SFHAs, communities can use a risk analysis program such as FEMA's Hazus methodology to estimate the incremental monetary impacts of future vs. existing coastal flooding. Such an analysis could be used to develop a benefit-cost ratio for potential flood and/or coastal erosion mitigation projects.

- Communities with coastal areas vulnerable to future conditions flooding in response to the 1-percent-annual-chance event due to a combination of shoreline retreat and wave overtopping may wish to analyze future impacts due to a less severe flood event (such as a 10-, 2-, etc., percent-annual-chance event). This could further inform planning and development of benefit-cost analyses for potential mitigation strategies.

9. List of Preparers

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Appendices

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Appendix A. San Francisco Transect Layout

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Appendix B. U.S. Geological Survey Shoreline Change Data Inventory

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Appendix C. Combined Shoreline Change and TWL Results

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Appendix D. Future Conditions SFHA Mapping for San Francisco Pilot Study Area

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Appendix E. Flood Risk Database Data Dictionary

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Appendix F. Comparison Mapping for FEMA's Sea Level Rise Pilot Study

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Appendix G. Comparison with Our Coast Our Future

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