Climate Science and Climate Impacts

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4 Climate Science and Climate Impacts

4.1 Introduction

A summary of local- and regional-level climate information has been compiled that provides historical, current, and projected conditions. This chapter provides an overview of the climate change–related information. More detailed background information is presented in Appendix B.

This chapter also describes the preparation of new inundation maps for the two sea level rise (SLR) scenarios evaluated for the project: specifically, 16 inches (40 centimeters [cm])[2] by midcentury and 55 inches (140 cm) by the end of the century, consistent with the *State of California Sea-Level Rise Interim Guidance Document* (CO-CAT 2010). The two SLR scenarios are also compatible with previous SLR planning efforts in San Francisco Bay led by the San Francisco Bay Conservation and Development Commission (BCDC) and the U.S. Geological Survey (USGS), which formed the foundation for this effort.

The new inundation maps were used to assess the depth of inundation along the transportation assets to inform the vulnerability rating of the transportation assets (Chapter 5) and to evaluate the potential for overtopping along the Alameda County shoreline to inform potential adaptation strategies (Chapter 7). This process is described in Figure 4.1. The inundation maps and the related products are presented in Chapter 6, and the detailed methodologies are presented in Appendix B. This chapter also provides a list of the major caveats and uncertainties associated with the inundation maps. The analysis performed to develop the inundation maps is appropriate for a high-level planning effort and is not intended to represent, or take the place of, detailed engineering analyses. The process used for the analysis is described in Table 4.1.

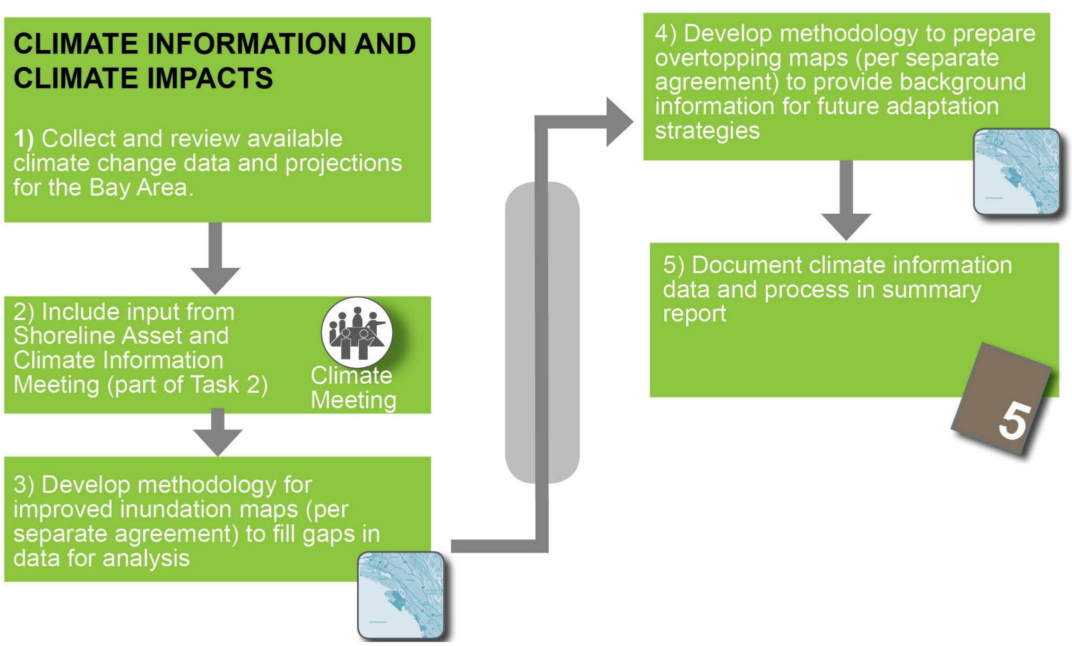

Figure 4.1 Climate Science and Climate Impacts Process

[2] Due to the international data referenced in this chapter, both metric and imperial units are used, to be consistent with the research produced.

Table 4.1 SLR Projections Using 2000 as the Baseline

Year	Emissions Scenario	Range of Models, inches (cm) above 2000*	Average of Models, inches (cm) above 2000*
2030		5-8 in (13-21 cm)	7 in
2050		10-17 in (26-43 cm)	14 in (36 cm)
2070	Low (B1)	17-27 in (43-70 cm)	23 in (59 cm)
	Medium (A2)	18-29 in (46-74 cm)	24 in (62 cm)
	High (A1FI)	20-32 in (51-81 cm)	27 in (69 cm)
2100	Low (B1)	31-50 in (78-128 cm)	40 in (101 cm)
	Medium (A2)	37-60 in (95-152 cm)	47 in (121 cm)
	High (A1FI)	43-69 in (110-176 cm)	55 in (140 cm)

Source: California Ocean Protection Council (CO-CAT) 2010.

*Note: Rahmstorf and Vermeer's paper presents values using 1990 as a baseline. Here the values are adjusted by subtracting1.3 inches / 3.4 centimeters, which represents 10 years of SLR that has already occurred, at an average rate of 0.1 inches / 3.4 millimeters per year.

4.2 Climate Information Summary

Sources presenting historical, current, and projected data were reviewed to summarize local- and regional-level climate information for use in assessing the vulnerability of transportation infrastructure to climate change effects (FHWA 2010). A detailed summary of climate information is presented in Appendix B.

Climate change is already affecting California. Sea level has risen by as much as 7 inches along the California coast over the last century, increasing erosion and adding pressure to the state's infrastructure, water supplies, and natural resources (California Natural Resources Agency 2009). During this period, and despite annual variations in weather patterns, California has also seen a trend of increased average temperatures, more extreme hot days, fewer cold nights, longer growing seasons, less winter snow, and earlier snowmelt and rainwater runoff (California Natural Resources Agency 2009).

An increase in the rate of SLR is one of the primary effects of climate change (Knowles 2009). SLR has the potential to cause major damage to residential, commercial, and industrial structures in low-lying areas near the shoreline, as well as to important habitats and wildlife resources. For this reason, planning for SLR has become a higher priority in California. Through the use of innovative efforts to identify vulnerable areas, California will be better prepared to protect communities and the environment from the potentially devastating impacts of SLR.

According to the State of California Ocean Protection Council Science Advisory Team, future SLR projections should not be based on linear extrapolation of historic sea level observations. For estimates beyond one or two decades, linear extrapolation of SLR based on historic observations is considered inadequate and would likely underestimate the actual SLR because of expected nonlinear increases in global temperature and the unpredictability of complex natural systems (CO-CAT 2010). Table 4.1 provides an overview of the SLR projections provided in the Ocean Protection Council's interim guidance document. The two SLR scenarios selected for the pilot project represent a high-end estimate for midcentury (16 inches of SLR) and a midrange estimate for the high-emission scenario for the end of the century (55 inches of SLR). These two SLR scenarios are also compatible with previous SLR planning efforts in San Francisco Bay led by BCDC and USGS.

In addition to SLR, scientists predict that global warming will increase the frequency of major storms. With increasing storm intensity, the potential exists for storm-generated waves to increase in height, resulting in an overall change in the San Francisco Bay wave climate. When large storm events coincide with high tides or extreme coastal water levels, there is a greater potential that existing shore protection infrastructure would be overtopped, resulting in a potentially larger inundation area. Therefore, a thoughtful evaluation of the risks associated with SLR would include an assessment of extreme coastal water levels and increasing wave heights.

4.3 Inundation Mapping

This chapter presents the methodology for developing the new SLR inundation maps produced for the pilot project. Two modeling efforts were leveraged for this study, and this chapter, along with the detailed methodology presented in Appendix B, documents how the model output from these efforts was used to develop the inundation maps. In addition, the major caveats and assumptions associated with the inundation maps are described.

4.3.1 INUNDATION MAPS

Six inundation scenarios were evaluated as part of this effort. Each SLR scenario—16 inches (40 cm) by midcentury and 55 inches (140 cm) by the end of the century—is evaluated under three storm/tide conditions: inundation associated with high tides, also known as mean higher high water (MHHW); inundation associated with 100-year extreme water levels, also known as stillwater elevations (100-yr SWEL); and inundation associated with 100-year extreme water levels coupled with wind waves. The three storm/tide conditions were selected as they represent a reasonable range of potential inundation conditions. The inundated area associated with high tides under each SLR scenario is representative of the area that would be subjected to frequent or permanent tidal inundation. This level of inundation could correspond to slow and regular degradation of infrastructure, including shoreline protection. Although storm conditions represent a lower frequency event, they come with a larger potential flooded area, with deeper flooded depths, higher velocities, and a greater likelihood of wind-driven waves that could overtop existing shore protection infrastructure. Most of the near-term damage that SLR is expected to cause on developed areas is from storm conditions that occur at the same time as high tides (SPUR 2011).

Three maps were created for each SLR scenario as described above:

- 16 -inch SLR + MHHW
- 16 -inch SLR + 100-yr SWEL
- 16 -inch SLR + 100-yr SWEL + wind waves
- 55 -inch SLR + MHHW
- 55 -inch SLR + 100-yr SWEL
- 55 -inch SLR + 100-yr SWEL + wind waves

The inundation maps are presented in Chapter 6, including overall maps for the project area and five focus area maps that provide a more detailed look at the inundated depth and extent overlain with the selected transportation assets. The detailed methodologies used to create the inundation maps are presented in Appendix B. New inundation maps were created for the pilot study region for several reasons:

- The previous inundation maps created by Knowles (2009, 2010) for the San Francisco Bay area did not include depth of inundation. The new inundation maps provide the extent of inundation for each scenario, as well as the depth of inundation for the entire inundated area. The depth of inundation along the shoreline assets and at the transportation asset locations was considered to be an important factor in assessing vulnerability to SLR.

- The previous inundation maps did not account for the level of flood protection provided by the region's flood protection levees and other shoreline protection structures. Inundation maps that more accurately characterized the existing shoreline assets would provide a better understanding of the potential risk to future inundation.
- The previous inundation maps did not account for wind waves. Wind wave generation within San Francisco Bay is an important process to consider when evaluating the potential for shoreline overtopping and inundation in nearshore coastal areas.
- The new mapping effort also benefited from an assessment of hydraulic connectivity, using inundation mapping methodologies developed by the National Oceanic and Atmospheric Administration Coastal Services Center to exclude low-lying areas that are below the inundated water surface elevation but would not be hydraulically connected to the inundated areas.
- The previous study relied on older Light Detection and Ranging (LIDAR) elevation data with less vertical and horizontal accuracy. This study benefits from the 2010 LIDAR data collected by USGS for South San Francisco Bay.

4.3.2 SHORELINE OVERTOPPING POTENTIAL

Information on the depth of inundation was extracted along the shoreline assets described in Chapter 2 to provide a high-level assessment of the potential for shoreline overtopping. "Overtopping potential" refers to the condition where the water surface elevation associated with a particular SLR scenario exceeds the elevation of the shoreline asset. This assessment is considered a planning-level tool only, as it does not account for the physics of wave runup and overtopping. It also does not account for potential vulnerabilities along the shoreline protection infrastructure that could result in complete failure of the flood protection infrastructure through scour, undermining, or breach after the initial overtopping occurs. The detailed methodology used for the shoreline overtopping potential analysis is presented in Appendix B.

The depth of inundation was extracted along the shoreline asset delineation described in Chapter 2. Although the delineation in Chapter 2 defines wetlands and beaches as shoreline asset categories, the delineation for the assessment of overtopping potential was moved inland in select areas to the topographic feature that could control inundation, such as levees, berms, or road embankment crests, which act as barriers to inland inundation. Chapter 6 presents the resulting overtopping potential maps for each SLR scenario and storm/tide condition, including a detailed look at five focus areas within the pilot region.

The shoreline delineation was also subdivided into "systems" that act together to prevent or influence inland inundation. This approach was taken to develop meaningful metrics for assessing the vulnerability of the transportation assets and identifying potential adaptation strategies. A system could be defined as a reach of levee along the shoreline between two adjacent tributaries. Alternatively, a system could be defined as the combination of several asset types (e.g., levees, nonengineered berms, roadway embankments) that act together to influence the inundation of an inland area with similar topographic elevation. Although smaller systems could technically be defined within any given system, the size of the systems were selected to be small enough to provide meaningful metrics relating to the transportation assets yet large enough to be manageable within the context of this high-level assessment. The results of the analysis by system are presented in Chapter 6. Each figure shows three panels, representing the MHHW, 100-yr SWEL, and 100-yr SWEL + wind waves scenarios, to highlight the progression of overtopping under the three storm/tide conditions.

The following primary metrics were used to evaluate shoreline overtopping potential:

- *Potential overtopped length of each system*. The length of shoreline that is overtopped within each system can be an indication of the overall vulnerability of the system. For example, a system could have an overtopped length of 0 feet, 100 feet, or 1,000 feet. A system with an overtopped length of 1,000 feet may require more extensive adaptation strategies to reduce inland inundation.

- *Percent of shoreline overtopped for each system*. Although the size of each system may vary, the percent of shoreline overtopped is a useful metric for comparing the performance of the systems under the six storm/tide conditions. For example, a system may have less than 5 percent of its length overtopped under 16 inches of SLR and 100-yr SWEL, while 50 percent of its length is overtopped with the addition of waves.

- *Average depth of inundation along a segment*. The average depth of inundation along the shoreline assets was evaluated on a segment level, looking at the actual areas where the shoreline assets could be overtopped. This metric is useful for indentifying the initial flow path for the inland inundation. For example, for the Oakland International Airport, the engineered flood protection levees on the inland edge of Bay Farm Island are overtopped first, resulting in inundation of the airport. Portions of the shoreline system that are not overtopped (overtopping depth = 0) were not included in the average overtopping depth calculation. As sea level rises from the 16" to 55" SLR scenarios, additional lengths of shoreline are inundated within each system; therefore, the average overtopping depth increase between the two scenarios is less than the 39" increase in sea level.

- *Distance of each transportation asset from the nearest overtopped segment along the shoreline assets*. This metric was evaluated to differentiate between transportation assets that may be protected by the same system. Transportation assets closer to the shoreline could have a more limited range of potential adaptation strategies, such as building larger engineered flood protection levees along the shoreline or relocating the transportation asset.

4.3.3 TRANSPORTATION ASSET INUNDATION POTENTIAL

In a manner similar to that described in Section 4.3.2, the depth of inundation information was extracted along the transportation assets described in Chapter 2 to inform the vulnerability of the transportation assets under the two SLR scenarios and the three storm/tide conditions. The results of this assessment are described in more detail in Chapter 5.

4.3.4 UNDERLYING ASSUMPTIONS AND CAVEATS

The inundation maps are intended only as a screening-level tool for performing the vulnerability and risk assessment. Although the inundation maps do account for additional processes and they rely on new data, they are still associated with the following series of assumptions and caveats:

- The bathymetry of San Francisco Bay and the topography of the landward areas, including levees and other flood and shore protection features, would not change in response to SLR and increased inundation (e.g., the morphology of the region is constant over time).

- The maps do not account for the accumulation of organic matter in wetlands or potential sediment deposition and/or resuspension that could alter San Francisco Bay hydrodynamics and/or bathymetry.

- The maps do not account for erosion, subsidence, future construction, or levee upgrades.

- The maps do not account for the existing condition or age of the shore protection assets. No degradation or levee failure modes have been analyzed as part of the inundation mapping effort.

- The levee heights and the heights of roadways and/or other topographic features that may impact flood water conveyance are derived from the USGS 2010 LIDAR at a two meter horizontal grid resolution. Although this data set represents the best available topographic data, and the data has undergone a rigorous QA/QC by a third party, the data has not been extensively ground-truthed. Levee crests and other topographic features may be over or under-represented by the LIDAR data.

- The inundation depth and extent shown on the MHHW maps are associated with the highest high tides, in an attempt to approximate the maximum extent of future daily tidal inundation. This level of inundation can also be referred to as “permanent inundation,” as it represents the area that would be inundated regularly. Tides in San Francisco Bay exhibit two highs and two lows in any given day, and the daily high tide on any given day may be less than the calculated MHHW tidal elevation.

- The inundation depth and extent shown on the 100-yr SWEL maps is associated with a 100-year extreme water level condition—in other words, an extreme tide level with a 1-percent chance of occurring in any given year. This inundation is considered “episodic inundation” because the newly inundated areas (the areas not inundated under the MHHW scenario) would be inundated only during extreme high tides. It should be noted that extreme tide levels with greater return intervals (i.e., 500-yr SWEL with a 0.2-percent chance of occurring in a given year) can also occur and would result in greater inundation depths and a larger inundated area.

- The depth of inundation is not shown for the extreme coastal storm event conditions (i.e., 100-yr SWEL + waves) because the physics associated with overland wave propagation and wave dissipation are not included in this study. These processes would have a significant effect on the ultimate depth of inundation associated with the large coastal wave events, resulting in a potential reduction in the depth of inundation in most areas. Alternatively, the wave heights used in this analysis are associated with existing 10-year wave heights, and as sea level rises and bay water depths increase, the potential for larger waves to develop in the nearshore environment increases. This dynamic could result in increases in the depth of inundation, particularly directly adjacent to the shoreline assets.

- The inundation maps focus on the potential for coastal flooding associated with sea level rise and coastal storm events. The inundation maps do not account for localized inundation associated with rainfall-runoff events, or the potential for riverine overbank flooding in the local tributaries associated with large rainfall events.

- The maps do not account for inundation associated with changing rainfall patterns, frequency, or intensity as a result of climate change.

4.4 Recommended Refinements to the FHWA Conceptual Model

This section provides feedback on the FHWA conceptual model and its application in the selected Alameda County subregion in terms of the climate change data collection process and the development of the inundation maps.

4.4.1 CLIMATE SCIENCE DATA GATHERING

The San Francisco Bay region benefits from a wealth of available climate science data, including sea level rise inundation mapping completed by the USGS (Knowles 2009, 2010) before the initiation of this pilot study. However, the existing inundation maps did not provide depth of inundation within the study area, and the project team believed that the depth of inundation under various SLR scenarios was a critical element for assessing the vulnerability of transportation assets to climate change. The project produced new inundation maps, and associated products such as the shoreline overtopping potential, that were not anticipated at the outset of the project and were therefore not included within the project schedule.

4.4.2 LESSONS LEARNED

The following lessons were learned as part of the pilot project with respect to the inundation mapping effort:

- The project team was able to develop new inundation maps for the project in a cost-effective manner using data leveraged from other studies: the previous USGS (Knowles 2009) SLR study, the FEMA San Francisco Bay Coastal Hazard Analysis study, and the USGS 2010 LIDAR. If these data sets were not available to the project, the vulnerability analysis of the transportation assets would have been more limited.
- The information available from existing inundation maps can vary greatly, both in form and content. The project team found that the most important piece of information gleaned from the inundation mapping effort was the depth of information.
- Inundation maps should be developed using topographic data that is capable of resolving the shore protection assets, such as flood protection levees. Accurately characterizing the shore protection assets lends greater credibility to the maps, and therefore the entire vulnerability and risk assessment process.
- The mapping exercise was very time consuming, in particular extracting the relevant depth information for each transportation asset at for each SLR scenario.

4.4.3 RECOMMENDATIONS

Recommendations for the climate science and climate impacts component of the process include the following:

- Depending on the geographic area where the risk assessment is being carried out, it may be sufficient to use existing climate science information. However, this study shows how further mapping of the likely climate impacts is an integrated piece of understanding transportation asset vulnerability (the model could highlight that there may need to be considerable effort spent on categorizing shoreline assets, and undertaking new inundation mapping (and overtopping analysis) for projects addressing sea level rise). This mapping work was important to help assess the vulnerability of the transportation assets.
- An indication of the time consuming nature of additional mapping should be provided in the model.
- It should be noted in the model that climate science is continually evolving so vulnerability and risk assessments will also need regular updating as new modeling becomes available.

4.5 References

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