CALTRANS CLIMATE CHANGE VULNERABILITY ASSESSMENTS

January 2018

District 4
Technical Report

CONTENTS

TABLES

FIGURES

ACRONYMS AND ABBREVIATIONS

BCDC	Bay Conservation and Development Commission
ADAP	Adaptation Decision-Making Assessment Process
CalFire	California Department of Forestry and Fire Protection
Caltrans	California Department of Transportation
CCC	California Coastal Commission
CEC	California Energy Commission
CGS	California Geological Survey
CMIP3	Coupled Model Intercomparison Project 3
CoSMoS	Coastal Storm Modeling System
DWR	California Department of Water Resources
FEMA	Federal Emergency Management Agency
GCM	Global Climate Model
GFDL	Geophysical Fluid Dynamics Laboratory
GIS	Geographic Information System
IPCC	Intergovernmental Panel on Climate Change
LIDAR	Light Detection and Ranging
LOCA	Localized Constructed Analogues
MHHW	Mean Higher High Water
NOAA	National Oceanic and Atmospheric Administration
NRA	Natural Resources Agency
NRC	National Research Council
PCM	Parallel Climate Model
PG&E	Pacific Gas and Electric Company
RCP	Representative Concentration Pathway
Scripps	The Scripps Institute of Oceanography
SLR	Sea Level Rise
SRES	Special Report Emissions Scenarios
USACE	US Army Corps of Engineers
USFS	US Forest Service
USGS	US Geological Survey
VHT	Vehicle Hours Traveled

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1. INTRODUCTION

The following report was developed for the California Department of Transportation (Caltrans) to summarize a vulnerability assessment conducted for assets in Caltrans District 4. The assessment was developed to specifically identify the potential effects of climate change on the State Highway System in District 4. This is the first of 12 such studies that will eventually cover each region in the State.

Climate change and extreme weather events have received increasing attention worldwide as potentially one of the greatest challenges facing modern society. Many state agencies—such as the California Coastal Commission (CCC), the California Energy Commission (CEC), and the California Department of Water Resources (DWR)—have developed approaches for understanding and assessing the potential impacts of a changing climate on California's natural resources and built environment. State agencies have invested significant resources in defining the implications of climate change, and many of California's academic institutions are engaged in developing resources for decision-makers. Caltrans initiated the current study to better understand the vulnerability of California's State Highway System and other Caltrans assets to future changes in climate. The study has three objectives:

- Understand the types of weather-related and longer-term climate change events that will likely occur with greater frequency and intensity in future years,

- Conduct a vulnerability assessment to determine those Caltrans assets vulnerable to various climate-influenced natural hazards, and

- Develop a method to prioritize candidate projects for actions that are responsive to climate change concerns, when financial resources become available.

The current study focuses on the 12 Caltrans districts, each facing its own set of challenges regarding future climate conditions and potential weather-related disruptions.

1.1. Purpose of Report

The *District 4 Technical Report* is one of two documents that describe the work completed on this study, specific to Caltrans District 4. This report should be considered a companion document to the *District 4 Summary Report*. The *Technical Report* provides the reader with background information on the data used in the study, the methods employed, and the decisions made in applying climate data to determine the potential exposure of the District 4 California State Highway System and other Caltrans assets to future changes in climate. The *Summary Report* provides information on the potential implications of climate change conditions and presents additional material on how data collected for this effort can be applied. It is intended to orient non-technical readers on how climate change may affect the State Highway System in District 4. It outlines other approaches or policy concerns that may be of interest to a larger audience. *The Technical Report* is intended to provide a more in-depth discussion of the issues and is intended primarily for District 4 staff. The reader should note that there is some overlap in the material and information provided in both documents; however, those interested in the complete analysis of potential climate change-related impacts on the State Highway System in District 4 should examine both documents.

The *Technical Report* provides technical background on how the information presented in both reports was developed and has been written for an audience interested in better understanding the methods employed and replicating them, if desired. The report is divided into sections by climate stressor

(precipitation, sea level rise, storm surge, etc.) and presents information specific to each stressor. Where it was possible to identify specific Caltrans assets that may be at risk from certain stressors, those assets were identified and a summary of the potential impacts was prepared. Where climate and/or asset data was not readily available to provide such detail (high quality Light Detection and Ranging [LIDAR]/asset data and stream flow data for precipitation effects, etc), an assessment is presented of how changes to traditional climate variables (precipitation and temperature) would be anticipated to change traditional design practices.

Finally, this *Technical Report* outlines a recommended framework for prioritizing a list of projects that could occur in the future. This framework was developed based on research into prioritization frameworks used by other transportation agencies and other methods that have been developed to guide decision-making when considering climate-change effects.

A database containing geospatial data indicating the current and future locations of various natural hazards and their impacts to Caltrans roadways was also developed as part of this project. The maps included in this report and the Technical Report draw upon data contained in this database. Using this data, Caltrans intends to help evaluate the vulnerability of other transportation modes through partnership and data sharing with local and regional agencies. This database is expected to be a valuable resource for ongoing Caltrans resiliency efforts and coordination with stakeholders.

1.2.   District 4 Characteristics

This report is specific to Caltrans District 4, which covers the San Francisco Bay Area, including (from approximate north to south) Sonoma, Napa, Marin, Solano, Contra Costa, Alameda, San Francisco, San Mateo, and Santa Clara Counties. The geography of the district ranges from the coastal areas to the west, to bay shore hills and flat tidal marshes in the north and east, to the more mountainous areas to the south. It includes the second-largest metropolitan area in California and coastal areas along the western boundary. The region is home to over 7.5 million people served by three major airports and an extensive transit system. Land uses vary from dense urban and suburban residential, to commercial and industrial, with more rural areas north of the bay shore. Of the total land area, approximately 27 percent is protected as parks, wildlife refuges, and open space. The region hosts a strong and diverse economy, contributing approximately 25 percent of California's output. In 2016, the Bay Area outpaced the rest of the state (and nation) in economic growth for the 5th consecutive year.[1] Caltrans District 4 manages seven major

Caltrans Districts

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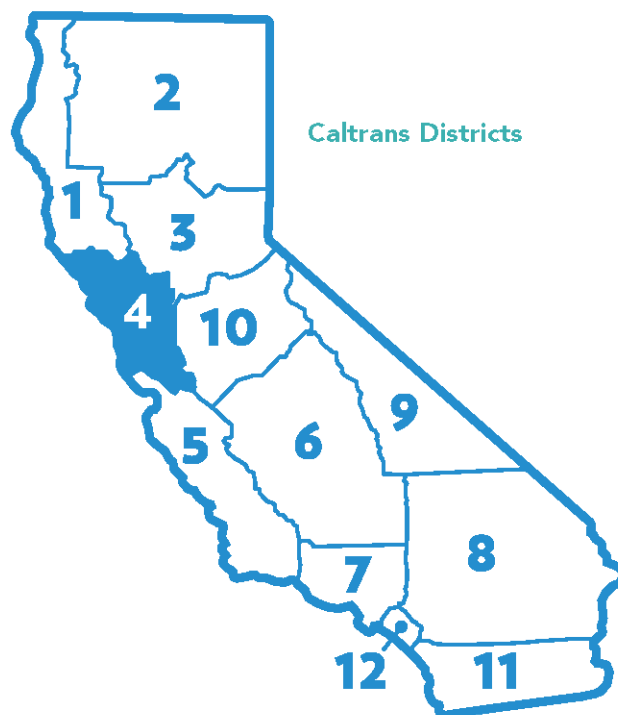
[1] Floum, Jessica, "Bay Area Economy Outpaces U.S., China," http://www.sfchronicle.com/business/article/Bay-Area-economy-outpaces-U-S-China-9289809.php, September 26, 2016

toll bridges[2] as well as 1,440 miles of the State Highway System, which includes 10 interstate highways, 38 state highways, and one U.S. highway. These assets provide critical transportation connection linkages that support the region.

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[2] "Division of Maintenance," Caltrans, http://www.dot.ca.gov/d4/maintenance/, n.d.

2. POTENTIAL AFFECTS FROM CLIMATE CHANGE ON THE STATE HIGHWAY SYSTEM IN DISTRICT 4

Climatic and extreme weather conditions in District 4 are expected to change, with atmospheric warming contributing to higher seas, changing precipitation patterns and higher temperatures. These changing conditions are anticipated to affect the District 4 State Highway System and other assets in a variety of ways and may increase exposure to environmental factors beyond the facilities' original design considerations, requiring adaptive responses. The project study team considered a range of changing climate conditions and extreme weather events, and how they tie into design criteria and other metrics specific to transportation systems.

FIGURE 1: CONSIDERATIONS FOR THE STATE HIGHWAY ASSESSMENT
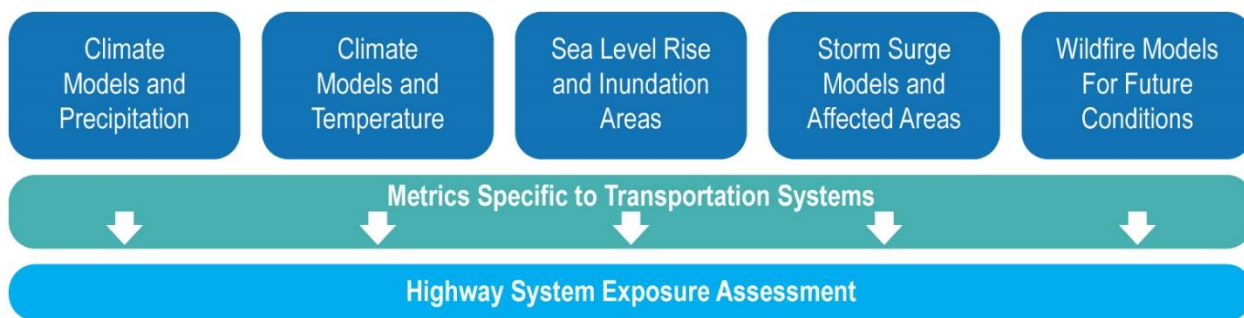
Changing climate conditions and associated extreme weather changes present a series of challenges to District 4 in delivering resilient transportation facilities for Bay Area residents. The primary concern is that changing conditions such as extreme weather events or permanent inundation may impact the public or the transport of goods and services. These events are already disrupting and damaging District 4 infrastructure, with the potential for impacts to become more severe in the future. The following are the climactic/extreme weather conditions that are currently affecting the District 4 State Highway System and may cause further impacts in the future, which were evaluated for this assessment.

- **Temperature** – Temperature increase is a direct outcome of increasing greenhouse gas emissions (GHGs). Temperature is a key consideration for pavement design, and therefore the amount and timing of temperature increase in California is important for identifying appropriate pavement mixes. Heat waves have directly damaged infrastructure in California, including pavement buckling in Sacramento and blackouts in San Jose.[3] Typically, temperatures are cooler in the Bay Area and District 4 will not face the same heat related impacts as more inland Districts. However, extreme heat events in the Bay is still likely to impact maintenance activities, causing increased maintenance due to material damage as well as changes in schedule during high heat to protect worker safety.

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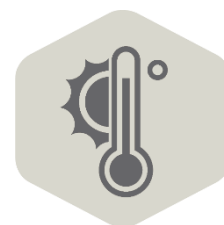
[3] Metcalfe, John, "The Western US Heat Wave is so Bad Pavement is Causing 2nd Degree Burns," https://www.citylab.com/environment/2013/07/western-us-heat-wave-so-bad-pavement-causing-2nd-degree-burns/6114/, July 4th, 2013

- **Precipitation** – Precipitation volatility is expected to increase in the future, due to energy and moisture in the atmosphere. Increases in heavy precipitation events combined with other changes in land use and land cover can increase the risk of flash flooding. The effects of precipitation were especially significant in District 4 this past winter (2016 to 2017). Rainstorms, mudslides, and flooding caused numerous road closures and severe damages across the state. The most expensive project was in District 4, where a 200-foot-long section of Highway 35 was washed out.[4] Other events in District 4 included Coyote Creek swelling to over 14 feet high, flooding downtown San Jose,[5] and a ten foot deep sinkhole opened up on Highway 13 in Oakland (see below).[6] Overall the costs to repair the state's roads, bridges, and highways came to over $860 million.[7] See the Appendix for a map of all storm damage sites that occurred during 2017 storm events, to the State Highway System in the Bay Area.

FIGURE 2: SINKHOLE ON HIGHWAY 13

- **Sea Level Rise** – Sea level rise (SLR) is a long-term threat in San Francisco Bay and along Bay Area coastal areas, caused by the effects of thermal expansion of ocean water combined with contributions from glacial and ice sheet melt. Sea level rise is already having affects in the District 4 area through periodic inundation during higher tide events. The King Tide has been known to flood the Embarcadero in San Francisco and has in the last two years.[8]

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[4] Serna, Joseph, "California Faces $860-Million Repair Bill for Roads Battered by Record Winter Storms," http://www.latimes.com/local/lanow/la-me-ln-caltrans-storm-damage-assessment-20170403-story.html, April 3rd, 2017

[5] Carr, Ada and Wright, Pam, "California Storm, Flood Damage Could Top $1 Billion, Governor's Office Says," https://weather.com/news/weather/news/california-flooding-impacts, February 25th, 2017

[6] May, Patrick, "Steve the Sinkhole gets Filled up," http://www.mercurynews.com/2017/01/24/steve-the-sinkhole-takes-his-leave-leaving-a-whole-sinkhole-subculture-behind-him/, January 24th, 2017

[7] Serna, Joseph, "California Faces $860-Million Repair Bill for Roads Battered by Record Winter Storms," http://www.latimes.com/local/lanow/la-me-ln-caltrans-storm-damage-assessment-20170403-story.html, April 3rd, 2017

[8] Veklerov, Kimberly, "7-Foot King Tides Bring Risk of Flooded Roadways to Bay Area," http://www.sfgate.com/bayarea/article/7-foot-king-tides-bring-risk-of-flooded-roadways-10790815.php#photo-9586869, December 12th, 2016

- **Storm Surge** – Storm surge is associated with different precipitation event recurrences, such as the 20- or 100-year storm events, which can cause tidal bay flooding in coastal areas. Increasing sea levels combined with new climatological changes to these storm patterns are expected to alter and increase the effects of storm surge in coastal areas. District 4 is already experiencing the effects of storm surge combined with sea level rise. Sea level rise combined with the storm events during the 2016 to 2017 winter is believed to have been a contributor to the levels of flooding across California. [9]

- **Wildfire** – Higher temperatures and extended drought periods in California are expected to influence the risk of wildfire over time. Decreased precipitation creates drier conditions and increases wildfire risk. For example, drought conditions along with periodic freezes and beetle infestation are affecting the health of 25-year-old trees in the Oakland Hills, and residents are concerned about a repeat of the 1991 wildfire. The East Bay Regional Park District as well as FEMA, UC Berkeley, and the City of Oakland have been managing tree removal in order to prevent a similar event from happening again.[10] Wildfires in the region could cause traffic, road blocks, or detours on the District 4 State Highway System. In addition to the direct impacts of wildfire, smoke can also affect visibility and cause health concerns for the traveling public or District 4 staff.

- **Combined Effects** – There are also areas where the combined effects of these stressors may have an impact on the highway system. These include the following:

  - **Wildfire and Flooding** – Wildfires can often have an impact on soils, making them less permeable (hydrophobic) and so reducing their ability to absorb rainfall. The result is flooding patterns that are inconsistent with original design assumptions since the land is no longer able to help control rainwater flows. Land stripped of vegetation is also more susceptible to shallow landslides during precipitation events. Flooding combined with mud and landslides occurred across the state, including District 4, during the 2016 to 2017 winter storm events. California agencies such as Department of Water Resources (DWR) and Cal Fire forewarned that the years of drought combined with wildfire would lead to more severe flooding and mudslides.[11]

  - **Sea Level Rise and Storm Surge** – Rising seas combined with various storm events causes greater areas of inundation and higher water elevations on land. For example, the San Francisco Public Utilities Commission uses an increase in sea level of 40 inches given a 100-year storm event for their assessment of the San Francisco area. Combined with one foot of sea level rise, they assume 52 inches of rise above Mean Higher High Water (MHHW).[12] Beyond the effects of increased inundation, sea level rise combined with storm surge can cause increased damages from wave action.

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[9] "Storms Preview Sea Level Rise Damage to Bay Area Roads, Cities," http://kron4.com/2017/01/30/storms-preview-sea-rise-damage-to-bay-area-roads-cities/, January 30th, 2017

[10] Swan, Rachel, "25 Years Later: Oakland Hills Ripe for another Firestorm," http://www.sfchronicle.com/bayarea/article/25-years-later-Oakland-hills-ripe-for-another-9984731.php, October 20th, 2016

[11] Russel, Kiley, "Drought, Wildfires Steepen Flood, Mudslide Risk," https://sfbay.ca/2016/10/24/drought-wildfires-steepen-flood-mudslide-risk/, October 24th, 2016

[12] http://www.adaptingtorisingtides.org/wp-content/uploads/2016/05/San-Francisco_SSIP_TO19_ClimateChangeAnalysis_-Subtask4_BaysideTM-CCA000006-FINAL.pdf

This study examined the potential effects of these stressors on Caltrans District 4 by using the "best available data" at the state and regional level.

3. ASSESSMENT APPROACH

3.1. General Description of Approach

The study of climate change effects is being undertaken by multiple agencies and academic institutions for various purposes in the Bay Area. The material presented in this report was developed in coordination with various local partners including:

- Caltrans District 4

- Metropolitan Transportation Commission (MTC)

- Pacific Gas and Electric Company (PG&E)

- San Francisco Bay Conservation and Development Commission (BCDC)

Coordination with Caltrans District 4 included several steps due to their position as a partner in developing this material. These efforts included:

- coordinating with staff on previous work sponsored by and completed by District 4 staff in partnership with other agencies to understand available data, findings and lessons learned

- coordinating on methodology and findings, including sharing various draft materials with District 4 staff for edits and review. These reviews included:

    o a coordination meeting to discuss the proposed methodology for completing the study,

    o a review of a prepared methodology report,

    o review of summary and technical reports prepared to summarize work completed in District 4 for all climate stressors.

The project study team met with MTC to discuss their previous U.S. Federal Highway Administration (FHWA) pilot studies conducted in coordination with BCDC for Alameda County. They provided background on the assets they considered and how adaptation options were developed, and discussed general sea level rise methodology with the project study team.

Consultant staff spoke with PG&E to understand their landslide model and develop upon their work to create a landslide model that incorporates future climate change. Landslides were not included in the current analyses but may need to be considered in future work.

The study team coordinated with BCDC as a regulatory agency focused on protecting and enhancing San Francisco Bay. They are responsible for providing permits for bayshore projects and lead the multi-agency effort to address the impacts of SLR on community resources. BCDC was made aware of the methodology utilized in this report, which differs from their own in the baseline data applied.

The methods used to develop the vulnerability assessments shown in the following pages included coordinating with those agencies, defining future scenarios, discussing the applicability of using that data for the purposes of completing the analysis, and identifying the metrics that were specific to transportation system decision-making by coordinating with professionals from various transportation disciplines.

3.2. State of the Practice in California

California has been on the forefront of climate change policy, planning, and research across the nation. State officials have been key in developing and implementing policies that drive greenhouse gas mitigation and the consideration of climate change. California agencies have been pivotal in creating climate change data sets which can be used to consider regional impacts across the state. At a more local level, regional efforts to plan for and adapt to climate change are underway in communities across the state. These practices are key to the development of climate change vulnerability assessments in California, for several reasons. The sections below provide some background to the current state of the practice and how they were considered/applied in the District 4 vulnerability assessment.

3.2.1. Policies

Various policies implemented at the state level have directly addressed not only GHG mitigation but also climate adaptation planning. These policies require state agencies to consider the effects of climate in their investment and design decisions, among other considerations. State adaptation policies that are relevant to Caltrans include:

- **Assembly Bill 32** (2006) or the "California Global Warming Solution Act" was marked as being the first California law to require a reduction in emitted GHGs. The law was the first of its kind in the country and set the stage for further policy in the future.[13]

- **Executive Order S-13-08** (2008) directs state agencies to plan for sea level rise (SLR) and climate impacts through the coordination of the state Climate Adaptation Strategy.[14]

- **Executive Order B-30-15** (2015) requires the consideration of climate change in all state investment decisions through: full life cycle cost accounting, the prioritization of adaptation actions that also mitigate greenhouse gases, the consideration of the state's most vulnerable populations, the prioritization of natural infrastructure solutions, and the use of flexible approaches where possible.[15]

- **Assembly Bill 1482** (2015) requires all state agencies and departments to prepare for climate change impacts through (among others) continued collection of climate data, considerations of climate in state investments, and the promotion of reliable transportation strategies.[16]

- **Senate Bill 246** (2015) establishes the Integrated Climate Adaptation and Resiliency Program to coordinate with regional and local efforts with state adaptation strategies.[17]

- **Assembly Bill 2800** (2016) requires that state agencies account for climate impacts during planning, design, building, operations, maintenance, and investments in infrastructure. It also requires the formation of a Climate-Safe Infrastructure Working Group represented by engineers with relevant experience from multiple state agencies, including the Department of Transportation.[18]

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[13] "Assembly Bill 32 Overview," https://www.arb.ca.gov/cc/ab32/ab32.htm, August 5, 2014
[14] "Executive Order S-13-08," https://www.gov.ca.gov/news.php?id=11036, 2008
[15] "Governor Brown Establishes Most Ambitious Greenhouse Gas Reduction Target in North America," Office of Governor Edmund Brown, https://www.gov.ca.gov/news.php?id=18938, April 29, 2015
[16] "Assembly Bill No. 1482," https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201520160AB1482, October 8, 2015
[17] "Senate Bill No.246," https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201520160SB246, 2015
[18] "Assembly Bill No. 2800," http://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201520160AB2800, September 24, 2016

These policies are among the factors state agencies consider when addressing climate change. Conducting an assessment such as this one for District 4 is a key step towards preserving Caltrans infrastructure and directly addresses the requirements of the relevant state policies above, such as Executive Order B-30-15, Assembly Bill 1482, and Assembly Bill 2800. The study team believes that it is important for Caltrans staff to be aware of the policy requirements surrounding the issue and how this assessment may be used to indicate compliance where applicable. Other policies, such as Executive Order S-13-08, stimulate the creation of climate data which state agencies benefit from.

One of the most pertinent climate adaptation policies out of these is Executive Order B-30-15. Guidance specific to the Executive Order and how state agencies can begin to implement it will be released in 2017. This guidance will help state agencies develop methodologies in completing vulnerability assessments specific to their focus areas and in making adaptive planning decisions. The Executive Order guidance will create a framework to be followed by other state agencies, and having a common framework is important in communicating the effects of climate across agencies.

3.2.2. Research

California has also been on the forefront of climate change research nationally and internationally. For example, Executive Order S-03-05, directs that state agencies develop and regularly update state guidance on climate change. These research efforts are titled the California Climate Change Assessments, which is in its fourth edition (Fourth Climate Change Assessment). To understand the research and datasets coming out of the Fourth Climate Change Assessment, which are utilized in this District 4 vulnerability assessment, some background is needed on Global Climate Models and emissions scenarios.

Global Climate Models (GCMs)

GCMs have been developed worldwide by many academic or research institutions to represent the physical processes to model or predict how the Earth's climate may change, and to project system responses to increasing GHG emissions.[19] These models are run to reflect the different estimates of GHG emissions or atmospheric concentrations of these gases, which are summarized for use by the Intergovernmental Panel on Climate Change (IPCC).

The IPCC is the leading international body recognized for its work in quantifying the potential effects of climate change, and its membership is made up of thousands of scientists from 195 countries. The IPCC periodically releases Assessment Reports (currently in its 5th iteration), which summarize the latest research on a broad range of topics relating to climate change. The IPCC updates research on GHG emissions and identifies scenarios that reflect research on emissions generation and estimates for how those emissions may change given international policies. The IPCC also summarizes estimates for how worldwide GHG emissions may result in atmospheric concentrations of GHG emissions to the end of the century.

There are dozens of climate models worldwide, which are used for various purposes by researchers. There are a set of GCMs that have been identified for use in California, as outlined in the following section.

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[19] "What is a GCM?" Intergovernmental Panel on Climate Change, http://www.ipcc-data.org/guidelines/pages/gcm_guide.html, June 18, 2013

Emissions Scenarios

There are two commonly cited sets of emissions data that the IPCC uses in various research efforts:

1. The Special Report Emissions Scenarios (SRES)
2. The Representative Concentration Pathways (RCPs)

The SRES report was released in 2000 and contained a range of emission scenarios. Two scenarios developed through the effort are typically used from their guidance and are referenced later in this report.[20] While the SRES report is 17 years old and new emissions scenarios have become available from the IPCC, the SRES emissions scenarios are still commonly used. Sometimes new models with updated emissions scenarios are not available and previously developed work must be referenced instead. The two SRES scenarios utilized in this report are:

1. **B1**, representing lower emissions, assumes the global population peaking by mid-century, the introduction of clean technologies, lower material intensity, and a global sense of environmental sustainability and equity.
2. **A2**, representing higher emissions, assumes an increasing global population, with eventual slowing of GHG emissions during the second half of the century.

RCPs represent the next generation of scenarios, established in IPCC Assessment Report Five. These scenarios use three main metrics: radiative forcing, emission rates, and emission concentrations.[21] Four RCPs were developed to reflect assumptions for emissions growth, and the resulting concentrations of GHG in the atmosphere. The RCPs developed are applied in GCMs to identify projected future conditions and enable a comparison of one against another. Generally, the RCPs are based on assumptions for GHG emissions growth and an identified point at which they would be expected to begin declining (assuming varying reduction policies or socioeconomic conditions). The RCPs developed for this purpose include the following:

RCP 2.6 assumes that global annual GHG emissions will peak in the next few years and then begin to decline substantially.

RCP4.5 assumes that global annual GHG emissions will peak around 2040 and then begin to decline.

RCP 6.0 assumes that emissions will peak near the year 2080 and then start to decline.

RCP 8.5 assumes that high GHG emissions will continue to the end of the century.[22]

California Fourth Climate Change Assessment

The California Fourth Climate Change Assessment is an inter-agency research and "model downscaling" effort for multiple climate stressors. The Fourth Climate Change Assessment is being led by the California Energy Commission (CEC), but other contributors include agencies such as the Department of Water Resources (DWR) and the Natural Resources Agency (NRA), as well as academic institutions such as the Scripps Institution of Oceanography (Scripps) and the University of California, Merced.

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[20] IPCC Special Report Emissions Scenario: Summary for Policymakers, Intergovernmental Panel on Climate Change, https://www.ipcc.ch/pdf/special-reports/spm/sres-en.pdf, 2000

[21] Wayne, G.P., "A Guide to the IPCC's New RCP Emissions Pathways," https://skepticalscience.com/rcp.php, August 30, 2013

[22] Meinshausen, M.; et al. (November 2011), "The RCP greenhouse gas concentrations and their extensions from 1765 to 2300 (open access)", Climatic Change, 109 (1-2): 213–241

The model downscaling is a statistical technique that refines the results of GCMs to a regional level. The model downscaling used in the Fourth Climate Change Assessment is a technique called Localized Constructed Analogs (LOCA), which "uses past history to add improved fine scale detail to GCMs."[23] This data source provides a finer grid system than is found in other techniques, enabling the assessment of changes in a more localized way than was previously available, since past models summarized changes with lower resolution. This effort was undertaken by Scripps.[24] Out of the 32 LOCA downscaled GCMs for California, 10 models were chosen by state agencies for high performance in California. This effort was led by the Department of Water Resources amongst other agencies to understand which models to use in their assessments and planning decisions.[25] The 10 representative GCMs for California are:

- ACCESS 1-0
- CanESM2
- CCSM4
- CESM1-BGC
- CMCC-CMS
- CNRM-CM5
- GFDL-CM3
- HadGEM2-CC
- HadGEM2-ES
- MIROC5

Data from these models are available on Cal-Adapt 2.0, California's Climate Change Research Center.[26] The Cal-Adapt 2.0 data is considered to be some of the best available data in California on climate change and, for this reason, selections of data from the GCMs described above were utilized in this study. The data used from the Fourth Climate Change Assessment depended upon what was available during the course of the Caltrans vulnerability assessments.

3.3.   Bay Area Efforts Underway

In addition to the statewide efforts outline above, the Bay Area is responsible for its own regional efforts surrounding climate change and has taken a very active approach in addressing sea level rise. As mentioned earlier, BCDC has been leading the activities in the region to determine the potential effects of sea level rise. In 2011, BCDC published *Living with a Rising Bay*, which presented the results of an initial vulnerability assessment of the Bay Area using two SLR projections: 16 inches (40 centimeters) by mid-century and 55 inches (140 centimeters) by end of century.[27] The assessment was focused on three planning areas: shoreline development, the Bay ecosystem, and governance. Conclusions were drawn

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[23] "Download Data," Cal-Adapt 2.0, http://cal-adapt.org/data/, 2017

[24] Pierce et al.,"Statistical Downscaling Using Localized Constructed Analogs," http://journals.ametsoc.org/doi/abs/10.1175/JHM-D-14-0082.1 , 2014

[25] "LOCA Downscaled Climate Projections," Cal-Adapt 2.0, http://beta.cal-adapt.org/data/loca/, 2017 (and http://www.water.ca.gov/climatechange/docs/2015/Perspectives_Guidance_Climate_Change_Analysis.pdf)

[26] For more information, visit http://beta.cal-adapt.org/

[27] The Bay Area Conservation and Development Commission, *Living with a Rising Bay*, http://www.bcdc.ca.gov/BPA/LivingWithRisingBay.pdf, 2011

on a few specific areas that may be heavily exposed to SLR including the San Francisco and Oakland Airports, critical natural habitats that need preservation, and the change in governing borders as SLR progresses.

BCDC was also a lead in co-founding the Adapting to Rising Tides (ART) Program, which leads and supports cross-jurisdictional projects in the Bay Area to study SLR and adaptation implementation. ART has partnered with other key stakeholders such as MTC, the California Coastal Conservancy, and the San Francisco Public Utilities Commission, amongst others.[28] The ART Program provides online tools and reference reports to serve as a resource for other jurisdictions that are planning to address climate change and sea level rise.

BCDC, in collaboration with Caltrans District 4, MTC and the Bay Area Regional Collaborative (BARC), is conducting a project funded through a Caltrans grant to complete a vulnerability assessment for the Bay Area. This vulnerability assessment will include transportation assets, vulnerable and disadvantaged communities, Priority Development Areas, and Priority Conservation Areas. The grant also provides funding to develop initial adaptation strategies for these assets. [29] BCDC has a history of addressing SLR across the Bay Area and continues to be an important partner for District 4 as concerns specific to the State Highway Network are defined and addressed.

Caltrans has also addressed sea level rise in the Bay through its own guidance. In 2011, Caltrans released the *Guidance on Incorporating Sea Level Rise* document for use by Caltrans Planning staff and Project Development Teams. The guidance provides initial criteria for consideration to determine whether or not sea level rise needs to be incorporated into project programming and design. Factors that should be considered include: the project design life, the existence of alternative routes, anticipated travel delays, evacuations, traveler safety, and environmental constraints. Sea level rise projections for this guidance are adopted from the OPC's 2011 guidance for the state.[30]

3.4.   General Methodology

The applied methodology varies from stressor to stressor—since each uses a different set of models, emissions scenarios, and assumptions—in order to base data on which to develop an understanding of potential future conditions. The specific methods employed are further defined in each stressor section; however, there are some general practices that apply across all analyses approaches.

3.4.1. Time Periods

It is desirable to present climate projections in a way that allows for consistent comparisons for various analysis periods and for different stressors. For this study, those analysis periods have been defined as the beginning, middle, and end of century and represented by the out-years 2025, 2055, and 2085, respectively. These years are chosen because some statistically derived climate metrics used in this report (e.g. the 100-year precipitation event) are typically calculated over 30-year time periods centered on the year of interest. Because currently available climate projections are only available through the end of the century, the most distant 30-year window runs from 2070 to 2099. 2085 is the center point of this time range and, thus, the last year in which statistically derived projections can defensibly be

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[28] Adapting to Rising Tides, "Regional Sea Level Rise Mapping and Shoreline Analysis," http://www.adaptingtorisingtides.org/project/regional-sea-level-rise-mapping-and-shoreline-analysis/, n.d.

[29] Adapting to Rising Tides, "ART Bay Area," http://www.adaptingtorisingtides.org/project/art-bay-area/, 2017

[30] Caltrans, *Guidance on Incorporating Sea Level Rise*, http://www.dot.ca.gov/ser/downloads/sealevel/guide_incorp_slr.pdf, May 16, 2011

made. The 2025 and 2055 out-years follow from the same logic, but applied to each of the prior 30-year periods (2010 to 2039 and 2040 to 2069, respectively).

3.4.2. Geographic Information Systems (GIS) and Geospatial Data

Developing an understanding of Caltrans assets exposed to sea level rise, storm surge, and projected changes in temperature, precipitation, and wildfire required complex geospatial analyses. The geospatial analyses were performed using Esri geographic information systems (GIS) software. The general approach for each hazard's geospatial analysis was as follows:

Obtain/conduct hazard mapping: The first step in all the GIS analyses was to obtain or create maps showing the presence and/or value of a given hazard at various future time periods under different climate scenarios. For example, extreme temperature maps were created for temperature metrics important to pavement binder grade specifications, maps of extreme (100-year) precipitation depths were developed to ascertain changes in rainfall, burn counts were compiled to produce maps indicating future wildfire frequency, and sea level rise and storm surge inundation maps were obtained to understand the impacts of future tidal flooding.

Determine critical hazard thresholds: Some hazards studied, namely temperature, precipitation, and wildfire, vary in intensity across the landscape. In many locations, the future change in these hazards is not projected to be high enough to warrant special concern whereas other areas may see a large increase in the hazard under climate change. To highlight the areas most affected by climate change, the geospatial analyses for these hazards involved a step to define, in conjunction with Caltrans officials, the critical thresholds for which the value of (or change in value of) a hazard would be great enough to be impactful. For example, the wildfire geospatial analysis involved several steps to indicate which areas are considered to have a moderate, high, and very high fire exposure based on the projected frequency of wildfire.

Overlay the hazard layers with Caltrans roadways to determine exposure: Once high hazard areas had been mapped, the next general step in the geospatial analyses was to overlay the Caltrans road centerlines on the hazard data to identify the segments of roadway most exposed to each hazard.

Summarize the miles of roadway affected: The final step in the geospatial analyses involved running the segments of roadway exposed to a hazard through Caltrans' linear referencing system. This step, performed by Caltrans, provides an output GIS file indicating the centerline miles of roadway impacted by a given hazard. Using GIS, this data can then be summarized in many ways (e.g. by district, county, municipality, route number, or some combination thereof) to provide useful statistics to Caltrans planners.

Upon completion of the geospatial analyses, GIS data for each step was saved to a database that was supplied to Caltrans at the conclusion of the study. Limited metadata on each dataset was also provided in the form of an Excel table that described each dataset and its characteristics. This GIS data will be useful to Caltrans for future climate adaptation planning activities.

FIGURE 3: SCREENSHOT OF GIS DATABASE

FIGURE 4: SCREENSHOT OF SPREADSHEET PROVIDED

4.   SEA LEVEL RISE

4.1.   How Climate Change Will Affect Sea Levels

The data sets considered for this analysis came from the U.S. Army Corps of Engineers (USACE), the National Research Council (NRC), the Scripps Institute of Oceanography (Scripps), and new state projections from the Ocean Protection Council.[31] Each of these sets of SLR scenarios were chosen for consideration in this analysis in order to: follow state guidance on SLR planning, identify for the reader that there are a fairly wide range of SLR projections, and incorporate a variety of options into the analysis for District 4 to use in decision making. These projections are paired with a hydrological model that includes sea level rise and storm surge, to identify approximately when potential impacts to the State Highway Network may occur in District 4. For more information on how the projections are used given the model, see Section 4.1.4 below.

4.1.1.   U.S. Army Corps of Engineers

The USACE scenarios come from an available online SLR calculator,[32] which generates SLR values for tidal gauges across the United States. Gauges were chosen for the San Francisco Bay Area (Alameda, Port Chicago, Point Reyes, Redwood City, San Francisco, and Coyote Creek gauges) and data was summarized for the High and Intermediate USACE scenarios. The USACE set of scenarios also includes a "Low" scenario, which was not used in this analysis because it assumes that SLR will continue at its current pace, which is no longer considered plausible by most practitioners.

4.1.2.   National Research Council

The NRC scenarios come from a 2012 report prepared for California, Oregon, and Washington by the California Coastal Commission.[33] At the onset of this study, this was still considered the standard set of scenarios to use in California, as recommended by the Ocean Protection Council's (OPC) California State Guidance on Sea Level Rise document. This document was updated as of April 2017.[34] The individual scenarios are A1F1, A1B, and B1, ranging from lowest to highest GHG emissions. The projections for each of these emissions scenarios are only given for three years: 2030, 2050, and 2100.

4.1.3.   Scripps Institute of Oceanography

Scripps is developing new research for the California Fourth Climate Change Assessment. The SLR estimates currently available use emissions scenarios RCP 4.5 and 8.5, where RCP 4.5 represents lower and RCP 8.5 represents higher emissions. A new element of these data is the development of percentile values for SLR, based on estimates for how each contributing factor may impact the overall estimate. As an example, a 50th percentile value would mean that 50 percent of all the simulations for SLR had a value below the one shown. These are among the most recently developed SLR scenarios for California and can be considered the "best available" projections.

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[31] State of California Sea Level Rise Guidance: 2018 Update, Ocean Protection Council, http://www.opc.ca.gov/webmaster/_media_library/2017/11/State-of-California-Sea-Level-Rise-Guidance_draft-final_11.15.17.pdf
[32] Sea-Level Change Curve Calculator, U.S. Army Corps of Engineers, http://www.corpsclimate.us/ccaceslcurves.cfm, November 19, 2014
[33] https://www.nap.edu/catalog/13389/sea-level-rise-for-the-coasts-of-california-oregon-and-washington
[34] Griggs, G, Árvai, J, Cayan, D, DeConto, R, Fox, J, Fricker, HA, Kopp, RE, Tebaldi, C, Whiteman, EA (California Ocean Protection Council Science Advisory Team Working Group). Rising Seas in California: An Update on Sea-Level Rise Science. California Ocean Science Trust, http://www.opc.ca.gov/webmaster/ftp/pdf/docs/rising-seas-in-california-an-update-on-sea-level-rise-science.pdf, April 2017

Many different data sources can lead to some confusion on their application, particularly given different base-year assumptions. Figure 5 shows the USACE, NRC 2012, and Scripps estimates, applying the same base year and vertical land movement assumptions. Since the NRC 2012 data is only given for three years, these projections are given as points in time, rather than curves. The chart also identifies the Coastal Storm Modeling System (CoSMoS) model increments explained on the following pages, which are represented on the y-axis. Note that before mid-century, the scenarios are very similar in their projections, but the range begins to widen as time goes on and uncertainty increases.

FIGURE 5: AVERAGE SEA LEVEL RISE PROJECTIONS: GAUGES LOCATED IN DISTRICT 4
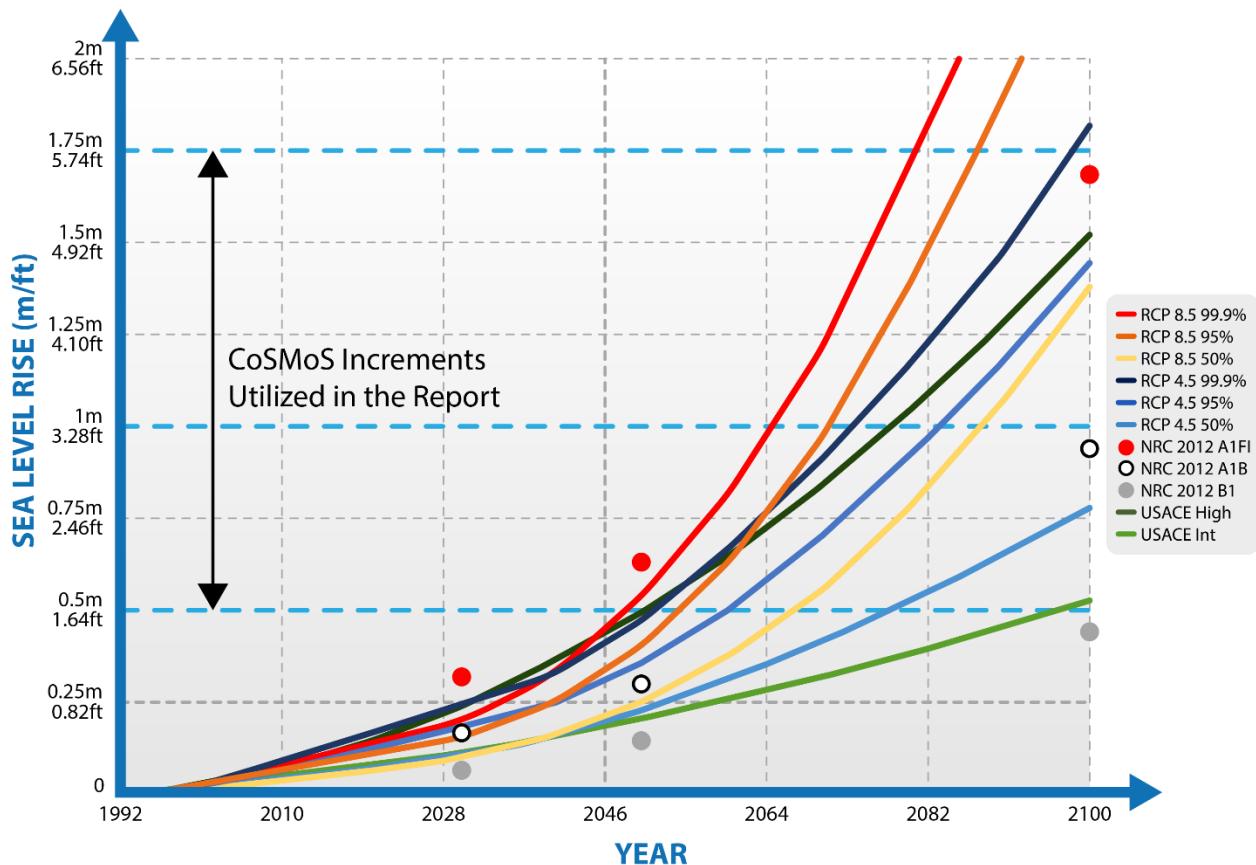
Notes:
Data represented are averaged from six gauges, except for B1 and A1FI which are estimates developed using only one gauge.
All SLR scenarios are estimates based upon existing datasets and a number of assumptions given vertical land movement and rates of SLR. Each dataset has been manipulated to a base year of 1992 for comparison.

There are uncertainties in SLR projections that come from variances from several factors, including GHG projections, rates of ice melt, rates of thermal expansion, and accuracy of climate models. While there is relative certainty in rising sea levels, it is unknown precisely how the oceans will rise in response to atmospheric GHG emissions. The appropriate use of these projections is to understand the range of scenarios and plan with uncertainty in mind, by understanding the implications of any adaptation strategies recommended.

4.1.4. State of California Sea Level Rise Guidance: 2018 Update (Draft)

As of November 2017, the Ocean Protection Council (OPC) and California Natural Resources Agency released the 2018 Draft update to the California Sea Level Rise Guidance document. In an effort to be as

comprehensive as possible, the projections utilized in the OPC report are also included in the figure below. These estimates of SLR were developed by a scientific panel and are based upon various projections of factors that drive SLR, such as thermal expansion and melting land ice. Research on these variables is ongoing and will be constantly updating, long after the completion of this report. These projections use a base year of 2000 that incorporates average sea level rise from 1992 to 2009, and are for San Francisco.

FIGURE 6: OPC 2018 DRAFT GUIDANCE SEA LEVEL RISE PROJECTIONS
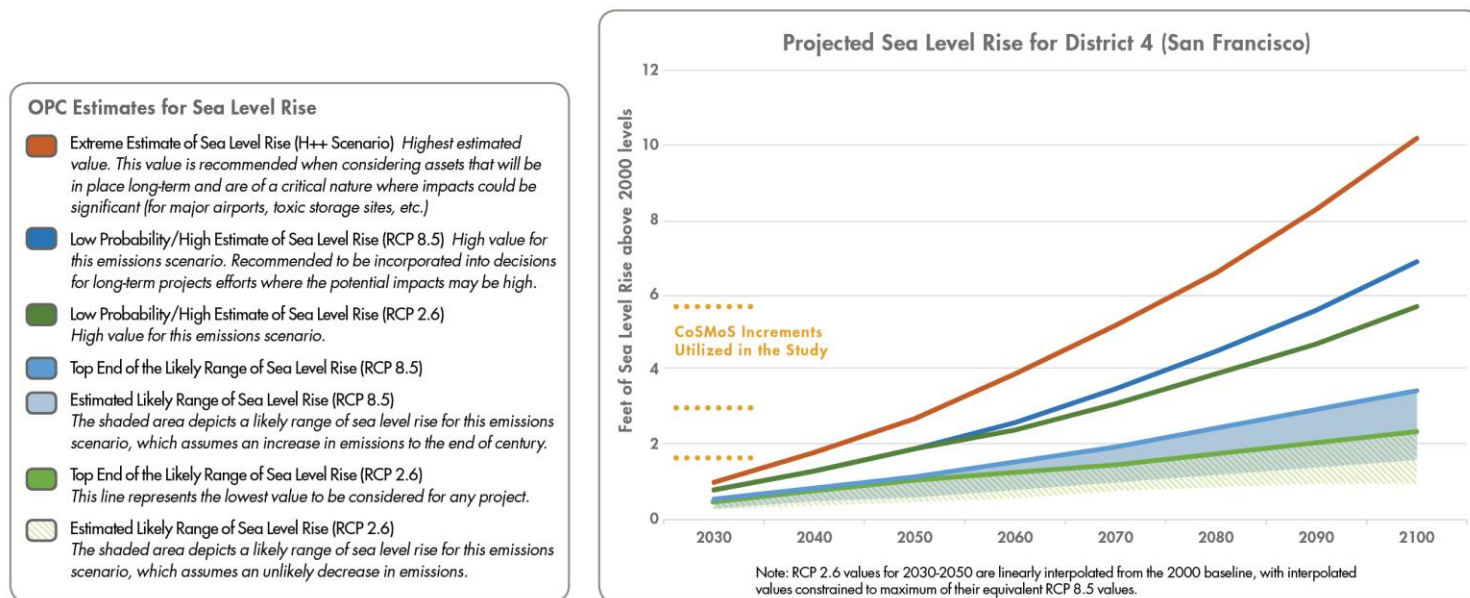
Note: The OPC guidance outlines an approach for incorporating sea level rise into planning, permitting, and investment decisions which recognizes the uncertainties for future SLR. The sea level rise estimates shown above are the values the guidance identifies that practitioners should consider. When making decisions, practitioners are advised to address the impacts of various water levels on project alternatives, identify possible adaptive designs that can be altered to adjust to changing future conditions, and consider the risk tolerance for assets. This approach is recommended for Caltrans assets, and a design approach that includes these considerations is outlined on page 32 of this document.

4.1.5. Model Used

The previous section outlines the estimates for SLR from various sources, while this section discusses the CoSMoS storm model applied for this study. The CoSMoS model was developed by the United States Geological Survey (USGS) and the data can be viewed and downloaded from the Our Coast Our Future site.[35] The model was funded by stakeholders to understand the associated impacts of various storm events combined with future SLR along the California coast and within San Francisco Bay.

The methodology for developing CoSMoS data varies significantly for the Bay Area, but is compatible with data created for the California coastline. The data is generated by applying: numerically modeled wind-wave heights, projected freshwater discharges from the Sacramento-San Joaquin Delta, the effects of ocean swell penetration in the Central Bay, vertical land motion, marsh acceleration/erosion, and uncertainties related to LIDAR, Digital Elevation Models (DEMs), and flood models.[36] The CoSMoS model

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[35] http://data.pointblue.org/apps/ocof/cms/
[36] US Geological Survey, "CoSMoS 2.1 San Francisco Bay," https://walrus.wr.usgs.gov/coastal_processes/cosmos/sfbay/index.html, November 17, 2015

is very robust in the variables considered and is conservative in its estimates by always considering maximum water levels for simulated storm events.

CoSMoS data is available in GIS shapefiles and was developed for SLR from 0.00 to 2.00 meters, in quarter-meter increments, and 5.00 meters to reflect longer-term change. Analysis of the State Highway System was completed for all CoSMoS increments. However, the analysis presented in this report is specific to three increments of SLR developed by the model: 1.64, 3.28, and 5.75 feet (0.50, 1.00, and 1.75 meters). For estimates of when each CoSMoS increment may occur, see Figure 5 and Figure 6 to identify approximately when various SLR scenarios will reach the CoSMoS heights and the range between projections.

In addition to considering all increments of SLR rise on their own, the project study team also analyzed the effects from an annual storm event (a storm that happens on average once a year). A one year return period storm event was used to identify when the initial effects of SLR may begin to impact the District 4 State Highway System or other District 4 assets. For the purpose of this analysis, miles exposed to SLR include bridge centerlines. Exposed centerline miles are summarized in Table 1, which indicates counties most affected by sea level rise. District 4 may choose to prioritize adaptation in these counties first or identify specifically where these exposed roadways are, using the GIS data provided by the project study team.

TABLE 1 DISTRICT 4 ROADWAYS HIGHWAY CENTERLINE MILES EXPOSED TO SEA LEVEL RISE AND AN ANNUAL STORM

	Sea Level Rise		
	1.64 ft (0.50 m)	**3.28 ft (1.00 m)**	**5.74 ft (1.75 m)**
Sonoma County	3.6	4.8	5.2
Napa County	0.1	0.1	0.4
Marin County	5.9	11.8	17.2
Solano County	2.5	2.8	11.0
Contra Costa County	2.1	2.3	3.6
Alameda County	4.9	7.4	19.0
San Francisco County	5.0	5.1	5.7
San Mateo County	7.7	17.4	27.3
Santa Clara County	2.1	2.5	4.9

4.2. Bridge Exposure

When considering bridge exposure to climate change and associate sea level rise, it is important to note that facilities are often designed to historical conditions, and the changes to those conditions brought by SLR or storm surge may make a facility more vulnerable to damage. Leaving these potential impacts unconsidered would be an oversight of this analysis, so it is important that they be included and carried forward into later Caltrans efforts.

Figure 7 highlights a set of potential concerns for a bridge in addition to overtopping. They are presented to help set the broader context for the definition of facility risk when considering sea level rise. For bridges, this means that changing water levels can cause a wider range of impacts to a facility

up to and including overtopping. It will be important to Caltrans to consider all potentially at-risk facilities and pursue additional analysis as necessary. The list of concerns includes:

- A rising groundwater table may inundate supports on land that were not built to accommodate saturated soil conditions, leading to erosion of soils and loss of stability.

- Higher sea levels mean greater forces on the bridge during normal tidal processes, increasing scour effects on bridge structure elements.

- Higher water levels mean that storm surge will be higher and have more force than today. These forces would potentially impact scour on bridge substructure elements.

- Bridge approaches where the roadway transitions to the bridge deck may become exposed to surge forces and may become damaged during storms.

- Surge and wave effects may loosen or damage portions of the bridge, requiring securing, re-attaching, or replacing those parts.

FIGURE 7: BRIDGE EXPOSURE
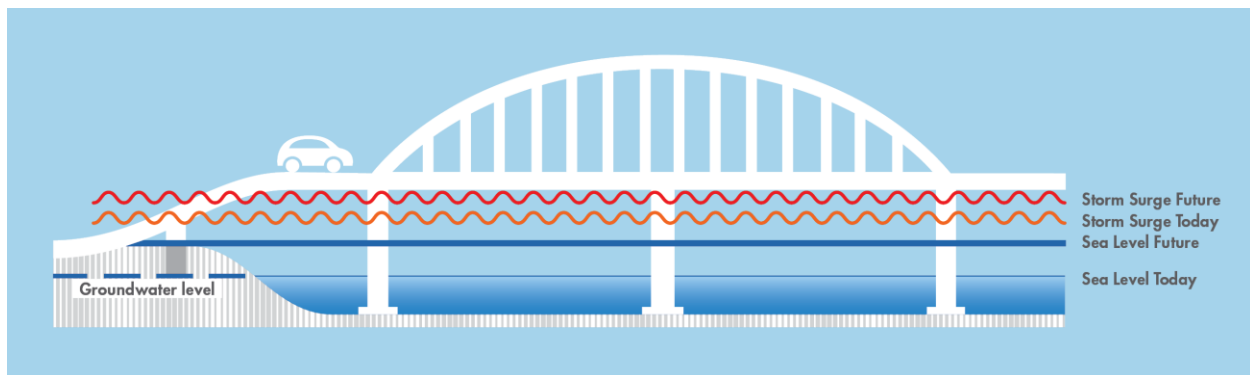
The maps presented on the following page depict the 1.64, 3.28, and 5.74 feet (0.50, 1.00, and 1.75 meter) CoSMoS increments for SLR and indicate roadways (including bridges) at risk of inundation or exposure from higher sea levels.

SEA LEVEL RISE IMPACTS TO THE CALTRANS STATE HIGHWAY SYSTEM

Legend:
- Exposed Roadway
- Inundated Land

1.64FT (0.5M) OF SEA LEVEL RISE

Caltrans Transportation Asset Vulnerability Study, District 4, Caltrans No. 74A0737. Sea level rise and storm surge data provided by the U.S. Geological Survey from the Coastal Storm Modeling System (CoSMoS). GIS data from CoSMoS can be viewed and downloaded from the Our Coast Our Future interactive map available here: http://data.pointblue.org/apps/ocof/cms/

FIGURE 9: EXPOSURE TO 3.28 FEET (1.00 METER) SEA LEVEL RISE

SEA LEVEL RISE IMPACTS TO THE CALTRANS STATE HIGHWAY SYSTEM

Exposed Roadway
Inundated Land

3.28FT (1M) OF SEA LEVEL RISE

Caltrans Transportation Asset Vulnerability Study, District 4, Caltrans No. 74A0737. Sea level rise and storm surge data provided by the U.S. Geological Survey from the Coastal Storm Modeling System (CoSMoS). GIS data from CoSMoS can be viewed and downloaded from the Our Coast Our Future interactive map available here: http://data.pointblue.org/apps/ocof/cms/

FIGURE 10: EXPOSURE TO 5.74 FEET (1.75 METERS) SEA LEVEL RISE

SEA LEVEL RISE IMPACTS TO THE CALTRANS STATE HIGHWAY SYSTEM

Exposed Roadway
Inundated Land

5.74FT (1.75M) OF SEA LEVEL RISE

Caltrans Transportation Asset Vulnerability Study, District 4, Caltrans No. 74A0737. Sea level rise and storm surge data provided by the U.S. Geological Survey from the Coastal Storm Modeling System (CoSMoS). GIS data from CoSMoS can be viewed and downloaded from the Our Coast Our Future interactive map available here: http://data.pointblue.org/apps/ocof/cms/

5.   STORM SURGE

5.1.   How Climate Change Will Affect Storm Surge

Rising seas translate into more water that can be in motion during storm surge events, increasing long-term risks to infrastructure. Any estimate of future storm surge must also consider the contributory effects of new storm types caused from climate change – that is, the possible effect on storm intensities from a warming ocean or atmosphere. Figure 11 identifies the basic elements of storm surge and how it is different from normal tidal conditions. The graphic, supplied by the National Oceanic and Atmospheric Administration (NOAA) and edited for this study, shows the effect and movement of surge over the land and the additional concern of waves at the shoreline.

 Studies have shown that the San Francisco Bay/Sacramento-San Joaquin Delta estuary system could be subject to high storm surge that in future years could have a significant impact on the surrounding land and the levees that protect this land.[37] Table 2 shows some of the potential impacts of storm surge combined with sea level rise on transportation infrastructure in the Bay Area.
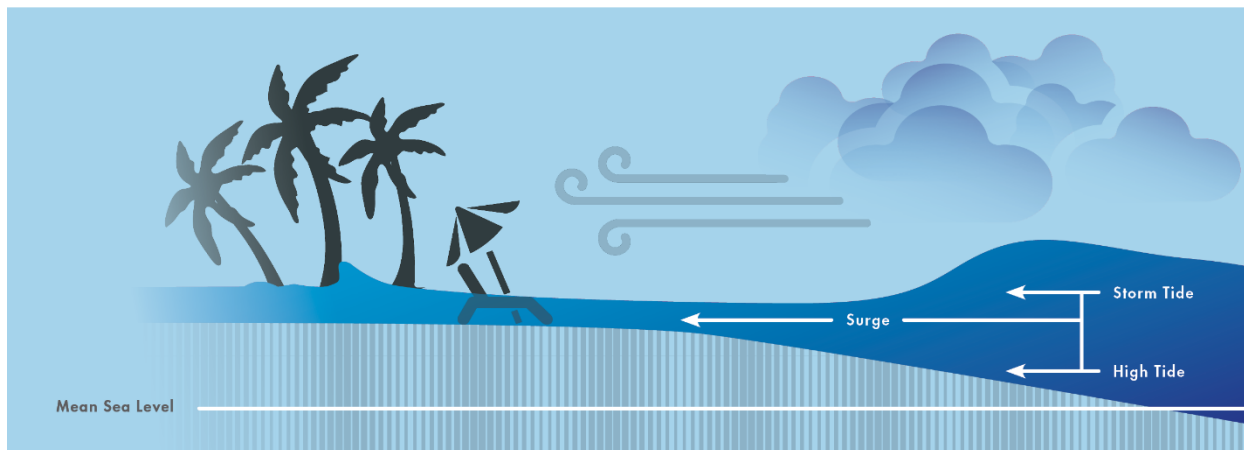
FIGURE 11: BASIC ELEMENTS OF STORM SURGE

USGS has developed estimates of future storm surge with the CoSMoS model. CoSMoS models the effects of SLR combined with storm surge events for coastal California. For the purposes of this study, estimates for storm surge effects on Caltrans roadways are displayed for 1.64, 3.28, and 5.74 feet (or 0.50, 1.00, and 1.75 meters) of SLR combined with the 100-year storm event.

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[37] See, for example, Bromirski and Flick, "Storm Surge in the San Francisco Bay/Delta and Nearby Coastal Locations," *Shore and Beach*, " Vol. 76, No. 3, Summer 2008. Accessed at, http://www.bayplanningcoalition.org/downloads/dmc10/compendium/01_Bromirski_Flick_2008.pdf; and Biging, Greg S., John D. Radke, and Jun Hak Lee (University of California, Berkeley). "Impacts of Predicted Sea-Level Rise and Extreme Storm Events on the Transportation Infrastructure in the San Francisco Bay Region." California Energy Commission. Publication number: CEC-500-2012-040. 2012. Accessed at, http://www.energy.ca.gov/2012publications/CEC-500-2012-040/CEC-500-2012-040.pdf.

TABLE 2: POTENTIAL IMPACTS OF CLIMATE CHANGE ON TRANSPORTATION

Potential Impact	Potential Operational Impact
Coastal road flooding	Disruption of traffic, delay of evacuation and emergency response, increased congestion. Permanent breaks in the topological structure of the overall transportation network
Railway flooding	Disruption of traffic, delay, increased risk of hazardous material spill
Underground tunnels and subway flooding	Disruption and slowdown of subway traffic resulting in increased car, bus, and train commuting
Erosion of coastal roads and rails	Potential road slump or failure, potential railbed instability or failure
Port flooding and damage	Negative impact on commerce and manufacturing from delays in cargo handling
Bridge scour	Erosion of sediment from around bridge abutments or piers, adding to increased maintenance, potential failure, and periodic bridge closures
Inundation of airport runways in coastal areas	Closure or slowdown in flight arrivals and departures, need for levee construction
Higher tides at ports facilities	Erosion of shoreline adding to increased maintenance, need for levee construction, and periodic traffic disruption

Source: Biging, Radke, and Lee, op cit.

The 100-year storm event is a design standard for infrastructure projects and is the Base Flood Elevation as determined by the Federal Emergency Management Agency (FEMA). For this reason, the 100-year storm event is an important design metric despite its infrequent occurrence, and is one many infrastructure projects should be prepared to withstand. Table 2 summarizes, by county, the centerline lengths of the Caltrans District 4 roadways and bridges that would be exposed during the 100-year storm event. To some extent, the January, 2017 extreme storms accompanied by storm surge in the Bay Area and associated coastal flooding was a preview of what could happen more frequently and severely in the future.

TABLE 2: DISTRICT 4 HIGHWAY CENTERLINE MILES EXPOSED TO SEA LEVEL RISE AND THE 100-YEAR STORM EVENT

	Sea Level Rise		
	1.64 ft (0.50m)	3.28 ft (1.00m)	5.74 ft (1.75m)
Sonoma County	4.7	5.0	6.4
Napa County	0.1	0.1	0.4
Marin County	10.6	13.5	19.5
Solano County	2.6	2.9	11.7
Contra Costa County	2.3	2.3	4.4
Alameda County	5.6	10.0	25.3
San Francisco County	5.1	5.1	6.7
San Mateo County	15.9	25.7	30.4
Santa Clara County	2.3	4.3	5.4

The modeling and analysis show that the State Highway Network will be most exposed to the 100-year storm event in Marin, Alameda, and San Mateo Counties. With 5.74 feet of sea level rise (the high end of plausible values for the end of the century per the latest science) the 100-year storm could affect around 20 miles of Caltrans roadways in Marin County, 25 miles in Alameda County, and 30 miles in San Mateo County (note that this includes potential impacts to bridges across the Bay). This illustrates the scale of the challenge facing District 4 with respect to this hazard. The following maps identify specific locations exposed to the future 100-year storm event throughout the district. As can be seen, portions of State Route 37 and US 101 near the Bay are particularly exposed.

FIGURE 12: EXPOSURE TO 1.64 FEET (0.50 METERS) SEA LEVEL RISE AND 100-YEAR STORM EVENT

100-YEAR STORM SURGE IMPACTS TO THE CALTRANS STATE HIGHWAY SYSTEM

Exposed Roadway
Inundated Land

1.64FT (0.5M) OF SEA LEVEL RISE

Caltrans Transportation Asset Vulnerability Study, District 4, Caltrans No. 74A0737. Sea level rise and storm surge data provided by the U.S. Geological Survey from the Coastal Storm Modeling System (CoSMoS). GIS data from CoSMoS can be viewed and downloaded from the Our Coast Our Future interactive map available here: http://data.pointblue.org/apps/ocof/cms/

FIGURE 13: EXPOSURE TO 3.28 FEET (1.00 METER) SEA LEVEL RISE AND 100-YEAR STORM EVENT

100-YEAR STORM SURGE IMPACTS TO THE CALTRANS STATE HIGHWAY SYSTEM

— Exposed Roadway
■ Inundated Land

3.28FT (1M) OF SEA LEVEL RISE

Caltrans Transportation Asset Vulnerability Study, District 4, Caltrans No. 74A0737. Sea level rise and storm surge data provided by the U.S. Geological Survey from the Coastal Storm Modeling System (CoSMoS). GIS data from CoSMoS can be viewed and downloaded from the Our Coast Our Future interactive map available here: http://data.pointblue.org/apps/ocof/cms/

FIGURE 14: EXPOSURE TO 5.74 FEET (1.75 METERS) SEA LEVEL RISE AND 100-YEAR STORM EVENT

100-YEAR STORM SURGE IMPACTS TO THE CALTRANS STATE HIGHWAY SYSTEM

Exposed Roadway
Inundated Land

5.74FT (1.75M) OF SEA LEVEL RISE

Caltrans Transportation Asset Vulnerability Study, District 4, Caltrans No. 74A0737. Sea level rise and storm surge data provided by the U.S. Geological Survey from the Coastal Storm Modeling System (CoSMoS). GIS data from CoSMoS can be viewed and downloaded from the Our Coast Our Future interactive map available here: http://data.pointblue.org/apps/ocof/cms/

6. WILDFIRE

Wildfire frequency and intensity is expected to be affected by changes in climate due to increasing temperatures, changing precipitation patterns, and resulting changes to land cover.

Wildfire is a direct concern for:

- Driver safety

- System operations

- Caltrans infrastructure.

Wildfires can indirectly contribute to:

- Landslide and flooding exposure, by burning off soil-stabilizing land cover and reducing the capacity of the soils to absorb rainfall.

- Wildfire smoke, which can impact visibility and the health of the public and Caltrans staff.

The information gathered and assessed to develop wildfire vulnerability for D4 included research on the impact of climate change on wildfire recurrence. This is of interest to several agencies, including the U.S. Forest Service (USFS), which has developed models to assess wildfire occurrence. One such wildfire model created by the USFS is the MC1 Dynamic Global Vegetation Model, developed in collaboration with Oregon State University. This model considers projections of future temperature and precipitation and the changes these will have on vegetation types. The model outputs available at the time of this report made use of the older IPCC Coupled Model Intercomparison Project 3 (CMIP3) dataset. The next generation of the wildfire model, MC2, was being developed and run using the more recent CMIP5 climate projections (which involve the RCP emissions scenarios) at the time the analyses for this report were being undertaken. The outputs of MC2 are now available but this analysis uses the MC1 outputs since the MC2 modeling was not available in time for inclusion.

Two GCMs were utilized to generate the temperature and precipitation inputs used in the wildfire modeling: the Geophysical Fluid Dynamics Laboratory (GFDL) model and the Parallel Climate Model (PCM). Also, two emissions scenarios, the B1 and A2 scenarios, had been processed through the wildfire model by USFS. Since the B1 scenario is widely regarded as being overly optimistic regarding the ability to reduce GHG emissions, only the A2 scenario, which assumes a moderate increase in GHG concentrations, was analyzed for this report.

The wildfire projections were developed for the three future 30-year time periods identified for use in this study. These land on the approximate median years of 2025, 2055, and 2085 and are represented as such on the wildfire maps below. However, these median years represent thirty year averages, where 2025 is the average between 2010 and 2039, and so on.

The MC1 wildfire model is raster based. The output of the model indicates whether, for a given time period, a fire occurs in each cell. The raster cell size is 30 arc seconds per side. Arc seconds is a measure of latitude and longitude, where there are 60 arc minutes in a degree of latitude or longitude and 60 arc

seconds in an arc minute. Lines of latitude (the east to west lines on the globe) are essentially evenly spaced when measuring north to south, however, lines of longitude (the north-south lines on the globe, used to measure east-west distances) get more tightly spaced as they approach the poles where they eventually converge. Because of this, the cells in the fire raster are rectangular instead of square and are of different sizes depending on where one is (i.e. they are shorter when measured east-west as you go farther north). Generally, the cells wind up being about 0.5 miles on a side in California.

For this project, the research team was interested in determining the number of times, in each 30-year period, a road may need to be closed due to fire. This was assumed to occur if (1) a fire occurred in the cell the road traversed or (2) a fire occurred in the cell adjacent to the one the road traversed. The rationale for including the latter item is that a fire very close to the road may still require it to be closed due to smoke or as a general precaution. To calculate the metric of interest, the project study team first summed up the number of fires that occurred in each cell during each 30-year analysis period. Next, a GIS routine was undertaken that examined each cell, and all its neighboring cells, and assigned the maximum fire count from among these to the cell of interest; this accounted for possible closures due to fires in nearby cells. Note that cells primarily comprising agricultural or urban areas (as determined by CalFire) were assumed to have no wildfire potential and were assigned fire counts of zero.

The above counting procedure was undertaken for each of the three future 30-year time periods for both climate models (i.e., six total maps were produced). To show the degree of agreement between the models, a classification routine was undertaken that enabled only three maps to be presented (one for each out year). To accomplish this, first the neighborhood-based counts in each cell were divided into the following classes denoting low, medium, and high fire counts:

- Low: 0–2 fires per period
- Medium: 3–5 fires per period
- High: 6+ fires per period

Next, an analysis was performed to find the degree of agreement between the GFDL and PCM-based wildfire model outputs. It was assumed that if both models indicated a high fire count for a cell, the final map would label that cell as having "Very High" fire exposure. If one model indicated the cell would have a high fire count and the other model a medium count, the exposure was classified as "High." If both models indicated a medium fire count for the cell or one model showed a high count and another a low count, then the fire exposure for that cell was classified as "Medium." If one model indicated the cell would have a medium fire count and the other model indicated a low fire count, the cell was classified as having "Low" exposure. Finally, if both models indicated a low fire count for the cell, the fire exposure was classified as being "Very Low." This information is summarized in the table below.

TABLE 4: WILDFIRE EXPOSURE CLASSIFICATION SCHEME

		GFDL Model		
		High	Med	Low
PCM Model	**High**	Very High	High	Medium
	Med	High	Medium	Low
	Low	Medium	Low	Very Low

Using the classification scheme shown in the table, the maps on the following pages identify the District 4 areas that may be more exposed to wildfire as climate changes. Only areas of medium, high, and very high exposure are shown to better emphasize the areas of greatest concern. Graphic icons highlight those Caltrans roads that are likely to be most exposed to wildfire.

FIGURE 15: INCREASE IN WILDFIRE EXPOSURE 2025

INCREASED LIKELIHOOD OF WILDFIRES
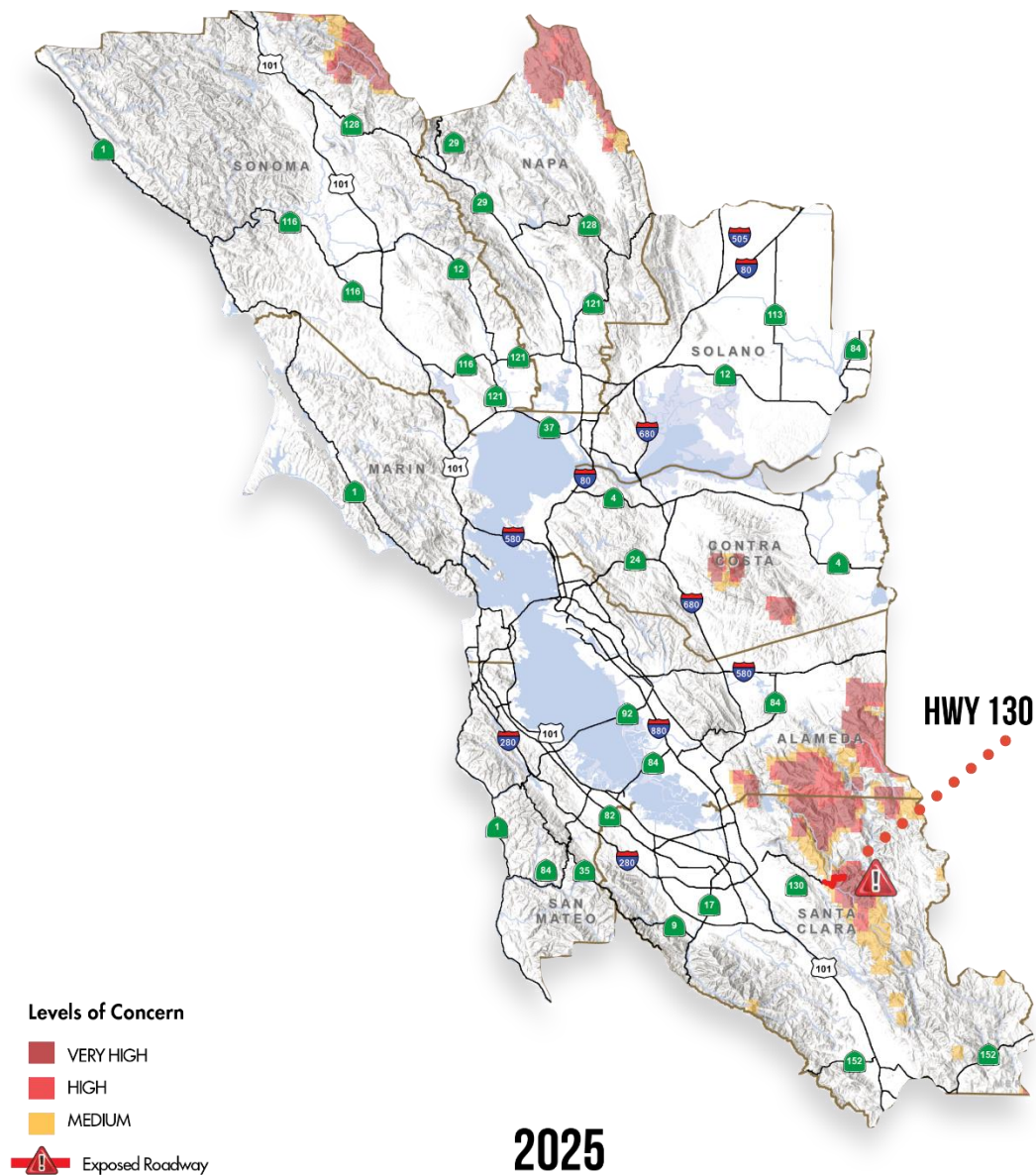
HWY 130

Levels of Concern

VERY HIGH
HIGH
MEDIUM
Exposed Roadway

2025

Increased Likelihood of Caltrans State Highway System Exposed to Wildfires within District 4 in Future Years

Caltrans Transportation Asset Vulnerability Study, District 4. Caltrans No. 74A0737. Fire projections developed using the MC1 fire model by John B. Kim and Bear (G. Stephen) Pitts of the USDA Forest Service Pacific Northwest Research Station.

FIGURE 16: INCREASE IN WILDFIRE EXPOSURE 2055

Increased Likelihood of Caltrans State Highway System Exposed to Wildfires within District 4 in Future Years

Caltrans Transportation Asset Vulnerability Study, District 4. Caltrans No. 74A0737. Fire projections developed using the MC1 fire model by John B. Kim and Bear (G. Stephen) Pitts of the USDA Forest Service Pacific Northwest Research Station.

FIGURE 17: INCREASE IN WILDFIRE EXPOSURE 2085

INCREASED LIKELIHOOD OF WILDFIRES

Levels of Concern

- VERY HIGH
- HIGH
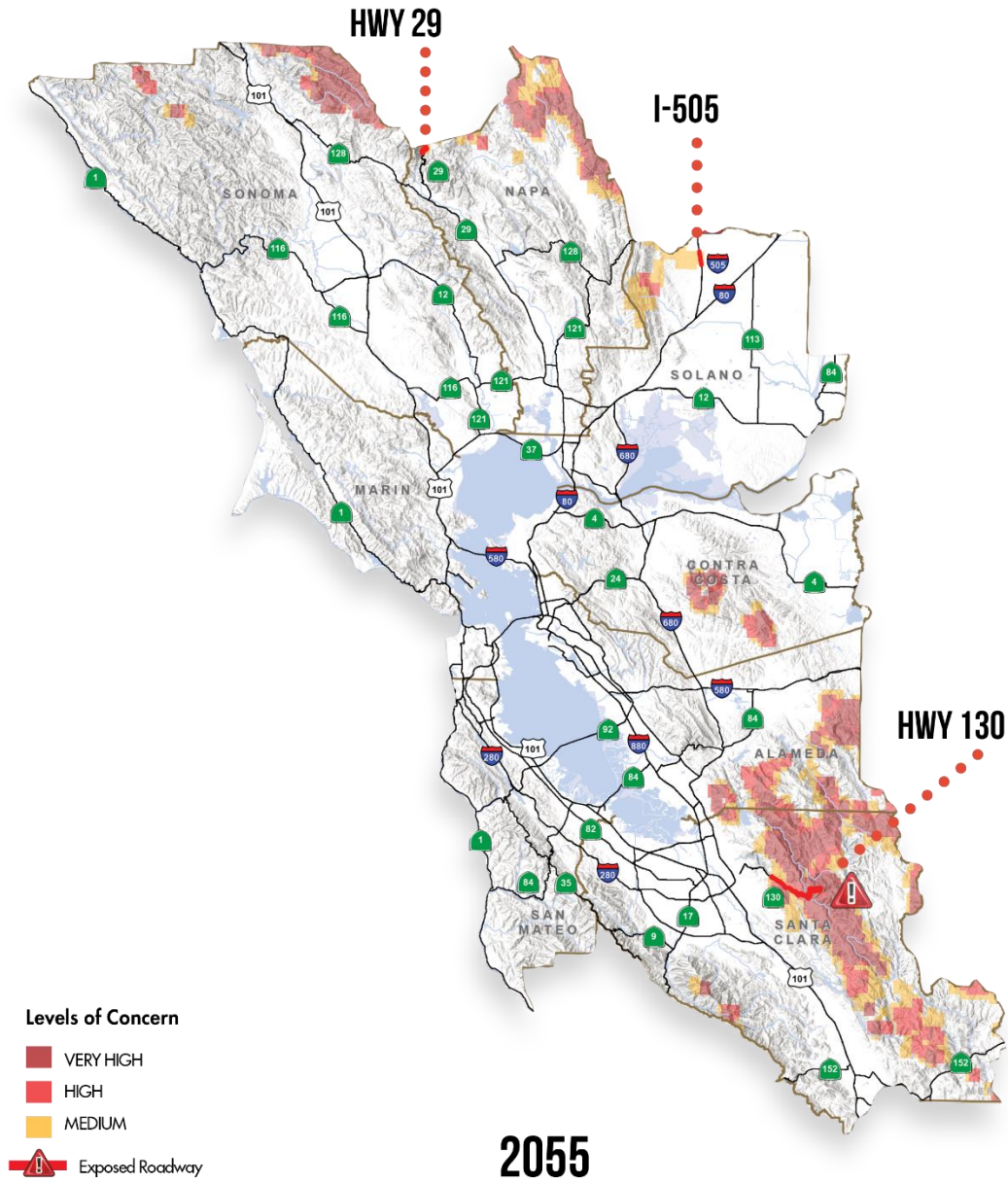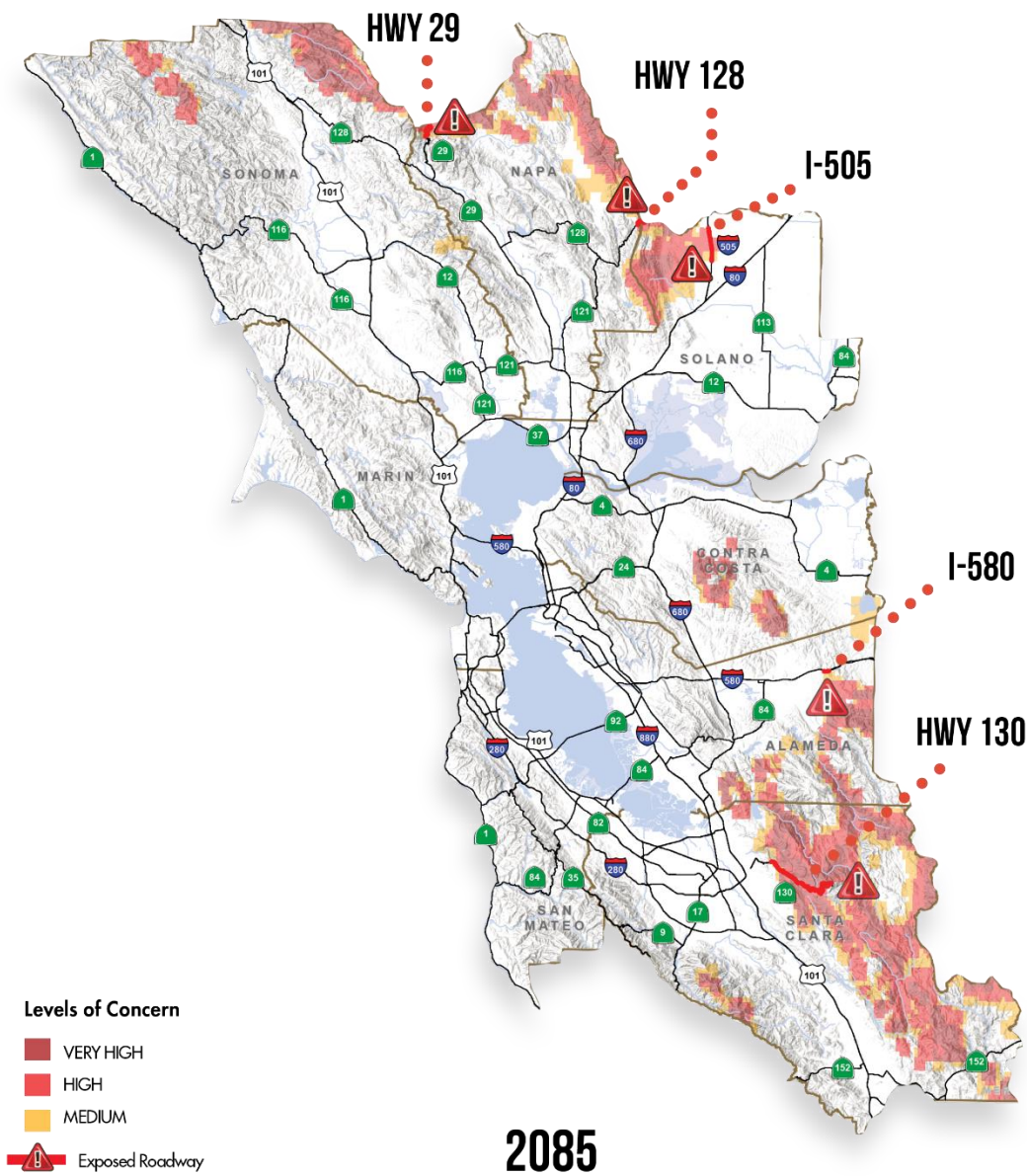- MEDIUM
- Exposed Roadway

2085

Increased Likelihood of Caltrans State Highway System Exposed to Wildfires within District 4 in Future Years

Caltrans Transportation Asset Vulnerability Study, District 4. Caltrans No. 74A0737. Fire projections developed using the MC1 fire model by John B. Kim and Bear (G. Stephen) Pitts of the USDA Forest Service Pacific Northwest Research Station.

7. TEMPERATURE

7.1. How Climate Change Will Affect Temperatures

Temperature rise is an important facet of climate change. Summer temperatures are projected to continue rising, and a reduction of soil moisture, which exacerbates heat waves, is projected for much of the western and central U.S.[38] The potential impacts of extreme temperatures on District 4 assets will vary by asset type, and will depend on the specifications followed in the original design of the facility. For example, the following potential impacts of increasing temperatures have been identified in other studies in the United States.

7.1.1. Design

- Pavement design includes an assessment of temperature in determining recommendations for material.

- Ground conditions and more/less water saturation can alter the design factors for foundations and retaining walls.

- Temperature may affect expansion/contraction allowances for bridge joints.

7.1.2. Operations and Maintenance

- Extended periods of high temperatures will affect safety conditions for employees who work long hours outdoors, such as those working on infrastructure reconstruction and maintenance activities.

- Right-of-way landscaping and vegetation must be able to survive longer periods of high temperatures.

- Extreme temperatures could result in increased maintenance activities, such as replacing pavement sections that have experienced discontinuities and deformation.

Resources available for this study did not allow for a detailed assessment of all the impacts temperature will have on Caltrans activities. Instead, it was decided to take a close look at one of the ways in which temperature will affect Caltrans: the selection of a pavement binder grade. Binder is essentially the "glue" that ties together the aggregate materials in asphalt. Selecting the appropriate and recommended pavement binder is reliant, in part, on the following two temperature metrics relating to high and low temperatures:

- **Low temperature** – The mean of the annual lowest temperatures expected over a pavement's design life.

- **High temperature** – The mean of the highest mean seven consecutive day high temperatures expected during a pavement's design life.

These climate metrics are critical to determining the extreme pavement temperatures a roadway may experience over time. This is important to understand because a binder must be selected that is able to

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[38] U.S. National Climate Assessment, http://nca2014.globalchange.gov/report/our-changing-climate/extreme-weather

maintain pavement integrity under both extreme cold conditions (which leads to contraction) and high heat (which leads to expansion).

The work completed for this effort included assessing the expected low and high temperatures for pavement binder specification in three future 30-year periods centered on the years 2025, 2055 and 2085. Understanding the metrics for these periods will enable Caltrans to gain insights on how pavement design may need to shift over time. Asphalt pavements are typically put in place for a period of approximately 20 years so their design lives match closely the 30-year analysis periods used in this report. Because of their relatively short design lives, asphalt overlays of different specifications can be used as climate conditions change.

Climate model data were assessed to determine potential concerns due to changing temperatures. The project study team used the LOCA climate data developed by Scripps for this purpose,[39] which has a spatial resolution of 1/16 of a degree or approximately 3.5 to four miles.[40] This data set was queried to determine the annual lowest temperature and the mean seven-day consecutive high temperature. Temperature values were identified for each 30-year period. The values were derived separately for each of the 10 California appropriate GCMs, for both RCP scenarios, and for the three time periods noted. These values were identified for each cell in the climate data to enable comparisons across the many different physiographic regions in California.

The maps shown are for the model that represents the median change across the state, among all California approved climate models for RCP 8.5 (data for RCP 4.5 has also been analyzed but for brevity is not shown here). The maps highlight the temperature change expected for both the maximum and minimum metrics. Changes to both temperature metrics become greater over time with the maximum temperature changes generally being greater than the minimum changes. Some areas may experience change in the maximum temperature metric upwards of 12 degrees Fahrenheit by the end of the century. Finally, for both metrics, temperature changes are generally greater the further inland one goes, due to the moderating influence of the Pacific Ocean.

The change values shown on the maps can be added to Caltrans' current source of historical temperature data to determine the final design value for the future. This summary data can be used by Caltrans to identify how pavement design practices may need to shift over time given the expected changes in temperature in the future, and to help inform decisions on how to provide the best pavement quality for California highway users.

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[39] A more detailed description of the LOCA data set and downscaling techniques can be found at the start of this report.
[40] "LOCA Downscaled Climate Projections," http://beta.cal-adapt.org/data/loca/, 2017

CHANGE IN AVERAGE MINIMUM TEMPERATURE

▇	-0.9 - 0.1°F
▇	0.5 - 1.9°F
▇	2.0 - 3.9°F
▇	4.0 - 5.9°F
▇	6.0 - 7.9°F
▇	8.0 - 9.9°F
▇	10.0 - 11.9°F
▇	12.0 - 12.8°F

Climate Model for CA
(HadGEM2-CC)

2025 RCP 8.5,
50TH PERCENTILE

Caltrans Transpotation Asset Vulnerability Study, District 4. Caltrans No. 74A0737. Climate data provided by the Scripps Institution of Oceanography. The data shown were generated by downscaling global climate outputs using the Localized Constructed Analogs (LOCA) technique.

FIGURE 19: CHANGE IN AVERAGE MINIMUM TEMPERATURE 2055

CHANGE IN AVERAGE MINIMUM TEMPERATURE

Legend:
- -0.9 - 0.1°F
- 0.5 - 1.9°F
- 2.0 - 3.9°F
- 4.0 - 5.9°F
- 6.0 - 7.9°F
- 8.0 - 9.9°F
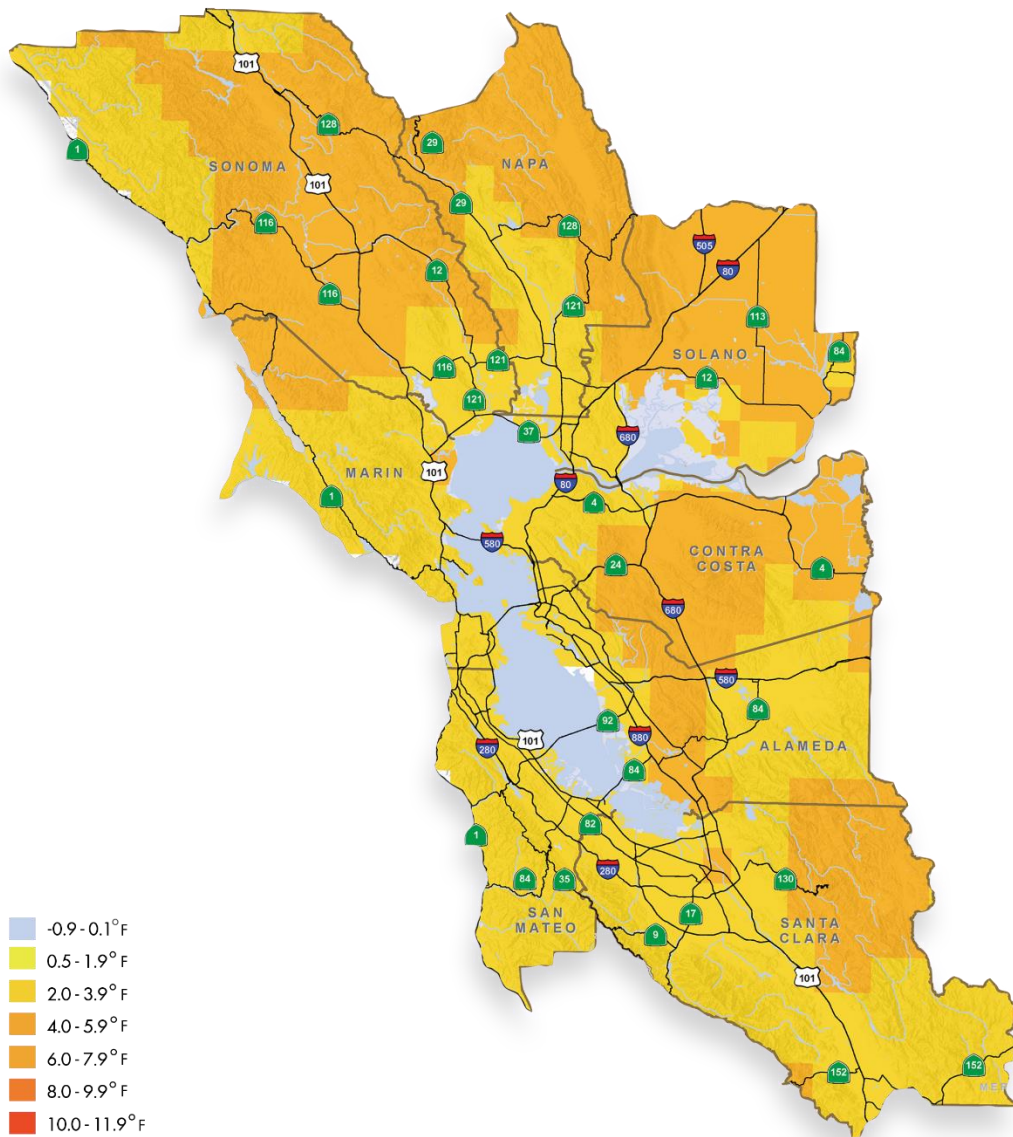- 10.0 - 11.9°F
- 12.0 - 12.8°F

Climate Model for CA
(HadGEM2-CC)

2055 RCP 8.5,
50TH PERCENTILE

Caltrans Transpotation Asset Vulnerability Study, District 4. Caltrans No. 74A0737. Climate data provided by the Scripps Institution of Oceanography.
The data shown were generated by downscaling global climate outputs using the Localized Constructed Analogs (LOCA) technique.

CHANGE IN AVERAGE MINIMUM TEMPERATURE

Legend:
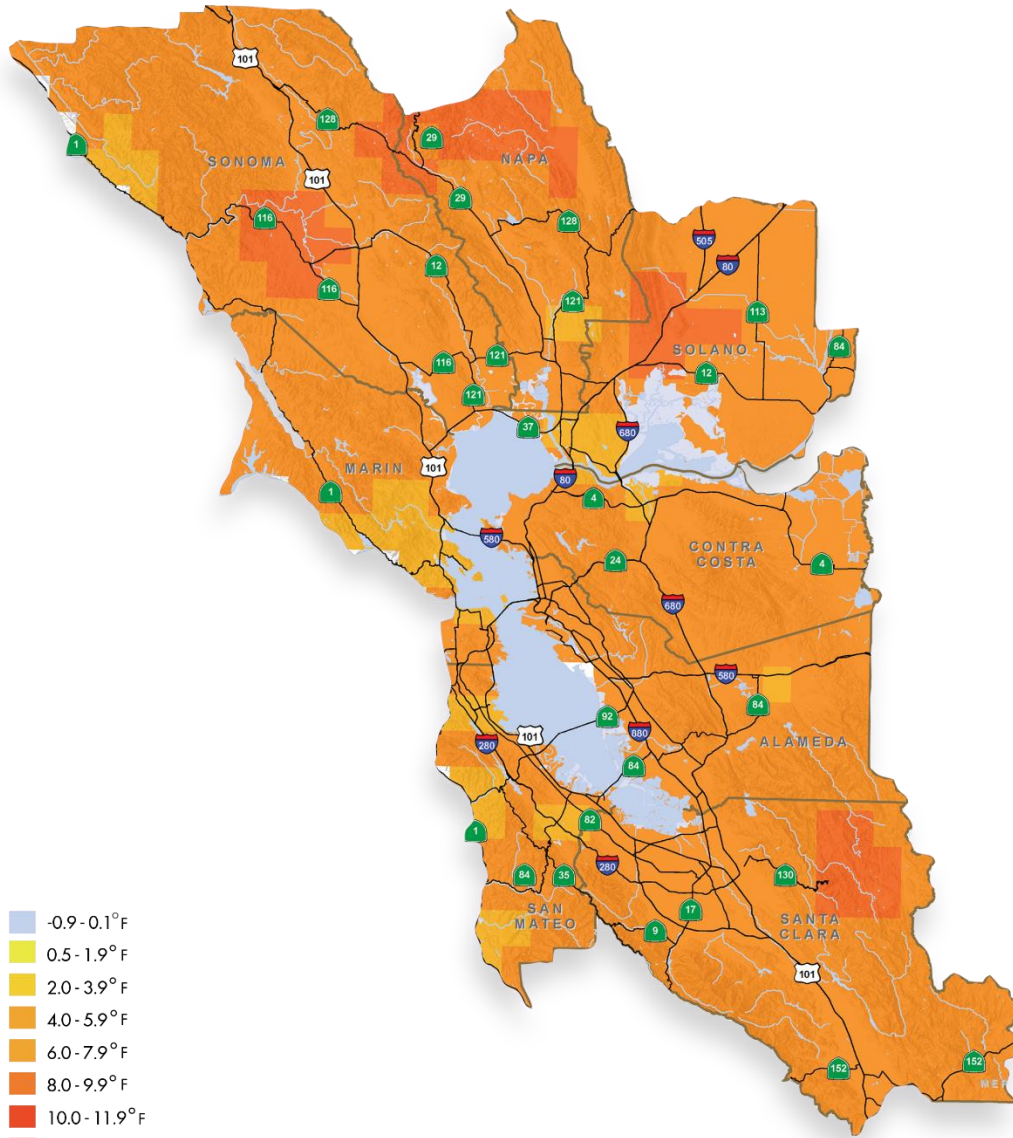- -0.9 - 0.1°F
- 0.5 - 1.9°F
- 2.0 - 3.9°F
- 4.0 - 5.9°F
- 6.0 - 7.9°F
- 8.0 - 9.9°F
- 10.0 - 11.9°F
- 12.0 - 12.8°F

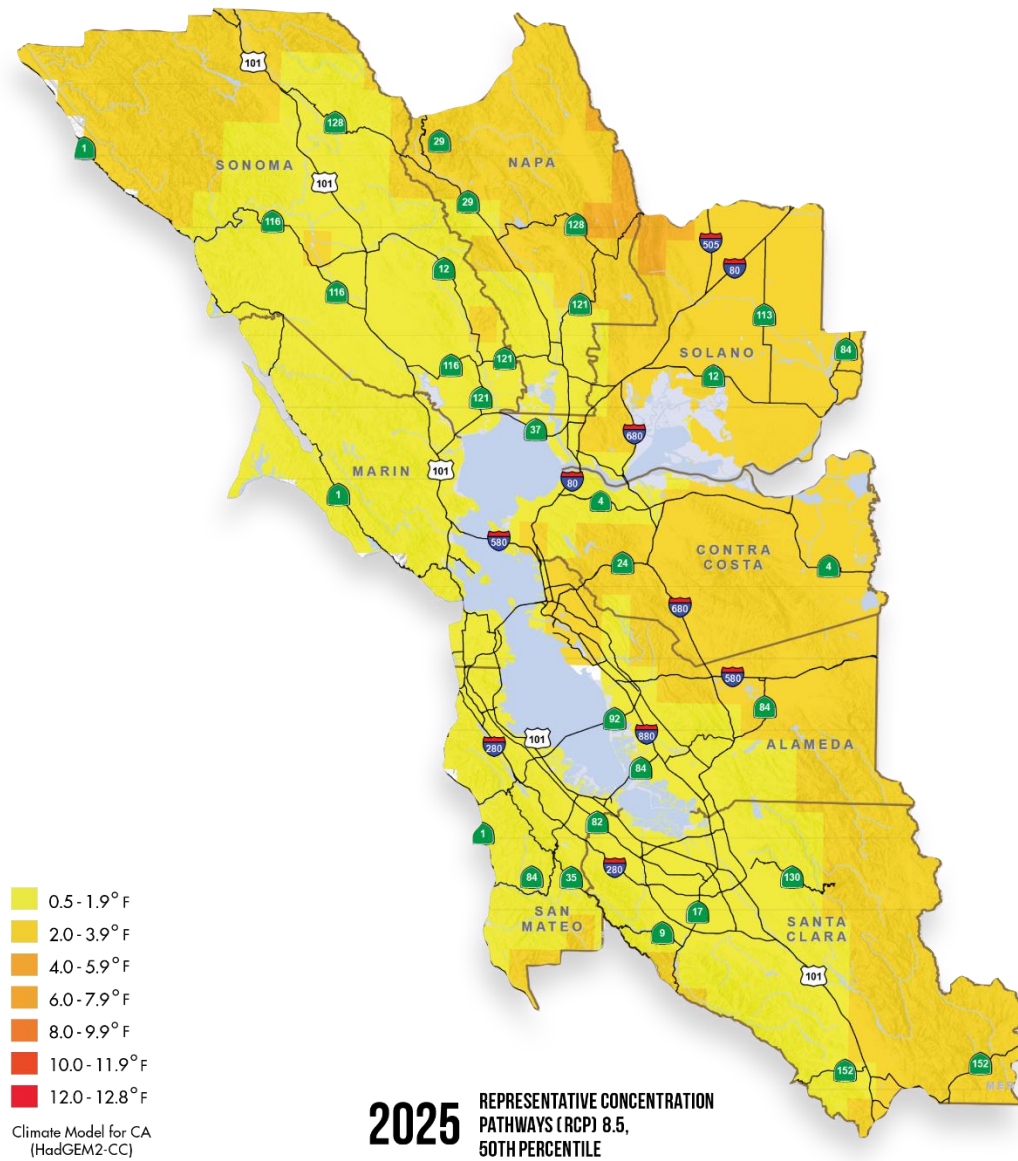Climate Model for CA
(HadGEM2-CC)

2085 RCP 8.5,
50TH PERCENTILE

Caltrans Transpotation Asset Vulnerability Study, District 4. Caltrans No. 74A0737. Climate data provided by the Scripps Institution of Oceanography.
The data shown were generated by downscaling global climate outputs using the Localized Constructed Analogs (LOCA) technique.

FIGURE 21: CHANGE IN AVERAGE MAXIMUM TEMPERATURE 2025

CHANGE IN AVERAGE MAXIMUM TEMPERATURE

0.5 - 1.9°F
2.0 - 3.9°F
4.0 - 5.9°F
6.0 - 7.9°F
8.0 - 9.9°F
10.0 - 11.9°F
12.0 - 12.8°F

Climate Model for CA
(HadGEM2-CC)

2025 REPRESENTATIVE CONCENTRATION PATHWAYS (RCP) 8.5, 50TH PERCENTILE

Change in Average 7-day Maximum Temperature, Worst Case Scenario for Future Greenhouse Gas Emission Concentrations, 2025, 2055, and 2085

Caltrans Transpotation Asset Vulnerability Study, District 4. Caltrans No. 74A0737. Climate data provided by the Scripps Institution of Oceanography. The data shown were generated by downscaling global climate outputs using the Localized Constructed Analogs (LOCA) technique.

CHANGE IN AVERAGE MAXIMUM TEMPERATURE

0.5 - 1.9° F
2.0 - 3.9° F
4.0 - 5.9° F
6.0 - 7.9° F
8.0 - 9.9° F
10.0 - 11.9° F
12.0 - 12.8° F

Climate Model for CA
(HadGEM2-CC)

2055 REPRESENTATIVE CONCENTRATION PATHWAYS (RCP) 8.5, 50TH PERCENTILE

Change in Average 7-day Maximum Temperature, Worst Case Scenario for Future Greenhouse Gas Emission Concentrations, 2025, 2055, and 2085

Caltrans Transpotation Asset Vulnerability Study, District 4. Caltrans No. 74A0737. Climate data provided by the Scripps Institution of Oceanography. The data shown were generated by downscaling global climate outputs using the Localized Constructed Analogs (LOCA) technique.

FIGURE 23: CHANGE IN AVERAGE MAXIMUM TEMPERATURE 2085
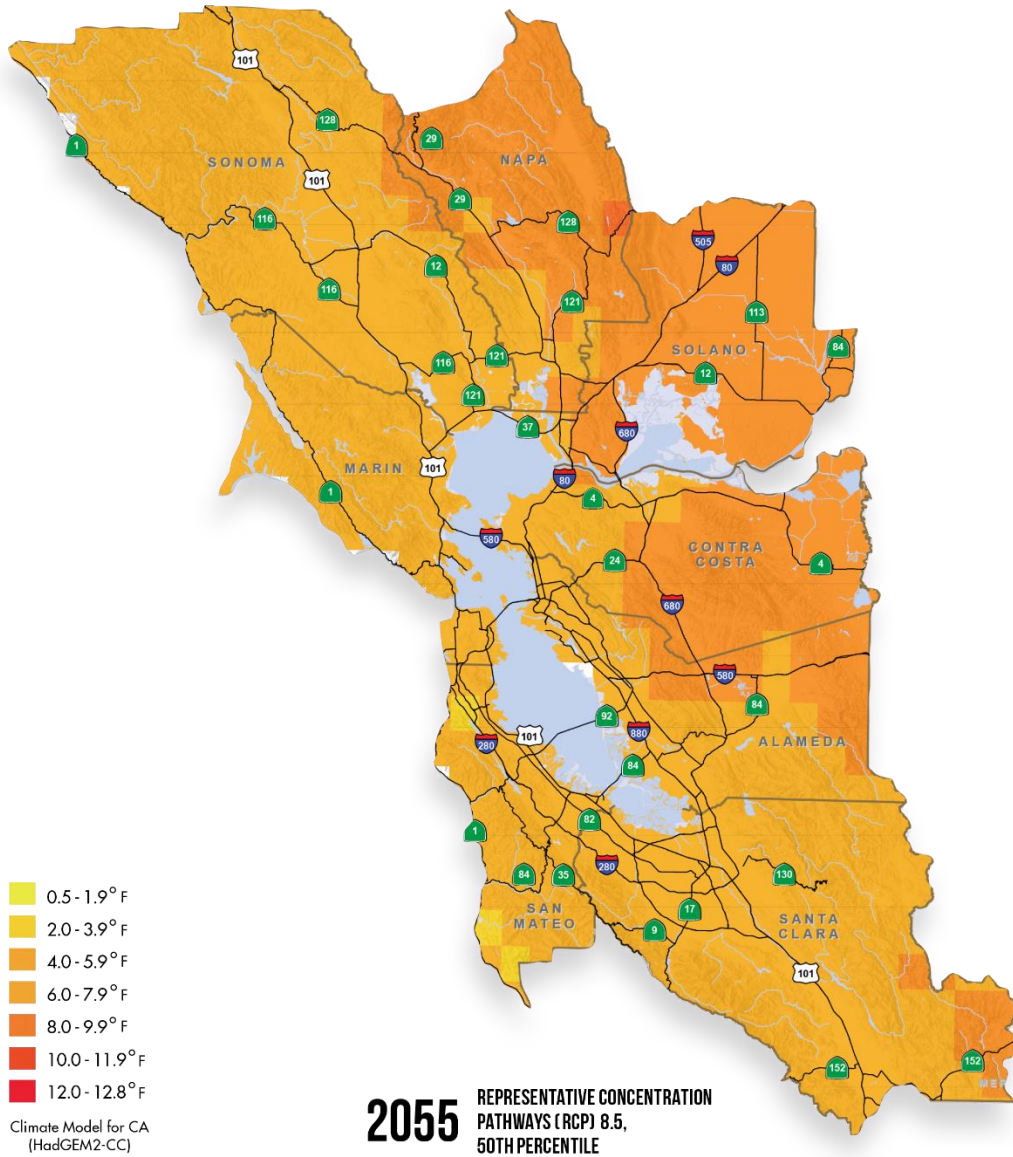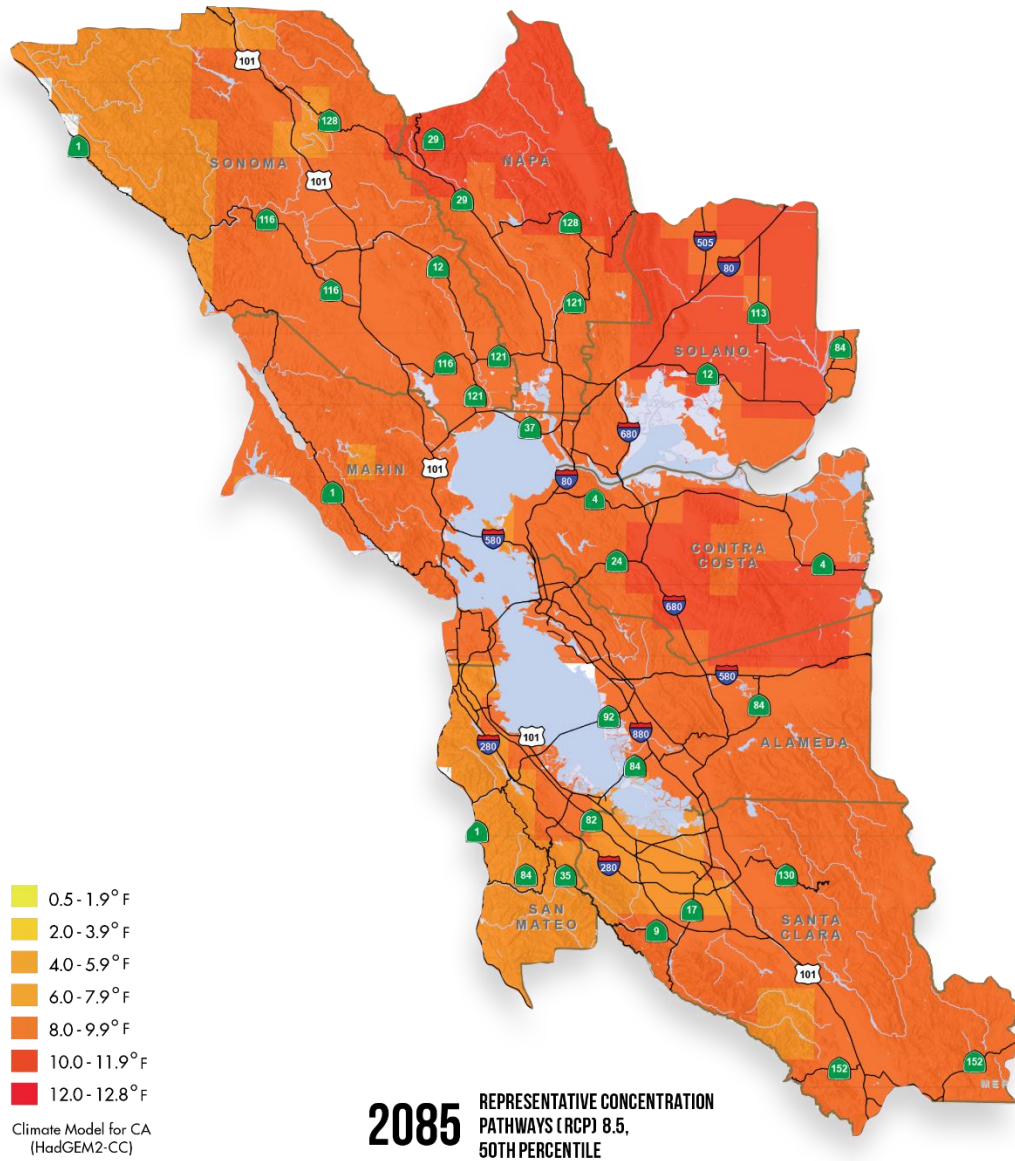
CHANGE IN AVERAGE MAXIMUM TEMPERATURE

Change in Average 7-day Maximum Temperature, Worst Case Scenario for Future Greenhouse Gas Emission Concentrations, 2025, 2055, and 2085

Caltrans Transpotation Asset Vulnerability Study, District 4. Caltrans No. 74A0737. Climate data provided by the Scripps Institution of Oceanography. The data shown were generated by downscaling global climate outputs using the Localized Constructed Analogs (LOCA) technique.

8. PRECIPITATION

8.1. How Climate Change Will Affect Precipitation

The Southwest region of the United States has been identified in previous studies[41] as expecting less precipitation overall in the future, but with the potential for heavier individual precipitation events with more precipitation falling as rainfall. These conditions were experienced in the Bay Area at the start of 2017, where heavy precipitation caused over $250 million to District 4 assets (see the APPENDIX for a map of affected areas). The precipitation section of this report focuses on how these heavy precipitation events may change and become more frequent over time. Current transportation design utilizes return period storm events as a variable to include in asset design criteria (for bridges, culverts, etc.). A 100-year design standard is often applied in the design of transportation facilities and is cited as a design consideration in Section 821.3, Selection of Design Flood, in the Caltrans Highway Design Manual.[42] Therefore, this metric was analyzed to determine how 100-year storm rainfall is expected to change over time.

Precipitation data is traditionally used at the project level by applying statistical analyses of historical rainfall, most often through the NOAA Atlas 14.[43] Rainfall values from the program are estimated across various time periods—from 5 minutes to 60 days. This data also shows how often rainfall of certain depths may occur in any given year, from an event that would likely occur annually, to one that would be expected to happen only once every 1,000 years. This information has been assembled based on rainfall data collected at rain gauges across the country.

Rather than using historical data, it is important to look forward to assess how those conditions will change. This viewpoint of looking forward is similar to other design inputs that use future data (such as land use changes and population growth) to identify final recommendations. Doing so may avoid damages and associated costs from having designed to a historic standard, when future precipitation and flooding events may be more severe in the project area.

Analysis of future precipitation is in many ways one of the most challenging tasks in assessing long-term climate risk. Modeled future precipitation values can vary widely. Thus, analysis of trends is considered across multiple models to identify predicted values and to help drive effective decisions for Caltrans. Assessing future precipitation was done by analyzing the broad range of potential effects predicted by a set, or ensemble, of models.

Transportation assets in California are impacted by precipitation in a variety of ways—from inundation/flooding, to landslides, washouts, or structural damage from heavy rain events. An effort to better understand future rainfall in California is underway at the Scripps Institution for Oceanography and is being compiled as a part of California 4th Climate Assessment. The intent of these efforts is to develop a better understanding of how climate change, including precipitation, may affect District 4 in the future.

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[41] Melillo, Jerry M., Terese (T.C.) Richmond, and Gary W. Yohe, Eds., 2014: Climate Change Impacts in the United States: The Third National Climate Assessment. U.S. Global Change Research Program, 841 pp. doi:10.7930/J0Z31WJ2.
[42] http://www.dot.ca.gov/hq/oppd/hdm/hdmtoc.htm
[43] http://nws.noaa.gov/oh/hdsc/index.html

GCMs often comprise very large grids covering extended land area and therefore do not provide the level of specificity desired for discerning or developing changing precipitation patterns across an area with diverse precipitation patterns like California. The LOCA downscaling method developed by Scripps, in response to this concern, provides a more refined understanding of future precipitation and helps to guide decision-making. The data can be used to identify variables like snow cover, run off, soil moisture and humidity projected into the future. The study of precipitation is obviously one of great concern in California, especially after the winter rainfall events of 2016–2017.

As noted above, for the purposes of analyzing how precipitation change may affect exposure of the Caltrans highway system, the project study team was interested in determining how a 100-year event may change over time. Scripps currently maintains daily rainfall data for a set of climate models (as listed below) and two future emissions estimates for every day to the year 2100. The project study team worked with researchers from Scripps to estimate how change may occur in extreme precipitation. Specifically, the team requested precipitation data across the set of 10 international climate models that were identified as having the best applicability in determining climate change impacts in California.

This data was identified for the RCP 4.5 and 8.5 emissions scenarios (the only two scenarios available) and was further analyzed for three specific periods to determine how precipitation may change to the end of the century and to provide some interim metrics. The years shown represent the mid-points of the same 30-year statistical analysis periods as used for the temperature metrics.

The project study team analyzed the models to understand a few major points for consideration in design, specifically:

- Were there indications of change in return period storms across the models that should be considered in decision-making when considering estimates for future precipitation?

- What was the magnitude of change for a 100-year return-period storm that should be considered as a part of facility design looking forward?
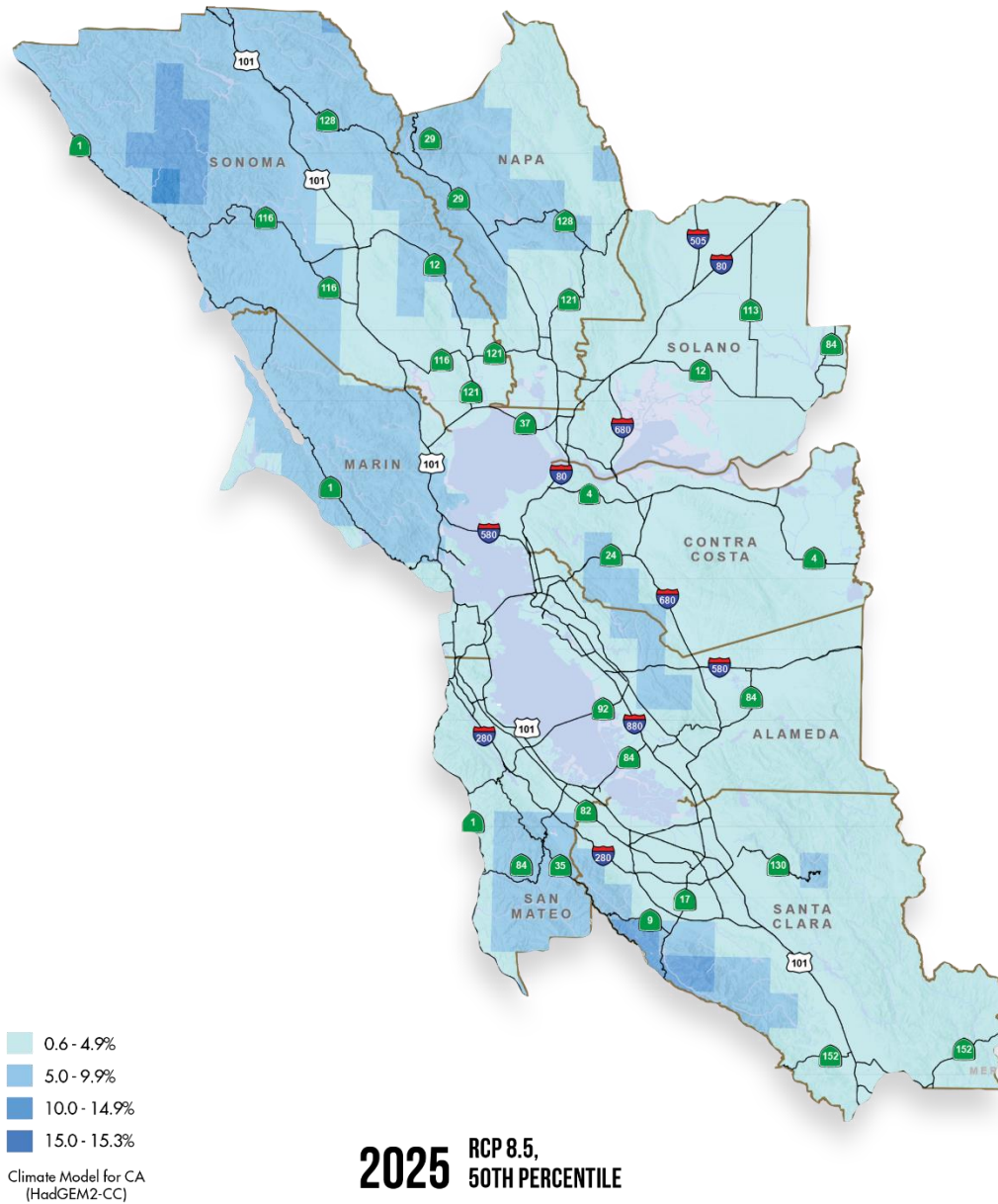
The results of this assessment follow in the maps prepared for District 4. The three maps depict the percentage change in the 100-year storm rainfall event predicted for the three analysis periods, and for the RCP 8.5 emissions scenario (for brevity, the RCP 4.5 results are not shown). The median model for the state was used in this mapping. Note that the change in 100-year storm depth is positive throughout District 4, indicating heavier rainfall during storm events. The pattern is relatively consistent over time; unlike with temperature, the change generally does not become greater over time. Also, changes are generally expected to be greater in the western, coastal portions of the district due to orographic lift (the tendency for the coastal mountains to squeeze out moisture from eastward moving storm systems). Some locations on the western slopes of the coastal mountains could see precipitation changes upwards of 15% during the 100-year storm.

At first glance, the precipitation increases may appear to conflict with the wildfire analysis, which shows that wildfire is expected to increase due to drier conditions. However, as noted above, precipitation conditions in California are projected to change so that there are more frequent drought periods, but heavier, intermittent rainfall. An analysis of future predicted precipitation data is insightful in analyzing the viability of existing and planned transportation infrastructure. Understanding the implications of rainfall estimates like those shown can help the designer implement a design solution, which minimizes

risk and incorporates future predicted rainfall into decision-making. That said, a hydrological analysis of flood flows is necessary to determine how this data will affect specific bridges and culverts.

FIGURE 24: CHANGE IN 100-YEAR STORM EVENT 2025

CHANGE IN 100-YEAR STORM PRECIPITATION DEPTH

0.6 - 4.9%
5.0 - 9.9%
10.0 - 14.9%
15.0 - 15.3%

Climate Model for CA
(HadGEM2-CC)

2025 RCP 8.5, 50TH PERCENTILE

Percent Change in 100-year Storm Precipitation Depth, Worst Case Scenario for Future Greenhouse Gas Emission Concentrations, Caltrans District 4, 2025, 2055, and 2085

Caltrans Transpotation Asset Vulnerability Study, District 4. Caltrans No. 74A0737. Climate data provided by the Scripps Institution of Oceanography. The data shown were generated by downscaling global climate outputs using the Localized Constructed Analogs (LOCA) technique.

CHANGE IN 100-YEAR STORM PRECIPITATION DEPTH

0.6 - 4.9%
5.0 - 9.9%
10.0 - 14.9%
15.0 - 15.3%

Climate Model for CA
(HadGEM2-CC)

2055 RCP 8.5,
50TH PERCENTILE

Percent Change in 100-year Storm Precipitation Depth, Worst Case Scenario for Future Greenhouse Gas Emission Concentrations, Caltrans District 4, 2025, 2055, and 2085

Caltrans Transpotation Asset Vulnerability Study, District 4. Caltrans No. 74A0737. Climate data provided by the Scripps Institution of Oceanography. The data shown were generated by downscaling global climate outputs using the Localized Constructed Analogs (LOCA) technique.

FIGURE 26: CHANGE IN 100-YEAR STORM EVENT 2085

CHANGE IN 100-YEAR STORM PRECIPITATION DEPTH

0.6 - 4.9%
5.0 - 9.9%
10.0 - 14.9%
15.0 - 15.3%
Climate Model for CA
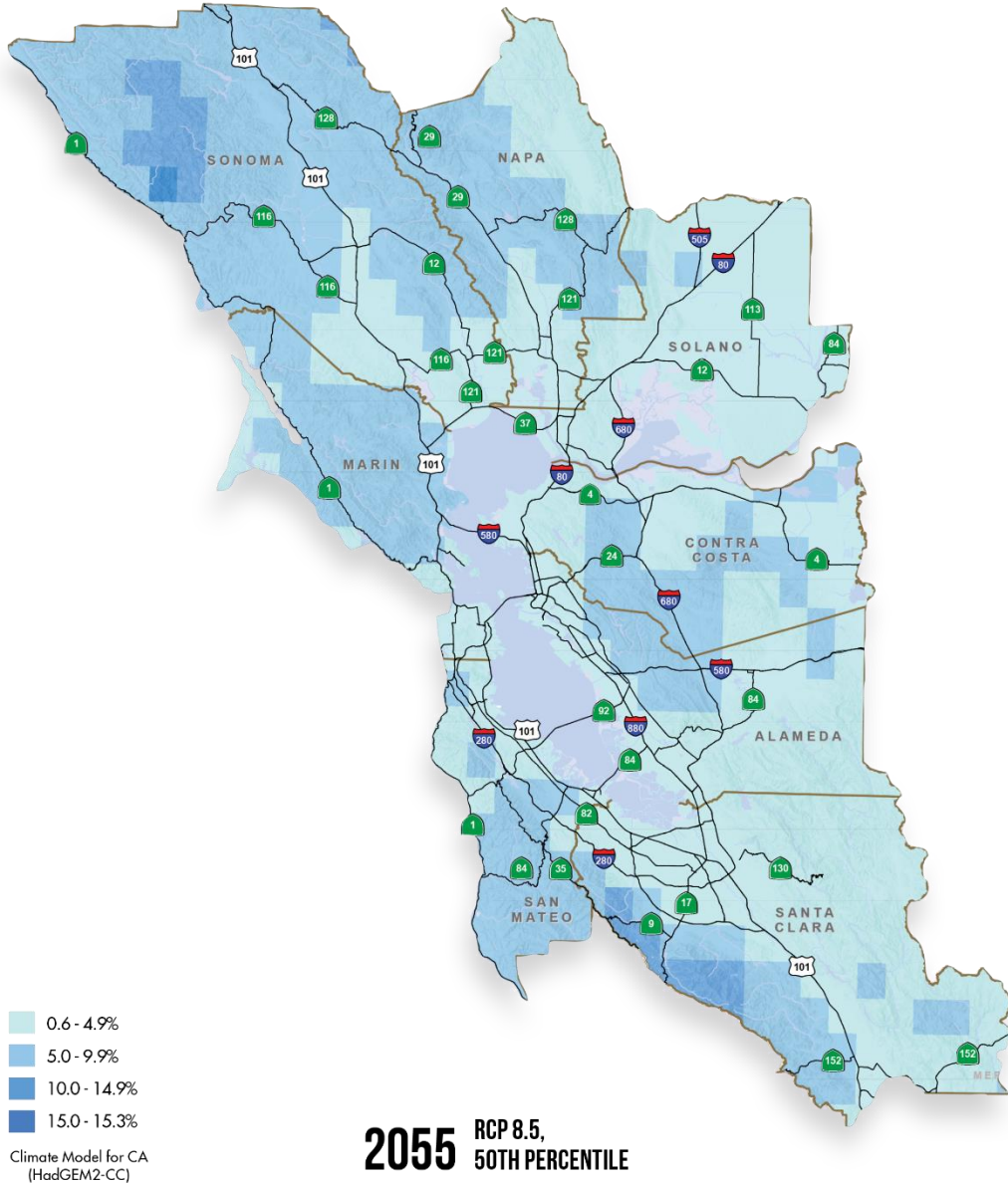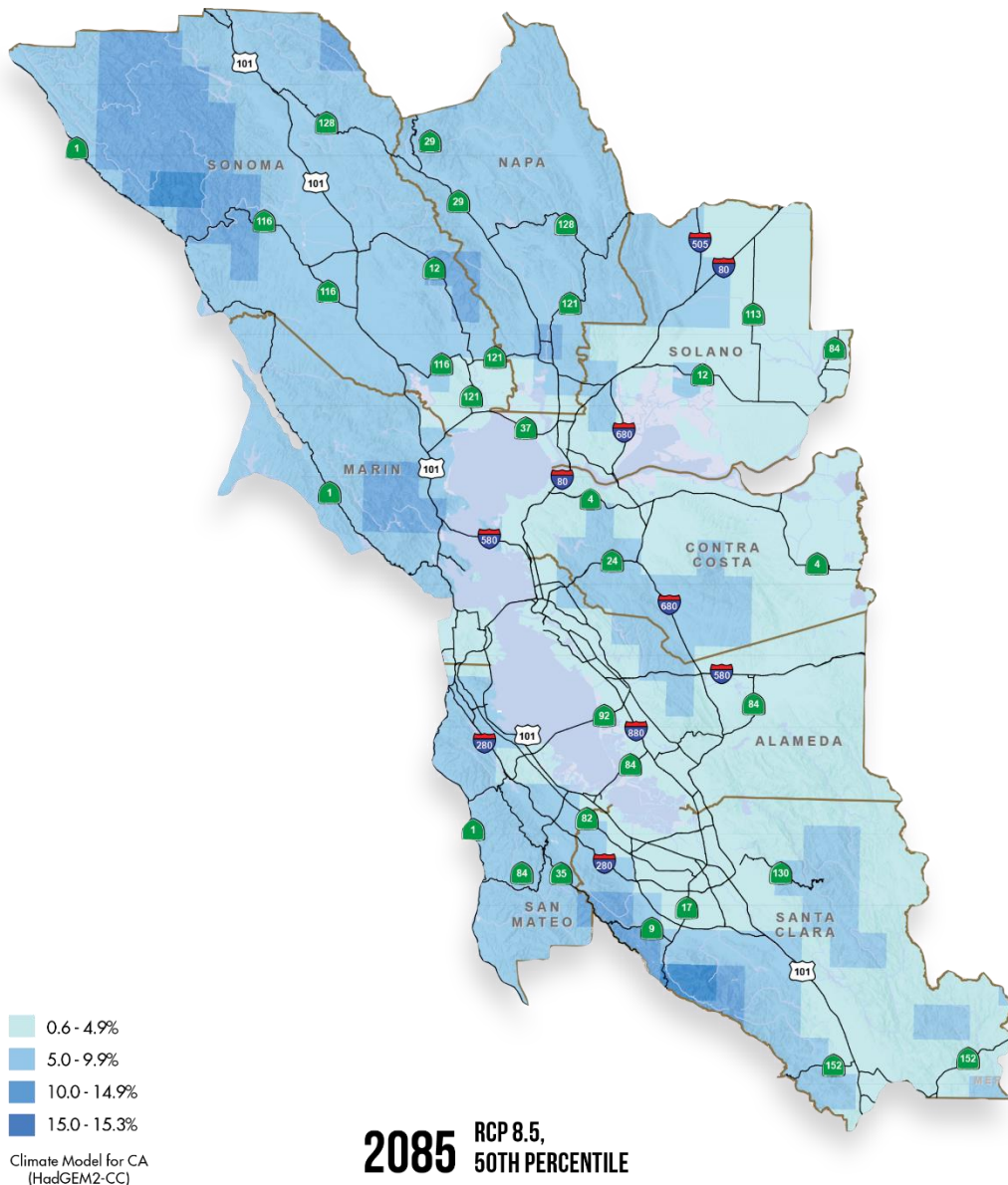(HadGEM2-CC)

2085 RCP 8.5,
50TH PERCENTILE

Percent Change in 100-year Storm Precipitation Depth, Worst Case Scenario for Future Greenhouse Gas Emission Concentrations, Caltrans District 4, 2025, 2055, and 2085

Caltrans Transpotation Asset Vulnerability Study, District 4. Caltrans No. 74A0737. Climate data provided by the Scripps Institution of Oceanography. The data shown were generated by downscaling global climate outputs using the Localized Constructed Analogs (LOCA) technique.

9. LOCALIZED ASSESSMENT FOR CLIMATE EXPOSURE

To highlight how climate change may impact a facility in District 4, an example Caltrans facility was selected to illustrate how projected climate changes can impact a roadway. This facility was US 101 near Corte Madera Creek in Marin County. The following discusses how evaluated factors impact this important stretch of highway.

Sea Level Rise and Storm Surge
As illustrated in Figure 27, a rise in sea level of 3.28 feet (one meter) may lead to nearly a mile of inundation of the roadway south of the Corte Madera Creek Bridge on a regular basis at high tides.[44] This impact is likely to occur by the second half of the 21st century according to more conservative SLR scenarios.

Storm surge, coupled with SLR, presents a nearer-term, though less frequent, threat to the facility. As shown in the second map, the 100-year storm surge begins to overtop US 101 south of the Corte Madera Creek Bridge with only 1.64 feet (0.50 meters) of sea level rise (see Figure 28). Nearly 1.5 miles of road could be affected. This situation could occur during severe storm events as soon as mid-century.

Changes in Wildfire
The roadway is in an urban setting and is not likely to be affected by wildfire either today or in the future based assessment of wildfire exposure for Caltrans assets.

Changes in Extreme Rainfall[45]
The Corte Madera Creek will likely experience higher peak flows in the future due to higher precipitation totals during extreme rainfall events. By the end of the century, precipitation could increase over the watershed by up to 10 to 14 percent under the RCP8.5 scenario. This could lead to increased riverine flooding along Corte Madera Creek that could exacerbate flooding of US 101 and cause scour of Corte Madera Creek Bridge.

Changes in Temperature
Warmer temperatures may necessitate the changing of asphalt binder-grade specifications for this stretch of US 101 later in the century. By the end of the century, mean annual minimum temperatures may increase by upwards of 6°F while mean annual maximum seven consecutive day high temperatures may increase by upwards of 8°F under RCP8.5.

Similar assessments for Caltrans assets throughout District 4 based on the analysis presented in this report should present the agency with a list of actions to take to assure the long-term resiliency of the system.

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[44] Impacts to US 101 are shown for 0.5 meters of SLR but there are, in fact, no impacts to the roadway with this amount of SLR. The false impacts shown for this SLR increment are a product of the bridge decks crossing Corte Madera Creek not being incorporated in the elevation data used for the impact mapping (the mapping assumes the bridge is not there and the road is not elevated). Similar false impacts are shown wherever inundation areas extend underneath bridge decks. However, that does not necessarily mean there will not be impacts to bridge infrastructure.

[45] Note that detailed engineering analyses are required to determine whether the projected precipitation changes would be enough to cause these impacts.

FIGURE 27: SEA LEVEL RISE IMPACTS TO US 101 AT CORTE MADERA CREEK
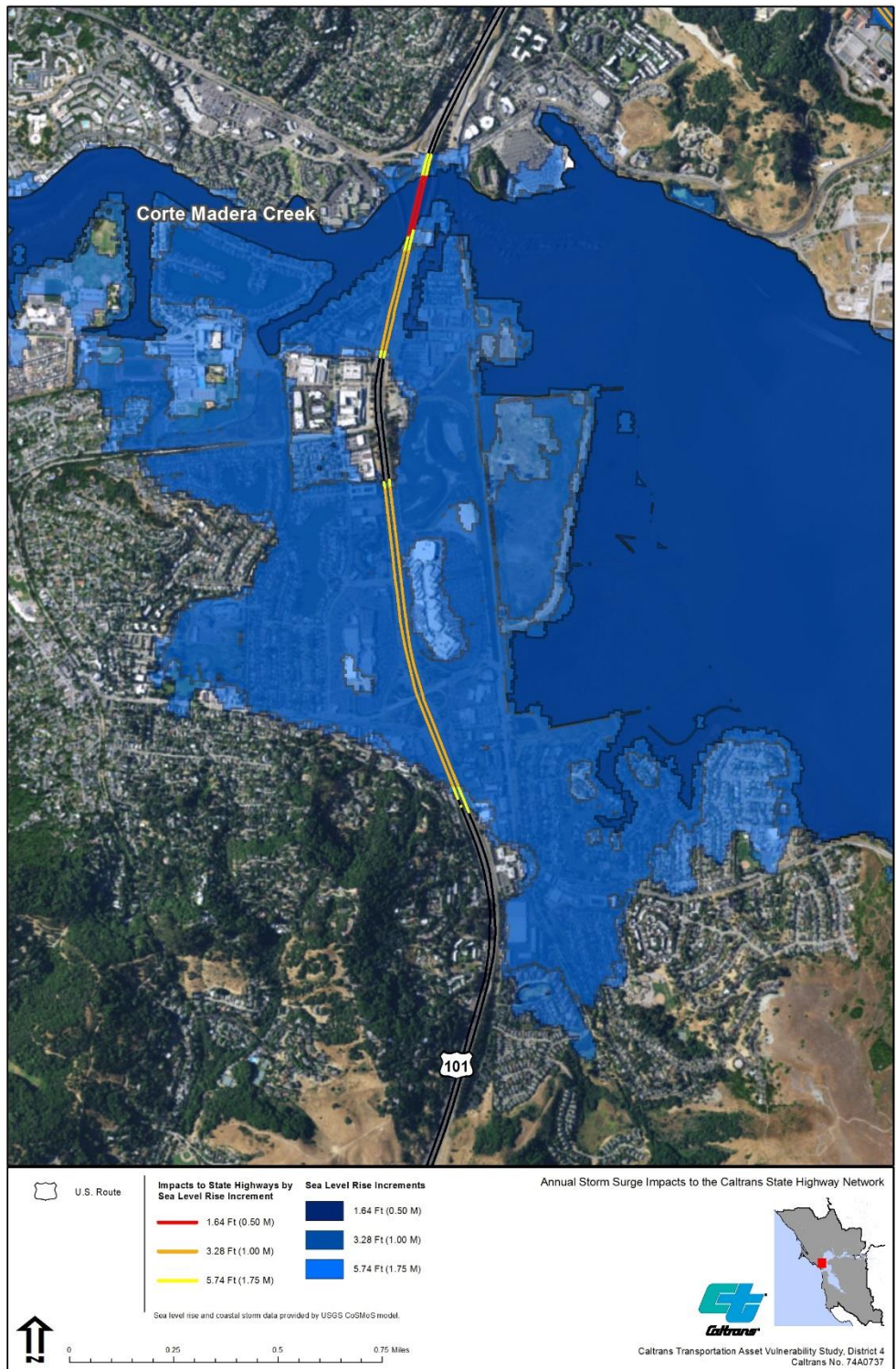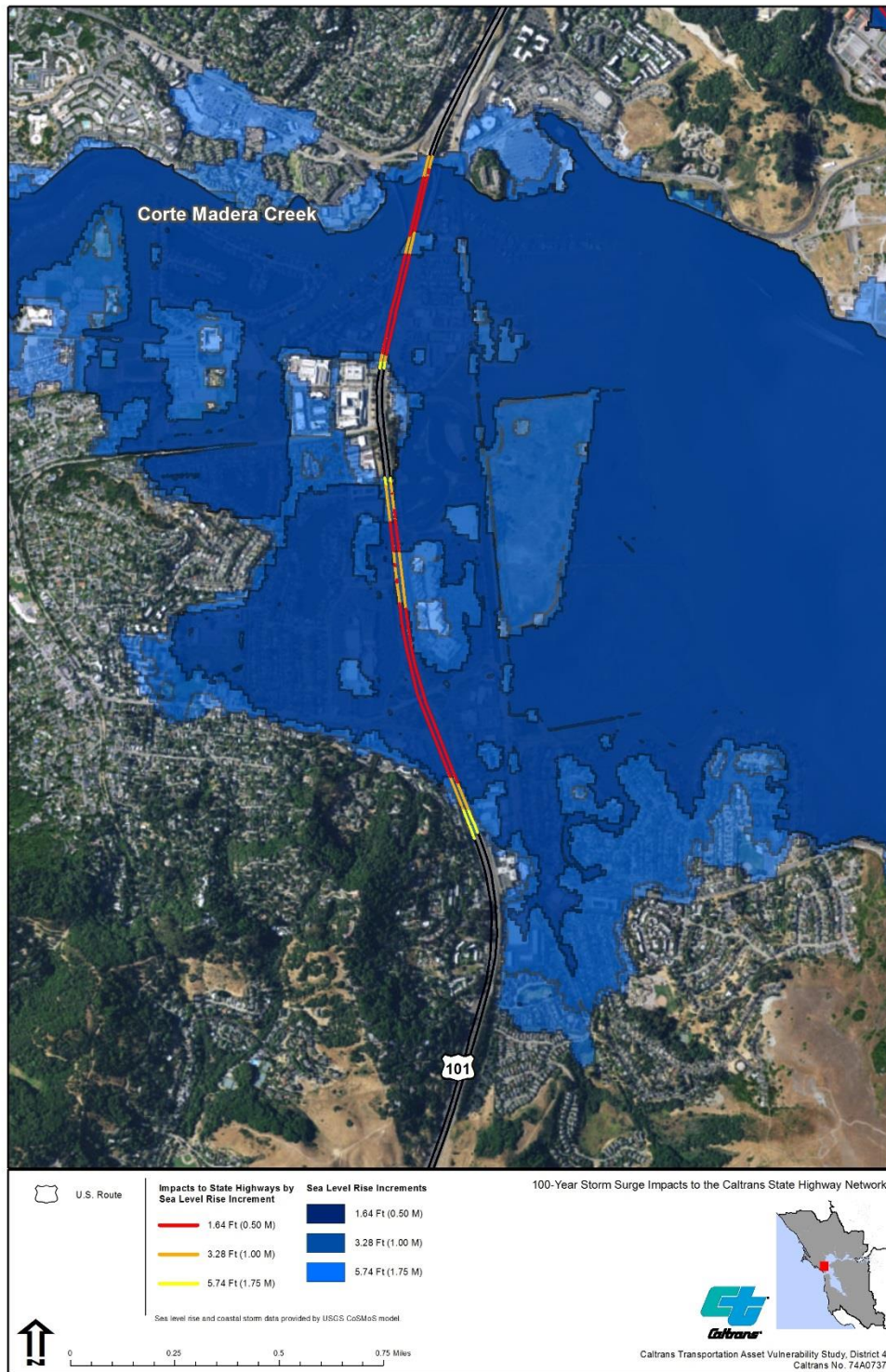
FIGURE 28: SEA LEVEL RISE IMPACTS TO US 101 AT CORTE MADERA CREEK AND THE 100-YEAR STORM EVENT

10. INCORPORATING CLIMATE CHANGE INTO DECISION-MAKING

10.1. Risk-Based Design

A risk-based decision approach considers the broader implications of damage and loss in determining the approach to design. Climate change is a risk factor that is often omitted from design. Incorporating climate change into asset-level decision-making has been a subject of research over the past decade, much of it led or funded by the Federal Highway Administration (FHWA), which undertook a few projects internally to assess climate change and facility design – including the Gulf Coast II project (Mobile, AL) and the Transportation Engineering Approaches to Climate Resiliency Study. Both assessed facilities of varying type, which were exposed to different climate stressors. They then identified design responses that could make the facilities more resilient to change.

One outcome of the FHWA studies was a step-by-step method for completing facility (or asset) design, such that climate change was considered and inherent uncertainties in the timing and scale of climate change were included. This method, termed the Adaptation Decision-Making Assessment Process (ADAP),[46] provides facility designers with a recommended approach to designing a facility when considering possible climate change effects. The key steps in ADAP are shown in Figure 29.

The first five steps of the ADAP process cover the characteristics of the project and the context. The District 4 Vulnerability Assessment has worked through these first steps at a high level and the data used in the assessment has been provided to Caltrans for future use in asset level analyses. These five steps should be addressed for every exposed facility, during asset level analyses.

Step five focuses on conducting a more detailed assessment of the performance of the facility. When analyzing one facility, is important to assess the highest impact scenario. This does not necessarily correspond to the highest temperature range, or largest storm event, in this case - the analysis should determine what scenarios will have the greatest effect on a facility. For example, a 20-year storm may cause greater impacts than a 100-year storm, depending on wind and wave directions. If the design criteria of the facility are met even under the greatest impact scenario, the analysis is complete. Otherwise, the process moves onto developing adaptation options.

Options should be developed that will adapt the facility to the highest impact scenario. If these options are affordable, they can move to the final steps of the process. If they are not, other scenarios can be considered in order to identify more affordable options. These alternative design options will need to move through additional steps to critique their performance and economic value. Then they also move to the final steps of the process. These last three steps are critical to implementing adaptive designs. Step nine involves considering other factors that may influence adaptation design and implementation. For example, California Executive Order B-30-15 requires consideration of:

- full life cycle cost accounting

- maladaptation,

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[46] https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/teacr/adap/index.cfm

- vulnerable populations,

- natural infrastructure,

- adaptation options that also mitigate greenhouse gases,

- and the use of flexible approaches where necessary.

At this step in the ADAP process, it is important to understand the greater context of the designs developed and whether they meet state, Caltrans, and/or other requirements. This also allows for the opportunity to consider potential impacts of the project outside of design and economics, including how it may affect the surrounding community and environment. After evaluating these additional considerations, a course of action can be selected and a facility management plan can be implemented.

FIGURE 29: FHWA'S ADAPTATION DECISION-MAKING PROCESS
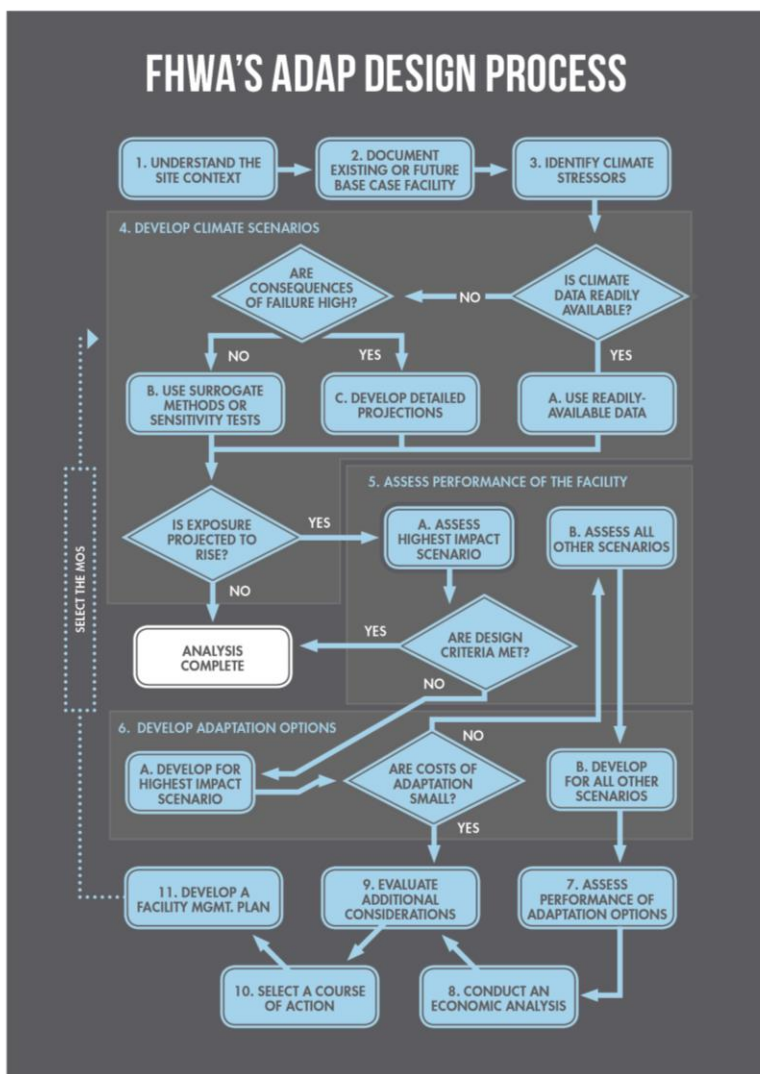
For additional information about ADAP please see the FHWA website at:
https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/teacr/adap/index.cfm

10.1.1. Devil's Slide Example

A District 4 project that already incorporates the effects of climate change are the Tom Lantos tunnels. These northbound and southbound tunnels were built to bypass the "Devil's Slide" area, a steep and unstable cliff side. The previous section of Highway 1 along Devil's Slide had experienced long closures due to rockslides and land slippage, with one such closure lasting 158 days and costing over three million dollars to repair. The tunnels were constructed in 2013 to avoid the frequent maintenance associated with the Devil's Slide region and the old Highway 1 section was turned over to San Mateo County to serve as a pedestrian and bike trail.[47]

FIGURE 30: OVERVIEW OF TOM LANTOS TUNNELS PROJECT PLAN

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[47] "Caltrans District 4 Devil's Slide Project," Caltrans, http://www.dot.ca.gov/dist4/dslide/, n.d.

10.2. Project Prioritization

The project prioritization approach outlined below is based on a review of the methods developed and lessons learned from other adaptation efforts. These methods—mostly developed and used by departments of transportation in other states—address long-term climate risks and are intended to inform project priorities across the range of diverse project needs. The method outlined below recognizes the following issues when considering climate change adaptation for transportation projects:

- The implications of damage or failure to a transportation facility due to climate change-related stresses

- The likelihood or probability of occurrence of an event

- The timeframe at which the events may occur, and the shifting of future risks associated with climate change

The recommended prioritization method is applied to those facilities with high exposure to climate change risk; thus, it is not applied to the entire transportation network. The method assumes that projects have been defined in sufficient detail to allow some estimate of implementation costs.

Some guiding principles for the development of the prioritization method included the following:

- It should be straightforward in application, easily discernable, describable and it should be relatively straightforward to implement with common software applications (Excel, etc.).

- It should be based on best practices in the climate adaptation field.

- It should avoid weighting schemes and multi-criteria scoring, since those processes tend to be difficult to explain and are open to interpretation among professionals with varying perspectives.

- It should be focused on how departments of transportation do business, reflect priorities for program delivery to stakeholders and recognize the relative importance of various assets.

- It should have the ability to differentiate between projects that may have different implications of risk—like near-term minor impacts and long-term major impacts—to set project priorities.

- It should facilitate decisions among different project types, for example, projects for repairs or for continuous minor damage as compared to one-time major damage events.

- It should enable the comparison among all types of projects, regardless of the stressor causing impacts.

The prioritization method requires the following information:

- Facility loss/damage estimates (supplied by Caltrans engineering staff) should capture both lower level recurring impacts and larger loss or damage. These should include a few key pieces of information, including:

  What are the levels for stressors (SLR, surge, wildfire, etc.) that would cause damage

and or loss?

What are the implications of this damage in terms of cost to repair and estimated time to repair?

- System impacts (supplied by Caltrans planning staff) – the impacts of the loss of the facility on the broader system. This could be in terms of increase in Vehicle Hours Traveled (VHT) if using a traffic model, or an estimated value using volume and detour length as surrogates.

- Probability of occurrence (supplied by Caltrans climate change staff through coordination with state climate experts) – the probability of events occurring as estimated from the climate data for chosen climate scenarios. Estimated for each year out to the end of the facility lifetime.

A project annual impact score is used to reflect two conditions, summarized by year:

- The expected cumulative loss estimated for the project over the project lifetime (full impact accounting).

- A method of discounting losses over years– to enable prioritization based on nearer term or longer-term expected impacts (timeframe accounting).

These two pieces of information are important to better understand the full cost of impacts over time. Figure 31 shows the general approach for the prioritization method.

FIGURE 31: APPROACH FOR PRIORITIZATION METHOD
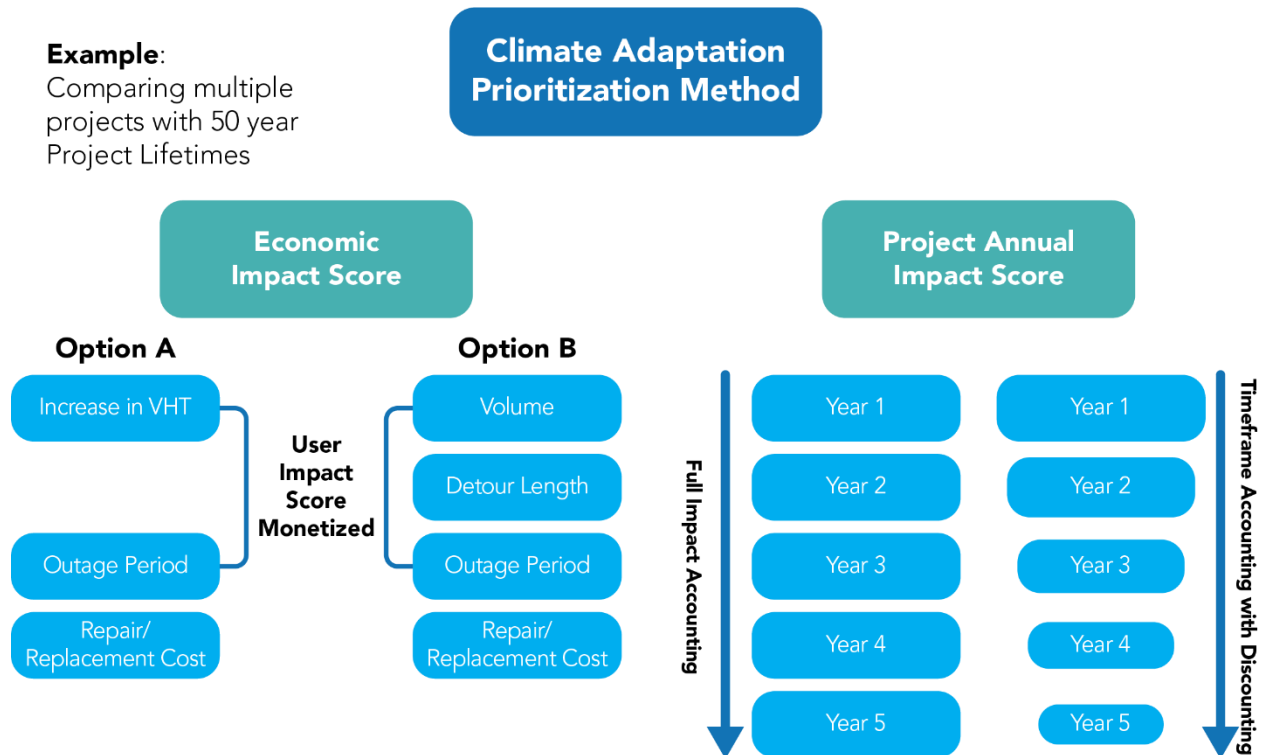
The two side-by-side charts represent various approaches to calculating values to be used for prioritization. The left side (Economic Impact Score) shows two methods for determining costs to the system user. The right-side show how costs could be counted in two ways, one which utilizes a full impact accounting that basically sums all costs to the end of the asset useful life while the other uses annual discounting to reflect "true costs" or current year dollar equivalent values to calculate the final impact score for the asset. These are presented as shown in part to provide an option for determining these values and in part to outline the various methods that are being used on similar projects nationally. The final selected method would require input and leadership from Caltrans to define the parameters for the approach to inform decisions.

The prioritization method would need estimates of at a minimum repair/replacement cost (dollars) and, if broadened, a system users impact (in dollar equivalents). System user costs would be summarized for this effort as transportation service impacts, and would be calculated in one of two ways:

- Estimate the impacts to a transportation system by identifying an expected detour routing that would be expected with loss of access or a loss/damage climate event. This value would be combined with average daily traffic and outage period values to result in an estimate of VHT increase associated with the loss of use of a facility.

- Utilize a traffic model to estimate the impacts on the broader State Highway System from damage/loss of a facility or facilities anticipated to occur as a result of a climate event. The impact on the system would be summarized based on the net increase in VHT calculated in the model.

The advantage of the system method is that it determines impacts of multiple loss/failure assessments consecutively and is not confined to only the assessment of each individual project as an individual project concern. It also allows for comparisons to the broader system and scores facilities with heavier use and importance to an integrated system as higher in terms of impact and prioritization.

Probabilities of an event occurring over each year would be used to summarize costs per year as well as a summarized cumulative total cost for the project over the lifetime. The resulting values would set the prioritization metric in terms of net present value for Caltrans to apply in selecting projects. The identification of an annual cost metric, which includes discounting, enables the important decision-making process on which project should advance given limited project resources. Table 5 highlights how the method would be implemented, with the project selected in the out years selected by the calculated annual cost metric. The impacts noted in the time period beyond the selected year (shown in shaded color) would be expected to have been addressed by the adaptation strategy. Thus, in the table, Project 1 at year 5 has the highest annual cost associated with disruptions connected to an extreme weather event. The project with the next greatest annual cost is Project 2, where this cost is reached at year 15. The next project is Project 3 at year 35 and the final project is Project 4 at year 45.

TABLE 5: EXAMPLE PROJECT PRIORITIZATION

Year	5	10	15	20	25	30	35	40	45	50
Project 1	$5	$5	$5	$5	$7	$7	$7	$9	$9	$9
Project 2	$4	$4	$6	$6	$6	$6	$8	$8	$8	$8
Project 3	$3	$3	$4	$4	$4	$6	$8	$8	$8	$8
Project 4	$2	$2	$2	$4	$4	$4	$6	$8	$10	$10

The project prioritization method outlined above requires the development of new approaches to determining how best to respond to climate change risks. It does not rely on existing methods as they are not appropriate to reflect climate risk effectively and facilitate agency level decision making. Climate change, with its uncertain timing and non-stationary weather/climate impacts, requires methods that incorporate this reality into Caltrans' decision-making processes.

It would be possible to implement a tiered prioritization process once work required to complete the steps as outlined above has been completed. Assets at risk from climate change with comparable present values could be compared for their capability to address other policy concerns – like goods movement, access for low income / dependent communities, sustainability measures, or other factors that would help Caltrans meet statewide policy goals. The primary focus of this assessment should be impacts to the system but these secondary measures can help clarify or reorder the final list and help guide implementation.

11. CONCLUSIONS AND NEXT STEPS

This report represents an initial effort to identify areas of exposure to potential climate change for facilities owned and operated by Caltrans District 4. The study utilized various data sources to identify how climatic conditions may change from today and where these areas of high exposure to future climate risks appear in District 4. The study distilled the larger context of climate change down to a more localized understanding of what such change might mean to District 4 functions and operations, District 4 employees, and the users of the transportation system. It is intended, in part, as a transportation practitioner's guide on how to include climate change into transportation decision-making.

Much of today's engineering design is based on historical conditions, and it is emphasized throughout this report that this perspective should change. A review of climate data analyzed for this study shows that, for those stressors analyzed (SLR, storm surge, wildfire, temperature, and precipitation), there are clear indications that future conditions will be very different from today's, with likely higher risks to highway infrastructure. These likely future conditions vary in terms of when threshold values will occur (that is, when sea levels, or precipitation and temperature values exceed a point at which risks will increase for assets) and on the potential impact to the State Highway System. This is an important consideration given that transportation infrastructure investment decisions made today will have implications for decades to come given the long lifetimes for roadway facilities.

This report provides District 4 with the information on areas of climate change exposure it can utilize to proceed to more detailed, project-level assessments. In other words, the report has identified where climate change risks are possible in District 4 and where project development efforts for projects in these areas should consider changing future environmental conditions. There are several steps that can be taken to transition from a traditional project development process based on historical environmental conditions to one that incorporates a greater consideration for facility and system resiliency. This process can incorporate the benefits associated with climate change adaptation strategies and use climate data as a primary decision factor. District 4 staff, with its recent history of assessing long-term risks associated with climate change, has the capacity to adopt such an approach and ensure that travelers in the region are provided with a resilient system over the coming years.

The following section provides some context as to what the next steps for Caltrans and District 4 may be, in order to build upon this work and create a more resilient State Highway System.

11.1. Next Steps

The work completed for this effort answers a few questions and raises many more, as is evidenced by the extended dialogue that has occurred across multiple agencies and the expanding number of topics discussed in the preparation of this report. The scope of this work was focused on determining what is expected in the future and how that may impact the transportation system. This analysis has shown that climate data from many sources indicates an expanded set of future risks – from higher seas and storm surge, to increased extreme precipitation, to higher temperatures, and an increase in wildfires – all concerns that will need to be considered by District 4.

There are a few steps that will be required to improve decision-making and help Caltrans achieve a more resilient State Highway Network in District 4. These include:

- Policy Changes

  - Agency leadership will need to provide guidance for incorporating findings from this assessment into decision making. This area is a new focus and requires a different perspective that will not be possible without strong agency leadership.

    - Addressing climate change should be integrated throughout all functional areas and business processes; including Planning, Environmental, Design, Construction, Maintenance and Operations.

  - Risk-based decision-making. The changing elements of climate change require the consideration of the implications of those changes and how they may affect the system. Caltrans will need to change its methods to incorporate measures of loss, damage and broader social or economic costs as a part of its policies. (See 10.1 Risk-Based Design).

- Acquisition of Improved Data for Improved Decision-Making

  - Determining potential impacts of precipitation on the state highway system will require additional system/environmental data to complete a system-wide assessment. This includes:

    - Improved topographic data across District 4 (and the state of California).

    - Improved asset data – including accurate location of assets (bridges, culverts) and information on the waterway opening at those locations.

  - The assessment of wildfire potential along the state highway system is an ongoing effort. Follow up will be required to determine the results of new research and whether updated models indicate any additional areas of risk.

  - The precipitation and temperature data presented in this report is based off a data set that is newly released. Methods to summarize this data across many climate models is ongoing and the conclusions of that work may yield information that may more precisely define expected future changes for these stressors.

  - There are efforts underway to refine the understanding of other stressors, including landslide potential, risks to the levee systems, and a refined understanding of coastal erosion. Further refinements of those efforts will require additional investment and coordination to complete. Research efforts are constantly being refined and Caltrans will need to be an active partner in participating in, and monitoring, the results of these efforts to determine how to best incorporate the results of these efforts into agency practices.

- Implementation

  - The data presented in this report indicates directions and ranges of change. These data points will need to become a part of Caltrans practice for planning and design for all future activities.

  - The use of this data will require the development of educational materials and the training of Caltrans staff to ensure effective implementation.

Not every concern and future requirement could be addressed or outlined in this report. It should be considered the first step of many that will be required to address the implications of climate change. There remains much work to be done to create a resilient State Highway System in District 4.

12. GLOSSARY

100-year design standard: Design criteria for highway projects that address expected environmental conditions for the 100-year storm. Also considered Base Flood Elevation by Federal Emergency Management Agency.

Cal-Adapt: A web-based data hub and information guide on recent California-focused climate data and analysis tools. Visualization tools are available to investigate different future climate scenarios.

Climate change: Change in climatic conditions expected to occur due to the presence of greenhouse gas concentrations in the atmosphere. Examples include changing precipitation levels, higher temperatures, and sea level rise.

Downscaling: An approach to estimate climate predictions at a more localized level based on the outcomes of models that predict future climate conditions at a much larger scale of application.

Emissions Scenarios: Assumed future states of the climate and weather conditions based on assumptions regarding greenhouse gas concentrations in the atmosphere.

Exposure: The degree to which a facility or asset is exposed to climate stressors that might cause damage or disrupt facility operations or asset condition.

Global Climate Model (GCM): Models used by climate scientists to predict future climate conditions. This term is sometimes used interchangeably with General Circulation Model.

Representative concentration pathways (RCP): Scenarios of future greenhouse gas emission concentrations based on assumed future releases of greenhouse gas emissions given economic development, population growth, technology, etc.

Resilient transportation facilities: Transportation facilities that are designed and operated to reduce the likelihood of disruption or damage due to changing weather conditions.

Return period storm event: Historical intensity of storms based on how often such level of storms have occurred in the past. A 100-year storm event is one that has the intensity of a storm that statistically occurs once every 100 years.

State Highway System (SHS): The designated highway network in California for which Caltrans is responsible.

Stressor: Climate conditions that could possibly apply stress to engineered facilities. Examples include temperature and precipitation.

Vulnerability assessment: A study of those areas likely to be exposed to future climate and weather conditions that will add additional stress to assets, in some cases, levels of stress that might exceed the assumed conditions when the asset was originally designed.

13. APPENDIX

BAY AREA STORM DAMAGE SITES 2017
110 Locations and Over $250 Million to Date

Damage Site

N

0   3.75   7.5   15
Miles

MAP ID	County	Route	Post Miles	Total Estimate ($1000)
1	ALA	13	4.4	6,150
2	ALA	13	9.2	2,000
3	ALA	24	1.9/6	3,300
4	ALA	84	12/13	530
5	ALA	84	22.2/22.5	2,150
7	ALA	92	2.6/4.7	2,000
8	ALA	185	0.4/3.2	5,000
9	ALA	238	14.4/16.6	2,000
10	ALA	580	1.5/3.9	2,000
11	ALA	580	36.7/38.9	750
12	ALA	680	0.4	500
13	ALA	880	16.5/18.3	2,400
14	ALA	880	22/30	6,500
15	CC	24	8/9	2,800
16	CC	80	0/10.1	1,500
17	CC	80	10.7/13	7,250
18	CC	680	12.7/17.6	5,300
19	MRN	1	1.6/2.5	2,530
20	MRN	1	4/5	7,200
21	MRN	1	4.6	2,150
22	MRN	1	10.8	14,400
23	MRN	1	10.9	3,200
24	MRN	1	33.4	2,630
25	MRN	1	43.3	291
26	MRN	1	6.6	6,380
27	MRN	1	7.7/7.8	7,490
28	MRN	1	8.1	2,300
29	MRN	1	8.2/8.5	3,990
30	MRN	1	0.1	960
31	MRN	1	11.5	5,200
32	MRN	1	22.8	4,250
33	MRN	1	35.3	960
34	MRN	37	11.7/12	8,000
35	MRN	101	21.7/22.8	1,180
36	MRN	580	2.7	TBD
41	NAP	121	17.5/18.3	1,410
48	NAP	128	17.8	410
55	SCL	9	0/4.8	1,510
56	SCL	9	0/5	3,410
57	SCL	17	3/3.1	2,110
58	SCL	17	5.8	2,660
59	SCL	35	9.1/10.5	1,010
60	SCL	35	9.5	3,200
61	SCL	35	10.5	21,750
62	SCL	35	12.4	1,400
63	SCL	130	9.3	3,150
64	SCL	152	1.5	2,510
65	SCL	152	17	2,005
66	SCL	152	7.9/9.4	3,000
70	SM	1	17/17.5	3,210
71	SM	1	13.5	2,520
72	SM	1	14.7/14.8	TBD
73	SM	1	15.1	TBD
74	SM	35	9.8	3,210
75	SM	35	11.5	6,200
76	SM	35	13.1	1,950
77	SM	35	9.85	1,100
78	SM	35	26.1/28.9	620
79	SM	84	15.4/15.5	3,700
80	SM	84	16	3,300
81	SM	84	17.6	3,200
82	SM	84	7.8	1,130
83	SM	84	12	500
84	SM	92	0.9	1,550
86	SM	101	3.5/12.6	700
87	SM	101	17.5/26.1	1,500
88	SM	280	8.4/9.4	900
89	SM	280	20.4	780
90	SOL	12	7.5/13.6	5,500
91	SOL	113	1.5/5	500
92	SOL	113	5.5	1,010
93	SOL	113	0/18	9,525
94	SOL	128	0.4/0.5	810
95	SON	1	25.1/25.2	5,200
96	SON	1	31.4	900
97	SON	1	31.9	610
102	SON	12	17.6/18.5	365
103	SON	101	37.1/37.2	3,210
104	SON	101	1.2	1,000
105	SON	116	43.3	1,010
106	SON	116	39.9/40.2	1,900
107	SON	128	1.3	2,710
108	SON	128	16.2	1,510
109	SON	128	16.2/16.4	510
110	SON	128	15.4/17.4	3,185
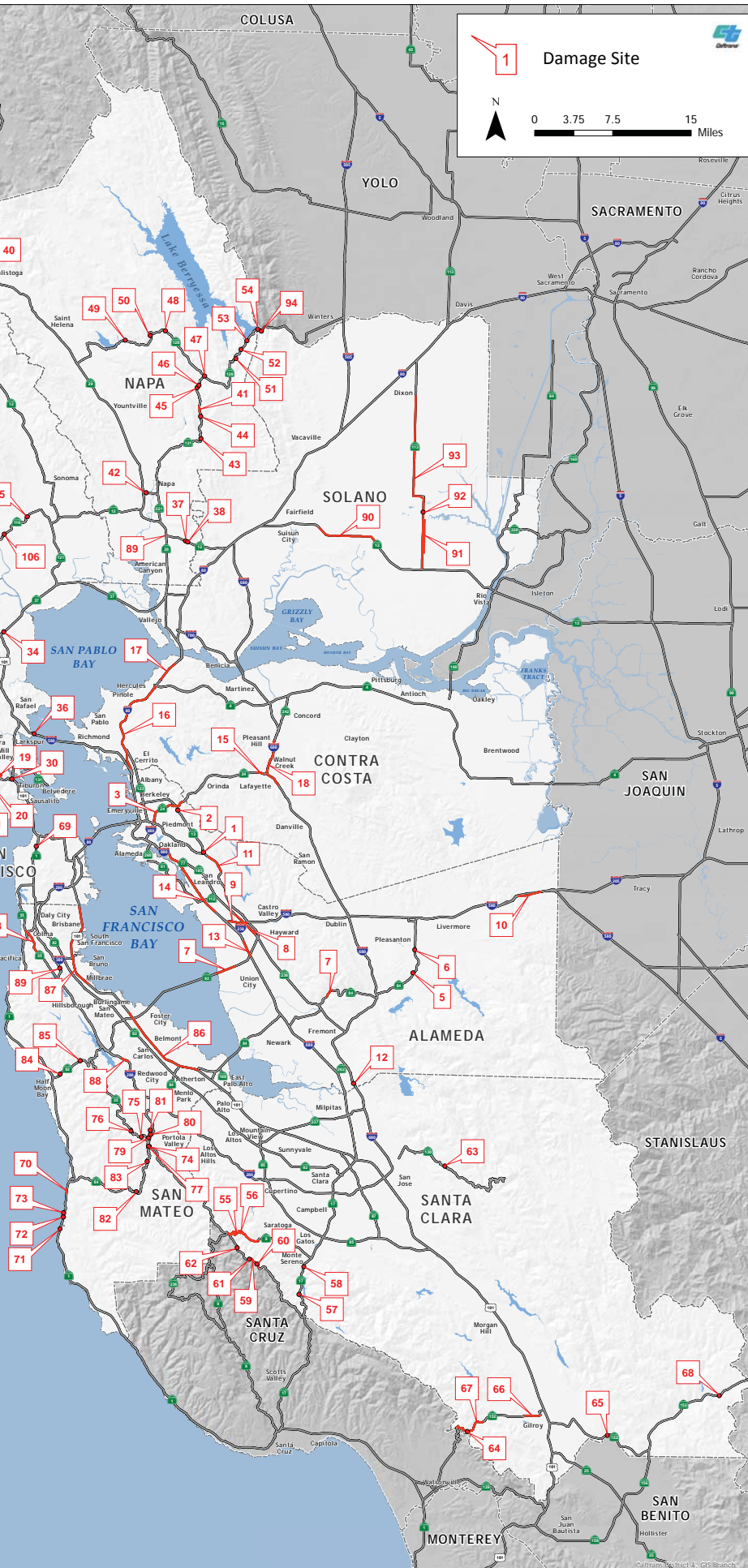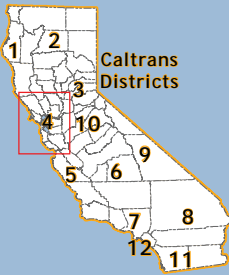
*26 damage sites are being monitored and not shown on the table

Caltrans Districts

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