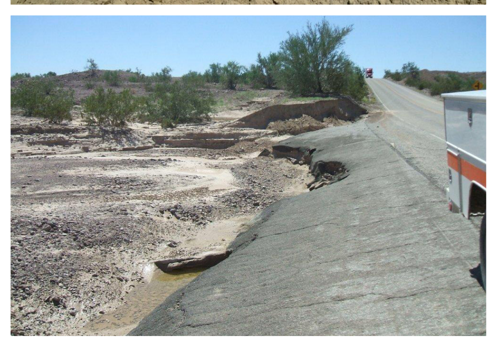
CALTRANS CLIMATE CHANGE VULNERABILITY ASSESSMENTS

2019



District 11

Technical Report

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ACRONYMS AND ABBREVIATIONS

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
CoSMoS	Coastal Storm Modeling System
EPA	Environmental Protection Agency
DWR	California Department of Water Resources
FEMA	Federal Emergency Management Agency
FHWA	Federal Highway Administration
GCM	Global Climate Model
GHG	Greenhouse Gas
GIS	Geographic Information System
IPCC	Intergovernmental Panel on Climate Change
LIDAR	Light Detection and Ranging
LOCA	Localized Constructed Analogs
MHHW	Mean Higher High Water
NOAA	National Oceanic and Atmospheric Administration
PCH	Pacific Coast Highway
RCP	Representative Concentration Pathway
Scripps	The Scripps Institution 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

This report was developed for the California Department of Transportation (Caltrans) to document an assessment of the vulnerability the State Highway System in District 11 to the potential effects of climate change. This is one of 12 such studies being performed, one for each of the 12 Caltrans districts.

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), branches of the University of California, 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 on the built environment, and for conveying this information to the public and decision-makers. Caltrans is doing its part by undertaking the current set of studies to better understand the vulnerability of California's State Highway System to future changes in climate. These studies have 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,
- Identify Caltrans assets vulnerable to various climate-influenced natural hazards, and
- Develop a method for prioritizing candidate projects, taking financial constraints (among other things) into consideration.

The vulnerability studies are being conducted at the district level in recognition of the fact that each of the 12 Caltrans districts faces its own set of challenges regarding future climate conditions and potential weather-related disruptions.

1.1. Purpose of Report

The purpose of the *District 11 Technical Report* is to provide readers 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 11 State Highway System and other Caltrans assets to future changes in climate. *The Technical Report,* which provides an in-depth discussion of the issues, is intended primarily for District 11 staff. A companion document, entitled *District 11 Summary Report*, summarizes the findings of the *Technical Report* for non-technical readers and outlines other approaches or policy concerns that may be of interest to a larger audience. Although there is some overlap in the material and information provided in these documents, those interested in the complete analysis of potential climate change-related impacts on the State Highway System in District 11 should read both documents.

In addition to the *Technical Report* and *Summary Report*, a database containing geospatial data indicating the current and future locations of various natural hazards and their impacts to Caltrans roadways was developed as part of this project. The maps included in this report and the *Summary Report* draw upon data contained in this database. Caltrans intends to use this data for further analysis of its own assets and 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 collaboration with stakeholders.

The *Technical Report* provides 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 for replicating them, if desired. The report is divided into sections by climate stressor (precipitation, wildfire, 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 (such as high quality Light Detection and Ranging [LIDAR]/asset data and stream flow data for precipitation effects, etc.), an assessment is presented of how changes in most often used 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 in light of future climate change. This framework was developed based on research on the prioritization frameworks used by other transportation agencies and reflects other methods that have been developed to guide decision-making when considering climate change effects.

1.2. District 11 Characteristics

Caltrans District 11 is located in Southern California. It stretches from the Pacific Ocean to Arizona and borders Mexico to the south; its headquarters is in San Diego. District 11 consists of two very different counties: urbanized San Diego County bordering the Pacific Ocean, and rural Imperial County bordering Arizona. As noted in the District's System Management Plan, District 11 is "one of the most geographically and culturally diverse areas in the country with a wide range of climates and terrain—from the temperate coastal region to chilly mountain peaks and blazing desert sands. Heading east from the San Diego coastline, the landscape of canyons and mesas climbs into mountains reaching more than 6,000 feet and then drops down to 230 feet below sea level in the low desert of Imperial County." San Diego County has 70 miles (110 km) of coastline.[1]

District 11 collaborates with many agencies that have various roles in the District's transportation system. The metropolitan planning organization (MPO) for Imperial County is the Southern California Association of Governments (SCAG), and the MPO for San Diego County is the San Diego Association of Governments (SANDAG). Imperial County also has a Transportation Commission. Other important participants in adaptation planning, besides the cities, include: The San Diego Unified Port District, San Diego County Regional Airport Authority, Imperial County Land Use Commission, Metropolitan Transit System, North County Transit District (NCTD), Imperial Valley Transit (IVT), San Diego County Water

[1] Caltrans, "District 11 System Management Plan," November 2016, http://www.dot.ca.gov/dist11/departments/planning/planningpages/dsmp.htm

Authority, and the Imperial Irrigation District. There are 19 federally recognized Native American Tribes and 20 reservations located in District 11.

District 11, crisscrossed by 17 State Highway routes, operates and maintains 1,009 centerline and 4,158 lane-miles of roadway.[2] The District has been very successful in expanding the capacity of the State Highway System. For example, over the past 20 years, the District and its transportation partners have doubled freeway lane-miles in San Diego County.

Figure 1 shows the State Highway System in District 11. Several of District 11's interstate highways have an important role in providing mobility and connectivity as part of California's State Highway System (note: the descriptions are from respective Caltrans reports).[3]

- I-5 serves interregional travel by linking the San Diego metropolitan area with Mexico to the south and Orange County and the Los Angeles metropolitan area to the north. I-5 is a heavily utilized commuter route providing direct access to the San Diego downtown as well as numerous other employment centers located within the corridor. I-5 provides truck access to San Diego's marine terminals, rail yards, and air freight terminals. Since I-5 parallels the coast, it provides access to a multitude of coastal recreational opportunities, as well as being a recreational gateway into Mexico. Its cross section varies from eight to fourteen general purpose lanes, depending on location.[4]

- I-15 is a major north-south freeway serving the inland portion of San Diego County mostly as an eight-lane freeway originating at the south junction with I-5 near downtown San Diego. It is the only State highway serving the major growth corridor from metropolitan San Diego to Riverside County and serves interregional travel by linking the metropolitan San Diego area with Mexico to the south.[5] I-15 is also a major truck route for goods movement, connecting the U.S.-Mexico border to San Diego County, Riverside County and San Bernardino County, then continuing northeast to Las Vegas.

- I-805 along with I-5 are the principal north-south interregional freeways for people and goods movement in the San Diego region, connecting the San Diego metropolitan area with Baja California and the greater Los Angeles basin to the north. Both are extensively used as commuter and truck routes and provide access to major employment centers in the region. I-805 is an eight-lane freeway with auxiliary lanes at various locations.[6]

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[2] "Caltrans District 11 Planning Division," Caltrans, last accessed May 7, 2019, http://www.dot.ca.gov/dist11/departments/planning/planningpages/tcr.htm

[3] Caltrans District 11, "Corridor System Management Plan (CSMP) Final Report Orange County Sr-55," March 27, 2014, http://www.dot.ca.gov/d12/planning/pdf/SR-55%20CSMP%20Final%20Technical%20Report.pdf

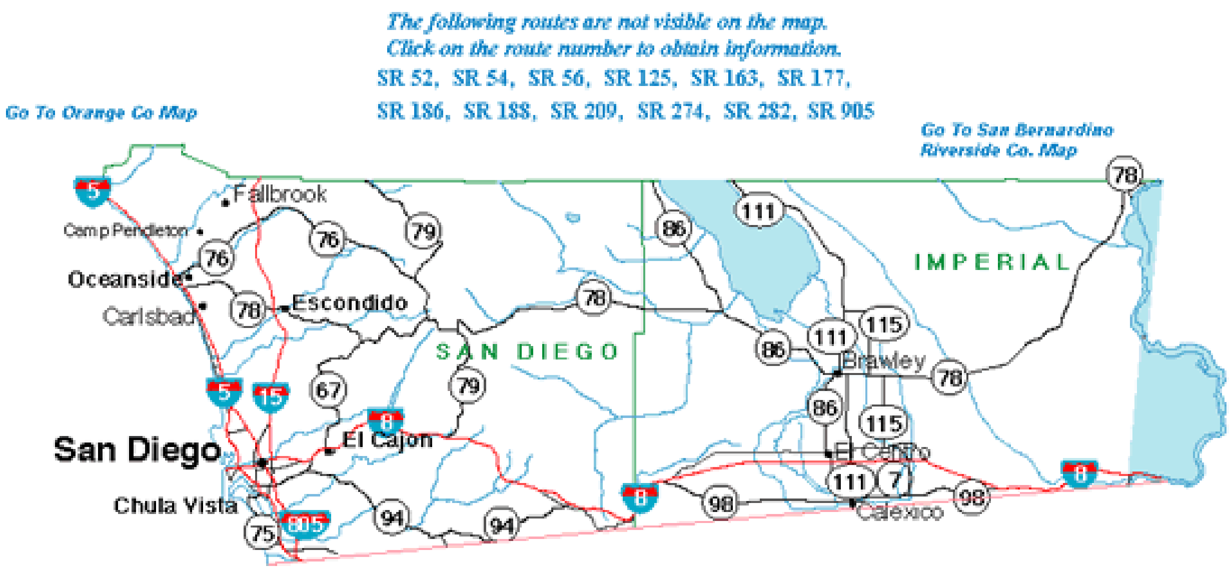
[4] Caltrans District 11, "Transportation Concept Report: Interstate 5," April 2017, http://www.dot.ca.gov/dist3/departments/planning/Systemplanning/Draft_I-5_TCR_04272017.pdf

[5] Caltrans, "Interstate 15 Corridor System Management Plan," January 2009, http://www.dot.ca.gov/dist11/departments/planning/pdfs/corridor/09_I15_CSMP.pdf

[6] SANDAG, "Interstates 805 / 5 South Corridor Study," June 2005, http://www.sandag.org/programs/transportation/roads_and_highways/i805-i5/2005_805_5_corrstudy.pdf

- I-8 in District 11 is 172 miles long, stretching from San Diego to the Arizona State Line.[7] Within San Diego County I-8 serves the urban core of San Diego as well as rural communities and tribal lands. In Imperial County, I-8 parallels the U.S./Mexico Border and the All-American Canal providing the east-west connection to rural communities and the City of El Centro and the City of Imperial. I-8 is used by Imperial County agricultural producers to ship products into San Diego. I-8 also connects distribution centers and consumers between San Diego to the Calexico/Mexicali region and other parts of the US. In Imperial County, I-8 experiences both heavy loads from freight trucking and adverse environmental conditions.

FIGURE 1: STATE HIGHWAY SYSTEM IN DISTRICT 11

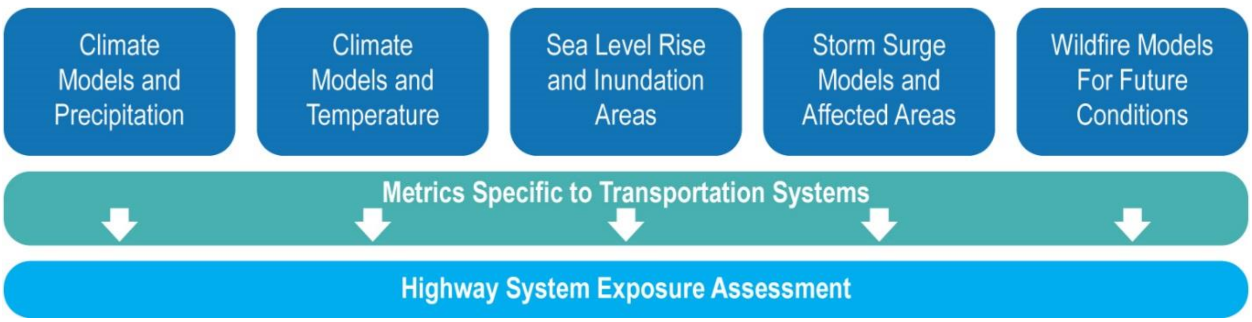


[7] Caltrans District 11, "Transportation Concept Report: Interstate 8," February 2016, http://www.dot.ca.gov/dist11/departments/planning/pdfs/tcr/2016_TCR_I_8.pdf

2. POTENTIAL CLIMATE CHANGE EFFECTS ON THE STATE HIGHWAY SYSTEM IN DISTRICT 11

Changing climate conditions and associated extreme weather changes present a series of challenges to District 11 in delivering resilient transportation facilities. The primary concern is that changing conditions may expose portions of the State Highway System to environmental factors beyond the district's facilities' original design parameters. Several climate models were used to study changing climatic conditions and extreme weather events. These climate models were considered in relation to the criteria, standards, and other metrics that influence how transportation facilities are designed. Figure 2 illustrates the various considerations that were used in building district-level exposure assessments. Note that some considerations are not applicable for every district.

FIGURE 2: CONSIDERATIONS FOR THE STATE HIGHWAY EXPOSURE ASSESSMENT

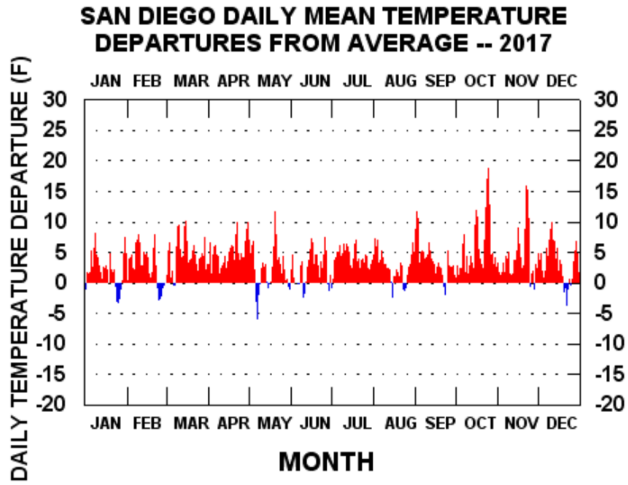


The following climactic/extreme weather conditions were evaluated for the District 11 assessment:

Temperature – San Diego County has a Mediterranean climate with relatively mild summers and winters. In recent years, the summers in District 11 have been hotter and longer and the winters drier - the San Diego area in the summer of 2017 experienced heat waves with periods of triple-digit temperatures lasting over a week.[8] The departure of daily mean temperature from historical average temperature during 2017 was dramatic, as displayed in Figure 3: San Diego Daily Mean Temperature Departures from Average – 2017 . This year was symptomatic of recent years where summers and winters were getting warmer compared to average temperatures over the past 50 years. Imperial County saw similar trends toward hotter temperatures. Death Valley National Park broke its 100-year-old record for the hottest month ever in July, 2017 when the average temperature was 107.4 degrees, eclipsing the 1917 record of 107.2 degrees, thus becoming the hottest month ever recorded in the US. The hottest day of the month reached 127 degrees.[9]

[8] Gary Robbins, "Temperature Records Tumble across San Diego County as Heat Wave Peaks," *San Diego Union-Tribune*, October 24, 2017, http://www.sandiegouniontribune.com/weather/sd-me-tuesday-heat-20171024-story.html
[9] Joseph Serna, "Death Valley Breaks 100-year-old Record for Hottest Month Ever in July," *Los Angeles Times*, August 3, 2017, http://www.latimes.com/local/lanow/la-me-ln-death-valley-heat-record-20170803-story.html

FIGURE 3: SAN DIEGO DAILY MEAN TEMPERATURE DEPARTURES FROM AVERAGE – 2017



Source: *https://www.climatestations.com/wp-content/uploads/2018/01/SD2017.gif*

Precipitation – Climate change may influence fluctuations in precipitation, with dry years becoming drier and wet years wetter. The years 2012 to 2014[10] were the three driest consecutive years in California's history; this period marks the second time a statewide emergency proclamation was issued for drought.[11]

Lower precipitation levels can have many negative effects in District 11 communities, perhaps the most significant being drought. In January 2014, Governor Jerry Brown declared a drought State of Emergency that lasted until April 2017 throughout most of California. Imperial County was declared a National Disaster Area by the US Department of Agriculture in 2017 due to drought-related agricultural losses and damages—this was despite the county's access to irrigation water from the Colorado River.

Wildfire – Historically, wildfires in the district have caused significant damage and transportation system disruption. In 2007, the Witch Creek Fire burned areas in north and northeast San Diego County and caused the evacuation of approximately 500,000 people from 346,000 homes. Many major roads were closed because of fires and smoke, including I-15 and I-5, and Amtrak service was suspended. The May 2014 San Diego County wildfires were comprised of 20 wildfires that were strengthened by severe Santa Ana Wind conditions, historic drought conditions, and a heat wave. Approximately 26,000 acres burned and 65 structures were destroyed. While the magnitude was not as great as in other areas, District 11 was significantly affected by the massive wildfires that occurred in California in 2017.

[10] Water years, as defined by the Department of Water Resources.
[11] California Department of Water Resources, "California's Most Significant Droughts: Comparing Historical and Recent Conditions," February 2015, https://water.ca.gov/LegacyFiles/waterconditions/docs/California_Signficant_Droughts_2015_small.pdf

Sea level rise – Sea level rise is a long-term threat in coastal areas. Thermal expansion of ocean water and melting ice sheets and glaciers contribute to higher sea levels worldwide. Higher sea levels will impact coastal infrastructure, particularly infrastructure historically designed for typical coastal conditions. More specifically, higher sea levels could inundate low-lying areas, damage substructure, and increase shoreline erosion. By the end of the century, San Diego sea levels are projected to be anywhere from 1.1 to 7 feet above current levels, with an extreme high of 10.2 feet (for more details on sea level rise projections, see Section 7).

Storm surge – Rising sea levels combined with storm pattern changes, are expected to alter and amplify the effects of storm surge in coastal areas, potentially causing extensive damage to infrastructure. Increased intensity of storm surge is expected to expose coastal infrastructure to higher forces during storms, and increase coastal erosion, shoreline retreat, landslides, and roadway flooding. Storm surge projections are currently considered in transportation system designs, but past designs did not account for more powerful surges.

Cliff retreat - Sea level rise will exacerbate the effects of cliff retreat, as water and waves erode rock that supports cliff faces. District 11 has already experienced the effects of storm surge on the State Highway System, specifically on the Pacific Coast Highway. Increased shoreline erosion and cliff retreat could affect the State Highway System if supporting shoreline is washed out.

Combined Effects –

- **Wildfire and Flooding** – In areas recently affected by wildfires, falling rocks, mud, and trees damaged by fire can wash down steep banks during periods of high intensity rain. This debris can cause road closures, often requiring detours on the District 11 State Highway System.

The following sections provide more detail on how each of these climate change stressors could affect the future performance of the Caltrans District 11 State Highway System. The study was based on the best data and science available from federal, state, regional and local agencies, as well as universities and science laboratories.

3. ASSESSMENT APPROACH

3.1. Stakeholder Involvement

The Caltrans study of potential impacts of climate change on the State Highway System has been based on research and work of multiple agencies and academic institutions across California. Caltrans District 11 staff helped in the preparation of this report in several ways:

- Met to discuss the methodology for undertaking the study, reviewed desired project deliverables, and identified District contacts.
- Provided reports and studies sponsored by or completed by District 11 staff.
- Identified available data on the State Highway System and noted the climate-related concerns in the district through the collection of photos showing recent events, and identification of available summary information on the impacts to the System.
- Reviewed the report and provided feedback on its findings and lessons learned.

The vulnerability assessment also included coordination with those California organizations responsible for climate modeling and data development. These agencies and research institutions will be discussed in the following section and referenced in the respective sections on each climate stressor – temperature, precipitation, sea level rise, storm surge, coastal erosion and wildfire).

3.2. State-of-the-Practice of Climate Policy and Research in California

California has been at the forefront of climate change policy, planning, and research nationally. State officials have been instrumental in developing and implementing policies that drive greenhouse gas (GHG) mitigation strategies and that foster the consideration of climate change factors in State decisions. California agencies have been pivotal in creating climate change datasets that can be used to consider regional impacts throughout the state.

Regional efforts to plan for and adapt to climate change are underway in communities across California. These practices provide additional data and information to climate change vulnerability assessments in California. The sections below provide some background on the current state-of-the-practice in vulnerability assessments and how the analysis methodologies were considered/applied in the District 11 study.

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 change 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 additional climate policy in the future.[12]

[12] "Assembly Bill 32 Overview," California Air Resources Board, last modified August 5, 2014, https://www.arb.ca.gov/cc/ab32/ab32.htm

- **Executive Order S-13-08** (2008) directs State agencies to plan for sea level rise (sea level rise) and climate impacts through the coordination of the State Climate Adaptation Strategy.[13]
- **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.[14]
- **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.[15]
- **Senate Bill 246** (2015) establishes the Integrated Climate Adaptation and Resiliency Program to coordinate with regional and local efforts with State adaptation strategies.[16]
- **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.[17]

These policies establish the foundation for the factors that State agencies consider when addressing climate change. Conducting a vulnerability assessment for District 11 is a key step towards preserving Caltrans' infrastructure against future climate change-related stresses, and directly relates to the requirements of the relevant State policies above, especially Executive Order B-30-15, Assembly Bill 1482, and Assembly Bill 2800. Other policies, such as Executive Order S-13-08, stimulate the creation of climate data.

Executive Order B-30-15 is one of the most important climate adaptation policies. Guidance specific to the Executive Order and how State agencies can begin to implement the order was released in 2017. This guidance, entitled *Planning and Investing for a Resilient California*, will help State agencies develop vulnerability assessments specific to their focus areas, and that support adaptive planning decisions.[18] The Executive Order guidance creates a framework for use by State agencies. Having such a common framework is important in communicating the effects of climate change across agencies.

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[13] "California Executive Order S-13-08 Requiring State Adaptation Strategy," Adaptation Clearinghouse, last accessed April 30, 2019, https://www.adaptationclearinghouse.org/resources/california-executive-order-s-13-08-requiring-state-adaptation-strategy.html

[14] "Governor Brown Establishes Most Ambitious Greenhouse Gas Reduction Target in North America," Office of Governor Edmund Brown, last modified April 29, 2015, https://www.ca.gov/archive/gov39/2015/04/29/news18938/

[15] "Assembly Bill No. 1482," California Legislative Information, October 8, 2015, https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201520160AB1482

[16] "Senate Bill No.246," California Legislative Information, October 8, 2015, https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201520160SB246

[17] "Assembly Bill No. 2800," California Legislative Information, September 24. 2016, http://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201520160AB2800

[18] Governor's Office of Planning and Research, "Planning and Investing for a Resilient California: a Guidebook for State Agencies," March 13th, 2018, http://opr.ca.gov/planning/icarp/resilient-ca.html

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 State agencies to develop and regularly update State guidance on climate change. These research efforts are called California Climate Change Assessments; the fourth edition of which was just released (California Fourth Climate Change Assessment). The research and datasets from the California Fourth Climate Change Assessment were used in the District 11 vulnerability assessment to the extent they were available at the time of the study. To understand how they were used, some context on Global Climate Models (GCMs) and emissions scenarios is necessary. The section below will provide the background necessary to understand how the data was applied in this assessment.

Global Climate Models

GCMs have been developed by many academic and research institutions around the world to represent the physical processes that cause the Earth's climate to change, and to project future GHG emissions given changes in these processes.[19] These models are run with different estimates of GHG emissions or atmospheric concentrations of GHG gases, assuming different scenarios of what might happen in the future. These scenarios, developed and summarized by the Intergovernmental Panel on Climate Change (IPCC), are used in almost every vulnerability assessment in the world.

The IPCC, the leading international body for quantifying the potential effects of climate change, has a membership 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 the latest research on emissions generation and estimates how these emissions may change given international GHG reduction policies and other factors that will affect the production of GHG emissions. The IPCC estimates are provided for different time periods to the end of the century.

Dozens of climate models are used by researchers and analysts for various purposes. Each vulnerability assessment identifies which of these models best reflect the climatic conditions of the study area. In the case of California, out of 32 downscaled GCMs for California, 10 models were chosen by State agencies as being most representative of climate change in California. This effort was led by the Department of Water Resources in order to understand which models to use in State assessments and planning decisions.[20] The representative GCMs for California are:

- ACCESS 1-0
- CanESM2
- CCSM4
- CESM1-BGC
- CMCC-CMS
- CNRM-CM5
- GFDL-CM3

[19] "What is a GCM?", Intergovernmental Panel on Climate Change, last accessed April 30, 2019, http://www.ipcc-data.org/guidelines/pages/gcm_guide.html
[20] "LOCA Downscaled Climate Projections," Cal-Adapt, last accessed April 30, 2019, http://cal-adapt.org/

- HadGEM2-CC
- HadGEM2-ES
- MIROC5

Data from these models are available on Cal-Adapt 2.0, California's Climate Change Research Center.[21] The Cal-Adapt 2.0 data platform provides some of the best available data in California on climate change and, for this reason, selected data from the GCMs above along with data from the *Fourth Climate Change Assessment* (if it was available during the study) were utilized in the Caltrans District 11 study.

Emissions Scenarios

There are two commonly cited sets of emissions data used by the IPCC:

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

RCPs represent the most recent generation of GHG scenarios produced by the IPCC and are used in this report. These scenarios use three main metrics: radiative forcing, emission rates, and emission concentrations.[22] Four RCPs were developed by the IPCC to reflect assumptions for emissions growth, and the resulting concentrations of GHG in the atmosphere. The RCPs are applied in GCMs to identify projected future conditions and enable a comparison of one future scenario 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 RCP assumptions are as follows:

- RCP 2.6 assumes that global annual GHG emissions will peak in the next few years and then begin to decline substantially.
- RCP 4.5 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, and beyond.[23]

California Fourth Climate Change Assessment

The California Fourth Climate Change Assessment was an interagency research and "model downscaling" effort for multiple climate stressors. The California Fourth Climate Change Assessment was 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, as well as academic institutions such as the Scripps Institution of Oceanography (Scripps) and the University of California, Merced.[24]

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

[22] "Representative Concentration Pathways," IPCC, last accessed April 30, 2019, http://sedac.ipcc-data.org/ddc/ar5_scenario_process/RCPs.html

[23] 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

[24] "California's Fourth Climate Change Assessment," State of California website (CA.gov), last accessed June 5th, 2019, http://www.climateassessment.ca.gov/

Model downscaling is a statistical technique that refines the results of GCMs to a regional level. The model downscaling used in the California Fourth Climate Change Assessment is a technique called Localized Constructed Analogs (LOCA), which "uses past history to add improved fine scale detail to GCMs."[25] This data source provides a finer grid system than is found in other data bases, enabling the assessment of changes in a more localized way than was previously available. This effort was undertaken by Scripps.[26]

3.3. Other Efforts to Address Climate Change

Concurrent with statewide efforts, several climate change-related efforts are underway at many other organizations in District 11.

3.3.1. Climate Action Plans

Many communities and county agencies in District 11 have either adopted Climate Action Plans (CAPs) designed to mitigate greenhouse gas emissions and reduce the impacts of climate change to their communities or have included such plans as part of their comprehensive plan. Some of the communities that have adopted CAPs include the City and County of San Diego, and the Cities of Calexico, Carlsbad, Chula Vista, Del Mar, Encinitas, Escondido, Imperial Beach, Oceanside and Vista. Both MPOs in District 11, the Southern California Association of Governments (SCAG) for Imperial County and SANDAG for the San Diego metropolitan area, have conducted climate change studies as well.

3.3.2. San Diego Regional Climate Collaborative

The San Diego Regional Climate Collaborative is a regional collaborative focused on promoting climate adaptation and mitigation strategies across the San Diego region.[27] The collaborative is one of seven in California that make up the Alliance for Regional Collaboratives for Climate Adaptation (ARCCA). Members include the Cities of Chula Vista, Del Mar, Encinitas, National City, Oceanside and San Diego, the County of San Diego, Port of San Diego, San Diego Airport Authority, San Diego Association of Governments, Cleantech San Diego, San Diego Climate Science Alliance, The San Diego Foundation, San Diego Gas & Electric, San Diego State University, UC San Diego, and University of San Diego.[28]

3.3.3. The San Diego Foundation

The San Diego Foundation has invested significant resources into improving the San Diego community in many different areas. On the topic of climate change, the Foundation has published 18 climate change research studies and supported local government technical assistance projects. Examples of technical assistance include the Foundation's work to support the production of the City of San Diego Climate Action Plan, City of Chula Vista's Water Stewardship Plan, and the Imperial Beach Sea level rise Assessment. The Foundation has also partnered with other climate preparedness groups in the San Diego region. For example, it is an active partner in San Diego's climate action efforts.

[25] "LOCA Downscaled Climate Projections," Cal-Adapt, last accessed April 30, 2019, http://cal-adapt.org/
[26] "LOCA Downscaled Climate Projections," Cal-Adapt, last accessed April 30, 2019, http://cal-adapt.org/
[27] "About Us," The San Diego Regional Climate Collaborative, last accessed May 7, 2019, https://www.sdclimatecollaborative.org/about_us
[28] "Members," The San Diego Regional Climate Collaborative, last accessed May 7, 2019, https://www.sdclimatecollaborative.org/members

3.3.4. San Diego County Action Plan

San Diego County has adopted a climate action plan that describes expected future climatic conditions.[29] Forecasts for the county, from the County Action Plan, include:

- A 5.5 °F increase in minimum temperatures by the end of century under the low emissions scenario examined in the plan (from a historical minimum temperature of 47.8 °F to 53.3 °F by 2099).
- A 9.9 °F increase in minimum temperatures by the end of century under the high emissions scenario examined in the plan (from a historical minimum temperature of 47.8 °F to 57.7 °F by 2099).
- An average of 33 extreme heat days projected from 2090 to 2099, which is an increase of approximately 29 days from the historical average (under the low emissions scenario).
- An average of 67 extreme heat days projected from 2090 to 2099, which is an increase of approximately 63 days from the historical average (under the high emissions scenario).
- 20,971 acres are expected to burn in 2050, under the high emissions scenario, and another 29,499 acres are projected to burn by 2099.
- Increased intensity and frequency of major storms, which could "…further augment flood problems in southern California" and even lead to indirect water quality impacts from flooding upstream, in the Sacramento-San Joaquin Delta. [30]

3.3.5. San Diego Association of Governments (SANDAG)

SANDAG has adopted a Climate Action Strategy that recommends considering climate change factors when designing transportation facilities. An example of how this strategy has been implemented is found in a joint SANDAG/Caltrans study of the North Coast corridor in which the SANDAG sea level rise analysis has been incorporated into project recommendations.[31] The corridor planning document included design water level guidance developed by SANDAG, which had recommended values and approaches for vertical datums, ocean water level, astronomical tides, storm surge, wave set-up, cyclic climatic patterns, tsunamis, local sea level rise, extreme ocean water level, fluvial water level, numerical model selection, downstream boundary condition, water levels at bridge crossings, combined water levels, and bridge freeboards. The types of strategies examined in the report included:

- Elevate new infrastructure for higher sea level rise scenarios.
- Install adaptable bridges and approaches.

[29] County of San Diego, "Climate Change Vulnerability Assessment County of San Diego," August 2017, https://www.sandiegocounty.gov/content/dam/sdc/pds/advance/cap/publicreviewdocuments/FinalPublicReviewDocs/CAPWebAttachments/a4capappendixdweb.pdf

[30] San Diego County Water Authority, "Climate Action Plan," March 2014, http://www.sdcwa.org/sites/default/files/Final%20Climate%20Action%20Plan.pdf

[31] SANDAG and Caltrans, "North Coast Corridor Public Works Plan/Transportation and Resource Enhancement Program, June 2014, http://www.dot.ca.gov/dist11/Env_docs/I-5PWP/2016/march/nccpwptrepfull.pdf

- Estimate conservatively high-water levels and raise new bridges based on the I-5 San Diego County coastal sea level rise analysis.
- Estimate new and less conservative high-water levels and raise new bridges on I-5.
- Conduct a site-specific analysis based on a design water level analysis methodology considering sea level rise.
- Periodically update design guidelines for high water levels.

3.3.6. Southern California Association of Governments (SCAG) Reports

The Southern California Association of Governments (SCAG) is a Joint Powers Authority, MPO, Regional Tranpsortation Planning Agency and Council of Governments representing Imperial, Los Angeles, Orange, Riverside, San Bernardio, and Ventura Counties. SCAG has conducted studies of climate change projections and impacts for Southern California and the regions it represents, which are available on their sustainability program portal. One of SCAG's most important reports on the topic is *Climate Change and the Future of Southern California,*[32] which examines future trends in Southern California and the strategies counties and communities can adopt to mitigate and adapt to changing climatic and extreme weather conditions.

3.3.7. California Department of Public Health, "Climate Change and Health Profile Report Imperial County"

This report was produced by the California Department of Public Health Office of Health Equality to "foster mobilization to prevent and reduce injury and disease related to climate change.[33] The following summaries examine the expected impacts of different climate stressors on Imperial County.

Temperature: Temperatures are expected to rise substantially in Imperial County throughout the century. The historic average temperature in the county is 73.4 °F and by 2099 this is expected to increase by 3.4 °F assuming a low emissions scenario and by 6.4 °F assuming a high emissions scenario.

Health Impacts of Heat: "Increased temperatures manifested as heat waves and sustained high heat days directly harm human health through heat-related illnesses (mild heat stress to fatal heat stroke) and the exacerbation of pre-existing conditions in the medically fragile, chronically ill, and vulnerable populations. Increased heat also intensifies the photochemical reactions that produce smog and ground level ozone and fine particulates (PM2.5), which contribute to and exacerbate respiratory disease in children and adults. Increased heat and carbon dioxide enhance the growth of plants that produce pollen, which are associated with allergies."

Health Impacts of Wildfires: "Devastating wildfires like the Rim Fire of 2013 impact watersheds and increase the risk of landslides or mudslides, and sediment in run-off that reduce water quality. In addition to fire-related injuries, local and regional transport of smoke, ash, and fine particles increases respiratory and cardiovascular risks."

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[32] Southern California Association of Governments, "Climate Change and the Future of Southern California," July 2009, http://scag.ca.gov/Documents/ClimateChange_Full_lores.pdf

[33] California Department of Public Health, "Climate Change and Health Profile Report Imperial County," February 2017, https://www.cdph.ca.gov/Programs/OHE/CDPH%20Document%20Library/CHPRs/CHPR025Imperial_County2-23-17.pdf

Health Impacts of Drought: "Drought may increase exposure to health hazards including wildfires, dust storms, extreme heat events, flash flooding, degraded water quality, and reduced water quantity. Dust storms associated with drought conditions have been associated with increased incidents of Valley fever, a fungal pathogen."

Food Security: "Climate change is expected to have global impacts on food production and distribution systems. This can cause food prices to increase, which makes food less affordable and increases food insecurity, obesity, and malnutrition in economically-constrained households."

Socio-economic Disruption: "Widespread social and economic disruption includes damage to the infrastructure for the delivery of health services and for general economic well-being. Health care facilities, water treatment plants, and roads for emergency responders and transportation for health care personnel can be damaged in climate-related extreme weather events."

The report also examined the equity impacts of climate change on different population groups in the county, which is discussed in the following section for all of District 11.

3.3.8. Disadvantaged and Low Income Populations and Environmental Justice

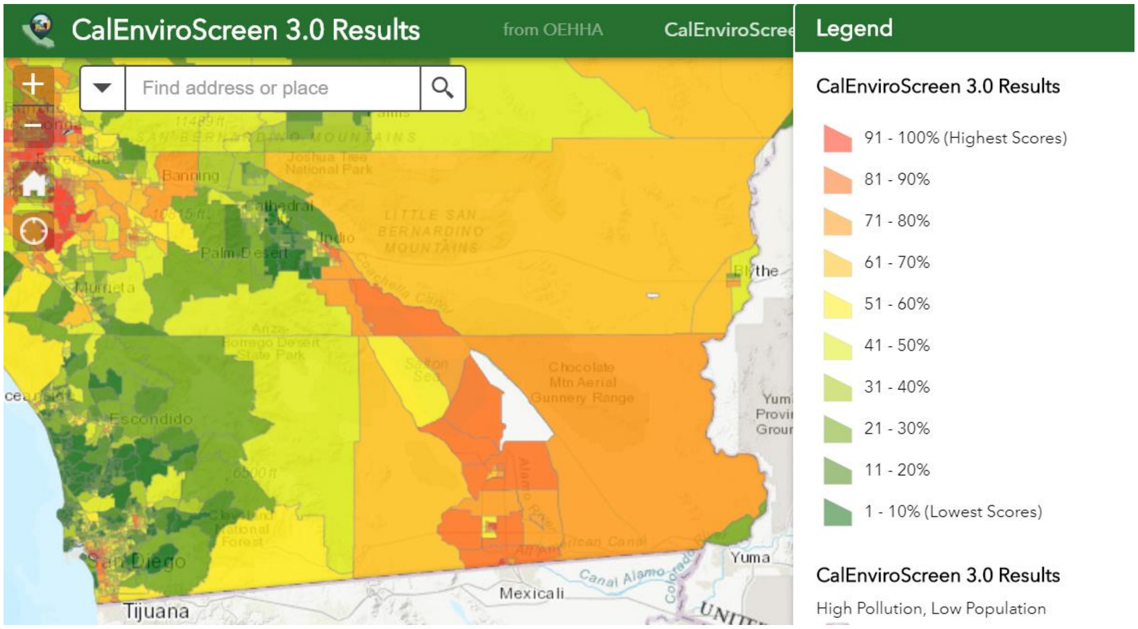
In 2012, the Legislature passed Senate Bill 535, directing that 25% of the proceeds from the Greenhouse Gas Reduction Fund go to projects that provide a benefit to disadvantaged communities (later legislation required that 25% of the proceeds be spent on projects in disadvantaged communities in addition to low income populations). The definitions of key terms are below:

- Disadvantaged Communities - Census tracts in the top 25% of CalEnviroScreen 3.0 scores, plus those census tracts that score in the highest 5% of CalEnviroScreen's Pollution Burden without an overall CalEnviroScreen score.[34]
- Low-income Communities - Census tracts that are either at or below 80% of the statewide median income, or at or below the threshold designated as low-income by the California Department of Housing and Community Development's (HCD) 2016 State Income Limits.
- Low-income Buffer Regions - Low-income communities as identified in (2) that are also within 1/2 mile of a disadvantaged community as identified in (1).

Figure 4 shows the portions of communities in District 11 that are considered disadvantaged and low income. Most of these areas are located in Imperial County. Executive Order B-30-15 requires that State agencies consider vulnerable populations in their decision-making. It is crucial that these communities and organizations be included in Caltrans processes.

[34] "CalEnviroScreen 3.0," California Office of Environmental Health Hazard Assessment, June 2018, https://oehha.maps.arcgis.com/apps/webappviewer/index.html?id=4560cfbce7c745c299b2d0cbb07044f5

FIGURE 4: DISADVANTAGED COMMUNITIES IN DISTRICT 11



Source: https://oehha.maps.arcgis.com/apps/webappviewer/index.html?id=4560cfbce7c745c299b2d0cbb07044f5

As noted earlier, the California Department of Public Health report on Imperial County devoted a section to vulnerable populations. The following excerpt comes from this section of the report.

> "In 2010, the age-adjusted death rate in Imperial County was nearly the same as the state average. Disparities in death rates among race/ethnicity groups highlight how certain populations disproportionately experience health impacts. Within the county, the highest death rate occurred among American Indians and the lowest death rate occurred among Hispanics/Latinos. In 2012, nearly 42% of adults (46,757) reported one or more chronic health conditions including heart disease, diabetes, asthma, severe mental stress or high blood pressure. In 2012, 14% of adults reported having been diagnosed with asthma. In 2012, approximately 42% of adults were obese (statewide average was 25%). In 2012, nearly 13% of residents aged 5 years and older had a mental or physical disability (statewide average was 10%). In 2005-2010, there was an annual average of 135 heat-related emergency room visits and an age-adjusted rate of 78 emergency room visits per 100,000 persons (the statewide age-adjusted rate was 10 emergency room visits per 100,000 persons).

> "In 2010, Imperial County had approximately 6,366 outdoor workers whose occupation increased their risk of heat illness. In 2010, roughly ten percent of households did not own a vehicle that could be used for evacuation (statewide average was 8%). In 2009, approximately 32% of households were estimated to lack air conditioning, a strategy to counter adverse effects of heat (statewide average was 36%). In 2011, tree canopy, which provides shade and other environmental benefits, was present on 2% of the county's land area (statewide average was 8%)."

3.4. General Methodology

The methodology used to determine the vulnerability of assets varies from one climate stressor to another. Each stressor type uses a different set of models, emissions scenarios, and assumptions, and leads to different types of adaptation strategies that relate to stressor-specific expected future conditions. The methods employed for each stressor analyzed for the District 11 study are described more fully in each stressor section; however, there are some general practices that apply for all approaches.

3.4.1. Time Periods

Climate projections should be presented in a way that allows for consistent comparisons among various analysis periods and for different stressors. For this study, analysis periods were defined as the beginning, middle, and end of century and were represented by the out-years of 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. The year 2085 is the center point of this time range and thus the last year in which statistically-derived projections can defensibly be made. The 2025 and 2055 out-years follow from the same logic, and are 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. These 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 given changing climate conditions. 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 were 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, provided 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 after the study (see Figure 5). Limited metadata on each dataset was also provided in the form of an excel table that described each dataset and its characteristics (see Figure 6). This GIS data will be useful to Caltrans in future climate adaptation planning activities.

FIGURE 5: SCREENSHOT OF GIS DATABASE

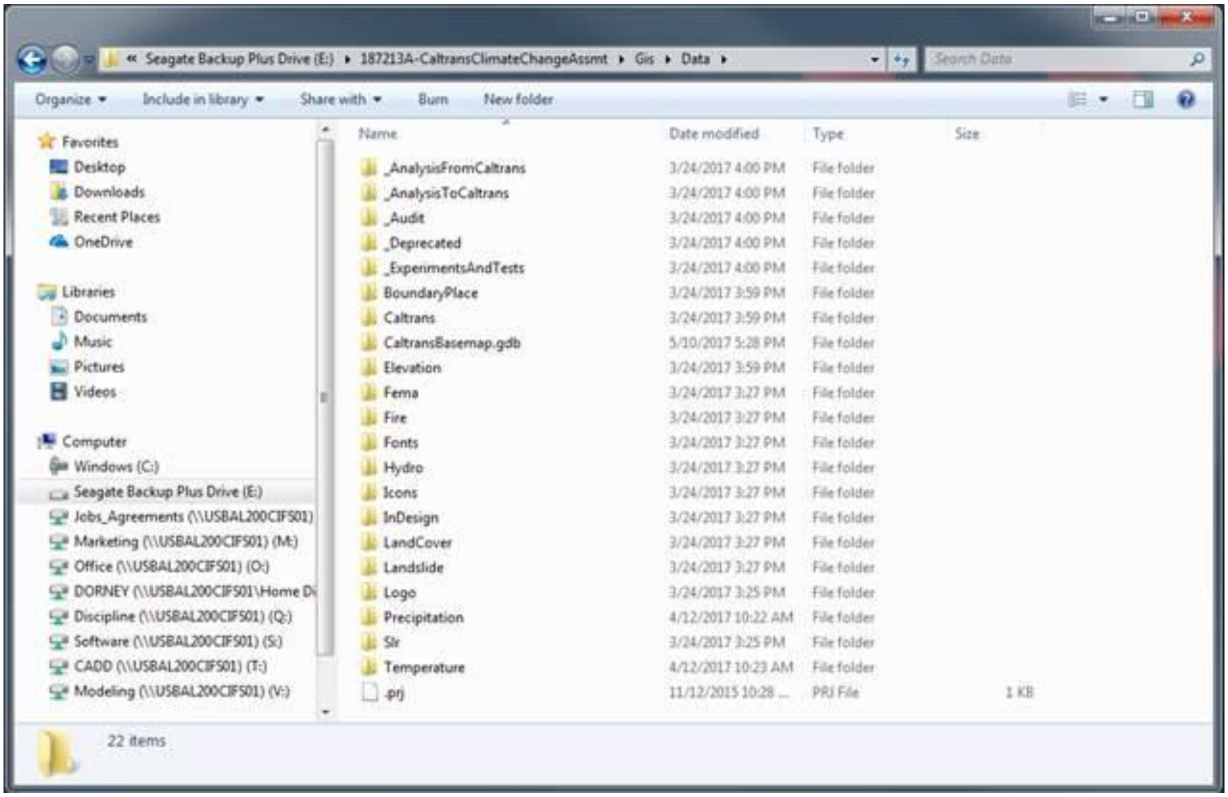
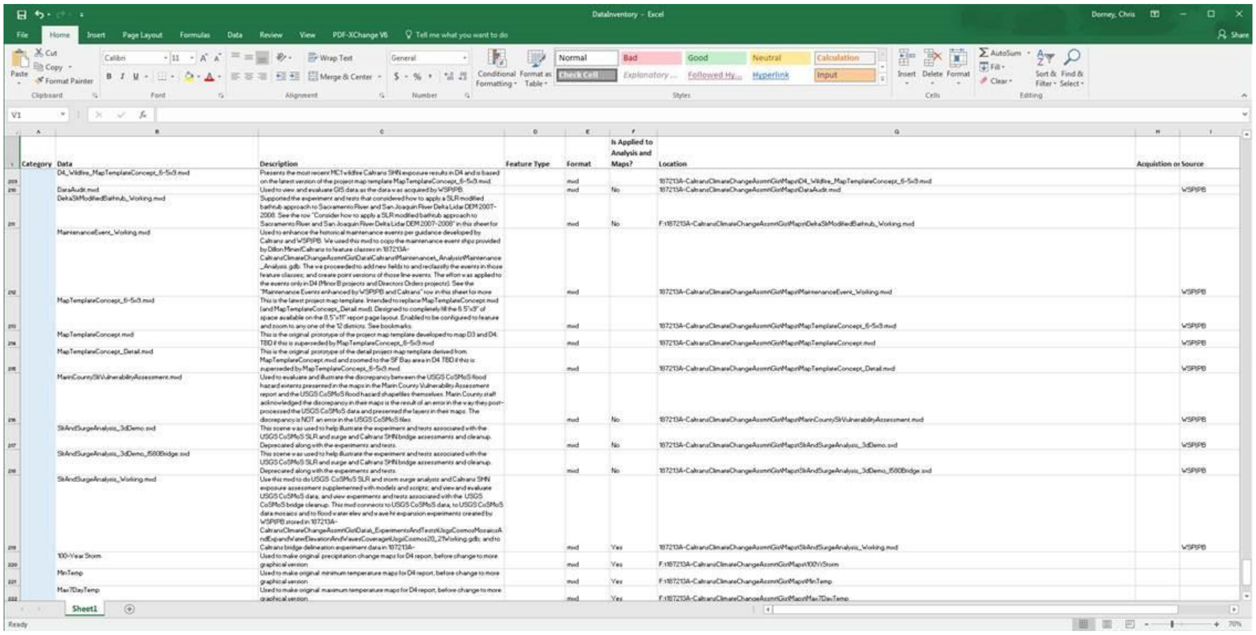


FIGURE 6: SCREENSHOT OF SPREADSHEET PROVIDED



4. TEMPERATURE

Temperature rise is an important facet of climate change. Summer temperatures are projected to continue rising, and a reduction of soil moisture, which is a direct result of heat waves, is projected for much of the western and central US.[35] The potential impacts of extreme temperatures on District 11 assets will vary by asset type and will depend on the specifications followed in the original design of a facility. For example, the following potential impacts of increasing temperatures have been identified in other studies in the US.

4.1. Design

- Pavement design includes an assessment of temperature in determining recommendations for the types of material used. With increasing temperatures, more durable materials might be necessary.
- 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.

4.2. 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 higher temperatures 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 relies, 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 for determining the extreme pavement temperatures a roadway may experience over time. This is important because a binder must be able to maintain pavement integrity

[35] "Extreme Weather," U.S. National Climate Assessment, accessed April 29, 2019, http://nca2014.globalchange.gov/report/our-changing-climate/extreme-weather

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

The District 11 vulnerability assessment assessed 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. Per the *Caltrans Highway Design Manual (HDM*), the pavement design life for new construction and reconstruction projects shall be no less than 40 years. For roadside facilities, such as parking lots and rest areas, 20-year pavement design life may be used. The design life of asphalt pavements is close to the 30-year analysis periods used in this report. Because asphalt overlays of different specifications are often used to prolong roadway life, they can be used as short-term actions until it is clear how climate conditions are changing.

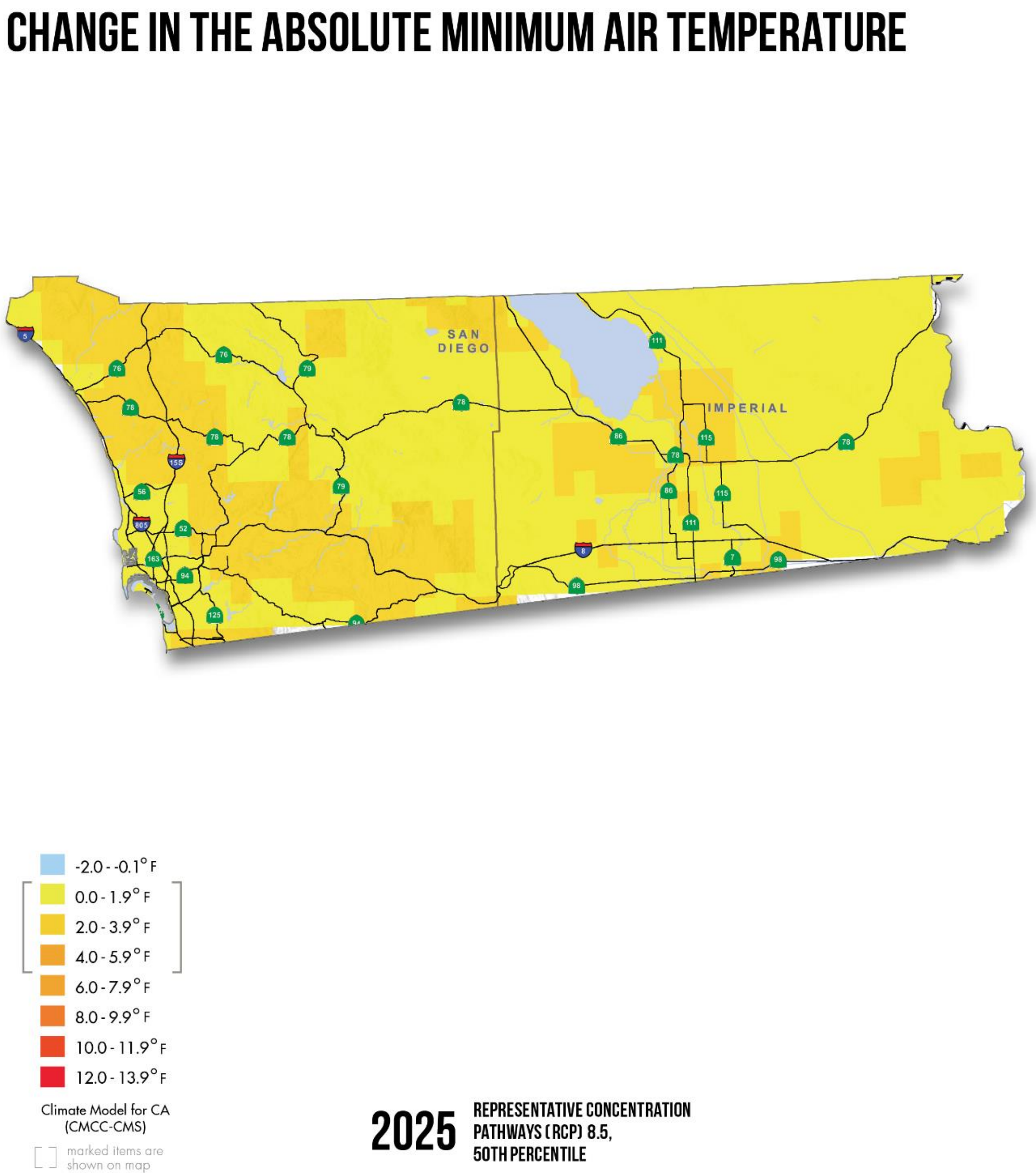
LOCA climate data served as the basis for predicting future temperature change. This data has a spatial resolution of 1/16 of a degree or approximately 3.5 to 4 miles.[36] This data set was queried to determine the annual lowest temperature and the mean seven-day consecutive high temperature for each 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 modeling data to enable comparisons across the many different physiographic regions in California.

The maps shown in Figure 7 to Figure 12 are for the model that represents the median change across California 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 values. Changes to both temperature metrics become greater over time with the maximum temperature changes generally being greater than those for the minimum temperature.

The change values shown on the maps can be added to Caltrans' current source of historical temperature data to determine the design values for the future. This summary data can be used by Caltrans to identify how pavement design practices might 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.

[36] "LOCA Downscaled Climate Projections," Cal-Adapt, last accessed May 1, 2019, http://cal-adapt.org/data/loca/

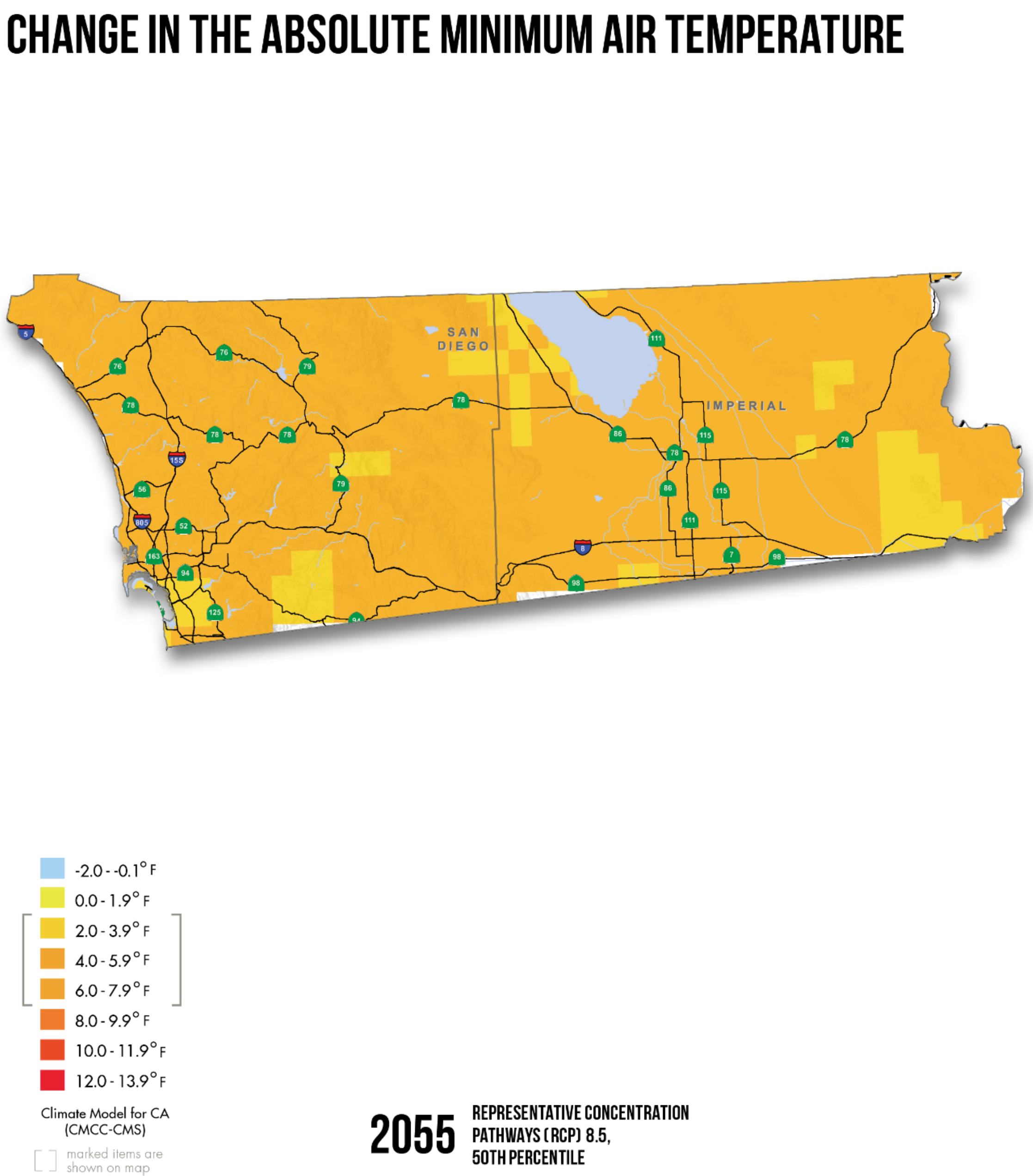
FIGURE 7: CHANGE IN ABSOLUTE MINIMUM TEMPERATURE, 2025



Future Change in the Absolute Minimum Air Temperature within District 11, Based on the RCP 8.5 Emissions Scenario

Caltrans Transportation Asset Vulnerability Study, District 11. Caltrans No. 74A0737. Climate data provided by the Scripps Institution of Oceanography. The data shown was generated by downscaling global climate outputs using the Localized Constructed Analogs (LOCA) technique.

FIGURE 8: CHANGE IN ABSOLUTE MINIMUM TEMPERATURE, 2055

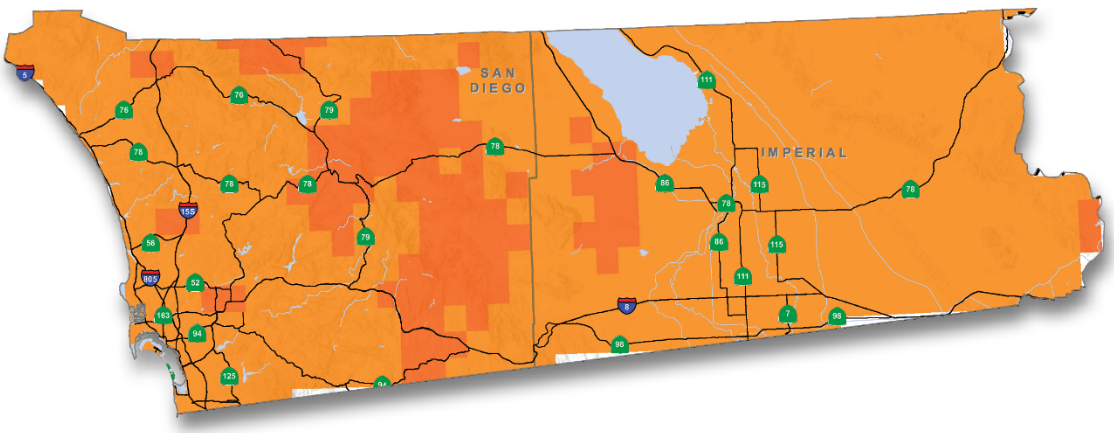


Future Change in the Absolute Minimum Air Temperature within District 11, Based on the RCP 8.5 Emissions Scenario

Caltrans Transportation Asset Vulnerability Study, District 11. Caltrans No. 74A0737. Climate data provided by the Scripps Institution of Oceanography. The data shown was generated by downscaling global climate outputs using the Localized Constructed Analogs (LOCA) technique.

FIGURE 9: CHANGE IN ABSOLUTE MINIMUM TEMPERATURE, 2085

CHANGE IN THE ABSOLUTE MINIMUM AIR TEMPERATURE



- -2.0 - -0.1° F
- 0.0 - 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 - 13.9° F

Climate Model for CA (CMCC-CMS)

[ ] marked items are shown on map

2085 REPRESENTATIVE CONCENTRATION PATHWAYS (RCP) 8.5, 50TH PERCENTILE

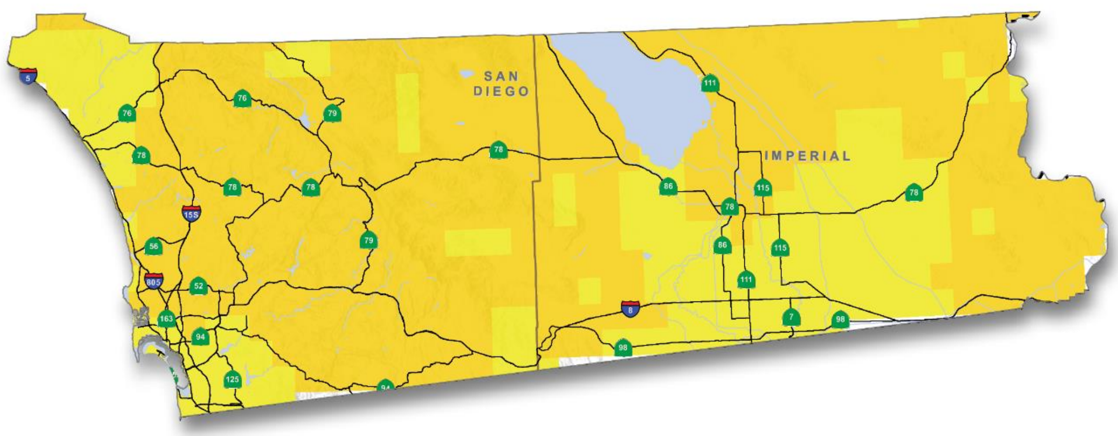
Future Change in the Absolute Minimum Air Temperature within District 11, Based on the RCP 8.5 Emissions Scenario

Caltrans Transportation Asset Vulnerability Study, District 11. Caltrans No. 74A0737. Climate data provided by the Scripps Institution of Oceanography. The data shown was generated by downscaling global climate outputs using the Localized Constructed Analogs (LOCA) technique.

FIGURE 10: CHANGE IN AVERAGE MAXIMUM TEMPERATURE OVER SEVEN DAYS, 2025

CHANGE IN THE AVERAGE MAXIMUM TEMPERATURE OVER SEVEN CONSECUTIVE DAYS

A REQUIRED MEASURE FOR PAVEMENT DESIGN



- -2.0 - -0.1° F
- 0.0 - 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 - 13.9° F

Climate Model for CA (CMCC-CMS)

[ ] marked items are shown on map

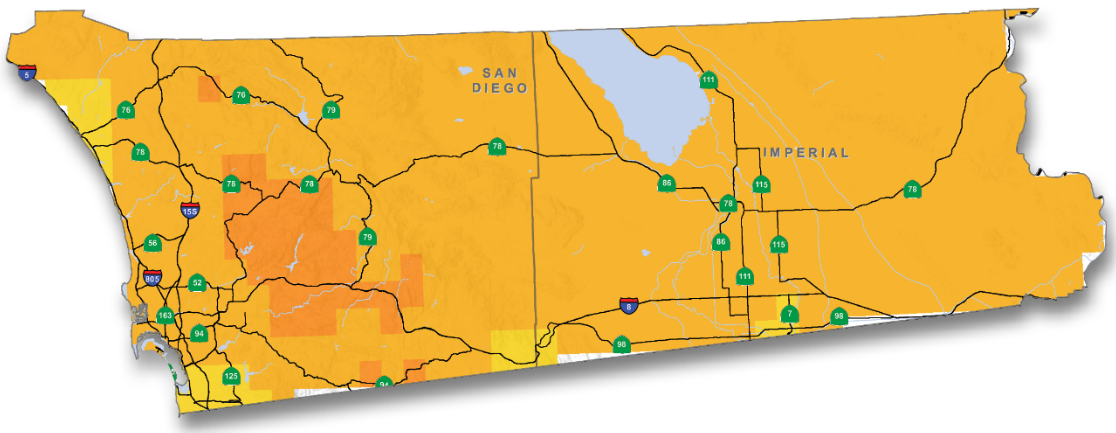
2025 REPRESENTATIVE CONCENTRATION PATHWAYS (RCP) 8.5, 50TH PERCENTILE

Future Change in the Average Maximum Temperature over Seven Consecutive Days within District 11, Based on the RCP 8.5 Emissions Scenario

Caltrans Transportation Asset Vulnerability Study, District 11. Caltrans No. 74A0737. Climate data provided by the Scripps Institution of Oceanography. The data shown was generated by downscaling global climate outputs using the Localized Constructed Analogs (LOCA) technique.

FIGURE 11: CHANGE IN AVERAGE MAXIMUM TEMPERATURE OVER SEVEN DAYS, 2055

CHANGE IN THE AVERAGE MAXIMUM TEMPERATURE OVER SEVEN CONSECUTIVE DAYS A REQUIRED MEASURE FOR PAVEMENT DESIGN



- -2.0 - -0.1° F
- 0.0 - 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 - 13.9° F

Climate Model for CA (CMCC-CMS)

[ ] marked items are shown on map

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

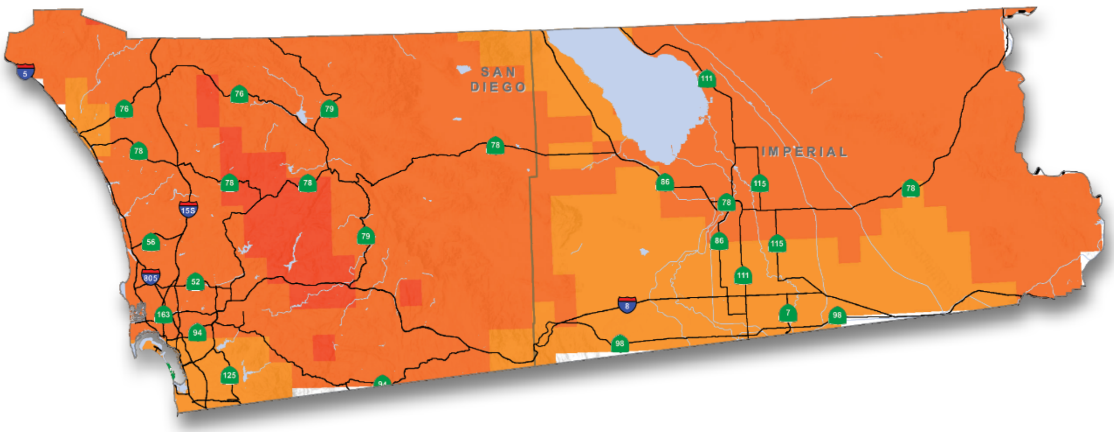
Future Change in the Average Maximum Temperature over Seven Consecutive Days within District 11, Based on the RCP 8.5 Emissions Scenario

Caltrans Transportation Asset Vulnerability Study, District 11. Caltrans No. 74A0737. Climate data provided by the Scripps Institution of Oceanography. The data shown was generated by downscaling global climate outputs using the Localized Constructed Analogs (LOCA) technique.

FIGURE 12: CHANGE IN AVERAGE MAXIMUM TEMPERATURE OVER SEVEN DAYS, 2085

CHANGE IN THE AVERAGE MAXIMUM TEMPERATURE OVER SEVEN CONSECUTIVE DAYS

A REQUIRED MEASURE FOR PAVEMENT DESIGN



- -2.0 - -0.1° F
- 0.0 - 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 - 13.9° F

Climate Model for CA (CMCC-CMS)

[ ] marked items are shown on map

2085 REPRESENTATIVE CONCENTRATION PATHWAYS (RCP) 8.5, 50TH PERCENTILE

Future Change in the Average Maximum Temperature over Seven Consecutive Days within District 11, Based on the RCP 8.5 Emissions Scenario

Caltrans Transportation Asset Vulnerability Study, District 11. Caltrans No. 74A0737. Climate data provided by the Scripps Institution of Oceanography. The data shown was generated by downscaling global climate outputs using the Localized Constructed Analogs (LOCA) technique.

5. PRECIPITATION

The southwest United States has been identified in previous studies[37] as likely to have less precipitation overall in the future, but with the potential for heavier individual precipitation events. In addition, more precipitation is expected to fall as rainfall in place of current snowfall in higher elevations. This section focuses on how such heavy precipitation events may change and become more frequent over time in District 11.

Current transportation project design utilizes the concept of return period storm events as part of the criteria for project design (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.[38] Because of the importance of the 100-year design event, changes in the 100-year storm rainfall was examined in this study. The study of precipitation is obviously one of great concern in California, especially after the winter rainfall events of 2016–2017.

Transportation assets in California are impacted by precipitation in a variety of ways—from inundation/ flooding, landslides, washouts or structural damage. Precipitation data is traditionally used for project development by applying statistical analyses of historical rainfall, most often through NOAA Atlas 14.[39] 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. Such data has been assembled from rain gauges across the country.

However, historical data is not a good precursor to future rainfall levels given expected changes in climatic conditions. This perspective of looking toward future climatic conditions is similar to other design inputs that use future data (such as land use changes and population growth) to identify final project characteristics. By looking at expected future climatic conditions, Caltrans can avoid damage and associated costs from future precipitation and flooding events that are likely to 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 depending on assumed conditions and different climate scenarios. The usual approach is to consider multiple model results to identify a range of predicted values and then analyze a broad range of potential effects predicted by this ensemble of models. An effort to better understand future rainfall in California is underway at the Scripps Institution for Oceanography and was compiled as a part of the California Fourth Climate Change Assessment.

GCMs often comprise very large grids covering extended land area and therefore do not provide the level of specificity needed for project development purposes. The LOCA downscaling method, developed by Scripps, provides a more refined understanding of future precipitation and helps to guide decision-

[37] 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.

[38] Caltrans, "Highway Design Manual," December 14, 2018, http://www.dot.ca.gov/hq/oppd/hdm/hdmtoc.htm

[39] National Oceanic and Atmospheric Administration, "Precipitation-Frequency Atlas of the United States," 2018, https://www.nws.noaa.gov/oh/hdsc/PF_documents/Atlas14_Volume11.pdf

making. The data can be used to identify variables like snow cover, run off, soil moisture and humidity projected into the future.

Scripps currently maintains daily rainfall data for a set of climate models and two future emissions estimates for every day to the year 2100. The study team worked with researchers from Scripps to estimate the expected change 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 scenarios (the only two scenarios available) and was further analyzed for three specific time periods. The years shown in the following figures represent the mid-points of the same 30-year statistical analysis periods that were used in the temperature analysis.

The study team analyzed the models to understand two major points in design, specifically:

- Were there indications of change in return period storms across the models that should be considered in decision-making when considering future precipitation?
- What was the magnitude of change for a 100-year return-period storm that should be considered as a part of future facility designs?

The figures on the following pages show the results of this analysis for District 11. The maps depict the percentage change in the 100-year storm rainfall event predicted for the three analysis periods for the RCP 8.5 emissions scenario, using the median model for California. Note that the change in 100-year storm depth is positive throughout District 11, indicating heavier rainfall during storm events. The pattern is relatively consistent over time. Also, changes are generally expected to be greater in the eastern sections of the district due to the tendency for the coastal mountains to squeeze out moisture from eastward moving storm systems.

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

FIGURE 13: CHANGE IN 100-YEAR STORM EVENT, 2025

PERCENT CHANGE IN 100-YEAR STORM PRECIPITATION DEPTH

- 0.0 - 4.9%
- 5.0 - 9.9%
- 10.0 - 14.9%
- 15.0 - 19.9%
- 20.0% - 24.9%

Climate Model for CA (HadGEM2-CC)

[ ] marked items are shown on map

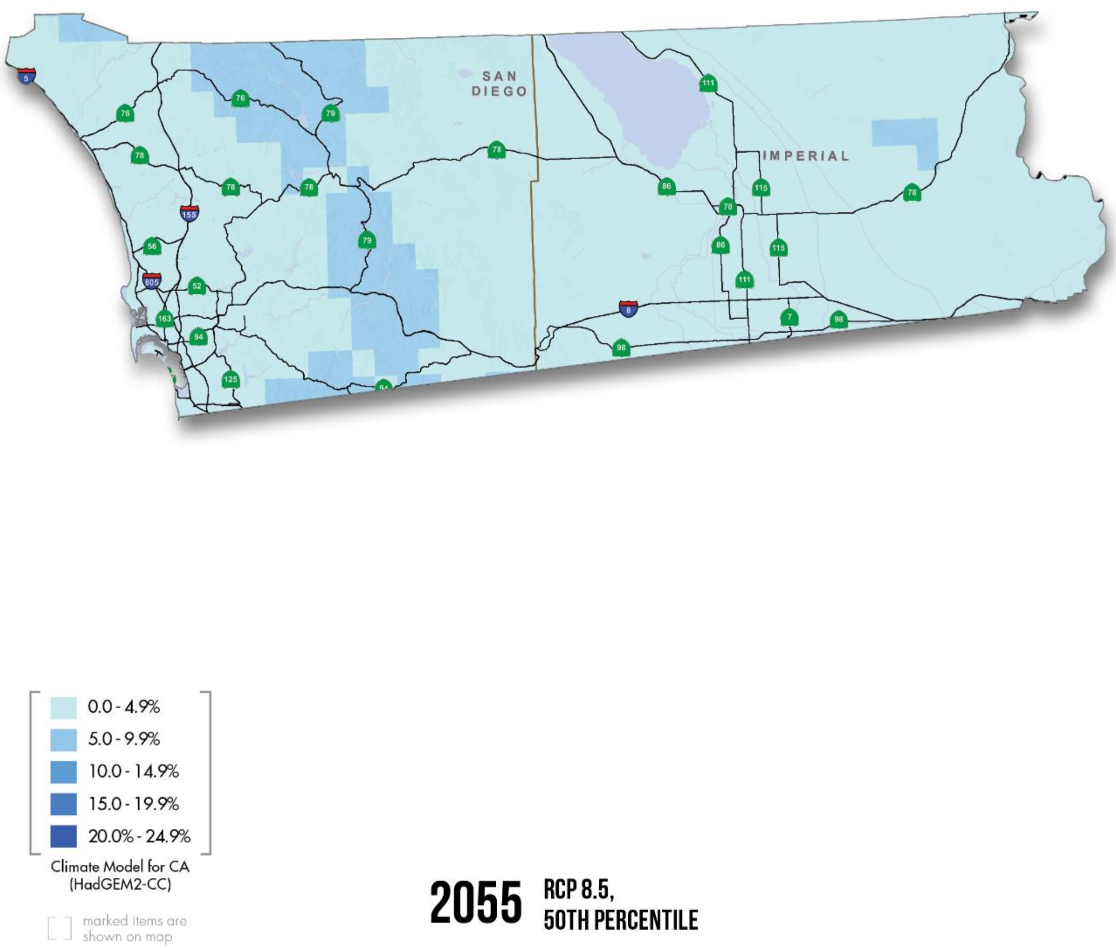
2025 RCP 8.5, 50TH PERCENTILE

Future Percent Change in 100-year Storm Precipitation Depth within District 11, Based on the RCP 8.5 Emissions Scenario

Caltrans Transpotation Asset Vulnerability Study, District 11. 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 14: CHANGE IN 100-YEAR STORM EVENT, 2055

PERCENT CHANGE IN 100-YEAR STORM PRECIPITATION DEPTH

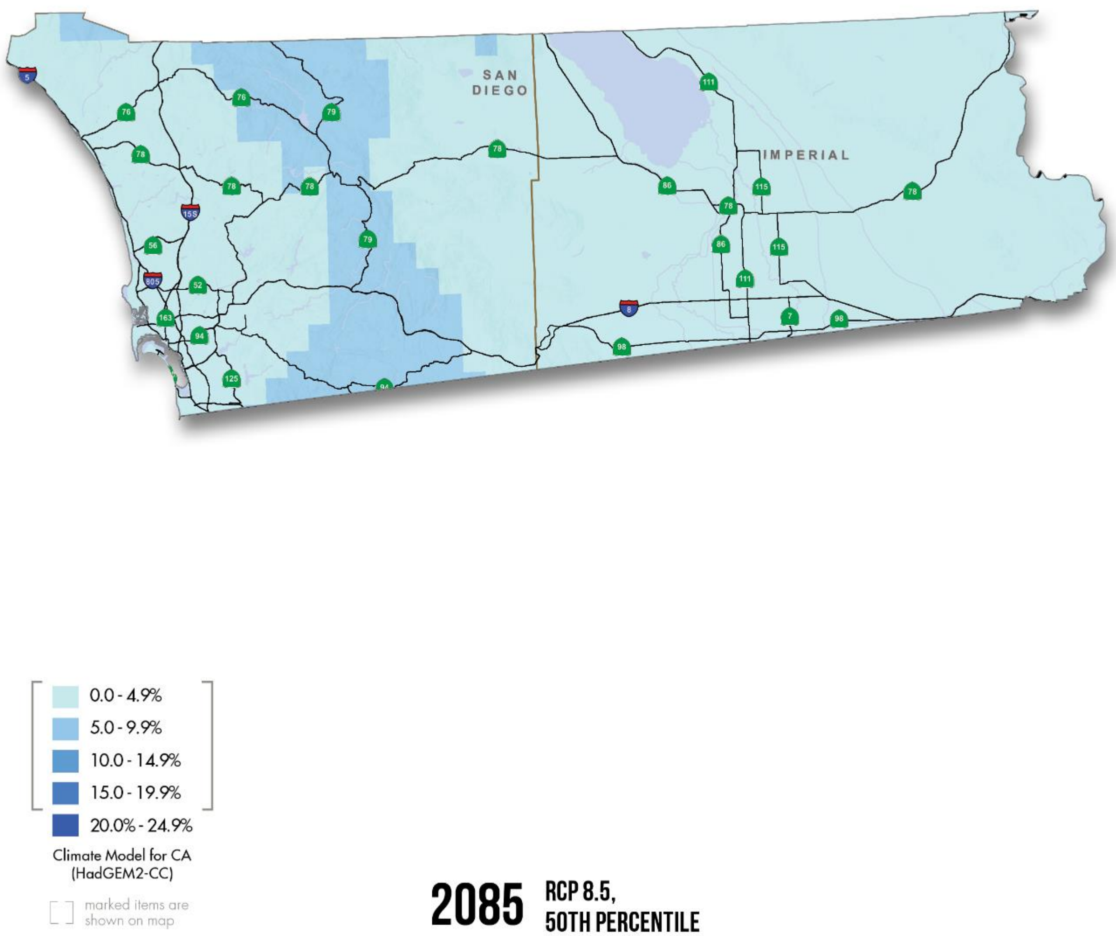


Future Percent Change in 100-year Storm Precipitation Depth within District 11, Based on the RCP 8.5 Emissions Scenario

Caltrans Transpotation Asset Vulnerability Study, District 11. 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 15: CHANGE IN 100-YEAR STORM EVENT, 2085

PERCENT CHANGE IN 100-YEAR STORM PRECIPITATION DEPTH



Future Percent Change in 100-year Storm Precipitation Depth within District 11, Based on the RCP 8.5 Emissions Scenario

Caltrans Transpotation Asset Vulnerability Study, District 11. 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.

6. WILDFIRE

Increasing temperatures, changing precipitation patterns, and resulting changes to land cover are expected to impact wildfire frequency and intensity in future years. Human influences, including the presence of electrical utility infrastructure, or other sources of fire (mechanical, open fire, intentional) may also influence the occurrence of wildfires.

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 last few months of 2017 have been notable for the significant wildfires that have occurred both in northern and southern California. These devastating fires caused significant property damage, loss of life, and damage to area roadways. The wildfires in Santa Barbara County stripped the land of protective cover and damaged the soils, such that subsequent rain storms led to disastrous mudslides that significantly impacted the city of Montecito and Highway 101 in Santa Barbara County. The costs to Caltrans for repairing such damage could extend for many months for individual events and could require years of investment to maintain the viability of the highway system for its users. The conditions that contributed to these impacts, notably a wet rainy season followed by very dry conditions and heavy winds, are likely to occur multiple times in the future as climate conditions change and the atmosphere becomes more dynamic with increased energy.

The information gathered and assessed to develop wildfire vulnerability data for District 11 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), EPA, and Calfire, with various predictive wildfire models being developed to assess the potential recurrence of future wildfires throughout the US and in California.

6.1. Ongoing Wildfire Modeling Efforts

Determining the potential impacts of wildfires on State highways included coordination with various agencies that have developed wildfire models for various applications. Models utilized for this analysis included the following:

- MC2 - EPA Climate Impacts Risk Assessment (CIRA) (John Kim, USFS)
- MC2 - Applied Climate Science Lab (ACSL) at the University of Idaho (Dominque Bachelet)
- University of California – Merced, CalAdapt, (Leroy Westerling)

The MC2 models are second generation models, developed from the original model, the MC1 model. The MC2 model, created by the USFS, is a 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 MC2 model outputs utilized for this project used the current IPCC Coupled Model Intercomparison Project 5 (CMIP5) dataset. This model was applied in two different studies of potential wildfire impacts at a broader scale by researchers at the US Forest Service at the University of Idaho. The application of the vegetation model and the expectation of changing vegetation and types associated with climate change is a primary factor of interest in the application of this model.

The second wildfire model utilized was developed by Leroy Westerling at the University of California, Merced. This statistical model was developed to analyze the conditions leading to past large fires (defined as over 1,000 acres) in California and then uses these patterns to predict future wildfires. Inputs to the model include climate, vegetation, population density, and fire history. This model then utilized future climate data and projected land use changes to project wildfire recurrence in California to the year 2100.

Each of these wildfire models used input from downscaled climate models to determine future temperature and precipitation conditions that were important for predicting future wildfires. The efforts undertaken by the EPA/USFS and UC/Merced utilized the LOCA climate data set developed by Scripps, while the University of Idaho effort utilized an alternative downscaling method, the Multivariate Adaptive Constructed Analogs (MACA). The downscaled model data enabled the development of future wildfire assumptions at a finer level of analysis than could be assumed by utilizing the output of the global climate models directly.

6.2. Global Climate Models Applied

Each of the efforts used a series of GCM outputs to generate projections of future wildfire conditions. In this analysis, the project study team[40] used the four recommended GCMs from Cal-Adapt for wildfire outputs (CAN ESM2, CNRM-CM5, HAD-GEM2-ES, MIROC5). In addition, all three of the modeling efforts used RCPs 4.5 and 8.5, representing realistic lower and higher ranges for future greenhouse gas emissions (see Section 3.2.2 for more information on GCMs and RCPs). Table 1 shows the wildfire models and GCMs used in the assessment.

TABLE 1: WILDFIRE MODELS AND ASSOCIATED GCMs USED IN WILDFIRE ASSESSMENT

Wildfire Models								
MC2 - EPA			MC2 - ACSC			UC Merced		
CAN ESM2	HAD-GEM2-ES	MIROC5	CAN ESM2	HAD-GEM2-ES	MIROC5	CAN ESM2	HAD-GEM2-ES	MIROC5

[40] Made up of WSP staff members.

6.3. Analysis Methods

The wildfire projections for all model data were developed for the three future 30-year time periods used in this study---those focused on the approximate median years of 2025, 2055, and 2085. These are represented as such on the wildfire maps below. As noted earlier, these median years represent 30-year averages, where 2025 is the average between 2010 and 2039, and so on.

The wildfire models output geospatial data in raster format, which is data that is expressed in individual “cells” on a map. The final wildfire projections for this effort provides a summary of the percentage of each of these cells that burns for each time period. The raster cell size applied is 1/16 of a degree square for the MC2 - EPA and UC Merced/Westerling models, which matches the grid cell size for the LOCA climate data applied in developing these models. The MC2 - University of Idaho effort generated data at 1/24 of a degree square, to match the grid cells generated by the MACA downscaling method.

The model data was collected for all wildfire/GCM combinations, for each year to the year 2100. 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) become 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). The study team ultimately summarized the data into the 1/16th grid to enable comparisons and also to summarize across multiple models. The resulting area contained within these grid cells ranged in area between 8,000 and 10,000 acres for grid cells sizes that were roughly 6 kilometers on each side.

An initial analysis of the results of the wildfire models for analysis periods for similar GCMs noted differences in the outputs of the models, in terms of the amount of burn projected for various cells. This difference could be caused by any number of factors, including the assumption of changing vegetation associated with climate change in the MC2 models, but not in the UC Merced/Westerling model, as well as other baseline assumptions.

An initial analysis of the results of the wildfire models for analysis periods for similar GCMs noted differences in the outputs of the models, in terms of the amount of burn projected for various cells. This difference could be caused by any number of factors, including the assumption of changing vegetation associated with climate change in the MC2 models, but not in the UCMerced/Westerling model as well as other baseline assumptions considered by the modeling teams. The specification of the source of the differences in the models was not the intent of this project, which was instead to apply available data to determine potential risks to transportation infrastructure. The effort at comparison and resolution would require an extended period of research.

6.4. Categorization and Summary

The final method selected to determine future wildfire risks throughout California takes advantage of the presence of three modeled data sets to generate a broader understanding of future wildfire exposure. The project team determined this would provide a more robust result than applying only one of the available wildfire models. A cumulative total of percentage cell burned was developed for each cell in the final dataset. This data is available for future application by Caltrans and its partners.

As a means of establishing a level of concern for wildfire impacts, a following classification was developed based on expected percentage cell burned:

- Very Low 0-5%,
- Low 5-15%,
- Moderate 15-50%,
- High 50-100%,
- Very High 100%+.[41]

Thus, if a cell were to show a complete burn or higher (8,000 to 10,000 acres+) over a 30-year period, that cell was identified as a very high wildfire exposure cell. Developing this categorization method included removing the CNRM-CM5 data point from the MC2 - University of Idaho and UC Merced/Westerling datasets to have three consistent points of data for each cell in every model. This was done to provide a consistent number of data points for each wildfire model.

Next, the project study team looked at results across all models to see if any one wildfire model/GCM model combination indicated a potential exposure concern in each grid cell. The categorization for any one cell in the summary identifies the highest categorization for that cell across all nine data points analyzed. For example, if a wildfire model result identified the potential for significant burn in any one cell, the final dataset reflects this risk. This provides Caltrans with a more conservative method of considering future wildfire risk.

Finally, the project study team assigned a score for each cell where there is relative agreement on the categorization across all the model outputs. In application, an analysis was completed to determine whether 5 of the 9 data points for each cell (a simple majority) were consistent in estimating the percentage of cell burned for each 30-year period.

The figures on the following pages show the results of this analysis, using the classification scheme explained above. These figures show projections for RCP 8.5 only and Caltrans highways that are likely to be most exposed to wildfire (in moderate to very high concern areas) are highlighted in red.[42] For a summary of mileage of the District 11 State Highway System exposed to wildfire risk by county, year, and emissions scenario, see Table 2 and Table 3.

[41] A cell can have greater than 100% burn if burned twice or more in the same time period

[42] Areas on the maps shown in white do not necessarily have no associated wildfire risk - the classification is below moderate.

TABLE 2: CENTERLINE MILES OF STATE HIGHWAY SYSTEM IN DISTRICT 11 EXPOSED TO MODERATE TO VERY HIGH WILDFIRE CONCERN UNDER RCP 8.5

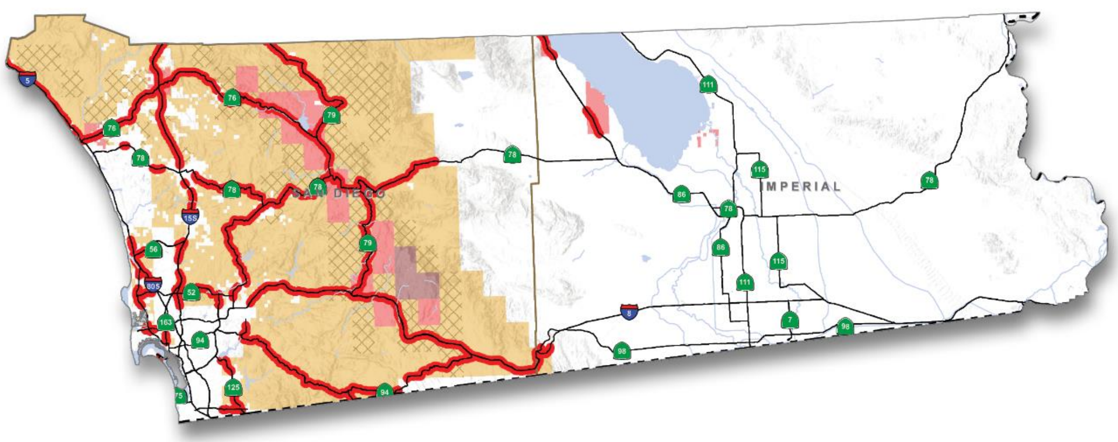
	Year		
District 11 County	**2025**	**2055**	**2085**
Imperial	16.3	21.3	44.9
San Diego	374.1	375.9	398.5

TABLE 3: CENTERLINE MILES OF STATE HIGHWAY SYSTEM IN DISTRICT 11 EXPOSED TO MODERATE TO VERY HIGH WILDFIRE CONCERN UNDER RCP 4.5

	Year		
District 11 County	**2025**	**2055**	**2085**
Imperial	7.7	11.9	7.7
San Diego	332.0	340.0	346.4

FIGURE 16: INCREASE IN WILDFIRE EXPOSURE, 2025

LEVEL OF WILDFIRE CONCERN



Levels of Concern

- VERY HIGH
- HIGH
- MEDIUM
- HIGH MODEL AGREEMENT*
- EXPOSED ROADWAY

2025 **RCP 8.5, MULTI-MODEL MAXIMUM**

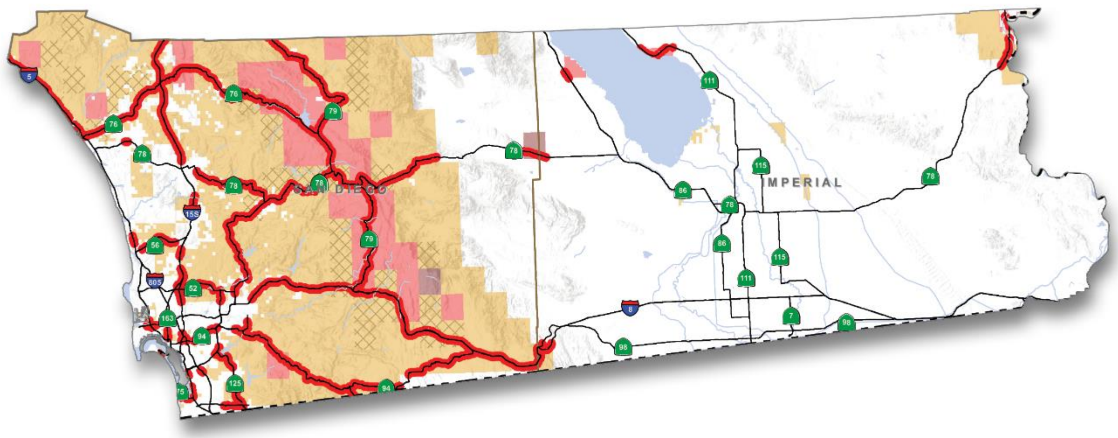
Future Level of Wildfire Concern for the Caltrans State Highway System within District 11, Based on the RCP 8.5 Emissions Scenario

The fire model composite summaries shown are based on wildfire projections from three models: (1) MC2 - EPA Climate Impacts Risk Assessment, developed by John Kim, USFS; (2) MC2 - Applied Climate Science Lab at the University of Idaho, developed by Dominque Bachelet, University of Idaho; and (3) University of California Merced model, developed by Leroy Westerling, University of California Merced. For each of these wildfire models, climate inputs were used from three GCMs: (1) CAN ESM2; (2) HAD-GEM2-ES; and (3) MIROC5. The maps show the multi-model maxima for each grid cell across the nine combinations of the three fire models and the three GCMs.

* The hashing shows areas where 5 or more of the 9 models fall under the same cumulative % burn classification as the one shown on the map.

FIGURE 17: INCREASE IN WILDFIRE EXPOSURE, 2055

LEVEL OF WILDFIRE CONCERN



Levels of Concern

- VERY HIGH
- HIGH
- MEDIUM
- HIGH MODEL AGREEMENT*
- EXPOSED ROADWAY

2055 RCP 8.5, MULTI-MODEL MAXIMUM

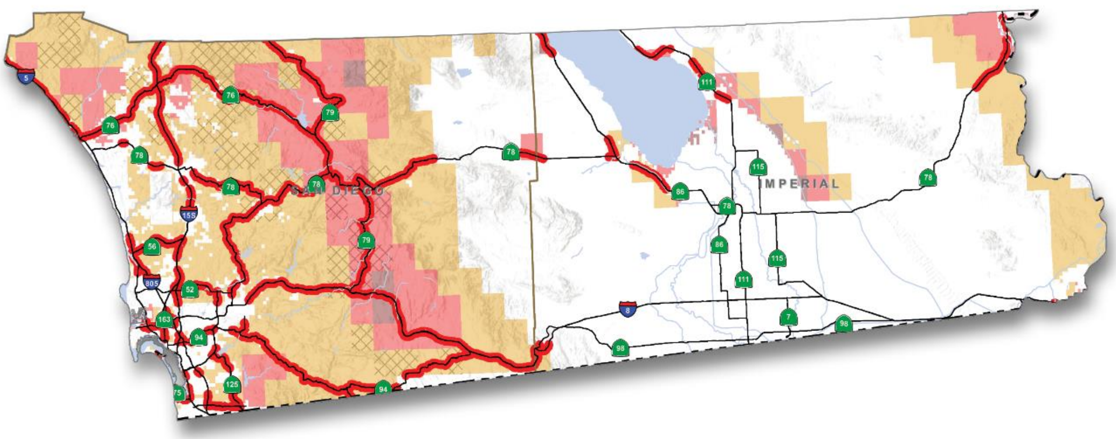
Future Level of Wildfire Concern for the Caltrans State Highway System within District 11, Based on the RCP 8.5 Emissions Scenario

The fire model composite summaries shown are based on wildfire projections from three models: (1) MC2 - EPA Climate Impacts Risk Assessment, developed by John Kim, USFS; (2) MC2 - Applied Climate Science Lab at the University of Idaho, developed by Dominque Bachelet, University of Idaho; and (3) University of California Merced model, developed by Leroy Westerling, University of California Merced. For each of these wildfire models, climate inputs were used from three GCMs: (1) CAN ESM2; (2) HAD-GEM2-ES; and (3) MIROC5. The maps show the multi-model maxima for each grid cell across the nine combinations of the three fire models and the three GCMs.

* The hashing shows areas where 5 or more of the 9 models fall under the same cumulative % burn classification as the one shown on the map.

FIGURE 18: INCREASE IN WILDFIRE EXPOSURE, 2085

LEVEL OF WILDFIRE CONCERN



Levels of Concern

- VERY HIGH
- HIGH
- MEDIUM
- HIGH MODEL AGREEMENT*
- EXPOSED ROADWAY

2085 **RCP 8.5, MULTI-MODEL MAXIMUM**

Future Level of Wildfire Concern for the Caltrans State Highway System within District 11, Based on the RCP 8.5 Emissions Scenario

The fire model composite summaries shown are based on wildfire projections from three models: (1) MC2 - EPA Climate Impacts Risk Assessment, developed by John Kim, USFS; (2) MC2 - Applied Climate Science Lab at the University of Idaho, developed by Dominque Bachelet, University of Idaho; and (3) University of California Merced model, developed by Leroy Westerling, University of California Merced. For each of these wildfire models, climate inputs were used from three GCMs: (1) CAN ESM2; (2) HAD-GEM2-ES; and (3) MIROC5. The maps show the multi-model maxima for each grid cell across the nine combinations of the three fire models and the three GCMs.

* The hashing shows areas where 5 or more of the 9 models fall under the same cumulative % burn classification as the one shown on the map.

7. SEA LEVEL RISE

The data sets considered for this analysis came from new State projections from the Ocean Protection Council (OPC).[43] This set of sea level rise scenarios was chosen for consideration in this analysis to follow State guidance on sea level rise planning and to use the best available sea level rise projections developed for California. For this analysis, these projections are paired with a model that includes sea level rise and storm surge, to identify approximately when potential impacts to the State Highway Network may occur in District 11. For more information on how the projections are used given the model, see Section 7.2 below.

7.1. State of California Sea Level Rise Guidance: 2018 Update

Estimates of sea level rise have been developed for California by various agencies and research institutions. Figure 19 below reflects estimates recently developed for San Diego by a scientific panel for the 2018 Update of the State of California Sea-Level Rise Guidance, an effort led by the Ocean Protection Council (OPC). These projections were developed for gauges along the California coast based on global and local factors that drive sea level rise such as thermal expansion of ocean water, glacial ice melt, and the expected amount of vertical land movement.

Sea level rise projection scenarios presented in the OPC guidance identify several values or ranges, including:

- A median (50%) probability scenario
- A likely (66%) probability scenario
- A 1-in-20 (5%) probability scenario
- A low (0.5%) probability scenario
- An extreme (H++) scenario to be considered when planning for critical or highly vulnerable assets with a long lifespan

Each of these values are presented for low (RCP 2.6) and high (RCP 8.5) emissions scenarios to provide information on the full range of potential projections over time. The OPC recommends using only RCP 8.5 for projects that have a lifespan to 2050, and using both scenarios for projects with longer lifespans. The OPC also recommends assessing a range of future projections before making decisions on projects, given the uncertainty inherent in modeling inputs. Guidance is provided for when best to consider certain projections, given the risks associated with projects of varying type:

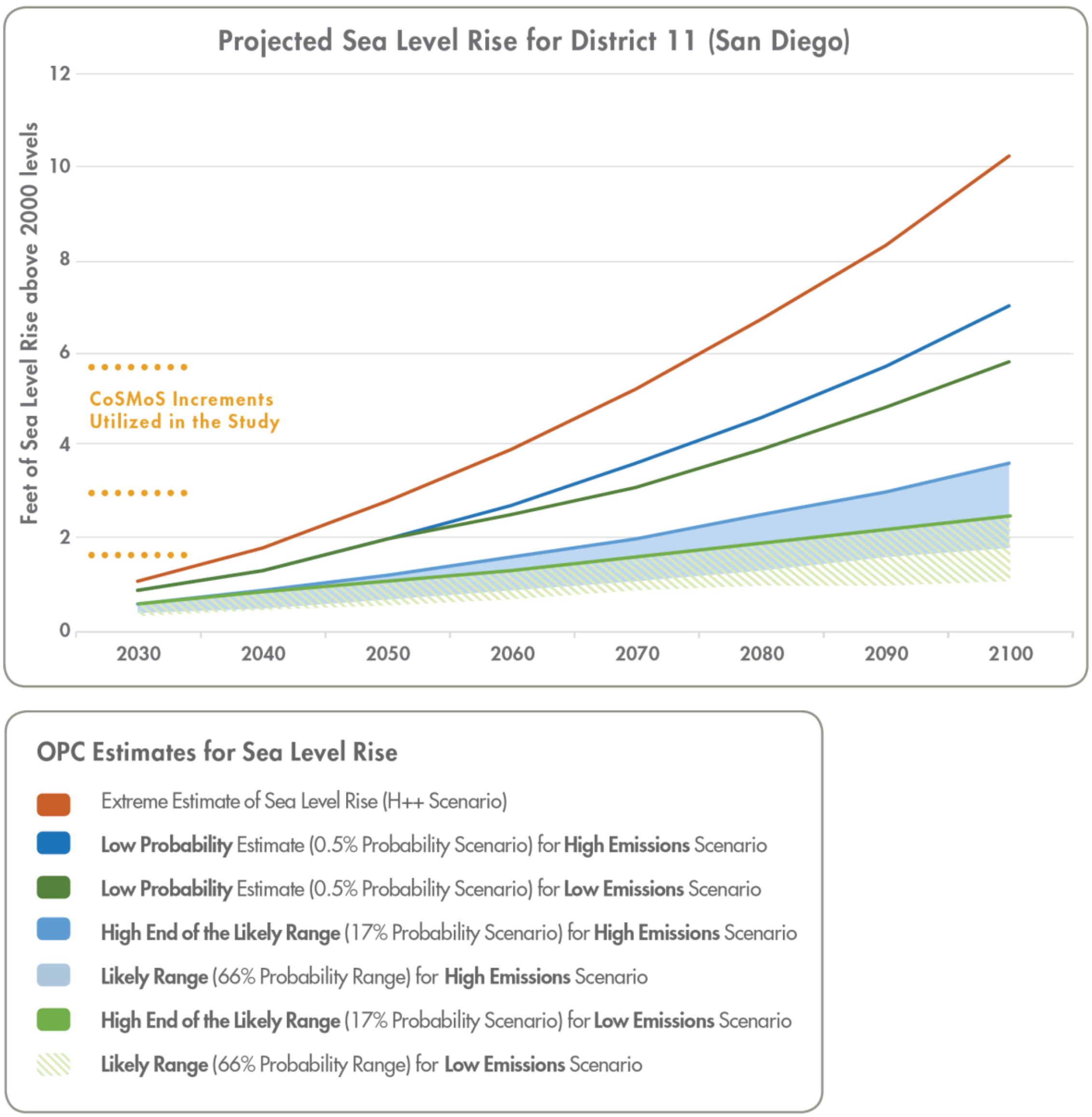
- For low risk aversion decisions, the OPC recommends using the likely (66%) probability sea level rise range. In the graphic to the right, this range is shaded in light blue for the RCP 8.5 scenario and is shaded in light green for RCP 2.6.
- For medium to high risk aversion decisions, the OPC recommends using the low (0.5%) probability scenario. This value is shown in dark green for RCP 2.6 and in dark blue for RCP 8.5 in the graphic to the right.

[43] California Ocean Protection Council, "State of California Sea-Level Rise Guidance: 2018 Update," March 14, 2018, http://www.opc.ca.gov/webmaster/ftp/pdf/agenda_items/20180314/Item3_Exhibit-A_OPC_sea level rise_Guidance-rd3.pdf.

- For high risk aversion decisions, the OPC recommends considering the extreme (H++) scenario. This projection is shown in dark orange in the graphic to the right.

This guidance was developed by the OPC to help State and local governments understand future risks associated with sea level rise and incorporate these projections into work efforts, investment decisions, and policy mechanisms. The OPC recognizes that the science surrounding sea level rise projections is still improving and anticipates updating their guidance at least every five years. Given that new findings are inevitable, Caltrans will use best-available sea level rise modeling, projections, and guidance as the science evolves over time, and will be working in the coming months to define how this data is incorporated into capital investment decisions.

FIGURE 19: OPC 2018 SEA LEVEL RISE PROJECTIONS FOR SAN DIEGO TIDAL GAUGE



7.2. Model Used

The previous section described estimated sea level rise levels from the OPC. This section discusses the CoSMoS storm model used in this study with these projections. The CoSMoS model was developed by the United States Geological Survey (USGS); data can be viewed and downloaded from the *Our Coast Our Future* site. The model was funded by stakeholders with interests to understand the associated impacts of various storm events combined with future sea level rise along the California coast and within San Francisco Bay. The CoSMoS model is 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 sea level rise from 0.00 to 2.00 meters, in quarter-meter increments, and for 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 sea level rise developed by the model: 1.64, 3.28, and 5.75 feet (0.50, 1.00, and 1.75 meters, respectively). See Figure 9 to identify approximately when the OPC sea level rise scenarios will reach the CoSMoS heights and the range between projections.

In addition to considering each increment of sea level rise rise, 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 sea level rise may begin to impact the District 11 State Highway System or other District assets.

Table 4 summarizes the centerline miles of District 11 State Highway System that are exposed to the three sea level rise increments provided in this report, with an annual storm. The table only includes centerline miles exposed in San Diego County, as Imperial County is landlocked. It is also important to note that these centerline miles include bridges, which may not necessarily be inundated under these sea level rise increments depending upon their freeboard. A detailed analysis of roadway and bridge elevations may be necessary to confirm overtopping. However, there are still other risks posed to bridges by sea level rise than flooding and inundation. See the following section on bridge impacts for more information.

TABLE 4: DISTRICT 11 ROADWAY CENTERLINE MILES EXPOSED TO SEA LEVEL RISE AND AN ANNUAL STORM

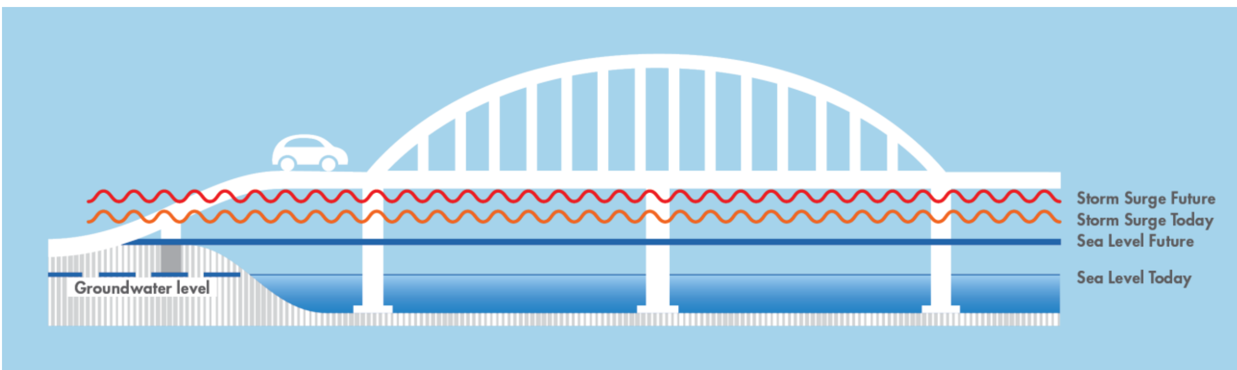
	Sea level rise (ft)		
District 11 County	**1.64**	**3.28**	**5.74**
San Diego	1.98	3.60	6.21

7.3. Bridge Exposure

When considering bridge exposure to sea level rise, it is important to note that facilities are often designed based on historical data as projected into the future. However, changes due to sea level rise or storm surge may make a facility more vulnerable to damage with future events. Figure 20 highlights a set of potential concerns for a bridge in addition to water overtopping the bridge deck. They are presented to help set a 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. Caltrans will need to consider all potentially at-risk facilities and pursue additional analysis as necessary. The list of concerns includes:

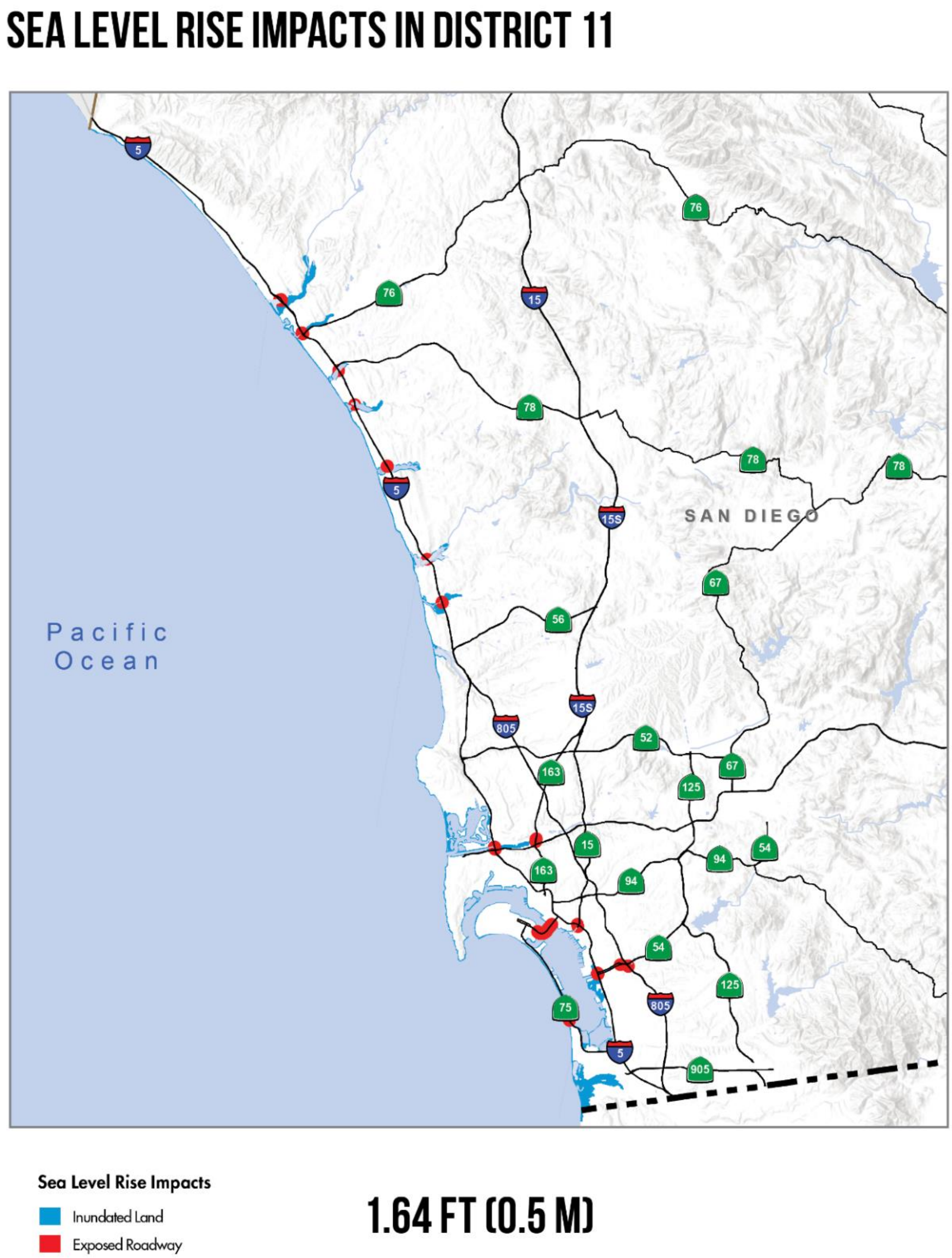
- A rising groundwater table may inundate supports on land that were not built to accommodate saturated soil conditions, leading to erosion of soils and loss of stability.
- Higher sea levels mean greater forces on the bridge during normal tidal processes, increasing scour effects on bridge structure 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 road 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 20 : BRIDGE EXPOSURE



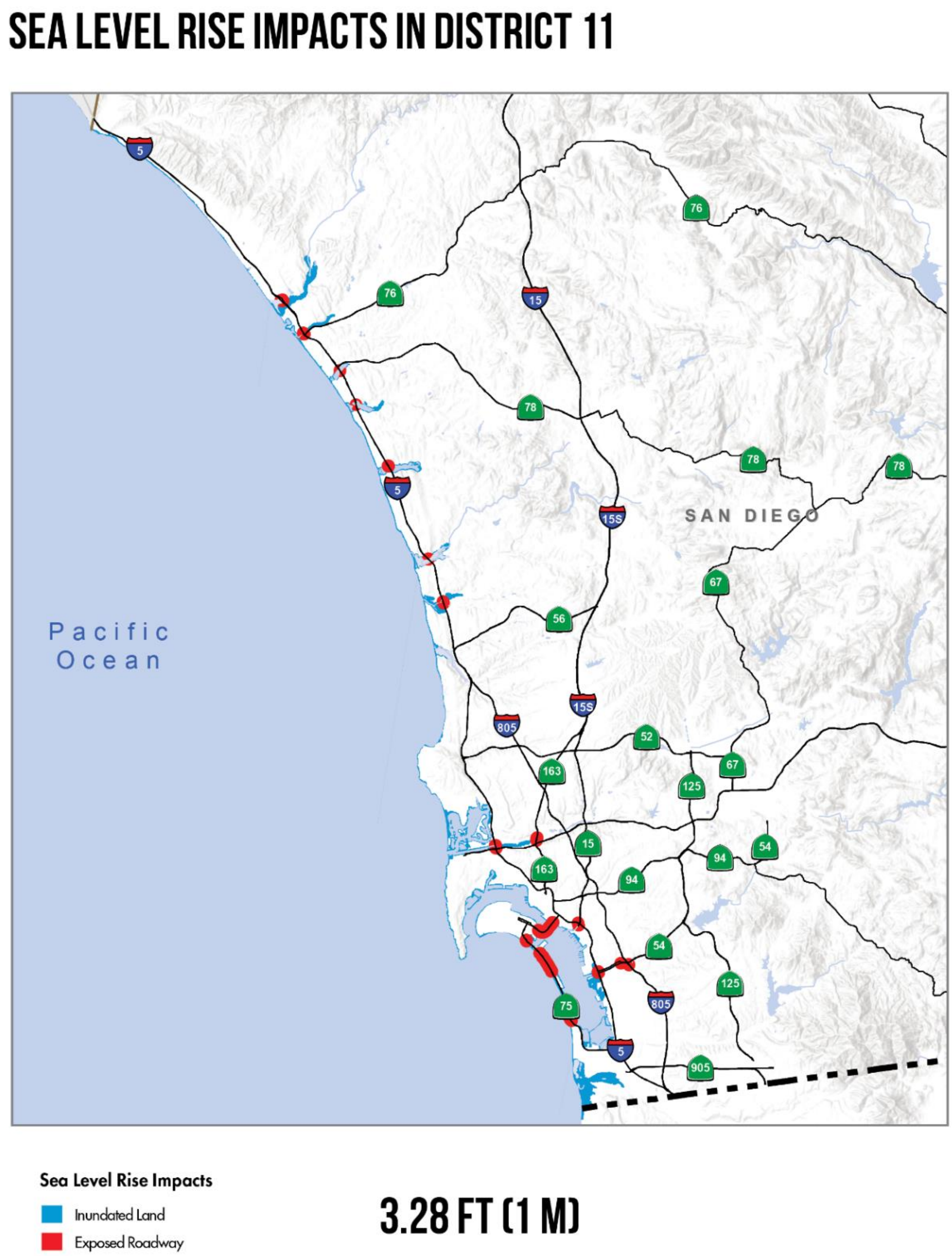
The maps presented in the following figures depict the 1.64, 3.28, and 5.74 feet (0.50, 1.00, and 1.75 meter, respectively) CoSMoS increments of sea level rise, and indicate District 11 roadways (including bridges) at risk of inundation or exposure from higher sea levels.

FIGURE 21: SEA LEVEL RISE IMPACTS TO THE CALTRANS DISTRICT 11 STATE HIGHWAY SYSTEM, 1.64 FT (0.50 M)



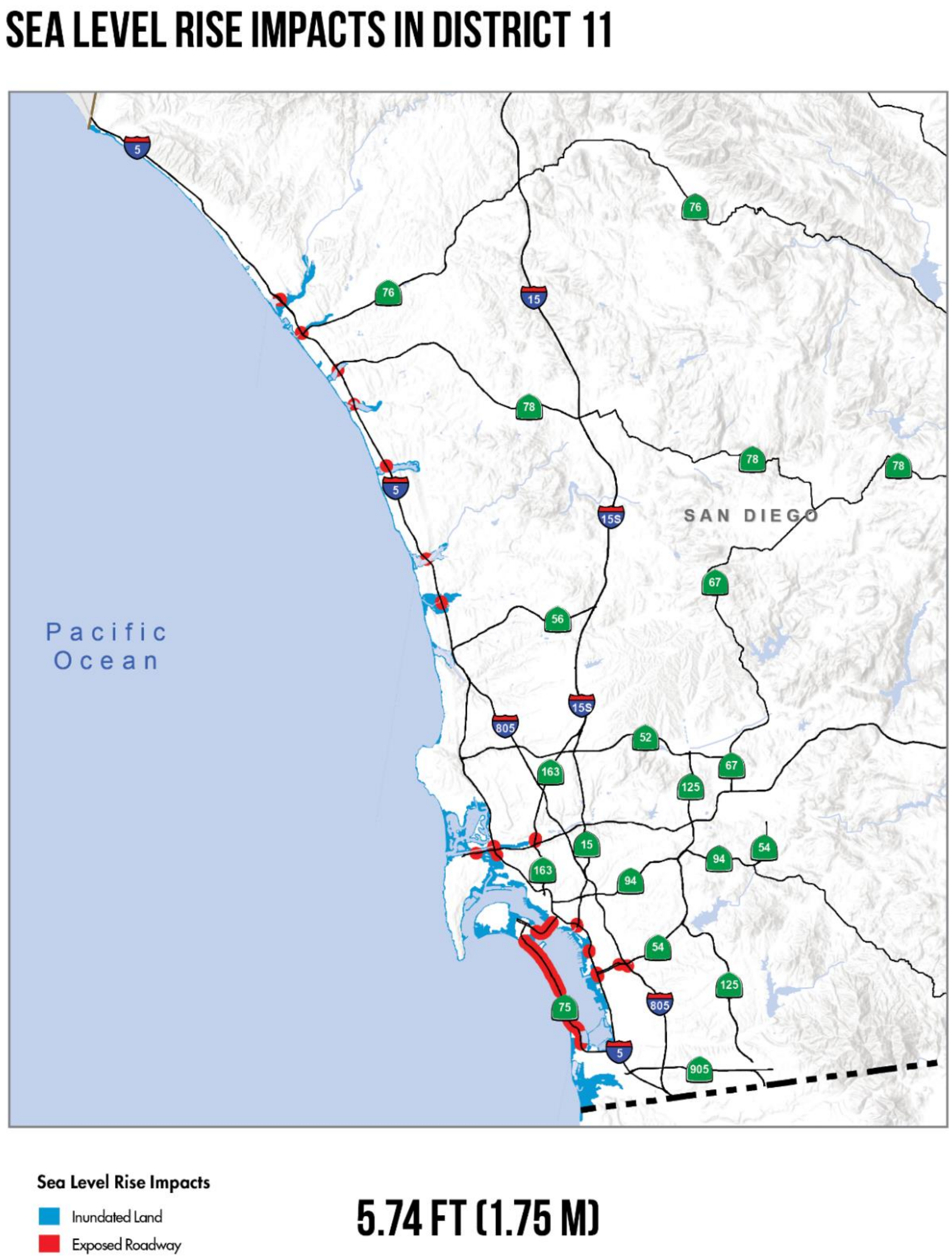
SEA LEVEL RISE AND ANNUAL STORM DATA ARE FROM THE US GEOLOGICAL SURVEY, COASTAL STORM MODELING SYSTEM (COSMOS). SEE Our Coast, Our Future AND THE USGS CoSMoS webpage FOR MORE INFORMATION ON THE MODEL.

FIGURE 22: SEA LEVEL RISE IMPACTS TO THE CALTRANS DISTRICT 11 STATE HIGHWAY SYSTEM, 3.28 FT (1.00 M)



SEA LEVEL RISE AND ANNUAL STORM DATA ARE FROM THE US GEOLOGICAL SURVEY, COASTAL STORM MODELING SYSTEM (COSMOS). SEE Our Coast, Our Future AND THE USGS CoSMoS webpage FOR MORE INFORMATION ON THE MODEL.

FIGURE 23: SEA LEVEL RISE IMPACTS TO THE CALTRANS DISTRICT 11 STATE HIGHWAY SYSTEM, 5.74 FT (1.75 M)

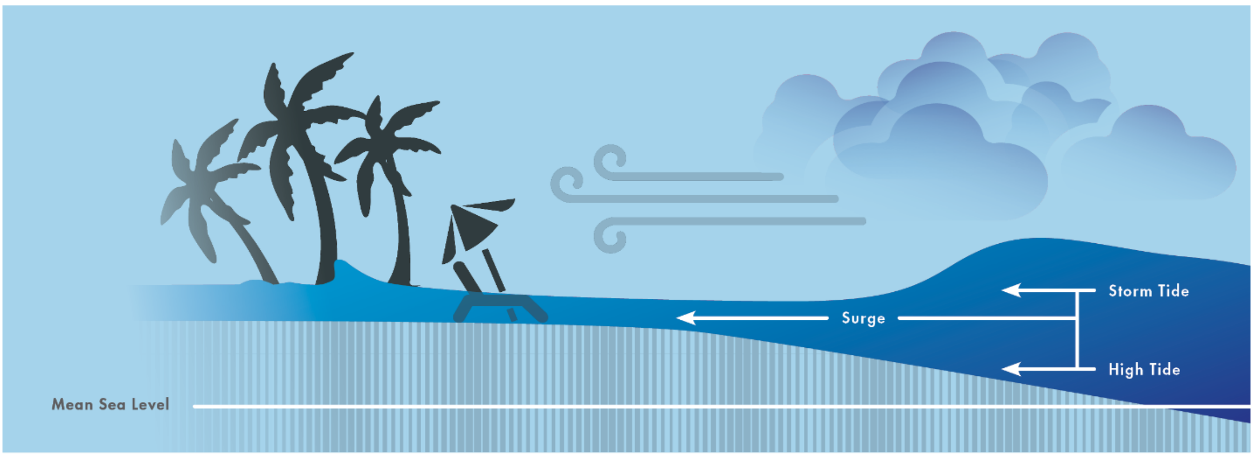


SEA LEVEL RISE AND ANNUAL STORM DATA ARE FROM THE US GEOLOGICAL SURVEY, COASTAL STORM MODELING SYSTEM (COSMOS). SEE [Our Coast, Our Future] AND THE [USGS CoSMoS webpage] FOR MORE INFORMATION ON THE MODEL.

8. STORM SURGE

As seas rise, more water is in motion during storm surge events. Increased inundation from higher water levels and more forceful storm surge will increase long-term risks to infrastructure. Figure 24 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 how water levels increase and reach farther on land in storm surge conditions than that of a regular high tide.

FIGURE 24: BASIC ELEMENTS OF STORM SURGE



SOURCE: NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

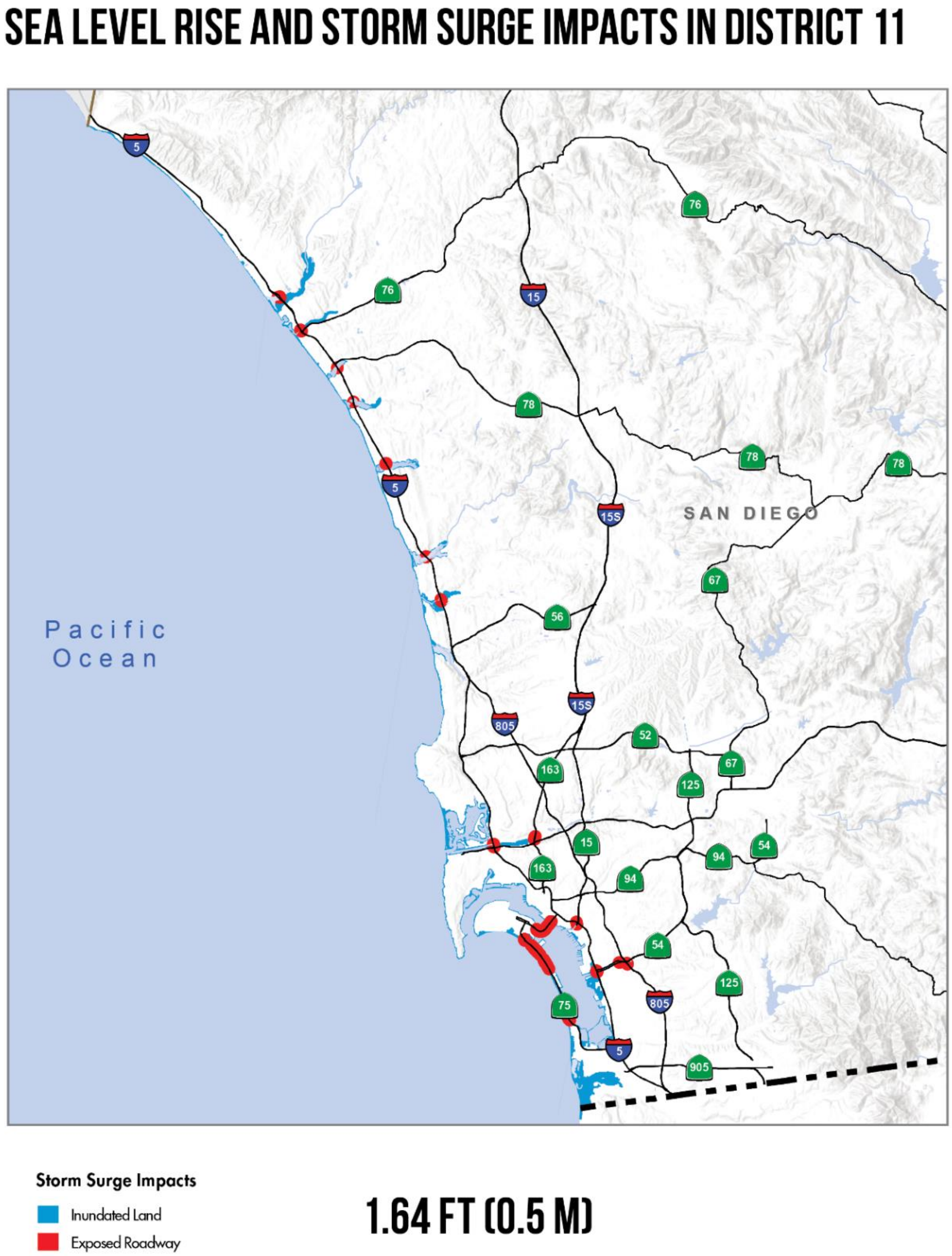
CoSMoS models potential inundation of storm surge combined with sea level rise for most of the California coast and the Bay Area. To estimate storm surge exposure for Caltrans District 11 roadways, the project study team mapped sea level rise of 1.64, 3.28, and 5.74 feet (or 0.50, 1.00, and 1.75 meters, respectively) combined with the 100-year storm event. The 100-year storm event is a design standard for infrastructure projects and is the Base Flood Elevation (BFE) as determined by the Federal Emergency Management Agency (FEMA). Therefore, the 100-year storm event is an important metric for Caltrans infrastructure.

Table 5 summarizes the centerline miles of the Caltrans District 11 highways and bridges that could be exposed from the 100-year storm event combined with sea level rise. As Imperial County is landlocked, it is not exposed to the impacts of sea level rise and is not included in the table mileage summary. Maps of sea level rise and storm surge impacts on the San Diego County coastline are provided in the following pages.

TABLE 5: DISTRICT 11 HIGHWAY CENTERLINE MILES EXPOSED TO SEA LEVEL RISE AND 100-YEAR STORM EVENT

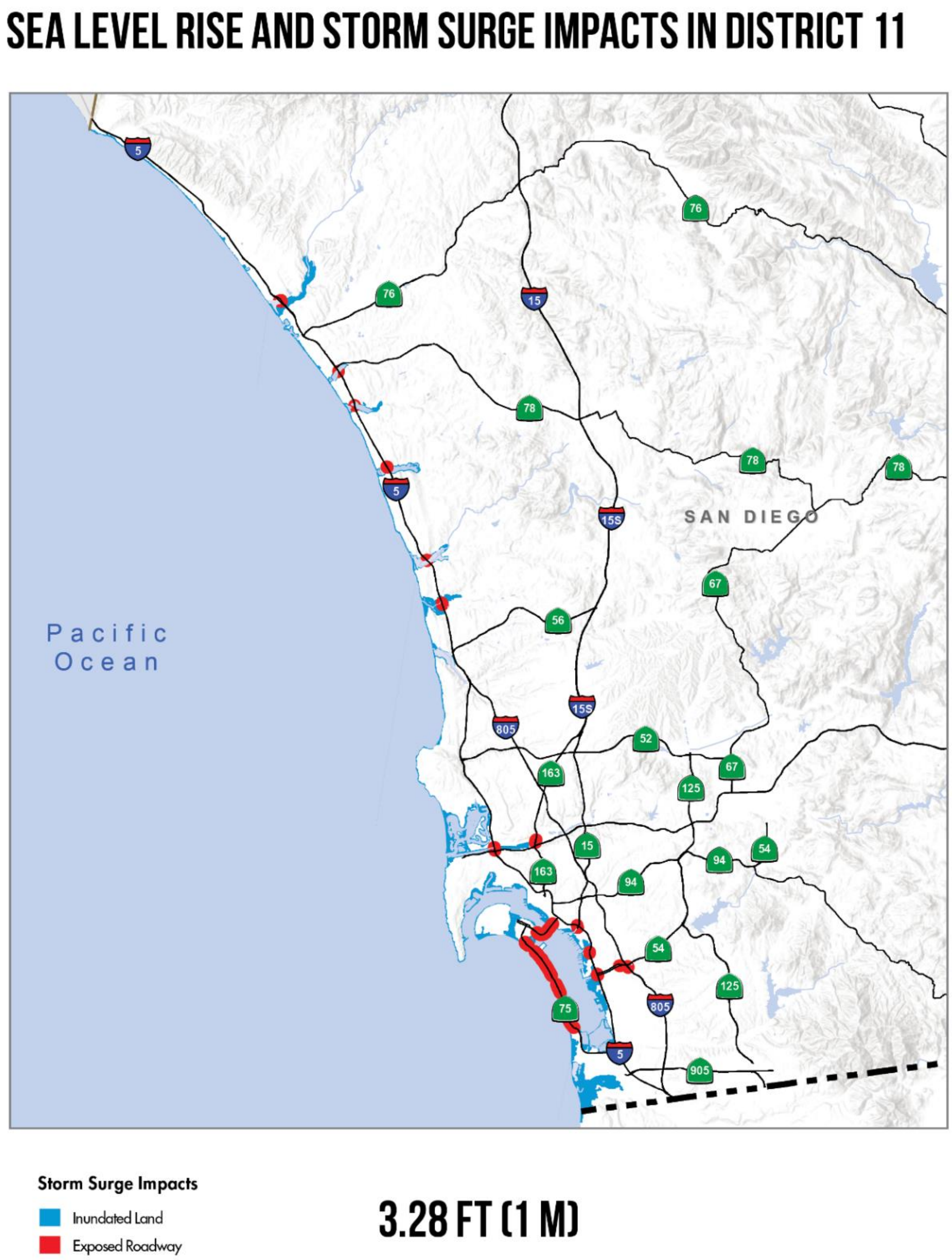
	Sea level rise (ft)		
District 11 County	**1.64**	**3.28**	**5.74**
San Diego	2.66	4.94	7.72

FIGURE 25: 100-YEAR STORM IMPACTS TO THE CALTRANS DISTRICT 11 STATE HIGHWAY SYSTEM, 1.64 FT (0.50 M)



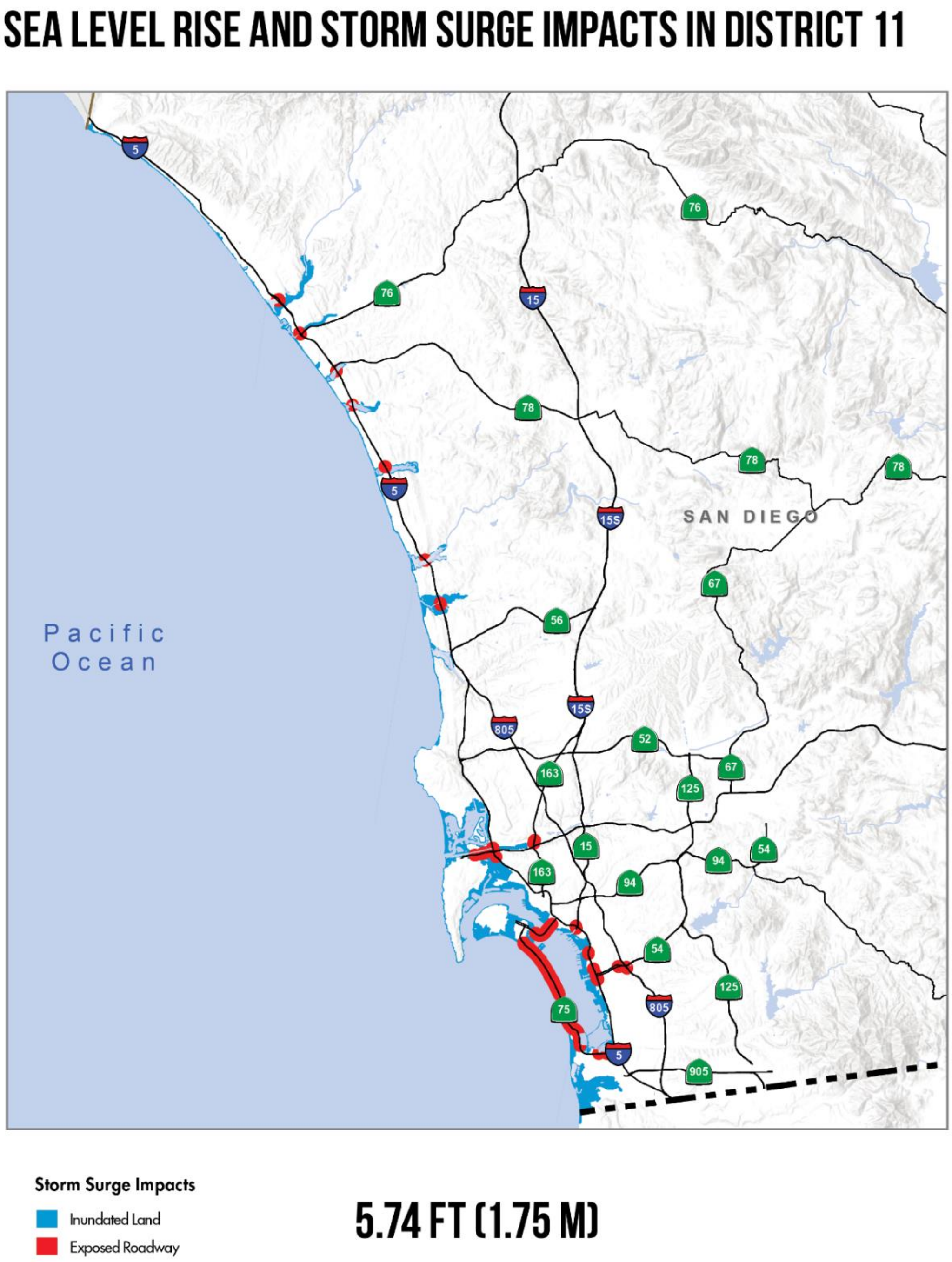
SEA LEVEL RISE AND STORM SURGE (100-YEAR STORM) DATA ARE FROM THE US GEOLOGICAL SURVEY, COASTAL STORM MODELING SYSTEM (COSMOS). SEE Our Coast, Our Future AND THE USGS CoSMoS webpage FOR MORE INFORMATION ON THE MODEL.

FIGURE 26: 100-YEAR STORM IMPACTS TO THE CALTRANS DISTRICT 11 STATE HIGHWAY SYSTEM, 3.28 FT (1.00 M)



SEA LEVEL RISE AND STORM SURGE (100-YEAR STORM) DATA ARE FROM THE US GEOLOGICAL SURVEY, COASTAL STORM MODELING SYSTEM (COSMOS). SEE Our Coast, Our Future AND THE USGS CoSMoS webpage FOR MORE INFORMATION ON THE MODEL.

FIGURE 27:100-YEAR STORM IMPACTS TO THE CALTRANS DISTRICT 11 STATE HIGHWAY SYSTEM, 5.74 FT (1.75 M)



SEA LEVEL RISE AND STORM SURGE (100-YEAR STORM) DATA ARE FROM THE US GEOLOGICAL SURVEY, COASTAL STORM MODELING SYSTEM (COSMOS). SEE [Our Coast, Our Future] AND THE [USGS CoSMoS webpage] FOR MORE INFORMATION ON THE MODEL.

9. CLIFF RETREAT

The 1100-mile California coastline has been shaped by various forces over time and is well known for its active areas of erosion, landslides, and cliff retreat. Estimates from a recent study of the coastline identified that approximately 72% of the California coast has eroding coastal cliffs due to the various forces at play in these areas, including the effects of ocean wave energy on beaches and cliffs.[44] Another study documenting past cliff erosion rates statewide noted that highest rates were found in San Onofre, Portuguese Bend, Palos Verdes, Big Sur, Martins Beach, Daly City, Double Point, and Point Reyes.[45]

The areas where land and oceans meet in California are some of the most highly valued in the country, and many of its vistas, communities, and infrastructure are recognizable worldwide. These areas serve as an important resource for State residents and visitors alike. The management of these areas has been an ongoing effort of many agencies, most notably the California Coastal Commission.

The more recent erosive effects of the oceans on cliffs in California has occurred during a period of rapid development in the State, and actions have been taken to reduce the continued loss of land. Over the past century, sea levels have risen roughly 6 inches[46] and climate change is anticipated to result in even higher sea levels, resulting in more regular inundation, higher tides and an increase in wave forces during coastal storms. The effects of all tidal and storm events are anticipated to stretch farther inland and with greater water and wave elevation than what has been observed and planned for in the past.

A few agencies have instituted research on the implications of climate change and resulting higher water levels on the California coastal environment, including a preliminary assessment of the potential effect on shorelines and cliffs. The US Geological Survey completed a multi-year study to develop three-dimensional survey information for current coastal conditions using Light Detection and Ranging (LIDAR) technology. This effort was the first of a series of efforts undertaken to develop a greater understanding of future sea level rise and how tidal, storm surge forces may reshape the coastline. One outcome of this effort was the development of the CoSMoS data on sea level rise and coastal storms, applied in this assessment.

For southern California (the area extending from Point Conception in Santa Barbara County to Imperial Beach in San Diego County), an updated version of the CoSMoS dataset was used to estimate erosion and cliff retreat, in addition to sea level rise and storm surge effects. As noted in the information provided in the technical documentation that accompanies the CoSMoS data: "As sea level rises, waves break closer to the sea cliff, more wave energy impacts the cliffs, [and] cliff erosion rates accelerate." The USGS effort developed two estimates of the future assuming two different conditions – one which included armoring the coast (hold the line), and one which assumed that cliff retreat continues unimpeded (do not hold the line).[47]

In this study, estimating future erosion and cliff retreat included assessing the potential effects using a range of models developed to estimate impacts. These models estimated wave height and the periods

[44] Cheryl Hapke & David Reid, "National Assessment of Shoreline Change, Part 4: Historical Coastal Cliff Retreat along the California Coast," U.S. Geological Survey Open-file Report 2007-1133 (2007), https://pubs.usgs.gov/of/2007/1133/of2007-1133.pdf

[45] University of California San Diego, "Study Identifies California Cliffs at Risk of Collapse," December 20, 2017, https://phys.org/news/2017-12-california-cliffs-collapse.html

[46] "Sea Level Trends," NOAA Tides & Currents, last accessed May 1, 2019, https://tidesandcurrents.noaa.gov/sltrends/sltrends.html

[47] "Cosmos Southern California V3.0 Phase 2 Projections of Coastal Cliff Retreat Due To 21st Century Sea-Level Rise," USGS, last accessed May 1, 2019, https://www.sciencebase.gov/catalog/item/57f4234de4b0bc0bec033f90

when expected wave heights would be expected to heavily impact cliff rock or sandy conditions at the shoreline. The final estimate of future cliff positions was generated by developing an average of the estimates of these models.

The impact of erosion and cliff retreat on transportation infrastructure is a significant concern, given the potential of eroding the land that forms the basis for roads and bridges. Caltrans already acts in many coastal areas to protect transportation infrastructure, and the designation of those assets at risk from this effect is a concern for long term planning and design decisions. The implications of cliff retreat will be even more important if the infrastructure footprint is to be maintained in place, requiring significant investment in the protection infrastructure to maintain system viability.

An analysis was conducted to determine those assets that may be impacted by shoreline change and cliff retreat. Data from the CoSMoS effort by USGS was assembled and an analysis using GIS tools was conducted for all sea level rise scenarios provided by USGS. The sea level rise increments that influence cliff retreat are the same increments used in the sea level and storm surge sections of this report –sea level rise of 1.64, 3.28, and 5.74 feet (0.50, 1.00, and 1.75 meters, respectively). For this analysis, the "Do Not Hold the Line" condition was used to identify areas along the coastline that would be damaged if the shoreline is not protected.

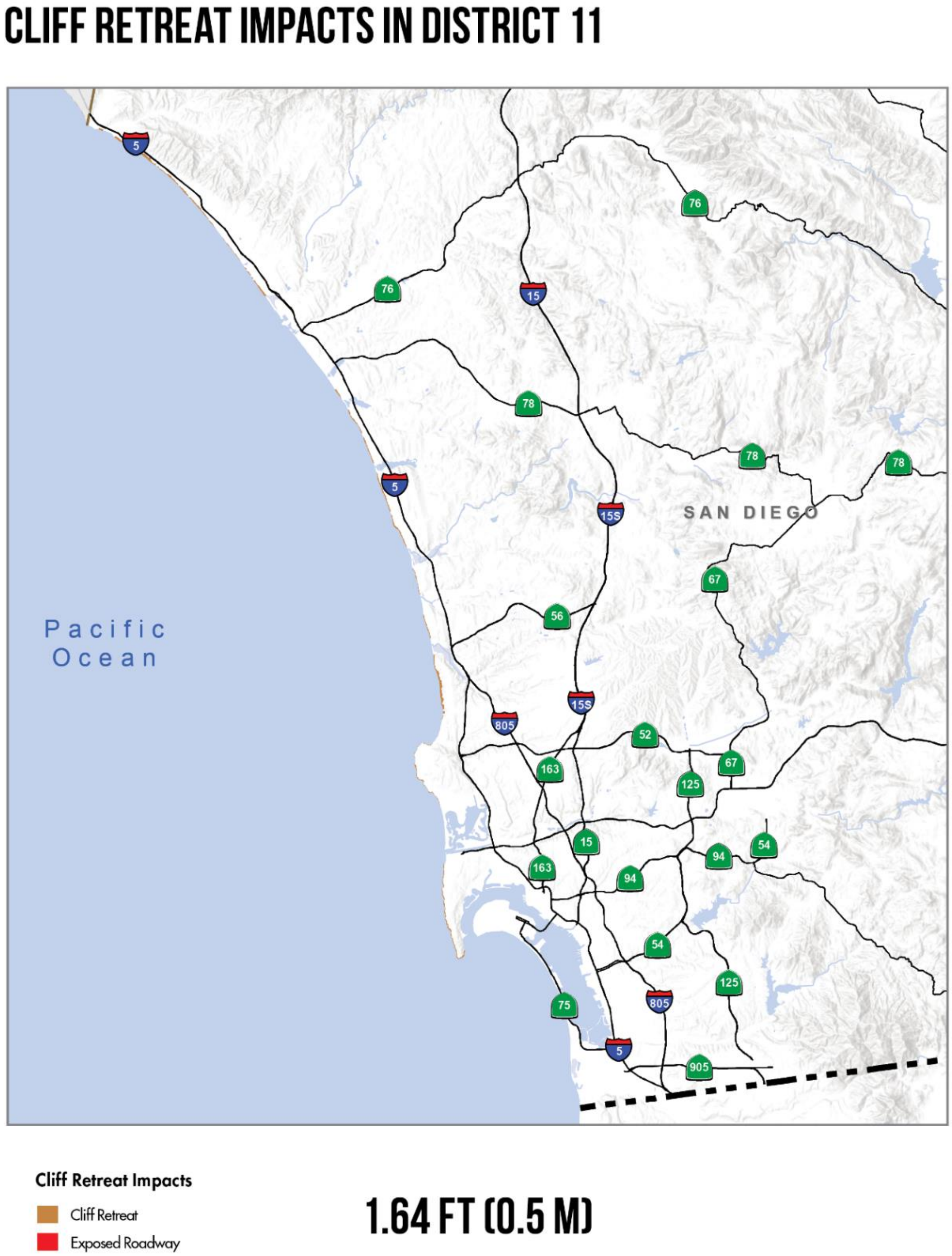
Table 6 summarizes the centerline miles of the District 11 highways and bridges that could be exposed to cliff retreat accelerated by sea level rise. Maps of projected cliff retreat in District 11 are provided on the following pages. Compared to other districts across the California coast, there are very minimal projected impacts to the State Highway System in District 11 from cliff retreat. Only one location is exposed, which is Interstate 5 in the northern part of the district.[48]

TABLE 6: DISTRICT 11 HIGHWAY CENTERLINE MILES EXPOSED TO CLIFF RETREAT

	Sea level rise (ft)		
District 11 County	**1.64**	**3.28**	**5.74**
San Diego	0	0	0.09

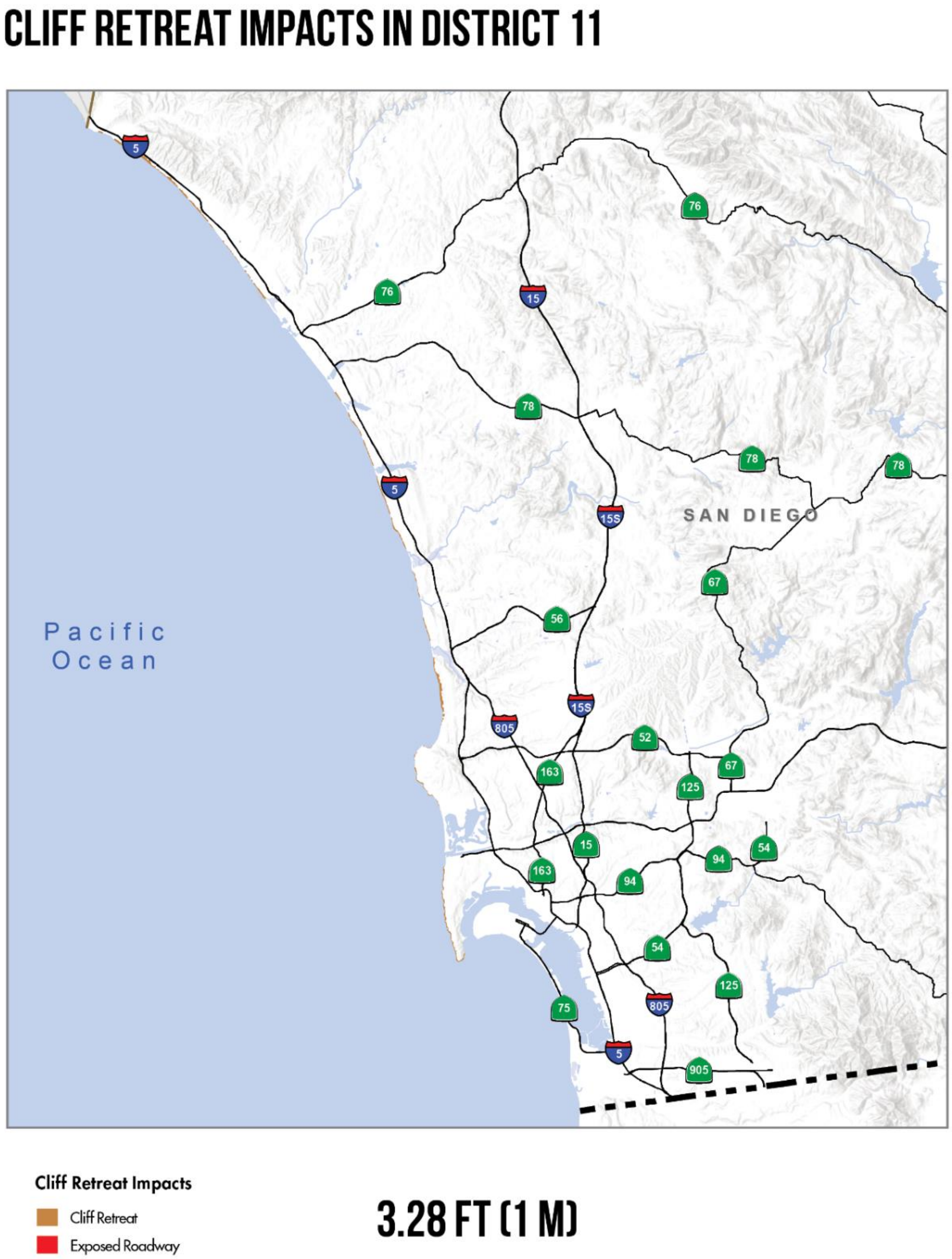
[48] Higher sea level rise projections may indicate more exposed areas on the State Highway System in San Diego County.

FIGURE 28: CLIFF RETREAT FROM 1.64 FT (0.50 M) OF SEA LEVEL RISE



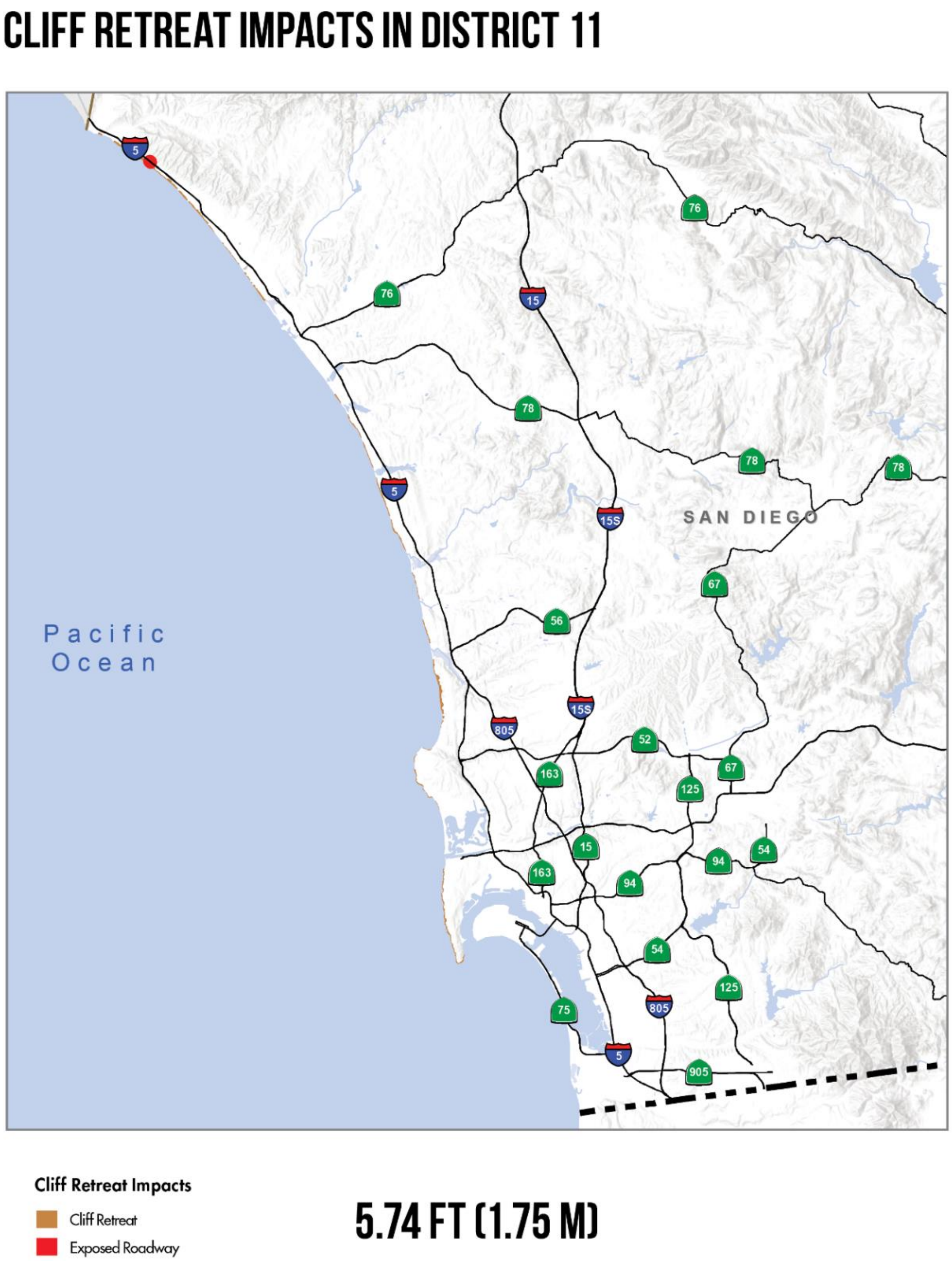
CLIFF RETREAT DATA ARE FROM THE US GEOLOGICAL SURVEY, COASTAL STORM MODELING SYSTEM (COSMOS). THIS DATA APPLIES THE "DO NOT HOLD THE LINE" MANAGEMENT OPTION, WHICH ASSUMES THAT CLIFF RETREAT CONTINUES UNIMPEDED. SEE Our Coast, Our Future AND THE USGS CoSMoS WEBPAGE FOR MORE INFORMATION ON THE MODEL.

FIGURE 29: CLIFF RETREAT FROM 3.28 FT (1.00 M) OF SEA LEVEL RISE



CLIFF RETREAT DATA ARE FROM THE US GEOLOGICAL SURVEY, COASTAL STORM MODELING SYSTEM (COSMOS). THIS DATA APPLIES THE "DO NOT HOLD THE LINE" MANAGEMENT OPTION, WHICH ASSUMES THAT CLIFF RETREAT CONTINUES UNIMPEDED. SEE Our Coast, Our Future AND THE USGS CoSMoS WEBPAGE FOR MORE INFORMATION ON THE MODEL.

FIGURE 30: CLIFF RETREAT FROM 5.74 FT (1.75 M) OF SEA LEVEL RISE



CLIFF RETREAT DATA ARE FROM THE US GEOLOGICAL SURVEY, COASTAL STORM MODELING SYSTEM (COSMOS). THIS DATA APPLIES THE "DO NOT HOLD THE LINE" MANAGEMENT OPTION, WHICH ASSUMES THAT CLIFF RETREAT CONTINUES UNIMPEDED. SEE Our Coast, Our Future AND THE USGS CoSMoS WEBPAGE FOR MORE INFORMATION ON THE MODEL.

10. LOCALIZED ASSESSMENT OF EXTREME WEATHER IMPACTS

To highlight how climate change may impact facilities in District 11, examples from recent events on the District road network have been highlighted below. These examples also illustrate the type of actions already being undertaken by District 11, and those that will be more commonplace in the future.

10.1. Interstate Actions

Caltrans' seismic retrofit program has been in place for many years and District 11 has implemented such projects, especially on critical freeway segments. Thus, District 11 is very aware of the critical portions of the freeway network and their vulnerability to seismic events. Similarly, storm surge, soil erosion and excessive heat/wind (in Imperial County) events have indicated areas of vulnerability for other types of disruption.

For example, the I-5 corridor is located mainly in the coastal zone, which contains several lagoons, rivers, and creeks that are within the 100-year floodplain. I-5 has already experienced erosion impacts due to storm surge at the lagoons. I-8 is the major East/West highway from the Pacific Coast to Arizona, which experienced major water main breaks in Mission Valley this past fall.

In Imperial County, sections of I-8 are inundated during heavy flooding events. While Imperial County is considered a desert region, it is subject to heavy rains which can cause flash flooding. I-8 crosses numerous canals, washes, and drainage ditches that can flood during heavy rainstorms. In San Diego County, I-8 is located within the floodplain of the San Diego River from its westward start to just past I-15 and is within the 500-year flood zones. Forester Creek borders a portion of the interstate in the City of El Cajon and is also within a 500-year flood zone.

Caltrans is taking steps to implement adaptive strategies for dealing with these potential incidents. For example, on I-8 in Imperial County, Caltrans will be placing continuously reinforced concrete pavement (CRCP) to provide a "long-life, superior roadway while at the same time reducing cost and improving safety for highway workers exposed to traffic by reducing maintenance time. The asphalt shoulders will also be replaced with CRCP reducing environmental impacts and increasing durability" due to heavy truck traffic and excessive heat.[49]

To assess whether an individual project will potentially be impacted by sea level rise, a three-part screening process has been developed involving an examination of the following three questions:

1. Is the project located on the coast or in an area vulnerable to sea level rise?
2. Will the project be impacted by the stated sea level rise?
3. Is the design life of the project beyond year 2030?

As noted in the District Transportation Concept Report for I-5, "new methods to increase the resiliency and adaptive capacity of the State Highway System must be developed to cope with the potential impacts of sea level rise."[50]

10.2. Maintenance Strategies

Given the potential of wildfires to seriously destroy road appurtenances made of wood, the District 11

[49] Caltrans, "Transportation Concept Report: Interstate 8," February 2016.
[50] Caltrans, "Transportation Concept Report: Interstate 5," June 2017.

maintenance staff requested a map of fire prone locations so that guard rail with wood posts could be replaced with metal posts. This was considered to be a long-term replacement program to be undertaken when funds became available or when replacement posts were needed as part of normal maintenance activities.

10.3. Culvert Assessment

Experience around the country suggests that culverts are one of the most important “weak links” when dealing with heavy precipitation and flooding. There are approximately 20,000 culverts in District 11. I-8 experienced a culvert collapse that shut down two eastbound travel lanes. Forensic investigation showed that water infiltration and sedimentation caused the fill surrounding the culvert to fail, thus creating a sinkhole and collapsing the freeway shoulders. The reconstruction of this segment of freeway took approximately 9 months and cost $6 million. Another location on I-8 (at Tavern Rd.) saw joints fail because of sedimentation, leading to a $7.5 million project to install another culvert under the freeway.

Due to increased concern for culvert failure, District 11 began an inspection program of all the culverts on the State Highway System, many of which were put in place over 30 years ago. Much has changed over this period, particularly expansion in urban areas (with large amounts of impervious surfaces). Over a 15-year period, no inspection of inside the culverts had been undertaken. As a preventive measure, funds from SB-1 were used to triple the size of the staff to conduct the inspections, which rated culverts as good, fair, or poor condition.

Additionally, Caltrans changed existing practices in response to climate stressors by replacing any plastic pipes (after wildfires) with more fire-resistant pipe materials.

10.4. SR 94 Bridge Replacement at Campo Creek

Caltrans determined that Campo Creek Bridge on SR 94 needed replacement due to abutment erosion and the progressive weakening of timber supports. Constructed in 1942 out of timber with a concrete bridge deck, the bridge had weakened to a point that Caltrans installed temporary shoring to support the structure. The estimated final cost of the project was $5.4 million, funded through the State Highway Operation and Protection Program (SHOPP). This project is highlighted here simply because the replacement design is exemplary of future projects Caltrans will likely find itself undertaking. The redesign considered changing climatic conditions and the impact on stream flow. Abutments, bridge supports and bridge deck elevation were all designed with such considerations in mind. Before and after photos of the bridge are shown in Figure 31.

FIGURE 31: BEFORE AND AFTER BRIDGE REPLACEMENT, CAMPO CREEK, SR 94

Before Bridge Replacement

After Bridge Replacement

11. INCORPORATING CLIMATE CHANGE INTO DECISION-MAKING

11.1. Risk-Based Design and Decision making

A risk-based decision approach considers the broader implications of damage and economic 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 FHWA, which undertook a few projects to assess climate change and facility design – including the Gulf Coast 2 project (Mobile, AL) and the Transportation Engineering Approaches to Climate Resiliency Study (TEACR). Both assessed facilities of varying types, 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),[51] 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 32.

The first five steps of the ADAP process cover the characteristics of the project and the context. The District 11 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 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:

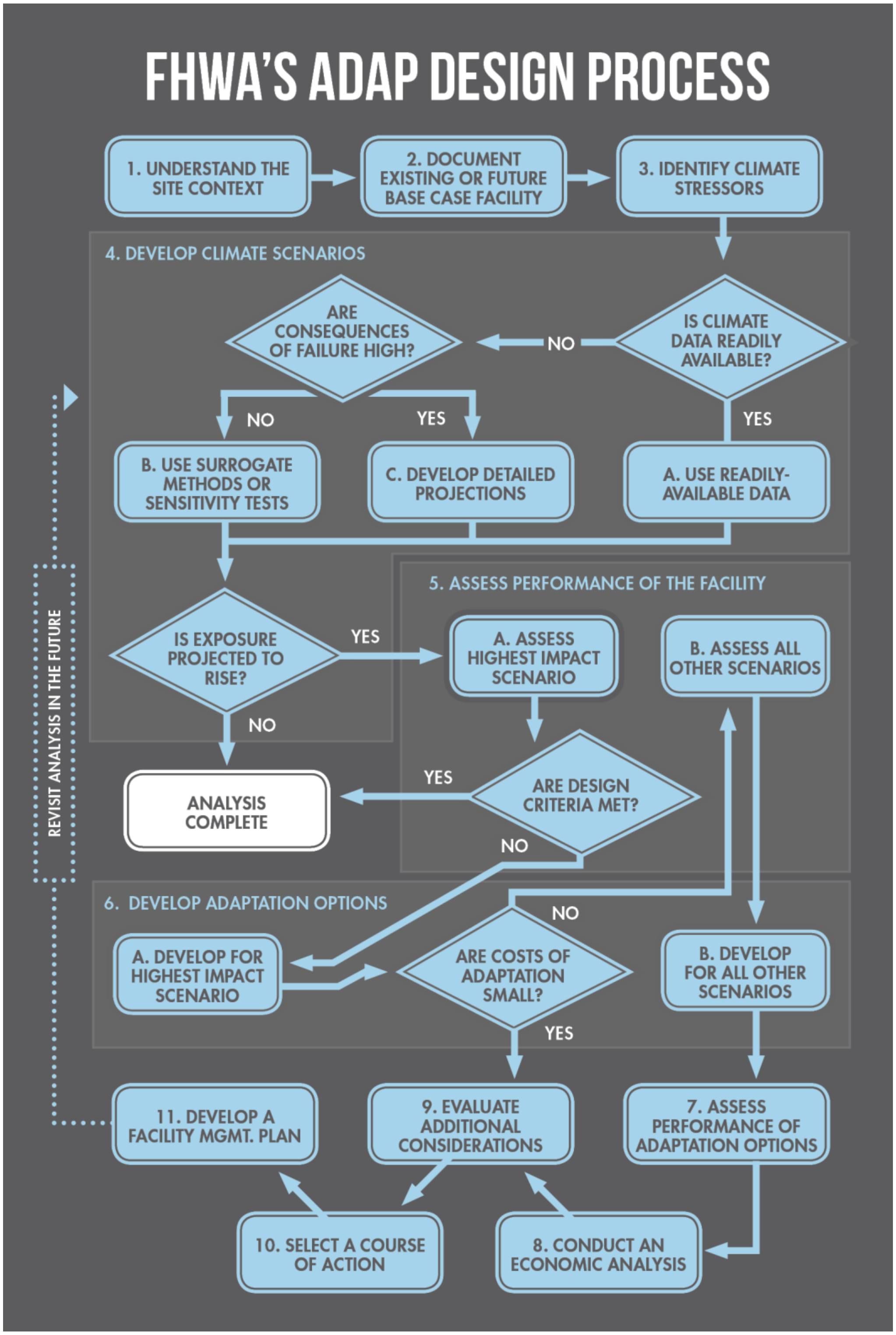
- full life cycle cost accounting
- maladaptation,

[51] "Adaptation Decision-Making Assessment Process," Federal Highway Administration, last modified January 12, 2018, 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 32: 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

11.2. Project Prioritization

The project prioritization approach outlined below is based on a review of the methods developed by other transportation agencies 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; 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 (sea level rise, 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?

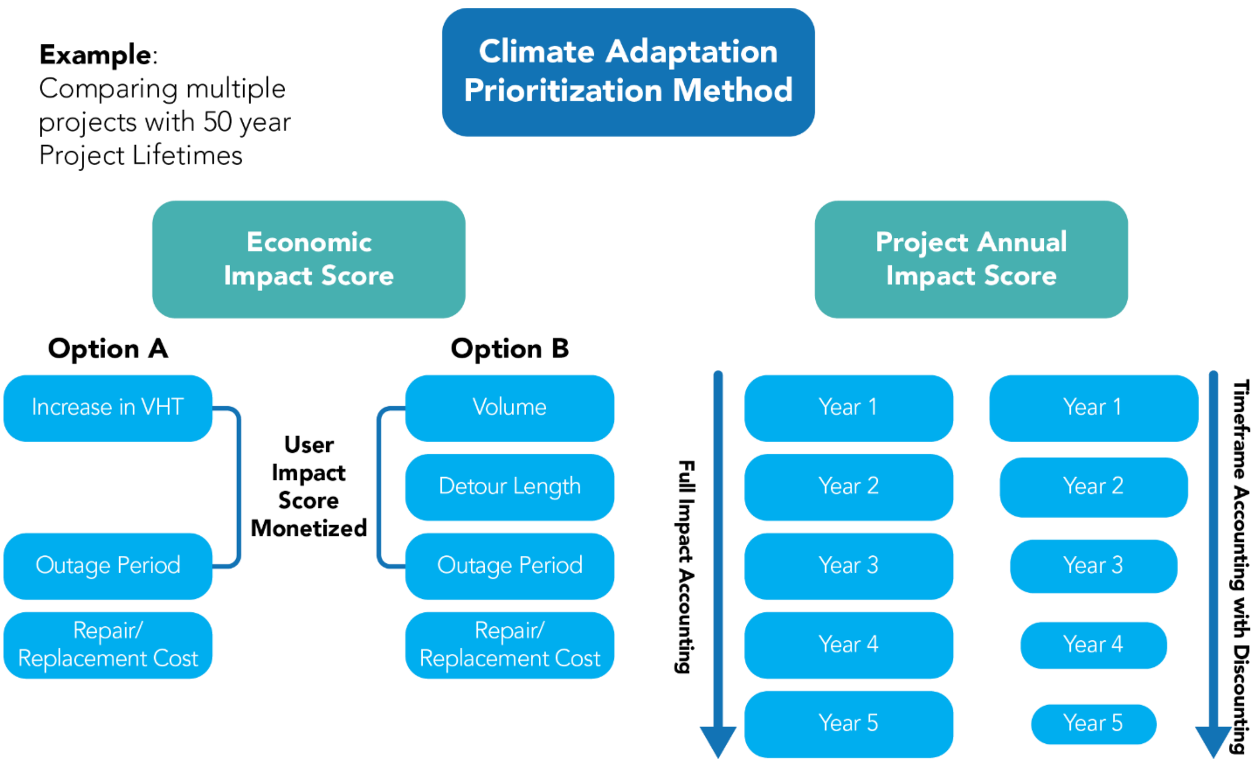
- System impacts (supplied by Caltrans planning staff) – the impacts of the loss of the facility on the broader system. This could be in terms of increase in Vehicle Hours Traveled (VHT) if using a traffic model, or an estimated value using volume and detour length as surrogates.
- Probability of occurrence (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 33 shows the general approach for the prioritization method.

FIGURE 33: 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 7 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 7: 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.

12. CONCLUSIONS AND NEXT STEPS

This report represents an initial effort to identify areas of exposure to potential climate change stresses for facilities owned and operated by Caltrans District 6. 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 11. The study distilled the larger context of climate change down to a more localized understanding of what such change might mean to District 11 functions and operations, District 11 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 (sea level rise, 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 11 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 11 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.

The following section provides some context as to what the next steps for Caltrans and District 11 may be, in order to build upon this work and create a more resilient State Highway System.

12.1. 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 11.

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 11. 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 11.1 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 11 (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. Much work remains to be done to create a resilient State Highway System in District 11.

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14. 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 Pathway (RCP): Scenario 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: 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.

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