CALTRANS CLIMATE CHANGE VULNERABILITY ASSESSMENTS

August 2019

District 12
Technical Report

CONTENTS

TABLES

FIGURES

ACRONYMS AND ABBREVIATIONS

ADAP	Adaptation Decision-Making Assessment Process
CalFire	California Department of Forestry and Fire Protection
Caltrans	California Department of Transportation
CAP	Climate Action Plan
CCC	California Coastal Commission
CEC	California Energy Commission
CMIP	Coupled Model Intercomparison Project
CoSMoS	Coastal Storm Modeling System
DWR	California Department of Water Resources
EPA	US Environmental Protection Agency
FHWA	Federal Highway Administration
GCM	Global Climate Model
GFDL	Geophysical Fluid Dynamics Laboratory
GHG	Greenhouse Gas
GIS	Geographic Information System
IPCC	Intergovernmental Panel on Climate Change
LIDAR	Light Detection and Ranging
LOCA	Localized Constructed Analogues
MACA	Multivariate Adaptive Constructed Analogs
MHHW	Mean Higher High Water
MPO	Metropolitan Planning Organization
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
OCTA	Orange County Transportation Agency
OPC	Ocean Protection Council
PCH	Pacific Coast Highway
RCP	Representative Concentration Pathway
RTPA	Regional Transportation Planning Agency
Scripps	The Scripps Institution of Oceanography
SHS	State Highway System
SLR	Sea Level Rise
SR	State Route
SRES	Special Report Emissions Scenarios
TEACR	Transportation Engineering Approaches to Climate Resiliency
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, developed for the California Department of Transportation (Caltrans), discusses the data and methodologies used to conduct a vulnerability assessment of the State Highway System (SHS) located in Caltrans District 12. This report served as the basis for information presented in the accompanying District 12 Vulnerability Assessment Summary Report.

Climate change and extreme weather events have received increasing attention worldwide as one of the greatest challenges facing modern society. Many state agencies—such as the California Coastal Commission (CCC), the California Energy Commission (CEC), and the California Department of Water Resources (DWR)—have developed approaches for understanding and assessing the potential impacts of a changing climate on California's natural resources and built environment. Many of the state's agencies are examining the implications of climate change on different sectors and population groups in the state. Many of California's academic institutions are engaged in developing the scientific basis for investment decision-making taking into consideration future climatic conditions.

Caltrans initiated the current study to better understand the vulnerability of California's SHS and other Caltrans assets to future changes in climate. The study has three objectives:

- Understand the types of weather-related and longer-term climate change events that will likely occur with greater frequency and intensity in future years,
- Conduct a vulnerability assessment to identify those Caltrans assets vulnerable to various climate-influenced natural hazards, and
- Develop a method to prioritize candidate projects for actions that are responsive to climate change concerns, when financial resources become available.

This District 12 report is one of 12 district reports that are currently in various stages of development.

1.1. Purpose of Report

The *District 12 Technical Report* is one of two documents that describe the District 12 SHS climate vulnerability assessment, the other being the *District 12 Summary Report*. The *Summary Report* provides an overview of the methodologies used for the assessment, the potential implications of climate change to Caltrans assets, and how climate data can be applied in Caltrans decision-making. It is intended to orient non-technical readers on how climate change may affect the SHS in District 12.

This *Technical Report* describes in more detail the approaches used to estimate the exposure of the District 12 SHS to future climate change stresses. Primarily intended for District 12 staff, it provides background on the methodologies used to develop material for the Summary Report and general information on how to replicate those methods, if desired. The report is divided into sections by climate stressor (e.g., wildfire, temperature, and precipitation). Each section presents:

- How that climate stressor is changing,
- The data used to assess SHS vulnerabilities to that stressor,
- The methodology for how the data were developed,

- Maps of the portion of district SHS exposed to that stressor, and
- Where applicable, the mileage of exposed SHS.

Finally, this *Technical Report* outlines a recommended approach for prioritizing a list of projects that might be considered by Caltrans in the future. This approach was developed based on reviews of prioritization frameworks used by other transportation agencies. Special emphasis was given to those approaches used that incorporated climate change considerations into agency decision-making.

The data used in the development of the District 12 Technical and Summary Reports were collected into a single database and provided to Caltrans. Caltrans will be able to use this data in its mapping efforts and analyses. It is expected to be a valuable resource for ongoing resiliency planning efforts. The contents of the District 12 database will also be available to the public in an online interactive mapping tool at the end of the study.

1.2. District 12 Characteristics

Caltrans District 12, headquartered in Santa Ana, is responsible for the SHS in Orange County, which lies between California's two largest cities--Los Angeles and San Diego. The jurisdictional boundaries of the District include a metropolitan area of 794 square miles, including 34 cities (three of the top 15 cities in California---Anaheim, Irvine, and Santa Ana) and a population of 3.2 million people (2016). As noted in the District 12 District System Management Plan,

> "Orange County lies at the crossroad where it provides connectivity to an international commercial route between Mexico and Los Angeles; in addition to, connecting the Inland Empire and the beach cities .... An estimated 40 percent of all rail container traffic out of the ports of Los Angeles and Long Beach travels through Orange County. Interstates 5, 405, and 605 along with State Route 91 within Orange County are vital components of the national truck network and serves as key corridors for goods movement from Los Angeles County's international ports to the Inland Empire and beyond."[1]

Orange County is also home to 11 public and 10 private colleges/universities, as well as two major military installations (Los Alamitos Joint Forces Training Base and Seal Beach Naval Weapons Station). Major tourist attractions include Disneyland and California Adventure Amusement Parks, Angel Stadium, Knott's Berry Farm, South Coast Plaza Shopping Center, Orange County Performing Arts Center, the Mission in San Juan Capistrano, and the beach communities of Dana Point, Huntington Beach, Newport Beach, Laguna Beach, Seal Beach, and San Clemente. These attractions, along with Orange County being

[1] California Department of Transportation (Caltrans), "District System Management Plan (DSMP)," District 12. 2014, http://www.dot.ca.gov/d12/planning/pdf/DSMP_Final_Signed_November_2014.pdf

one of the fastest growing regions in California, often result in high traffic volumes and recurring congestion levels on District 12 highways.

Many coastal cities are found in the district, which presumably would be greatly affected by climate change, especially rising sea levels, cliff retreat, and storm surge. These cities are subject to some of the state's strictest guidelines with respect to development in coastal areas and strategies for reducing greenhouse gases. These cities and Caltrans form a natural constituency for jointly considering how to make the entire district's road network (not just the SHS) resilient to climate change-induced disruption.

Crisscrossed by 17 state highway routes, District 12 maintains and operates 279 route-miles, just over 2,000 lane-miles of highway, and 226 directional-miles of High Occupancy Vehicle (HOV) or carpool lanes. Over the past 20 years, the District and its transportation partners have doubled freeway lane-miles in the county.

Several of District 12's state highways have an important role in providing mobility and connectivity as part of California's SHS.[2]

- SR 91 is a major east-west corridor in the county and links Riverside and San Bernardino Counties to Orange and Los Angeles Counties.
- SR 22 is also an east-west route in the county and is 13 miles long, stretching from the City of Seal Beach in the west to the City of Orange in the east. Average annual daily traffic (AADT) exceeds 250,000 at critical locations.
- I-5 is a major south-north route that runs throughout the state. It connects Orange County with Los Angeles County on the north and with San Diego County on the south. AADT exceeds 370,000 at critical locations.
- I-405 begins at the I-5 interchange (the El Toro Y) in Irvine and runs in a northwest direction, parallel to the ocean until it terminates and connects back to I-5 in the San Fernando Valley.
- SR 73 connects the I-5 corridor in San Juan Capistrano to the I-405 corridor in Costa Mesa. It runs through Crystal Cove State Park and the University of California at Irvine. From the northern terminus, the first three miles of SR 73 are called the Corona del Mar Freeway. The next 12 miles of the highway operate as a toll road, called the San Joaquin Hills Transportation Corridor.
- SR 1 connects to SR-55 at the southern end of the corridor, providing coastal access to Mendocino County. Because of its coastal alignment, SR 1 could be particularly vulnerable to sea level rise and storm surge.

These highways will have different issues relating to climate change stresses not only because of their different environmental contexts, but also because of the design criteria associated with facility design (e.g., Interstate design standards are more stringent than those for non-Interstate state highways).

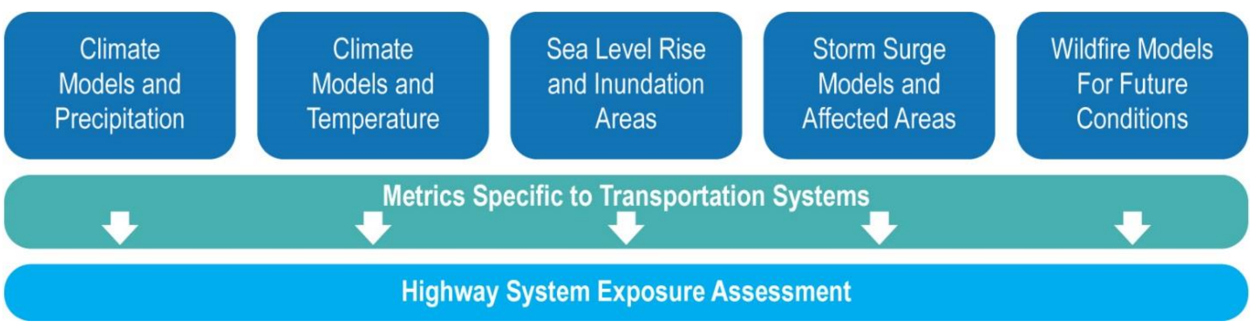
[2] Caltrans, "Corridor System Management Plan (CSMP) Final Report Orange County SR-55," District 12, 2014, http://www.dot.ca.gov/d12/planning/pdf/SR-55%20CSMP%20Final%20Technical%20Report.pdf

2. POTENTIAL EFFECTS FROM CLIMATE CHANGE ON THE STATE HIGHWAY SYSTEM IN DISTRICT 12

Changing climatic and extreme weather conditions in District 12 are expected to impact the SHS and other Caltrans assets in District 12. These impacts will likely appear in a variety of ways, increasing the exposure to environmental factors beyond those incorporated into the original design considerations. For example, user-related impacts might include increased delays due to closed roads due to flooding, coastal erosion, and poor visibility from wildfires. To the District, such impacts could require additional efforts at emergency response and the redesign of assets to better handle expected future environmental conditions (e.g., larger culverts in areas considered to be at high-risk for extreme flooding). The project study team considered a range of climate stressors and how they tie into Caltrans design criteria/other metrics specific to transportation systems.

Figure 1 illustrates the general process for deciding which metrics should be included in the overall SHS vulnerability assessment. First, Caltrans and the project study team considered which climate stressors will likely affect transportation systems. Caltrans and the project study team then identified the relevant metric that could be informed by the data available to conduct the vulnerability assessment. For example, precipitation data were formatted to show the 100-year storm depth (the amount of rainfall associated with a storm of such an intensity that it is expected to occur on average once every 100 years), as the 100-year storm is a criterion used in the design of many Caltrans assets.

FIGURE 1: CONSIDERATIONS FOR THE STATE HIGHWAY ASSESSMENT



Orange County has also undertaken studies to identify the types of transportation system disruptions that might be faced in the future. The Orange County Hazard Mitigation Plan, for example, identified four major hazards (in order of importance)—floods/storms, hazardous materials spills, wildland fire, and earthquakes. As noted in the plan, "Climate change was not included as a hazard in the last County Emergency Operations Plan revision so it is not specifically called out, but it is evident that it will be a major component of Orange County's hazard analysis process moving forward. Since many of the effects of climate change will serve to worsen the severity and frequency of other hazards (wildfire, flood/storm, tsunami (through sea level rise)), the hazard analysis process will increase in complexity."[3] The Plan noted that the effects of climate change will be considered more explicitly in the 2020 Plan update.

[3] Orange County and Orange County Fire Authority, "Local Hazard Mitigation Plan," 2015, http://cams.ocgov.com/Web_Publisher/Agenda07_12_2016_files/images/O00216-000668A.PDF

The following climatic/extreme weather conditions (also referred to as climate "stressors" and hazards in this report) were evaluated for the District 12 assessment:

Temperature – As greenhouse gas (GHG) emission concentrations increase in the atmosphere, so too have average surface temperatures on the Earth. This is certainly the case in California. Temperatures in Orange County have historically been relatively mild, but extreme heat waves during the past decade have resulted in triple digit temperatures that have set historical records. In September of 2017, there were week-long triple digit temperatures of 107 degrees in Yorba Linda, 105 degrees in Lake Forest and 103 degrees in Fullerton.[4] In October 2017, Fullerton recorded 107 degrees, which is considered the hottest single temperature recorded anywhere in the United States so late in the year. Even Death Valley had never recorded a temperature this high after October 16th in any year. In 2017, Orange County had its warmest average December temperatures since 1895.[5]

According to Cal-Adapt, the tool developed by the state for obtaining projections of future climate conditions, between 1961 and 1990, there were on average 4.3 days per year in Orange County with temperatures over 94°F (Cal-Adapt's definition of extreme heat). Assuming a scenario of global GHG emissions starting to decline around 2040 (RCP 4.5 as described later), the number of extreme heat days per year still rises to 12 for the 2070 to 2099 time period. Assuming a worst-case emissions scenario where GHG emissions do not decline over the next 80 years, the number of extreme heat days per year is estimated to be 24 days on average.[6]

Areas along the coast are expected to experience less temperature rise, while inland areas could suffer the greatest increases in temperature and high heat event frequency. Periods of drought could be made worse and become more common, though precipitation variations are difficult to predict for California. Scientists have suggested that the period of drought from 2012 to 2014 was most likely intensified by climate change by anywhere from 15 to 20 percent.[7]

Extreme temperatures, especially when occurring in consecutive days, can potentially affect highway durability of construction materials; heat exposure to system users, contractors, and Caltrans staff; and road landscape strategies; and exacerbate the frequency and severity of the consequences of high heat events such as drought and wildfires.

Precipitation – Most climate forecasts for California suggest that it will become hotter and more drought-prone, with intermittent and heavy storms. However, new research from UC-Riverside that was incorporated into California's Fourth Climate Change Assessment projected an overall wetter future.[8] Despite the uncertainty inherent in

[4] Kelly Puente, "Southern California Swelters in Triple-Digit Temperatures," *The Orange County Register*, September 1, 2017, https://www.ocregister.com/2017/09/01/california-swelters-in-triple-digit-temperatures/

[5] "Assessing the US Climate in 2017," National Oceanic and Atmospheric Administration (NOAA), National Centers of Environmental Information, last accessed July 2, 2019, https://www.ncei.noaa.gov/news/national-climate-201712

[6] "Extreme Heat Days and Warm Nights," Cal-Adapt, last accessed July 2, 2019, http://cal-adapt.org/tools/extreme-heat/#climatevar=tasmax&scenario=rcp85&lat=33.65625&lng=-117.71875&boundary=locagrid&units=fahrenheit

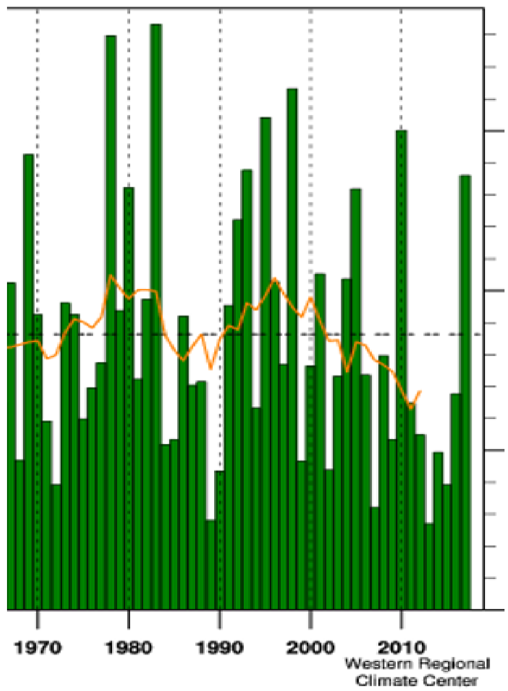
[7] Williams Park, Richard Seager, John Abatzoglou, Benjamin Cook, Jason Smerdon, and Edward Cook, "Contribution of Anthropogenic Warming to California Drought During 2012-2014," August 20, 2015. http://onlinelibrary.wiley.com/doi/10.1002/2015GL064924/full

[8] California's Fourth Climate Change Assessment Report, Report SUM-CCCM 2018-013, January 16, 2019, http://www.climateassessment.ca.gov/

precipitation projections, scientists agree that California can expect more extreme precipitation events due to a warmer atmosphere and increased water vapor in the air.[9]

One of the most important impacts of climate change is that it can cause large fluctuations in precipitation levels, with dry years becoming dryer and wet years wetter. This effect is shown in Figure 2 where the years 2013 to 2015 were some of the driest years in District 12 since 1970. Across the state, 2012 to 2014 was California's driest three-year[10] period in 119 years of records.[11]

FIGURE 2: SOUTH COAST REGION, ANNUAL PRECIPITATION, 1970 - 2017 (INCHES)



SOURCE: "CALIFORNIA CLIMATE TRACKER," WESTERN REGIONAL CLIMATE CENTER, LAST ACCESSED MAY 16, 2019, HTTPS://WRCC.DRI.EDU/CLIMATE/TRACKER/CA/

Changes in precipitation can result in many different impacts to Orange County. Lower precipitation levels would lead to a drought in the region, presenting its own set of challenges. In January 2014, Governor Jerry Brown declared a drought State of Emergency that affected most of the state until April 2017. Orange County had been in what officials declared as an

[9] Suraj Polade, Alexander Gershunov, Daniel Cayan, Michael Dettinger, and David Pierce, "Precipitation in a Warming World: Assessing Projected Hydro-climate Changes in California and Other Mediterranean Climate Regions," Scientific Reports 7, Article number: 10783, 2017, https://www.nature.com/articles/s41598-017-11285-y

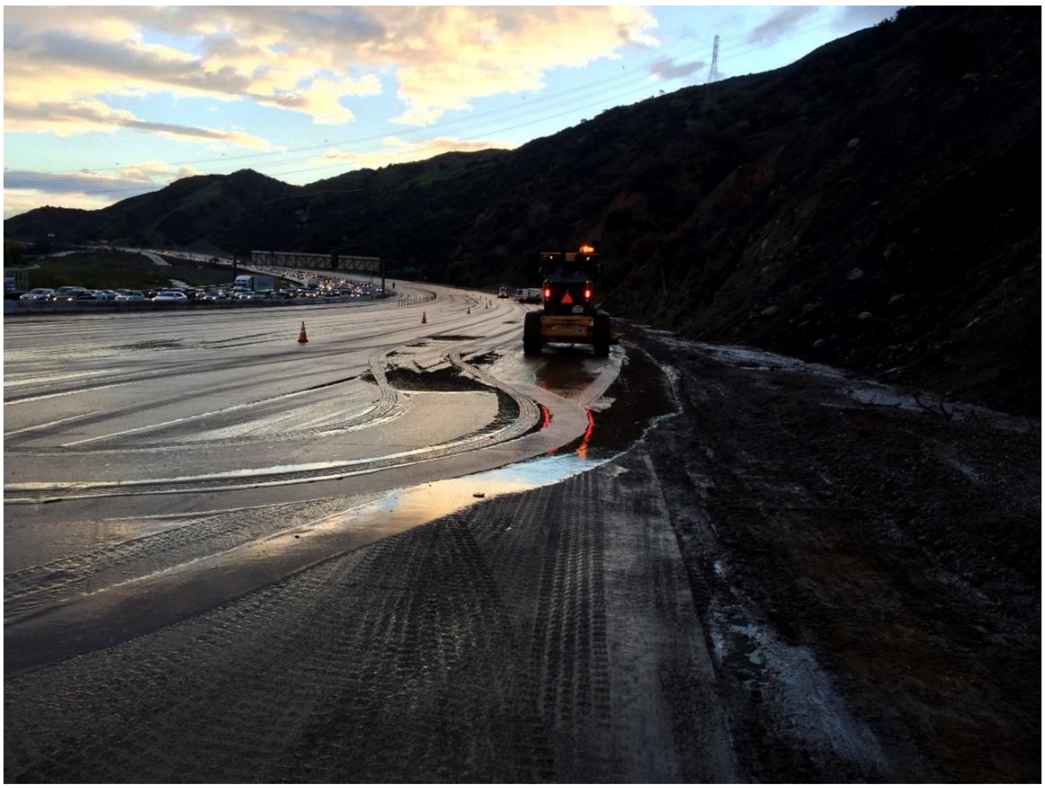
[10] These are "water years" defined by the California Department of Water Resources as "a time period of 12 months during which precipitation totals are measured… the time period is not a calendar year because precipitation in California starts to arrive at the start of the wet season in October and continues to the end of the dry season the following September." See Hydroclimate Report: Water Year 2015 for more information.

[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

'extreme drought' situation.[12] Higher-than-average winter temperatures meant less snowpack feeding the river basins that Orange County depends on for water during warmer months.

High intensity storms are another consequence of climate change and can cause their own disruptions. For example, storms in January 2017 caused widespread flooding and power outages in Orange County. Several local streets and pedestrian ways were closed due to flooding, downed trees, and rockslides. In Laguna Beach, after a three-day downpour, Ocean Avenue had accumulated 24 inches of rain, resulting in its closure.[13] With respect to the SHS, debris flows and flooding can close roads causing delays and disruptions to SHS users. District 12 has already experienced rockslides from excessive precipitation (see Figure 3).

FIGURE 3: TRAFFIC DISRUPTION FROM ROCKSLIDE ON SR 91



[12] NOAA, "State of the Climate: National Climate Report for December 2017," National Centers for Environmental Information, published online January 2018, https://www.ncdc.noaa.gov/sotc/national/201712.
[13] Bradley Zint, Bryce Alderton, and Ben Brazil, "Storms Bring Flooding, Power Outages and Hail to O.C." *The Los Angeles Times*, January 23, 2017, http://www.latimes.com/socal/daily-pilot/news/tn-dpt-me-weather-20170123-story.html

Sea Level Rise – Sea level rise (SLR) is a long-term threat to coastal areas. The effects of thermal expansion of ocean water combined with contributions from glacial and ice sheet melting result in higher sea levels around the world. Higher sea levels could damage coastal infrastructure, potentially inundating low-lying sections of roadway, damaging asset substructure, or contributing to increased erosion effects at the shoreline (and thereby threatening coastal roads).

Historic sea level rise in the Los Angeles area (closest tidal gauge to Orange County) has seen growth rates of around a third of an inch per year (one millimeter per year).[14] By the end of the century, the Los Angeles area SLR is projected to be anywhere from 0.7 to 6.7 feet above current levels, with an extreme high of 9.9 feet[15] (for more detail on SLR projections, see Section 8.1).

Storm Surge – A storm surge is short-term rising of sea levels due to low pressure weather systems and/or strong winds. For high-intensity storms, storm surge can be devastating to coastal areas. Increasing sea levels combined with changes to storm patterns are expected to alter and increase the effects of storm surge in coastal areas. Storm surge is currently considered in coastal transportation facility design but increasing water levels and more powerful future surges represent a very different stress than was likely considered in past designs. In addition, infrastructure originally assumed to be outside of the surge zone may now be exposed to the effects of storm surge. Storm surge is also expected to increase coastal erosion and landslides, causing shoreline retreat and exposing roadways to increased effects from flooding.

Wildfire – Higher temperatures, changing precipitation patterns, and extended periods of drought are expected to increase the risk of wildfire. The year 2017 was one of the most destructive wildfire seasons in California in terms of property damage, ending with 11,642 structures destroyed across the state. In October 2017, the Canyon 2 Fire in Orange County burned 9,200 acres and destroyed 25 structures.[16] Another major wildfire in Orange County was the Freeway Complex Fire, which burned over 30,000 acres in November 2008 (see Figure 4 below).

Wildfires can increase the likelihood of road closures even after the fire is extinguished as damaged trees could fall and result in road blocks or driver safety threats. Additionally, smoke from ongoing fires can decrease visibility for drivers and raise health concerns for highway maintenance crews responding to the road disruption.

[14] NOAA, "Relative Sea Level Trend: 9410660 Los Angeles California," NOAA Tides and Currents, last accessed May 16, 2019 from https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=9410660

[15] California Ocean Protection Council (OPC), "State of California Sea-Level Rise Guidance: 2018 Update," 2018, http://www.opc.ca.gov/webmaster/ftp/pdf/agenda_items/20180314/Item3_Exhibit-A_OPC_SLR_Guidance-rd3.pdf

[16] CalFire, "CalFire Statewide 2017 Incidents," CalFire, last accessed July 5th, 2019, https://www.fire.ca.gov/incidents/2017

FIGURE 4: FREEWAY COMPLEX FIRE

SOURCE: BLUEDV, [Creative Commons 3.0 License]

Cliff Retreat - Sea level rise will exacerbate the effects of cliff retreat as water and waves erode cliff faces along the California coast. To date, District 12 has not experienced the effects of cliff retreat on the SHS. However, increased shoreline erosion and cliff retreat could affect the SHS, especially along some parts of SR 1 (also known as the Pacific Coast Highway (PCH)) if the supporting shoreline is washed out.

Combined Effects – Disruptions to the transportation system due to extreme weather events are often magnified when one weather-related event exacerbates others that follow.

- **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 blocks and require detours. Several recent incidents relating to flooding and follow-on impacts illustrate the danger to District 12 communities. For example, in the latter part of 2017, authorities ordered evacuations near wildfire burn areas in Santa Barbara, Los Angeles, and Orange Counties. It was feared that potential debris flows coming from the burned land could restrict access for emergency responders. State and local officials were also concerned about the Canyon Fire 2 in Orange County due to the potential for flooding and mudslides during the rainy season.[17] Other state highways particularly prone to combined effects of wildfire and flooding include SR 74, SR 133, and SR 142.

[17] Kelly Puente, "O.C. Areas Vulnerable from Canyon Fire 2 Prepare for Possible Floods, Mudslides in Upcoming Storm," *The Orange County Register*, January 6, 2018, https://www.ocregister.com/2018/01/06/o-c-areas-vulnerable-from-canyon-fire-2-prepare-for-possible-floods-mudslides-in-upcoming-storm/

- **Sea Level Rise and Storm Surge** – Sea level rise will exacerbate the effects of coastal storm surge as water and waves will reach farther on shore and with more force. District 12 has already experienced the effects of storm surge on the SHS, specifically on the PCH. These storm events could lead to erosion, scour,[18] and washouts underneath the highway itself.

The following sections provide more detail on how each of these climate change stressors could affect the future performance of the Caltrans District 12 SHS. 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. The sources of the data are described in the following sections.

[18] Bridge scour is typically a result of swiftly moving water removing soil/sediment from around structural elements like abutments or piers. It can increase risk of failure for the structure.

3. POLICY CONTEXT

3.1. Stakeholder Involvement

The material presented in both the District 12 Summary and Technical Reports was reviewed by internal District 12 staff. Specific coordination efforts with district staff included:

- Communicating on previous work sponsored by and completed by District 12 staff to identify available data, and review findings and lessons learned.
- Participating in a kick-off meeting where the agenda included discussing the approach to be used in the study, the expected deliverables, and the manner in which district staff would be involved in the study.
- Obtaining photos, background information, and other report data.
- Reviewing draft and final versions of the report.

The project team also coordinated the preparation of the report with California organizations responsible for climate model and data development. These agencies and research institutions will be discussed in more detail in the following pages and in the respective sections on each stressor.

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

California has been at the forefront in the United States of climate change policy, planning, and research. State officials have been instrumental in developing and implementing policies that foster effective GHG mitigation strategies and the consideration of climate change in state decision-making. California agencies have also been instrumental in creating climate change data sets that can be used to understand climate change impacts statewide and in the state's regions. At a more local level, efforts to plan for and adapt to climate change are underway in communities across the state (some of which are discussed below). These practices provide important input into decisions (at all levels) that reflect future climate change risks.

The following sections describe some of the key legislative, governor, and Caltrans policies that should influence Caltrans climate change-influenced decision-making. Another section describes some of the underlying climate change models that were used in this study.

3.2.1 Climate Change-related Policies

Various state policies address 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 (AB) 32** (2006) or the "California Global Warming Solution Act" was the first California law to require a reduction in GHG emissions. The law was the first of its kind in the country and set the stage for future state climate change policies.[19]

[19] California Air Resources Board, "Assembly Bill 32 Overview," 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 SLR and climate impacts through the coordination of the state Climate Adaptation Strategy.[20]
- **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.[21]
- **AB 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.[22]
- **Senate Bill (SB) 246** (2015) establishes the Integrated Climate Adaptation and Resiliency Program to coordinate regional and local efforts with state adaptation strategies.[23]
- **AB 2800** (2016) requires that state agencies account for climate impacts during planning, design, building, operations, maintenance, and investments in infrastructure. It also required the formation of a Climate-Safe Infrastructure Working Group represented by engineers with relevant experience from multiple state agencies, including Caltrans.[24]

These policies establish the foundation for state agencies to consider climate change in its activities. This District 12 vulnerability assessment is a key step toward preparing Caltrans infrastructure for future extreme weather conditions and addressing the requirements of state policy. Some policies, such as Executive Order S-13-08, stimulate the creation of climate data that can be used by state agencies in their own adaptation planning efforts.

One of the most important climate adaptation policies of those listed above is Executive Order B-30-15. Guidance specific to the Executive Order was released in 2017, entitled *Planning and Investing for a Resilient California*. This guidance helps state agencies develop methodologies in completing vulnerability assessments specific to their responsibilities and in making adaptive planning decisions. *Planning and Investing for a Resilient California* created a framework for used by state agencies, which is important in communicating the effects of climate change consistently across state government.

3.2.2 Caltrans Climate Change-related Policies

Caltrans, as an organization, first started addressing concerns associated with climate change in 2007 with the creation of its Climate Change Branch. Since then, Caltrans has established internal policies and guidance regarding climate change adaptation. The following is a collection of the most relevant policies or agency statements.

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

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

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

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

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

Metropolitan Planning Organizations and Regional Transportation Planning Agency Guidance: Caltrans developed a guide for California Metropolitan Planning Organizations (MPO) and Regional Transportation Planning Agencies (RTPA) that outlined methods to incorporate adaptation into Regional Transportation Plans. Caltrans recommended in this document that every MPO and RTPA follow the basic evaluation steps of, (1) assessing the effects of climate conditions in their region, (2) considering how their five most important transportation assets could be affected, and (3) developing adaptation strategies for further study and inclusion in the Regional Transportation Plan.

California Coastal Commission Agreement: Caltrans signed an agreement with the California Coastal Commission (CCC) and its Integrated Planning Team to ensure effective collaboration between the agencies when considering SLR impacts. The agreement recognized that both the CCC and Caltrans have leadership roles in addressing SLR that complement each other. The CCC noted that Caltrans should follow the CCC's Sea Level Rise Policy Guidance in planning coastal development, which provides guidance on an adaptation planning process for Local Coastal Programs and Coastal Development Permits.

Guidance on Incorporating Sea Level Rise provided initial criteria for determining whether sea level rise needs to be incorporated into project programming and design. Factors that should be considered include: the project design life, the existence of alternative routes, anticipated travel delays, evacuations, traveler safety, and environmental constraints. Sea level rise projections for this guidance are adopted from the Ocean Protection Council's (OPC) guidance.[25]

Although not guidance per se, the Caltrans section of the "Sustainability Roadmap 2018-2019 Progress Report and Plan Update on Meeting the Governor's Sustainability Goals for State Departments," identifies the progress that has been made in satisfying state legislation and Executive Orders with respect to sustainability. A Climate Adaptation Roadmap was outlined as part of the overall Sustainability Roadmap that was intended to integrate climate change adaptation into all planning and investments (although the Climate Adaptation Roadmap primarily focused on buildings).[26] The state road section in the Roadmap highlighted the following topics as part of Caltrans' adaptation efforts: 1) use of natural infrastructure as an adaptation strategy and 2) use of full life-cycle cost accounting as part of project prioritization. The Roadmap also reported on progress of incorporating climate change into transportation planning efforts and plans, with many of the plans reported as having done so.[27]

These are just a selection of the most relevant guidance for Caltrans in considering climate change adaptation activities. As presented, there is a substantial legislative, Executive Order, and policy foundation for considering climate change adaptation in Caltrans. This guidance will likely grow as Caltrans continues to implement its path towards achieving a more resilient transportation system.

3.3 Other Orange County Efforts to Address Climate Change

In addition to state efforts to assess the impacts of climate change, other efforts have been taken or are underway in Orange County relating to climate change planning and preparedness. The following sections illustrate some of these efforts.

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[25] California Ocean Protection Council, "State of California Sea-Level Rise Guidance: 2018 Update." March 14, 2018, last accessed July 2, 2019. http://www.opc.ca.gov/webmaster/ftp/pdf/agenda_items/20180314/Item3_Exhibit-A_OPC_SLR_Guidance-rd3.pdf.

[26] Fox, D., J. Matsuo, and D. Miner. "Sustainability Roadmap 2018-2019 Progress Report and Plan Update on Meeting the Governor's Sustainability Goals for State Departments." Caltrans. https://green.ca.gov/Documents/CALTRANS/SustainabilityRoadmap10-31-18_rev5.pdf

[27] Most attention in the plans was on GHG emission reduction although the latest California Transportation Plan did discuss the need for adaptation.

3.3.1 Climate Action Plans

Many communities and county agencies in District 12 have either adopted Climate Action Plans (CAPs) designed to mitigate GHGs 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 cities of Fullerton, Huntington Beach, La Habra, Laguna Beach, Laguna Woods, Mission Viejo, San Clemente, and Santa Ana.

3.3.2 Integrated Regional Water Management Plan for North and Central Orange County

Regional water management programs in California are required to consider climate change impacts in their planning and decision-making processes. The *Climate Change Handbook for Regional Water Planning* (US EPA Region 9 and California DWR, November 2011) outlines a process for undertaking such an assessment for regional water management. Orange County Public Works has recently completed an Integrated Regional Water Management Plan for the north and central regions (still being finalized). In the plan, the following climate change stressors were identified as having the greatest impact on hydrological conditions in the county and thus potentially of concern to transportation officials as well[28] (only excerpts from the Plan reflecting climate conditions possibly relating to transportation impacts are referenced):

- "**Sea Level Rise.** Sea level rise could increase coastal erosion and impact coastal infrastructure and ecological resources such as estuaries and tidal wetlands. Sea level rise has implications not only for coastal areas but also for the management of the Sacramento-San Joaquin Delta …."

- **Warmer Temperatures Changing Mountain Snowpack Runoff.** "Rising average temperatures throughout California will ultimately reduce the amount of mountain snowpack as more precipitation will fall as rain instead of snow and warmer weather will cause more snowpack to melt earlier in the year. Mountain snowpack acts as natural water storage reservoir, releasing water gradually throughout the warmer periods of the year as snow melts …. "

- **Changes in Precipitation and Temperature Affecting Average Runoff Volume.** "The effects of climate change on annual precipitation and runoff are less clear, but of great potential importance. The existing amount of surface storage on most major streams and water storage reservoir in southern California provides a fair amount of capacity to accommodate shifts in inflows for most years ...."

- **Changes in Drought Persistence.** Droughts differ from typical emergency events such as floods or forest fires in that they occur slowly over a multi-year period .... Droughts in the western United States are often persistent, and the recent period (2012-2016) constituted one the most severe droughts over the past millennium. Although the change in precipitation that led to the recent drought was not tied to climate change, the slightly warmer temperatures resulted in higher evapotranspiration (ET) from the landscape and increased the severity of the drought."

- **Potential Increase in Water Demands for Landscape Use Due to Higher Temperatures.** "Higher temperatures, and associated higher ET rates, are likely to also change water demands throughout the state, although this will likely be limited by available supplies. The most

[28] South Orange County Watershed Management Area, "Integrated Regional Water Management (IRWM) Plan," July 2013, last accessed June 20 2019. http://prg.ocpublicworks.com/DocmgmtInternet/Download.aspx?id=1059

important effect is likely to be on agricultural water demands and landscape irrigation demands in urban areas.”

- **Increased Flood Flows and Flood Frequencies. “**Increased intensity and frequency of major storms, another anticipated effect of climate change, would further augment flood problems in southern California. With continued increases in floodplain urbanization and the associated increase in damage potential, flooding costs from climate change could exceed those of water supply. The effects of changes in flood flows on ecosystems are less well studied but could be significant…"

- **Damage to Trees and Increased Risk of Wildfire and Erosion.** “The recent drought, coupled with other accessories such as pests, has significantly affected the health of forests in California, which constitute the most important watersheds throughout the state. Recent analysis of aerial imagery has shown that nearly 100 million trees may be facing mortality in the recent drought. The presence of these dead trees has the potential to significantly enhance wildfire risk in the near term and increase the risk of erosion and adverse water quality over the slightly longer term. To the degree that the recent drought is indicative of future drier and warmer conditions, it may be a significant threat to California’s forests as well as its water supply. Additionally, we have seen in the wildfires of 2007 the ability for these fires to spread to urban areas and create tremendous damage to neighborhoods ….”[29]

The Orange County Integrated Regional Water Management (IRWM) Plan identifies priority concerns with expected climatic conditions focusing on water supply issues. However, for transportation agencies some of these priorities become important contexts for their own assessment of how serious climatic predictions are to transportation assets. The priority issues shown in Table 1 are a subset of those listed in the Plan that relate most to transportation concerns.

[29] Orange County Public Works, “The OC Plan for IRWM in North and Central Orange County: Draft, 2017, last accessed June 20, 2019, http://www.ocwatersheds.com/programs/waterways/stormwater/documentspr/theocplan

TABLE 1: VULNERABILITY ISSUES OF CONCERN TO BOTH WATER MANAGEMENT AND TRANSPORTATION OFFICIALS

Vulnerability Issue for Water Management Also a Concern for Transportation	Description	Priority
Demand for all sectors would increase.	Demand is expected to increase in the Region due to population growth. Climate change is expected to further increase demand due to higher temperatures increasing evapotranspiration and put strain on the region's limited supplies.	High
Episodes of flooding would increase.	Increases in the intensity of storms may increase the frequency of flooding as storms exceed the capacity of flood control facilities.	High
Higher drought potential (unmet demands).	The frequency, duration, and intensity of droughts are expected to increase with climate change and reduce both the local and imported supplies available.	Medium
Constituent of concern concentrations would increase	During general drought conditions, natural inflow is not available to maintain or improve assimilative capacity of groundwater basins. Reduced precipitation could further reduce natural inflow, and further reduce assimilative capacity.	Medium
Invasive species would increase.	A reduction in local water supply available to support native species may impact these species ability to compete with invasive species.	Low
Available necessary habitat would decrease.	Habitat for a few threatened or endangered species exists in the region (i.e. coastal sage scrub, grasslands, riparian, coastal California gnatcatcher, coastal cactus wren, and orange-throated whiptail). Changes in temperature and water available may cause shifts in the location and quality of habitat necessary for these species. Given that habitat has been designated for species in the region, this vulnerability issue has been designated to be of low priority.	Low
Erosion and sedimentation would increase.	Increases in the intensity of storms could increase erosion and sedimentation, which both impacts water quality and increases flood risk. This may be exacerbated with increases in wildfires. As the region does not currently have issues with erosion and sedimentation, this vulnerability issue has been prioritized as low.	Low
Impacts to water dependent species would increase.	Reduced surface water flows and increased water temperatures can negatively impact aquatic species. Though water dependent species are not currently experiencing issues, this is still an issue of concern for the region.	Low

Source: Orange County Public Works, "The OC Plan for IRWM in North and Central Orange County: Draft," 2017, http://www.ocwatersheds.com/programs/waterways/stormwater/documentspr/theocplan

3.3.3 University of Southern California Sea Grant Program

The University of Southern California (USC) Sea Grant program received funding from the California Coastal Conservancy to provide technical assistance and outreach on the Coastal Storm Modeling System (CoSMoS) model applications for the Southern California region. Th intent was to help build anlaysis capacity in coastal communities as they begin to plan for impacts from sea level rise.[30] Workshops were held in 2015 that summarized the model and how it could be used to predict SLR impacts. The workshops discussed the state of climate change collaboration among cities, agencies, industry, and nonprofit organizations within Orange County.

3.3.4 Orange County Rail Infrastructure Defense Against Climate Change Plan

Passenger and freight rail services parallel some of the major highway corridors in Orange County (e.g., I-5 and SR 91). The O*range County Rail Infrastructure Defense Against Climate Change Plan* is one of the first efforts to address climate change in these corridors. The Orange County Transportation Agency (OCTA) was awarded a Caltrans Adaptation Planning Grant in the 2018-19 grant cycle to support OCTA in conducting the study. The plan will determine if climate change conditions will negatively impact rail infrastructure, service, and operations of the Orange County, Inland Empire-Orange County, and 91/Perris Valley Metrolink lines. These three lines serve 11 Orange County stations and over 40,000 riders each day. The *Defense Against Climate Change Plan* will identify station amenity improvements to protect riders against high heat and extreme weather, adaptation strategies to protect rail infrastructure from flooding, landslides, and vegetation management strategies to ensure landscaping can withstand droughts and heavy precipitation.[31]

3.3.5 University of California (UC) Irvine FloodRISE program

Researchers at UC-Irvine have developed new computer modeling technology, FloodRISE, to “aid communities in managing flood risk.”[32] The model provides parcel-level information about the depth and extent of flooding under a variety of conditions. FloodRISE assists flood-prone communities by coupling detailed information about flood risk with communications strategies tailored to local conditions.[33] As noted in the program’s website, the general approach involves: ”(1) setting up and running metric resolution hydrodynamic flood models to simulate various flooding scenarios that are relevant to these communities, and (2) post-processing model scenario results to produce maps that visualize flood hazard information in ways that end-users find useful.” Household surveys and stakeholder consultations are used to address issues of accuracy, relevance, and clarity of the information conveyed.

3.3.6 California Climate Investments for Disadvantaged and Low-Income Populations

Considering the impact of infrastructure spending as well as climate change on disadvantaged and low-income populations is an important policy concern to the state. In 2012, the Legislature passed SB 535 directing that 25 percent of the proceeds from the Greenhouse Gas Reduction Fund go to projects that provide a benefit to disadvantaged communities (later legislation, AB 1550, required that 25 percent of

[30] University of Southern California, "Southern California Coastal Impacts Project," last accessed May 15, 2019, https://dornsife.usc.edu/uscseagrant/sccip/
[31] Orange County Transportation Authority, “Consultant Services to Prepare an OC Rail Infrastructure Defense Against Climate Change Plan,” Request for Proposals 8-2072, February 21, 2019
[32] University of California-Irvine, “FloodRISE,” last accessed 5/15/19 from http://floodrise.uci.edu/about/project-summary/
[33] Ibid.

the proceeds be spent on projects in disadvantaged communities and low-income populations). The definitions of key terms for such populations include the following:

- Disadvantaged Communities (per SB 535) - Census tracts in the top 25 percent of CalEnviroScreen 3.0 scores, plus those census tracts that score in the highest 5 percent of CalEnviroScreen's Pollution Burden without an overall CalEnviroScreen score.[34]
- Low-income Communities (per AB 1550) - Census tracts that are either at or below 80 percent 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.[35]
- Disadvantaged and Low-income Communities – Census tracts that are defined as both disadvantaged and low-income, per the definitions above.[36]
- Low-income Communities Near a Disadvantaged Community - Low-income communities as identified above that are also within 1/2 mile of a disadvantaged community as identified above.[37]

Figure 4 shows the portions of communities in Orange County that are considered disadvantaged and low-income households. Most these areas are in the cities of Anaheim, Fullerton, and Santa Ana. Executive Order B-30-15 requires that state agencies consider vulnerable populations in their decision-making, and it is thus important that these communities and organizations be included in Caltrans processes.

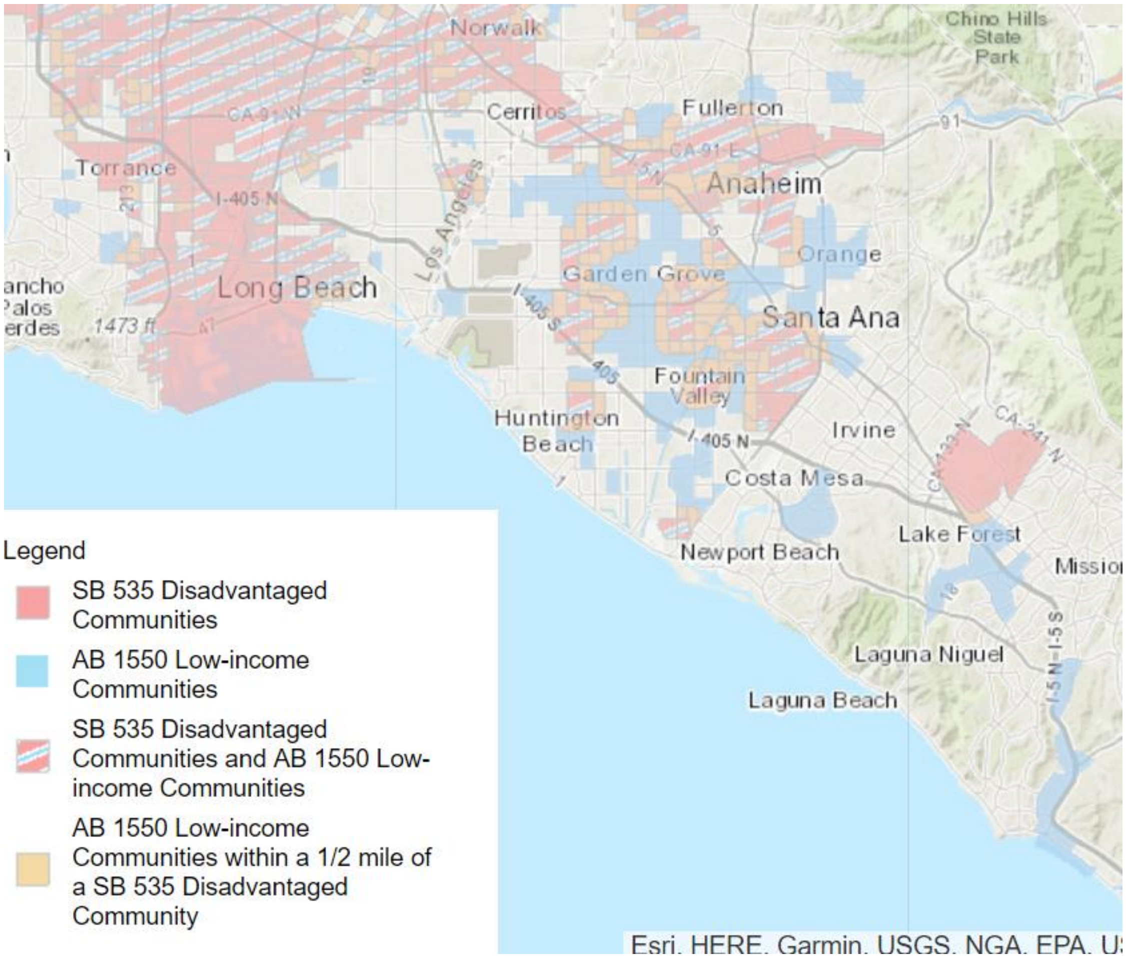
[34] Office of Environmental Health Hazard Assessment, "SB 535 Disadvantaged Communities," last accessed May 16, 2019 from https://oehha.ca.gov/calenviroscreen/sb535

[35] California Air Resources Board, "Priority Population Investments," modified October 1, 2018, last accessed June 30, 2019. https://www.arb.ca.gov/cc/capandtrade/auctionproceeds/communityinvestments.htm

[36] Ibid.

[37] Ibid.

FIGURE 4: DISADVANTAGED AND LOW-INCOME COMMUNITIES IN ORANGE COUNTY



4. ANALYSIS TOOLS: BACKGROUND

To understand how the analysis was conducted for individual climate change stressors, some context on the analysis tools used in this assessment is necessary. It is important that the use of global climate models and emissions scenarios is understood.

4.1. Global Climate Models (GCMs)

GCMs have been developed worldwide by academic or research institutions to represent the physical processes that interact to cause climate change. These are used to project future changes to GHG emission levels.[38] Model inputs include some estimate of future GHG emissions or atmospheric concentrations of these gases. These estimates, called emission scenarios, are widely used in climate change analyses. They are defined and developed by the Intergovernmental Panel on Climate Change (IPCC).

Model downscaling is a statistical technique that refines the results of GCMs to a regional level. The model downscaling used in the Fourth Climate Change Assessment is a technique called Localized Constructed Analogs (LOCA), which “uses past history to add improved fine scale detail to GCMs.”[39] This effort was undertaken by the Scripps Institution of Oceanography (Scripps) and provides a finer resolution than was previously found in other techniques, enabling the assessment of changes in a more localized way.[40] Out of the 32 LOCA downscaled GCMs relevant for California, 10 models were chosen by state agencies as being most relevant for California. The purpose of this effort, led by Department of Water Resources (DWR), was to identify which GCM models to use in state agency assessments and planning decisions.[41] The 10 representative GCMs for California are:

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

[38] Intergovernmental Panel on Climate Change (IPCC), “What is a GCM?”, last accessed April 30, 2019, http://www.ipcc-data.org/guidelines/pages/gcm_guide.html
[39] Cal-Adapt. “LOCA Downscaled Climate Projections,” last accessed July 2, 2019 from http://cal-adapt.org/
[40] David W. Pierce, Dan Cayan, and Bridget Thrasher, “Statistical Downscaling Using Localized Constructed Analogs,” April 16, 2014, last accessed June 30, 2019. http://journals.ametsoc.org/doi/abs/10.1175/JHM-D-14-0082.1
[41] California Department of Water Resources, “Perspectives and Guidance for Climate Change Analysis,” Climate Change Technical Advisory Group, August 2015, last accessed June 15, 2019. https://water.ca.gov/LegacyFiles/climatechange/docs/2015/1_14_16_PerspectivesAndGuidanceForClimateChangeAnalysis_MasterFile_FINAL_08_14_2015_LRW.pdf

- MIROC5

Data from these models are available on Cal-Adapt 2.0, California's Climate Change Research Center.[42] The Cal-Adapt 2.0 data are some of the best available data in California on climate change and, for this reason, selections of data from Cal-Adapt and the GCMs above were utilized in this study.

4.2. Emission Scenarios and Pathways

The IPCC, with participation of thousands of scientists from 195 countries, periodically releases *Assessment Reports* (currently in its 5th iteration) that summarize the latest research on a broad range of topics relating to climate change. The IPCC updates research on GHG emissions, identifies scenarios that reflect research on emissions generation, and estimates how those emissions may change given international policies. The IPCC also summarizes scenarios of atmospheric concentrations of GHG emissions to the end of the century.

Two commonly cited sets of emissions data used by the IPCC include:

1. The Special Report Emissions Scenarios (SRES)
2. The 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.[43] Four RCPs were developed to reflect assumptions for emissions growth, and the resulting concentrations of GHG in the atmosphere. The RCPs developed are applied in GCMs to identify projected future conditions and enable a comparison of one against another. Generally, the RCPs are based on assumptions for GHG emissions growth and an identified point at which they would be expected to begin declining (assuming varying reduction policies or socioeconomic conditions). The RCPs developed for this purpose include the following:[44]

- 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.[45]

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

[43] IPCC, Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. "Climate Change 2014: Synthesis Report," IPCC, Geneva, Switzerland, 151 pp., last accessed July 2, 2019. https://ar5-syr.ipcc.ch/topic_summary.php

[44] Malte Meinshausen, S.J. Smith, J.S. Daniel, et al. "The RCP Greenhouse Gas Concentrations and Their Extensions From 1765 To 2300 (Open Access)," *Climatic Change*, (2011) 109:213, last accessed June 29, 2019. https://doi.org/10.1007/s10584-011-0156-z

[45] The numbers in the RCP designation correspond to projected radiative forcing under each of those scenarios. [Radiative forcing is the difference between the solar energy absorbed by the Earth and the energy that is dissipated back out to space via long wave radiation. If the radiative forcing is positive, it means that the Earth is absorbing more energy than it is releasing to space]. For example - RCP 2.6 is the lowest emission scenario and the radiative forcing for 2100 projected under this scenario (compared to the year 1750) would be 2.6 watts/square meter. For more information, see chapter 2 of the Intergovernmental Panel on Climate Change AR 5 synthesis report at https://ar5-syr.ipcc.ch/topic_futurechanges.php

California's Fourth Climate Change Assessment used RCPs 4.5 and 8.5 as the emission pathways for its assessment efforts.

4.3. California's Fourth Climate Change Assessment Analysis Approach

The California Fourth Climate Change Assessment, an inter-agency research and "model downscaling" effort, examined multiple climate stressors for California, The Assessment was led by the California Energy Commission (CEC) and included other agencies such as the California Department of Water Resources (DWR) and the Natural Resources Agency, as well as academic institutions such as Scripps and the University of California-Merced. Because the Fourth Climate Change Assessment used RCPs 4.5 and 8.5 for its analyses, this District 12 study used Cal-Adapt data and all ten models noted above along with the RCP 4.5 and 8.5 emission scenarios. Note that in the case of SLR, the California Ocean Protection Council (OPC) also used RCP 2.6 as one of the emission scenarios in the assessment of SLR impacts on California coasts.

4.4. Time Periods

GCMs project future climatic conditions over specific time periods that in turn reflect the expected timing of GHG emission concentrations in the atmosphere. By using the same time periods, projections for different climate characteristics (e.g., temperatures and precipitation) can be compared consistently between the analysis periods. For this study (similar to most vulnerability studies), the analysis periods have been defined as the beginning, middle, and end of century, represented by the out-years 2025, 2055, and 2085, respectively. These years are chosen because the 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 the last year in which statistically-derived projections can defensibly be made. The 2025 and 2055 out-years follow the same logic and are applied to each of the representative 30-year periods (2010 to 2039 and 2040 to 2069, respectively).

4.5. Geographic Information Systems (GIS) and Geospatial Data

Developing an understanding of Caltrans assets exposed to SLR, storm surge, and projected changes in temperature, precipitation, and wildfire required complex geospatial analyses. The geospatial analyses were performed using ESRI geographic information systems (GIS) software (a screenshot of the GIS database is shown in Figure 6). The general approach for each hazard's geospatial analysis went as follows:

Obtain/conduct hazard mapping: The first step in each GIS analysis was to compile data or create maps showing the presence and/or value of a given hazard at various future time periods, and 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 show changes in rainfall; burn counts were compiled to produce maps indicating future wildfire frequency; and sea level rise, storm surge, and cliff retreat maps were made to understand the impacts of future tidal flooding and erosion.

Determine critical hazard thresholds: Some hazards, 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 hazard risk. To highlight the areas most affected by climate change, the geospatial analyses for these hazards defined the critical thresholds for which the value of (or the change in value of) a hazard would be a concern to Caltrans. For example, the wildfire geospatial analysis involved several steps to indicate which areas are considered to have a moderate, high, and very high fire exposure based on the projected frequency of wildfire (described in a later section).

Overlay the hazard layers with Caltrans SHS to determine exposure: Once high hazard areas had been mapped, the next general step in the geospatial analyses was to overlay the Caltrans SHS centerlines with 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 was performed by Caltrans and provided an output GIS file indicating the centerline miles of roadway affected 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. Limited metadata on each dataset was also provided in the form of an Excel table that described each dataset and its characteristics. This GIS data will be useful to Caltrans for future climate adaptation planning activities.

The analysis of each climate change stressor 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 Caltrans District 12 study are described more fully in the following chapters.

5. TEMPERATURE

The Earth's average surface temperature had risen over the past 100 years due primarily to the increased concentrations of GHGs in the atmosphere.[46] Temperatures in the west are projected to continue rising and heat waves are expected to become more frequent.[47] The potential effects of extreme temperatures on District 12 assets will vary by asset type and will depend on the specifications used in the original design of the facility. For example, the following have been identified in other studies in the United States as potential impacts of increasing extreme temperatures.

Design

- Pavement design includes an assessment of temperature in determining material.
- Ground conditions and more/less water saturation can alter the design factors for foundations and retaining walls.
- Temperature may affect expansion/contraction allowances for bridge joints.

Operations and Maintenance

- Extended periods of high temperatures will affect safety conditions for employees who work long hours outdoors, such as those working on maintenance activities.
- Right-of-way landscaping and vegetation must survive higher temperatures.
- Extreme temperatures could cause pavement discontinuities and deformation, which could lead to more frequent maintenance.

The scope of this study did not allow for detailed assessment at this time of all impacts of changing temperatures on Caltrans facilities. To illustrate such impacts, however, a close look was taken at one of the ways in which higher temperatures could 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 inputs:

- **Low temperature** – The mean of the absolute minimum air temperatures expected over a pavement's design life.
- **High temperature** – The mean of the maximum temperatures over seven consecutive days.

These climate metrics are critical to determine the extreme temperatures a roadway may experience over time. A binder must be selected that can maintain pavement integrity under both extreme cold

[46] National Aeronautics and Space Administration (NASA). 2010. "Global Warming." last accessed July 1, 2019. https://earthobservatory.nasa.gov/features/GlobalWarming/page2.php, and U.S. Global Change Research Program. 2018. "National Climate Assessment. Chapter on Our Changing Climate. Washington DC. last accessed Juley 1, 2019. https://nca2018.globalchange.gov/chapter/2/

[47] U.S. National Climate Assessment, U.S. Global Change Research Program, 2014, last accessed June 20, 2019. http://nca2014.globalchange.gov/report/our-changing-climate/extreme-weather

conditions (which leads to contraction) and high heat (which leads to expansion). Understanding the metrics for binder design in the future will enable Caltrans to gain insight on how pavement design may need to shift over time.[48]

This study examined expected low and high temperatures for pavement binder specification in three future 30-year periods centered on the years 2025, 2055, and 2085. 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, a 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 developed by Scripps were used for the analysis of future temperatures. The data were available at a spatial resolution of 1/16th of a degree or approximately three and a half to four miles.[49] This dataset was queried to determine the average absolute minimum temperature and the average maximum temperature over seven consecutive days. Temperature values were identified for each 30-year period. The values were derived separately for each of the 10 California-appropriate GCMs for both RCP 4.5 and 8.5 scenarios, and for the three time periods noted. The projected change in temperatures are shown in Figures 5 to 10.

These figures show the median change across the state (the CMCC-CMS), among all California-approved climate models for RCP 8.5 (data for RCP 4.5 was analyzed but for brevity is not shown here). The maps highlight the temperature change expected for both the high and low temperature metrics. Both temperature metrics increase over time, with the maximum temperature changes generally being greater than the minimum changes. Some areas may experience change in the maximum temperature metric upwards of 13.9 °F by the end of the century. Finally, for both metrics, temperature changes are generally greater farther inland due to the moderating influence of the Pacific Ocean.

The projected changes shown in Figure 5 through Figure 10 can be added to Caltrans' current source of historical temperature data to determine final pavement design value for future designs. More generally, this information can be used by Caltrans to identify how pavement design practices may need to shift over time given the expected changes in temperatures and help inform decisions on how to provide the best pavement quality for California SHS users.

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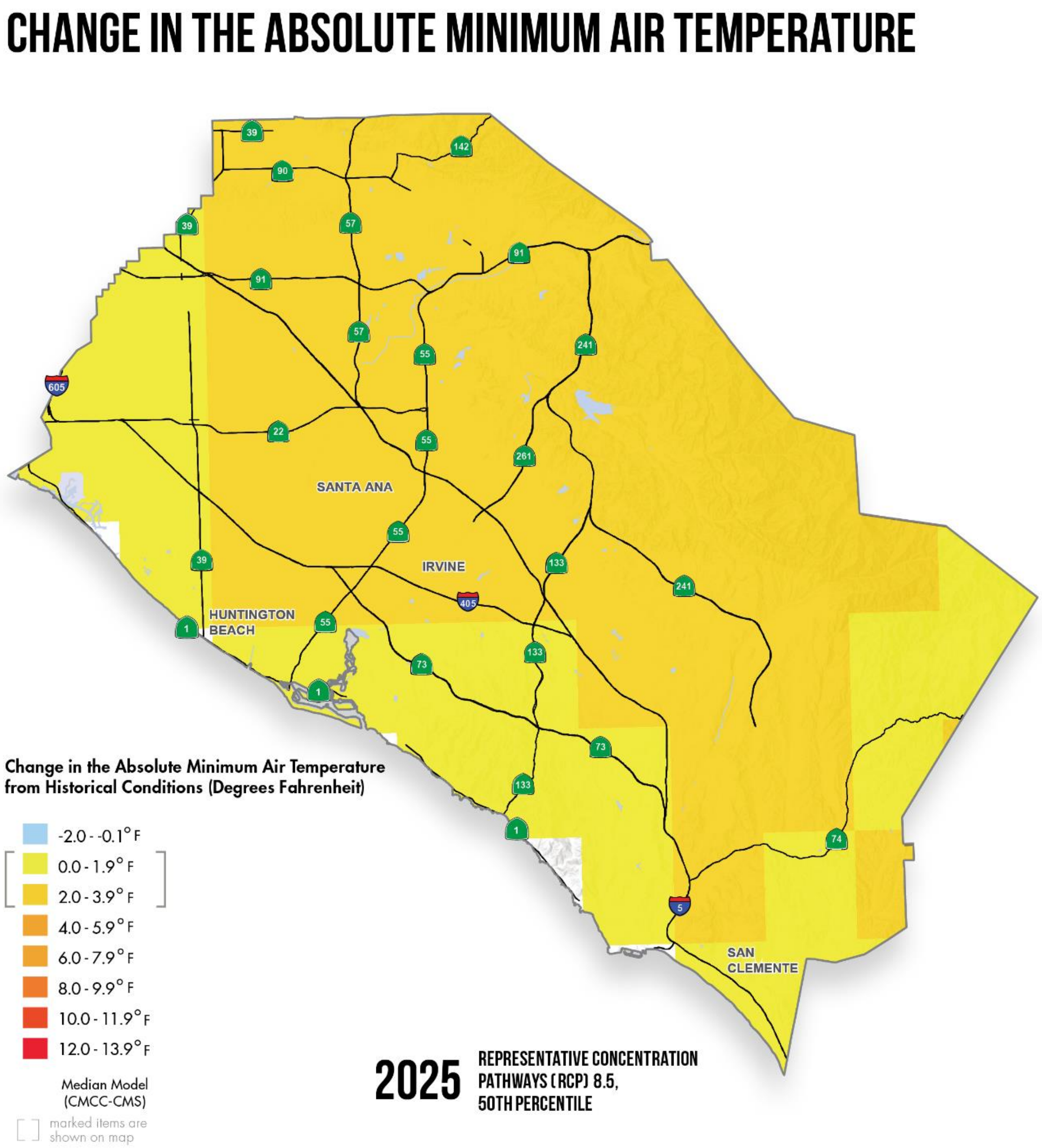
[48] Note: The ideal low temperature range varies based on the type of binder being used and, in some cases, the placement temperature. Per the Caltrans Highway Design Manual, there are potentially several different types of binder being used in District 12 (dense-graded HMA, open-graded HMA, and rubberized asphalt). Thus, there is no single value that covers all binder application in the district; the value is different for each binder type.

[49] Cal-Adapt, "LOCA Downscaled Climate Projections," last accessed May 16, 2019, https://cal-adapt.org/data/loca/

FIGURE 5: CHANGE IN THE ABSOLUTE MINIMUM AIR TEMPERATURE 2025

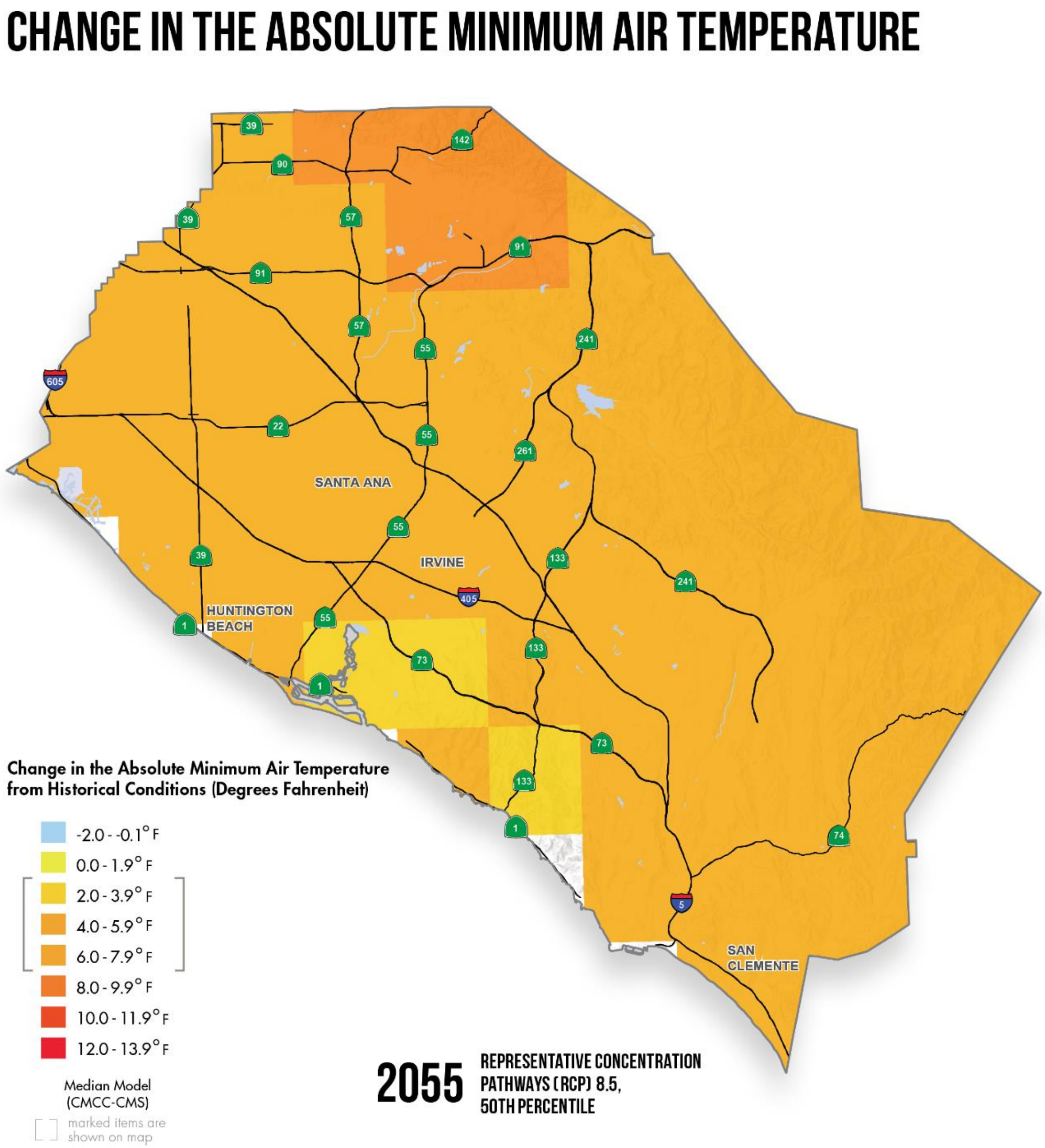


Future Change in the Absolute Minimum Air Temperature within District 12, Based on the RCP 8.5 Emissions Scenario

Caltrans Transportation Asset Vulnerability Study, District 12. 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.

Results represent the 50th percentile of downscaled climate model outputs under RCP 8.5 for the metric shown, as calculated across the state using the area weighted mean.

FIGURE 6: CHANGE IN THE ABSOLUTE MINIMUM AIR TEMPERATURE 2055

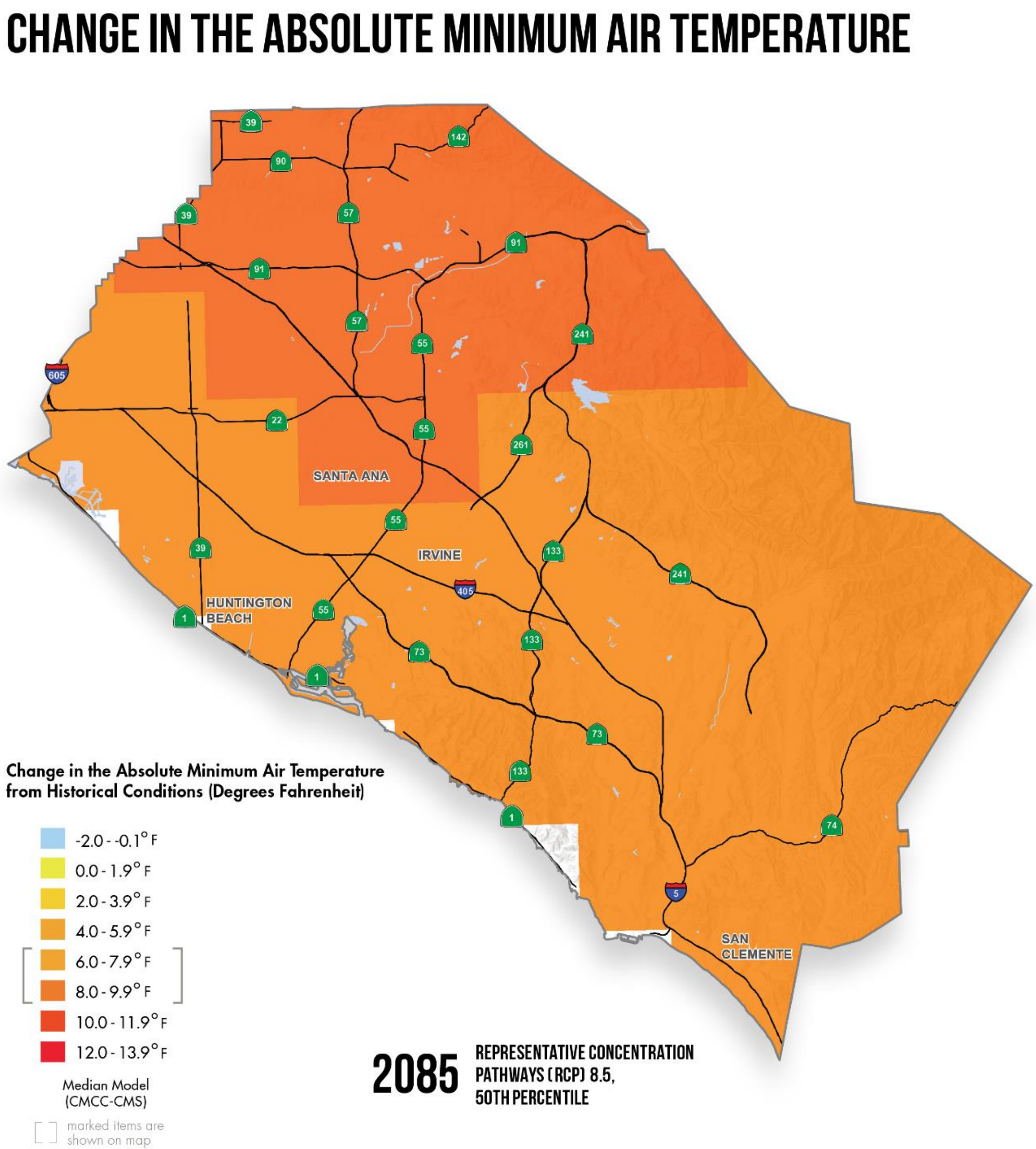


Future Change in the Absolute Minimum Air Temperature within District 12, Based on the RCP 8.5 Emissions Scenario

Caltrans Transportation Asset Vulnerability Study, District 12. 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.

Results represent the 50th percentile of downscaled climate model outputs under RCP 8.5 for the metric shown, as calculated across the state using the area weighted mean.

FIGURE 7: CHANGE IN THE ABSOLUTE MINIMUM AIR TEMPERATURE 2085

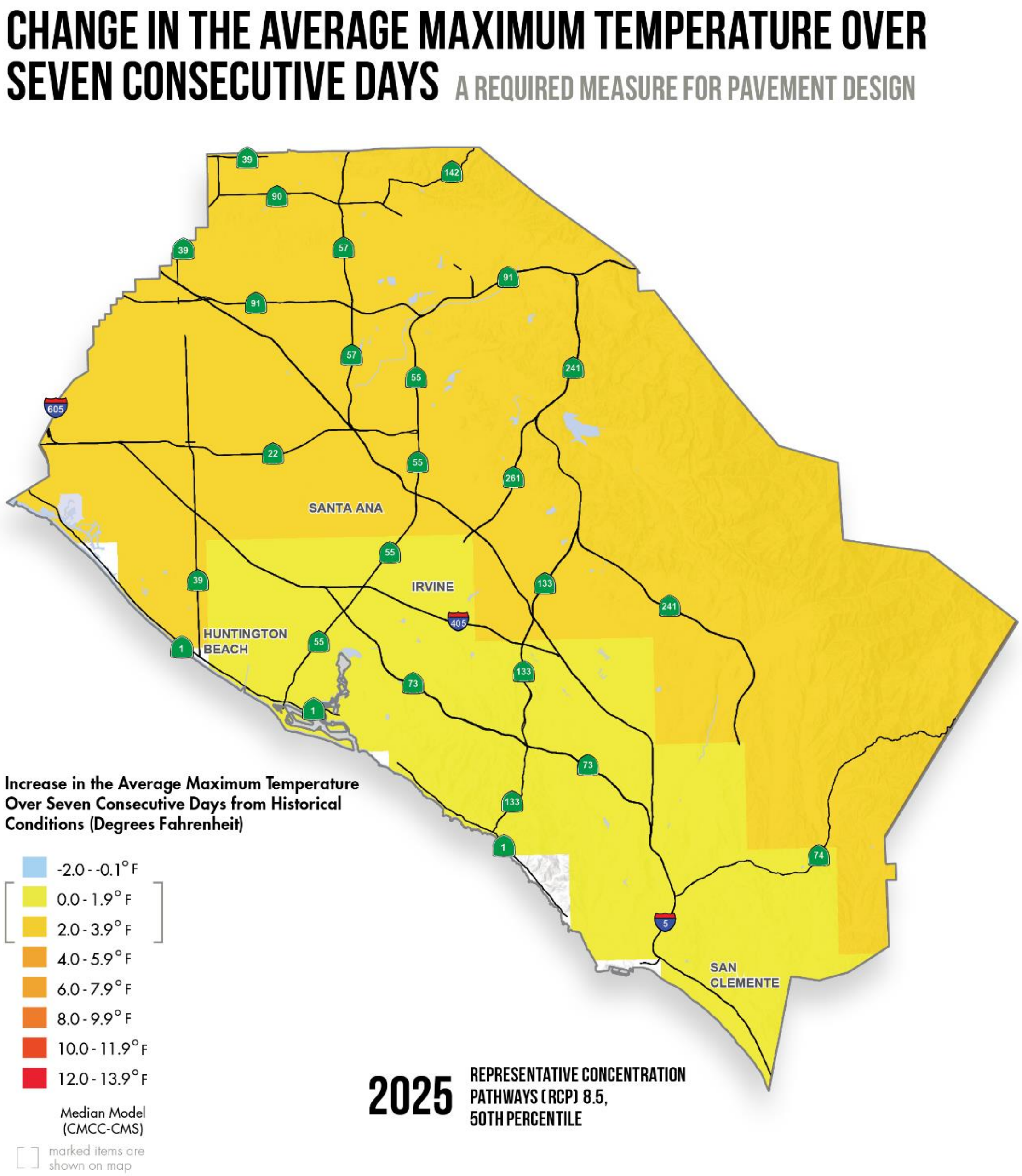


Future Change in the Absolute Minimum Air Temperature within District 12, Based on the RCP 8.5 Emissions Scenario

Caltrans Transportation Asset Vulnerability Study, District 12. 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.

Results represent the 50th percentile of downscaled climate model outputs under RCP 8.5 for the metric shown, as calculated across the state using the area weighted mean.

FIGURE 8: CHANGE IN THE AVERAGE MAXIMUM TEMPERATURE OVER SEVEN CONSECUTIVE DAYS 2025

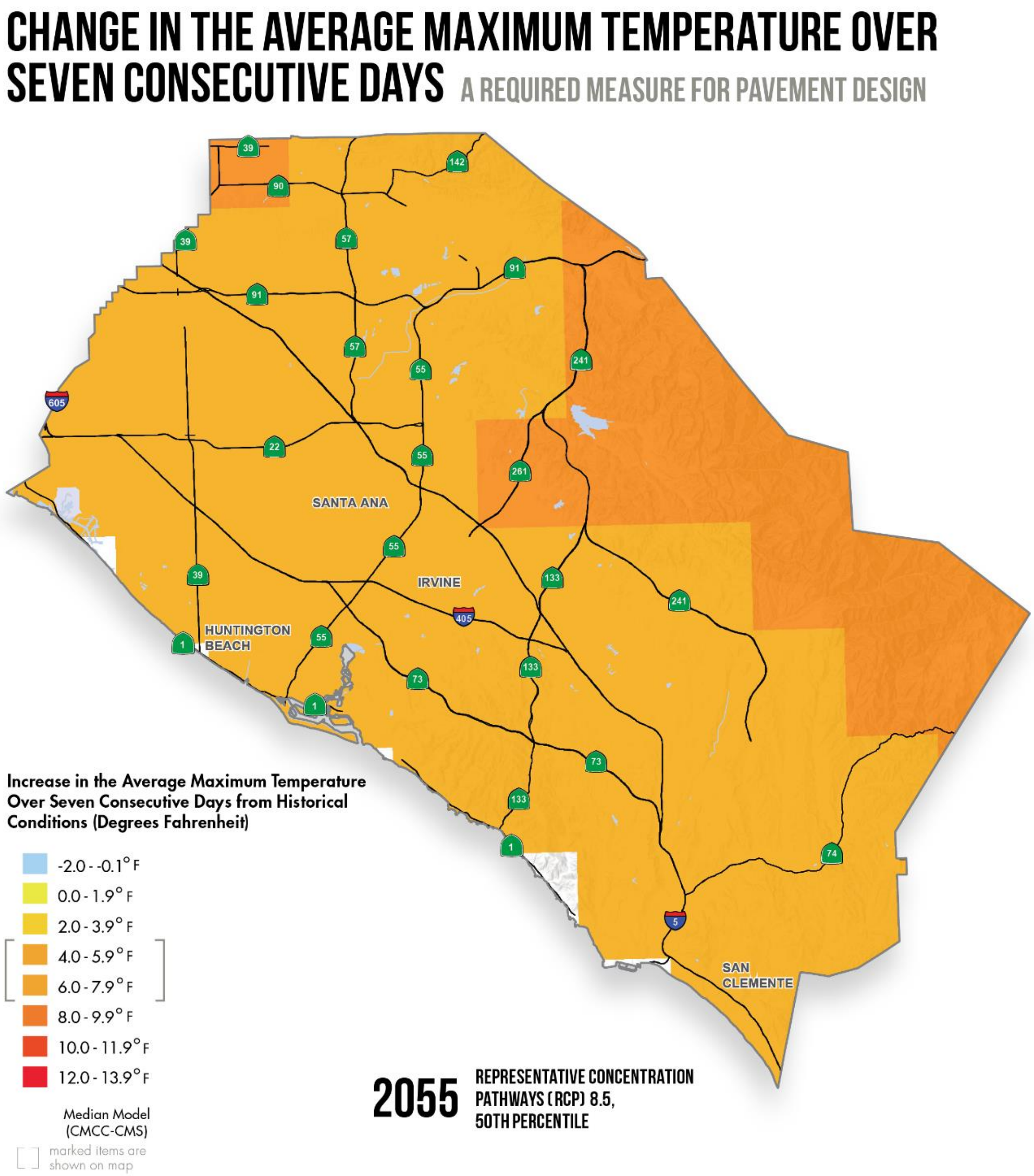


Future Change in the Average Maximum Temperature over Seven Consecutive Days within District 12, Based on the RCP 8.5 Emissions Scenario

Caltrans Transportation Asset Vulnerability Study, District 12. 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.

Results represent the 50th percentile of downscaled climate model outputs under RCP 8.5 for the metric shown, as calculated across the state using the area weighted mean.

FIGURE 9: CHANGE IN THE AVERAGE MAXIMUM TEMPERATURE OVER SEVEN CONSECUTIVE DAYS 2055



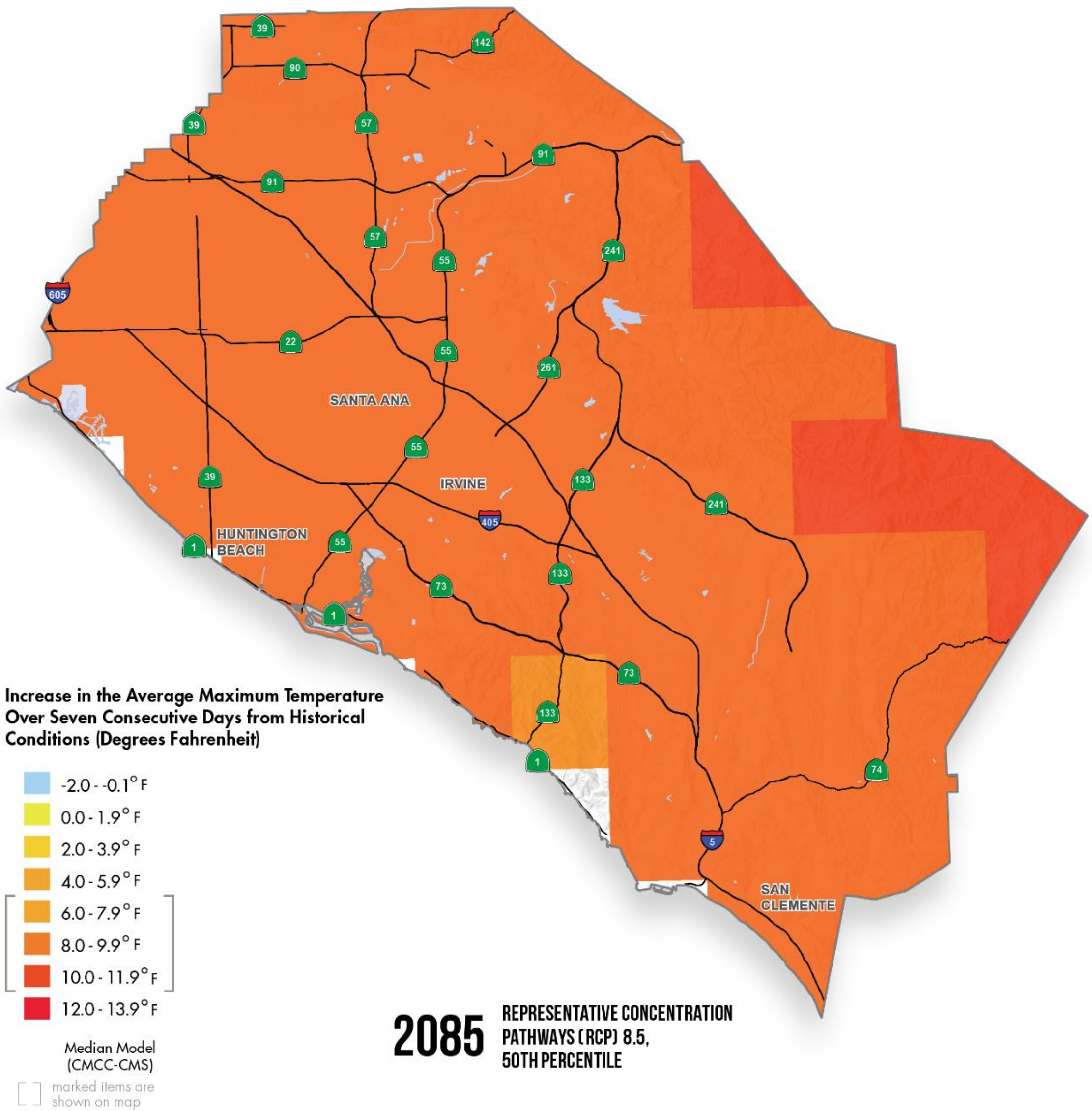
Future Change in the Average Maximum Temperature over Seven Consecutive Days within District 12, Based on the RCP 8.5 Emissions Scenario

Caltrans Transportation Asset Vulnerability Study, District 12. 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.

Results represent the 50th percentile of downscaled climate model outputs under RCP 8.5 for the metric shown, as calculated across the state using the area weighted mean.

FIGURE 10: CHANGE IN THE AVERAGE MAXIMUM TEMPERATURE OVER SEVEN CONSECUTIVE DAYS 2085

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



Future Change in the Average Maximum Temperature over Seven Consecutive Days within District 12, Based on the RCP 8.5 Emissions Scenario

Caltrans Transportation Asset Vulnerability Study, District 12. 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.

Results represent the 50th percentile of downscaled climate model outputs under RCP 8.5 for the metric shown, as calculated across the state using the area weighted mean.

6. PRECIPITATION

The Southwest region of the United States is expected to have less precipitation overall in the future,[50] but with the potential for heavier individual events, and with more precipitation falling as rainfall. This section of this report focuses on how heavy precipitation events may change and become more frequent/severe over time.

Analysis of future precipitation is, in many ways, one of the most challenging tasks in assessing long-term climate risk. Modeled future precipitation values can vary widely. Thus, analysis of trends is considered across multiple models to identify predicted values and help drive effective decisions. Future precipitation was analyzed through a broad range of potential effects predicted by a set, or ensemble, of models. There are several methodological challenges with using downscaled global climate model projections to derive estimations of future extreme precipitation events, addressable through vetted and available methods. Results should be compared across multiple models to conduct a robust assessment of how changing precipitation conditions may impact the highway system, and to make informed decisions.

Transportation assets in California are affected by precipitation in a variety of ways—from inundation/flooding, to landslides, washouts, or structural damage from heavy rain events. Current transportation design uses return period storm events as a variable to include in asset design criteria (e.g. for bridges or culverts). A return period storm event is the historical intensity of storms based on how often such level of storms have occurred in the past. 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*.[51] This metric was analyzed to determine how 100-year storm rainfall is expected to change, using best available precipitation projections available for the state.

The Scripps Institution for Oceanography, other academic institutions, and state agencies are working to better understand future precipitation projections. The most up-to-date precipitation research for the state was compiled as a part of *California's Fourth Climate Change Assessment*. Scripps and the researchers behind *California's Fourth Climate Change Assessment* developed daily rainfall data for a set of climate models, and RCPs 4.5 and 8.5, for every day to the year 2100. Climate change specialists from the study team worked with researchers from Scripps to estimate extreme precipitation changes over time. Specifically, the team requested precipitation datasets across the set of 10 international GCMs that were identified as having the best applicability for California, for both RCPs 4.5 and 8.5.[52]

These raw datasets were then processed to provide the percent change in the 100-year storm precipitation depth over a 24-hour period. The historical data used to calculate the percentage changes are synthetic historical backcasted data from the climate models over the period 1950 to 2005.[53] Standard practice in climate science is to derive the percentage changes using backcasted historical

[50] Jerry Melillo, 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. Accessed July 31, 2018, https://www.nrc.gov/docs/ML1412/ML14129A233.pdf
[51] Caltrans, "Highway Design Manual," July 2, 2018, http://www.dot.ca.gov/hq/oppd/hdm/hdmtoc.htm
[52] These were the only RCPs available.
[53] "Backcasted" data is when a GCM is ran in "reverse," or provides outputs for historical periods.

modeled data and future projected modeled data. This mitigates against model bias affecting the derivation of the percent change.

This newly processed data was analyzed for three time periods to determine how precipitation might change through the end of century. The years shown in the following figures represent the mid-points of the same 30-year statistical analysis periods used for the temperature metrics and explained in the Time Periods Section. To reiterate, these time periods are: 1) 2010 to 2039, where the mid-point year is 2025, 2) 2040 to 2069, where the mid-point year is 2055, and 3) 2070 to 2099, where the mid-point year is 2085.

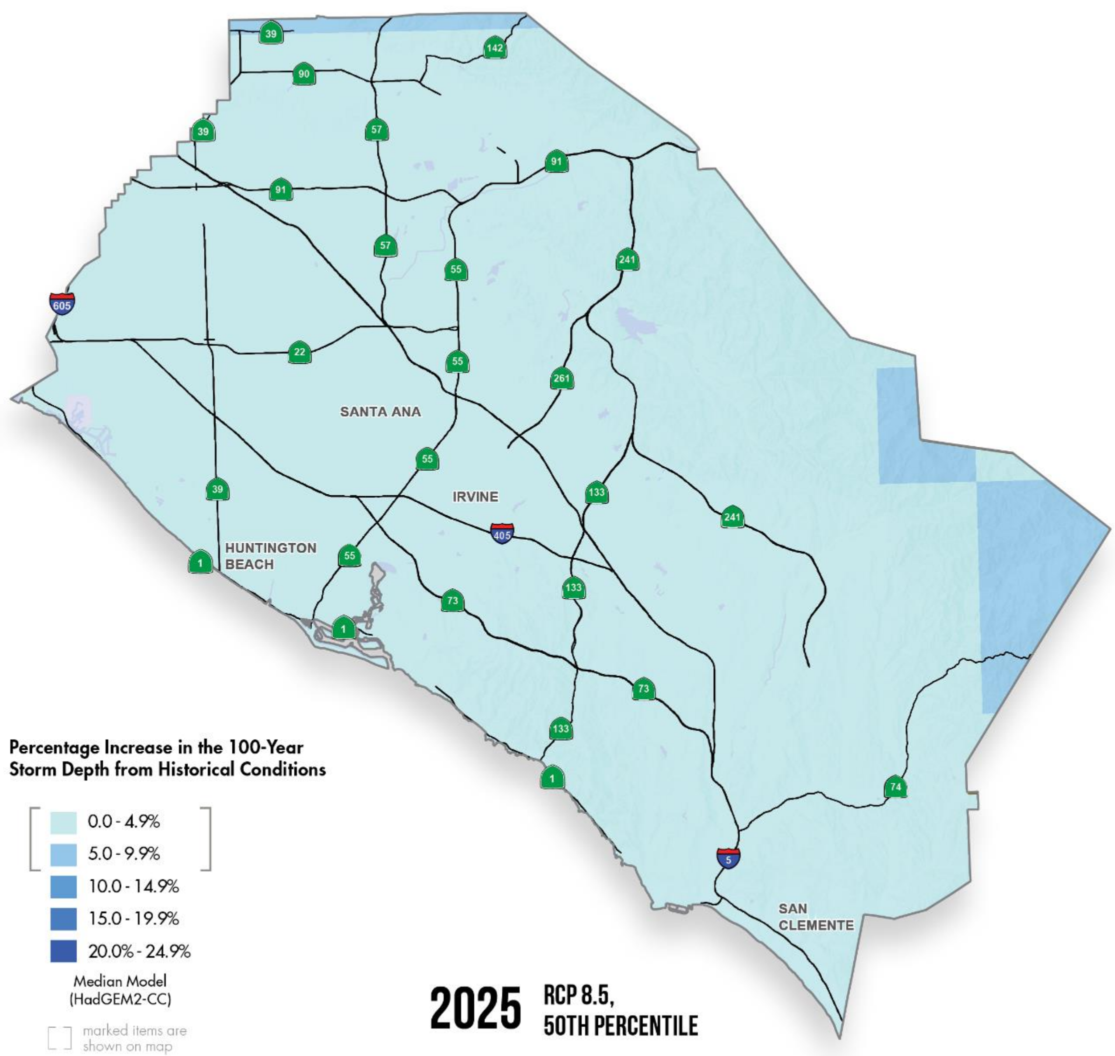
The results of this assessment are shown in the District 12 maps below. The three maps depict the percentage change in the 100-year storm rainfall event predicted for the three analysis periods, and for the RCP 8.5 emissions scenario (the RCP 4.5 results are not shown here). The median precipitation model (HadGEM2-CC) was used in this mapping.[54] Note that the change in 100-year storm depth is positive throughout District 12, indicating heavier rainfall during storm events.

Heavy storm events could have serious implications for the SHS. Understanding those implications will help Caltrans engineers and designers implement designs that are more adaptive to changing conditions. That said, site-specific, hydrological analysis of flood flows is necessary to determine how future projections of precipitation will affect bridges and culverts. These site-specific analyses should consider a range of models and future conditions to determine the best possible responses.

[54] There were two models that lay at the center point of the distribution. Only one of these models was chosen (HadCEM2-CC) because the best practice in climate science is not to merge the results of multiple climate models.

FIGURE 11: PERCENT CHANGE IN 100-YEAR STORM PRECIPITATION DEPTH 2025

PERCENT CHANGE IN 100-YEAR STORM PRECIPITATION DEPTH



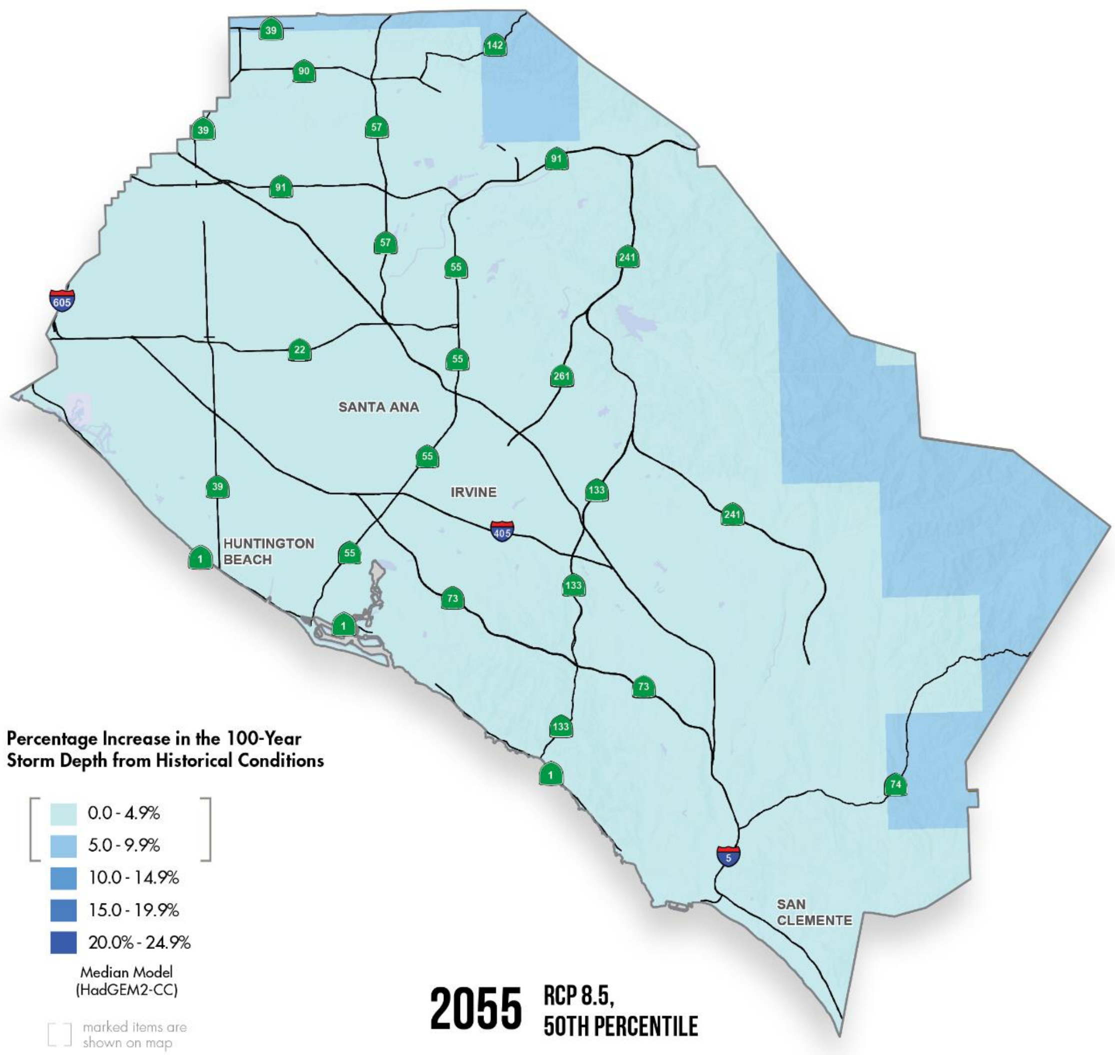
Future Percent Change in 100-year Storm Precipitation Depth within District 12, Based on the RCP 8.5 Emissions Scenario

Caltrans Transpotation Asset Vulnerability Study, District 12. 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.

Results represent the 50th percentile of downscaled climate model outputs under RCP 8.5 for the metric shown, as calculated across the state using the area weighted mean.

FIGURE 12: PERCENT CHANGE IN 100-YEAR STORM PRECIPITATION DEPTH 2055

PERCENT CHANGE IN 100-YEAR STORM PRECIPITATION DEPTH

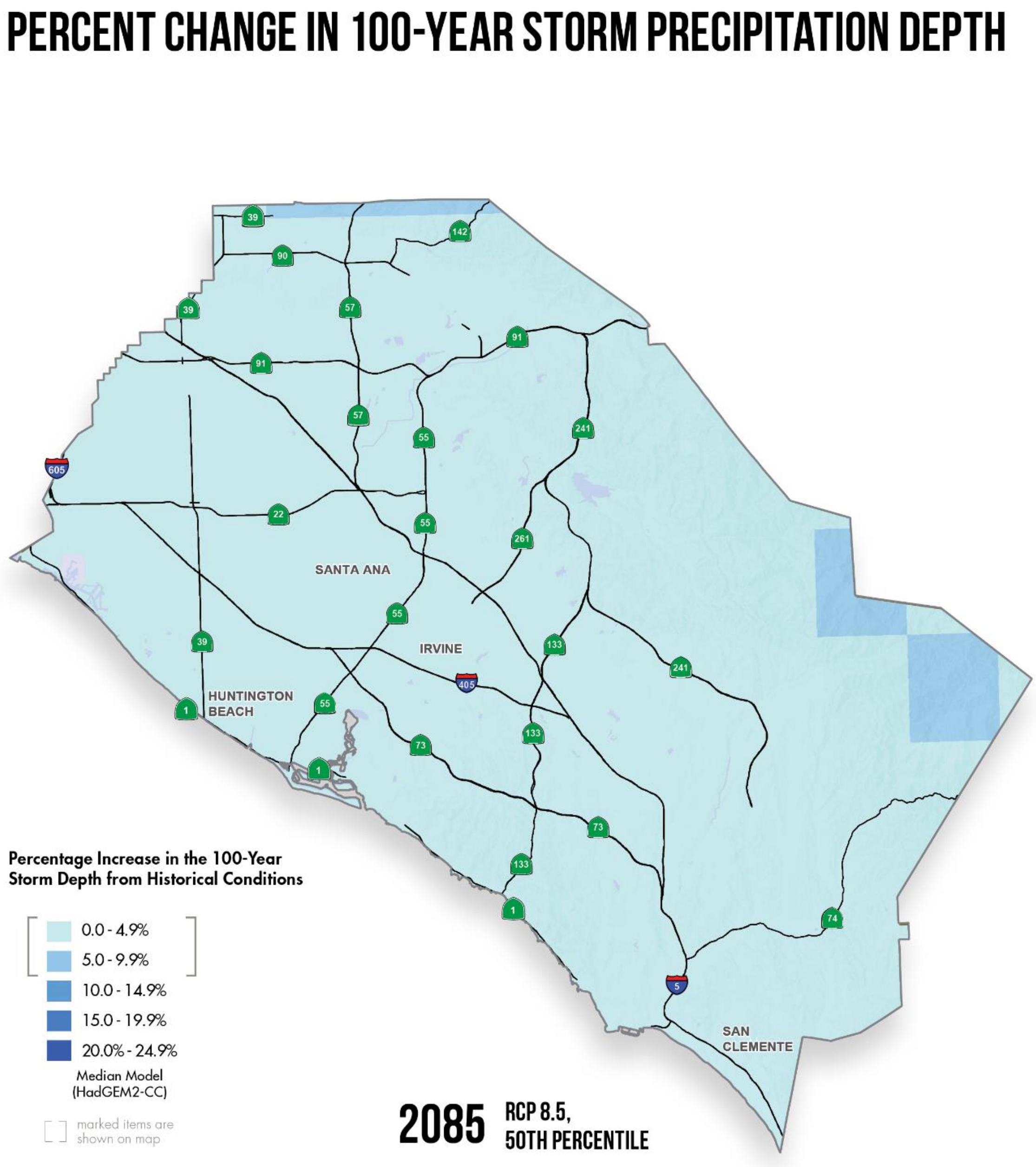


Future Percent Change in 100-year Storm Precipitation Depth within District 12, Based on the RCP 8.5 Emissions Scenario

Caltrans Transpotation Asset Vulnerability Study, District 12. 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.

Results represent the 50th percentile of downscaled climate model outputs under RCP 8.5 for the metric shown, as calculated across the state using the area weighted mean.

FIGURE 13: PERCENT CHANGE IN 100-YEAR STORM PRECIPITATION DEPTH 2085



Future Percent Change in 100-year Storm Precipitation Depth within District 12, Based on the RCP 8.5 Emissions Scenario

Caltrans Transpotation Asset Vulnerability Study, District 12. 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.

Results represent the 50th percentile of downscaled climate model outputs under RCP 8.5 for the metric shown, as calculated across the state using the area weighted mean.

7. WILDFIRE

Increasing temperatures, changing precipitation patterns, and resulting changes to land cover are expected to affect the frequency and intensity of future wildfires. The presence of electrical utility infrastructure or other sources of fire potential (e.g., mechanical, open fire, and accidental or intentional fires) may also influence the occurrence of wildfires. Wildfire is a direct concern for driver safety, SHS system operations, and the integrity of Caltrans infrastructure in wildfire exposure areas.

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.
- Smoke and poor air quality, which can affect visibility and the health of the public and Caltrans staff.

Damaging wildfires have occurred in the northern and southern areas of California in recent years. These devastating fires caused property damage, loss of life, and damage to roadways. The costs to Caltrans of repairing damages to the SHS extended over months for these individual events and could lead to years of investment to protect the SHS from future events.

Several agencies, including the US Forest Service (USFS), the Environmental Protection Agency (EPA) and the California Department of Forestry and Fire Protection (CalFire), have developed their own approaches and models to understand the trends of future wildfires throughout the US and in California. Some of these models were used in this vulnerability assessment study as described below.

FIGURE 14: SMOKE FROM CANYON FIRE, NEAR CALTRANS DISTRICT 12 OFFICE

7.1. Wildfire Modeling Efforts

The models used for this analysis included:

- **MC2 - EPA** Climate Impacts Risk Assessment (CIRA), developed by John Kim, USFS
- **MC2 - Applied Climate Science Lab (ACSL)** at the University of Idaho, developed by Dominique Bachelet
- **University of California-Merced model,** developed by Leroy Westerling, University of California-Merced

The MC2 models are second generation models developed from the original MC1 model created by the USFS. The MC2 model is a Dynamic Global Vegetation Model developed in collaboration with Oregon State University. This model considers projections of future temperature and precipitation, and the impact of changes in these factors on vegetation types/habitat area. The MC2 model outputs used for this assessment were taken from the IPCC Coupled Model Intercomparison Project 5 (CMIP5) dataset. This model had been applied in two different studies of potential wildfire impacts by researchers at USFS, University of Idaho. The use of the vegetation model and the expectation of changing vegetation ranges/types are primary factors of interest in the application of this model.

The second wildfire statistical model, developed by Leroy Westerling from UC-Merced, analyzed the conditions that led to past large fires (defined as over 1,000 acres) in California and uses these patterns to predict future wildfires. Inputs to the model included climate, vegetation, population density, and fire history. This model then incorporates future climate data and projected land use changes to estimate wildfire recurrence in California to the year 2100.

Each of these wildfire models used inputs from downscaled climate models to estimate the future temperature and precipitation conditions considered important for projecting future wildfires. The efforts undertaken by the EPA/USFS and UC-Merced used the LOCA climate data set developed by Scripps, while the University of Idaho model used an alternative downscaling method, the Multivariate Adaptive Constructed Analogs (MACA).

For the purposes of this report, these three available climate models will be identified from this point forward as:

- MC2 - EPA
- MC2 - University of Idaho
- UC Merced/Westerling

7.2. Global Climate Models Applied

Each of the wildfire models used a series of GCM outputs to generate projections of future wildfire conditions. In the District 12 analysis, the project study team 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 GHG emissions. Table 1 represents 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

7.3. Analysis Methods

The wildfire projections were developed for the three future 30-year time periods used in this study (median years of 2025, 2055, and 2085). These are represented in the wildfire figures that follow.

The wildfire models produce geospatial data in raster format, which represents data expressed in individual "cells" on a map. The final wildfire projections provided a summary of the percentage of each of these cells that burns for each time period. The raster cell size was 1/16th 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 1/24th of a degree square to match the grid cells generated by the MACA downscaling method. The model data were collected for all wildfire/GCM combinations for each year to the year 2100.[55] The study team ultimately summarized the data into the 1/16th of a degree grid to enable comparisons and to summarize across multiple models. The resulting area contained within these cells ranged in area between roughly 8,000 and 10,000 acres for grid cells sizes that are 6 kilometers on each side.

An initial analysis of the results of the wildfire models for the same time 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 that is included in the MC2 models, but not in the UC-Merced/Westerling model.

7.4. Categorization and Summary

Using three modeled datasets to generate a broader understanding of future wildfire exposure in California provides 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 (these data are available for future application by Caltrans and their partners).

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

- Very Low 0-5%

[55] 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 wildfire raster are rectangular instead of square and are of different sizes depending on where one is (they are shorter when measured east-west as you go farther north).

- Low 5-15%
- Medium 15-50%
- High 50-100%
- Very High 100%+[56]

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. 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. Red highlights show portions of the Caltrans SHS that are likely to be most exposed to wildfire (in the medium to high wildfire concern areas).[57] Large portions of District 12 are projected to be exposed to increased wildfire risk. The eastern portions of Orange County are most vulnerable to increased wildfire concern compared to coastal areas where the wildfire risk is limited. Areas shown in white on the maps include those areas classified as very low or low concerns. For a summary of the mileage of the District 12 SHS exposed to medium to high wildfire concern over time for both RCP 4.5 and 8.5, see the tables below.

[56] A cell can have greater than 100 percent burned if burned twice or more in the same time period.
[57] There is no risk above "high" in Orange County.

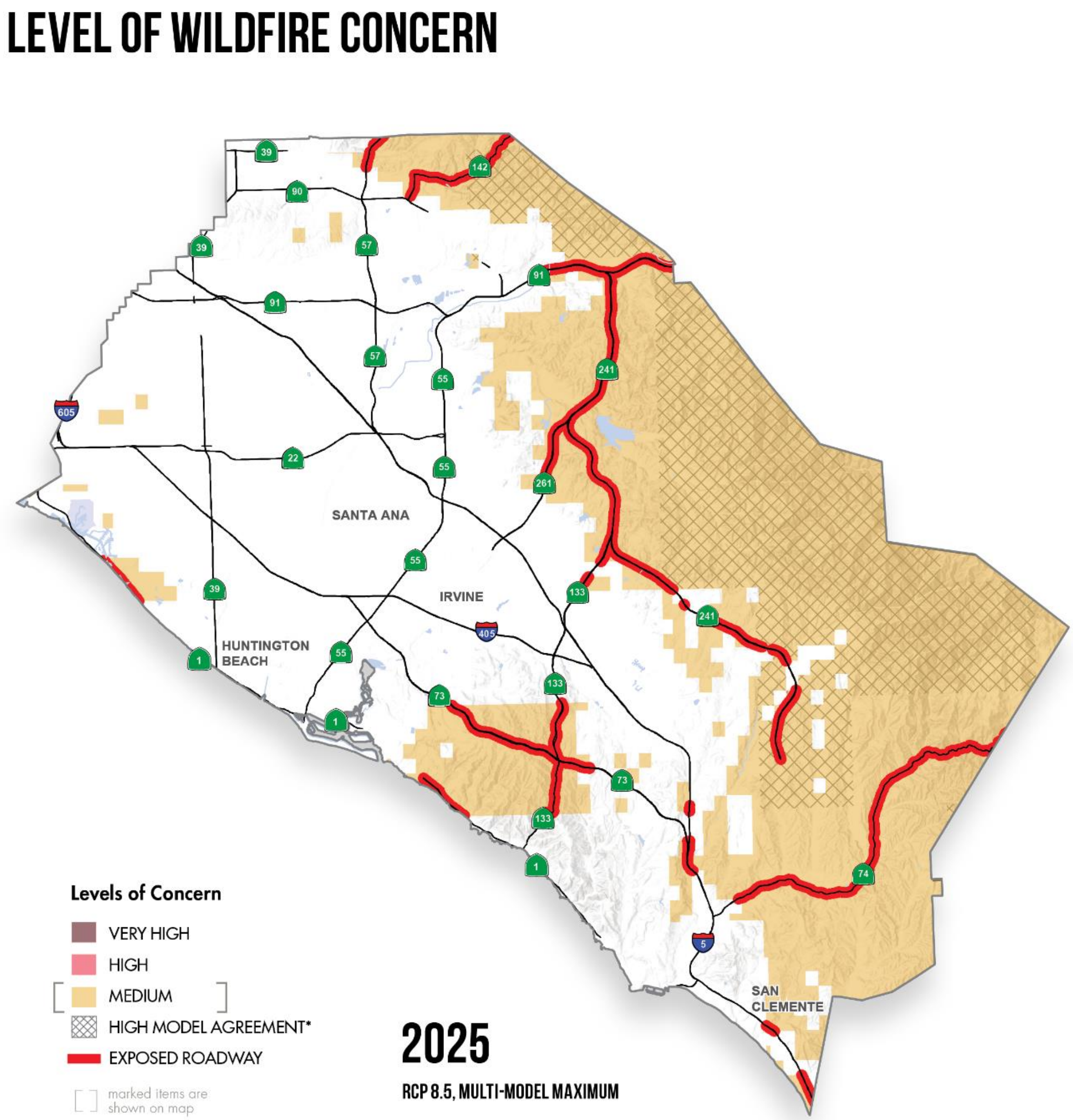
TABLE 2: MILES OF STATE HIGHWAY SYSTEM EXPOSED TO WILDFIRE FOR THE RCP 8.5 SCENARIO

	Year		
District 12 Counties	**2025**	**2055**	**2085**
Orange	71.4 miles	71.6 miles	72.5 miles

TABLE 3: MILES OF STATE HIGHWAY SYSTEM EXPOSED TO WILDFIRE FOR THE RCP 4.5 SCENARIO

	Year		
District 12 Counties	**2025**	**2055**	**2085**
Orange	55.6 miles	67.3 miles	71.8 miles

FIGURE 15: INCREASE IN WILDFIRE EXPOSURE 2025



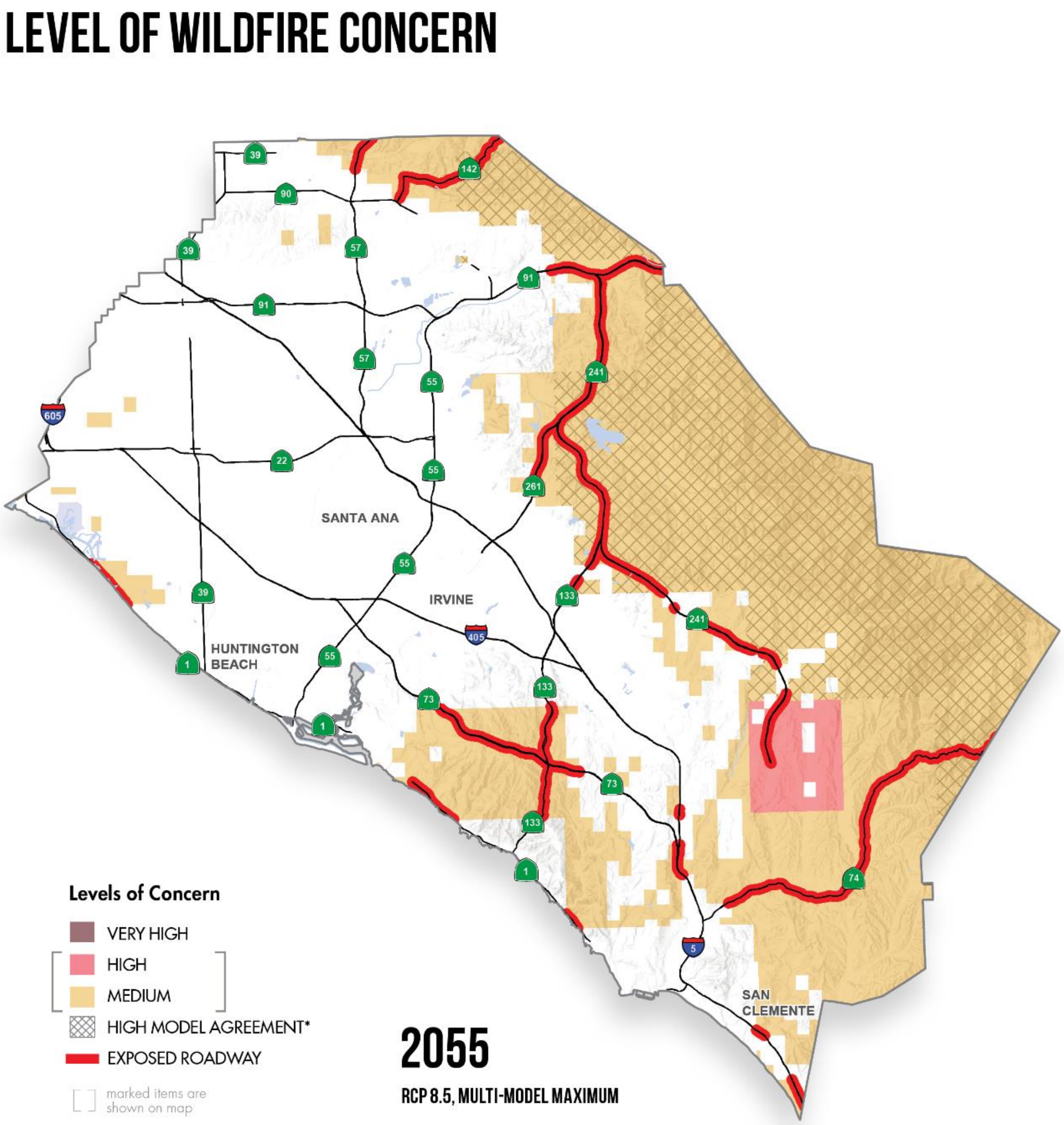
Future Level of Wildfire Concern for the Caltrans State Highway System within District 12, Based on the RCP 8.5 Emissions Scenario

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 Global Climate Models: (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.

Areas in white do not necessarily mean there is no wildfire risk, only that the risk classification is below moderate. More information on models used and the classifications for levels of concern can be found in the associated Technical Report.

* 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 16: INCREASE IN WILDFIRE EXPOSURE 2055



Future Level of Wildfire Concern for the Caltrans State Highway System within District 12, Based on the RCP 8.5 Emissions Scenario

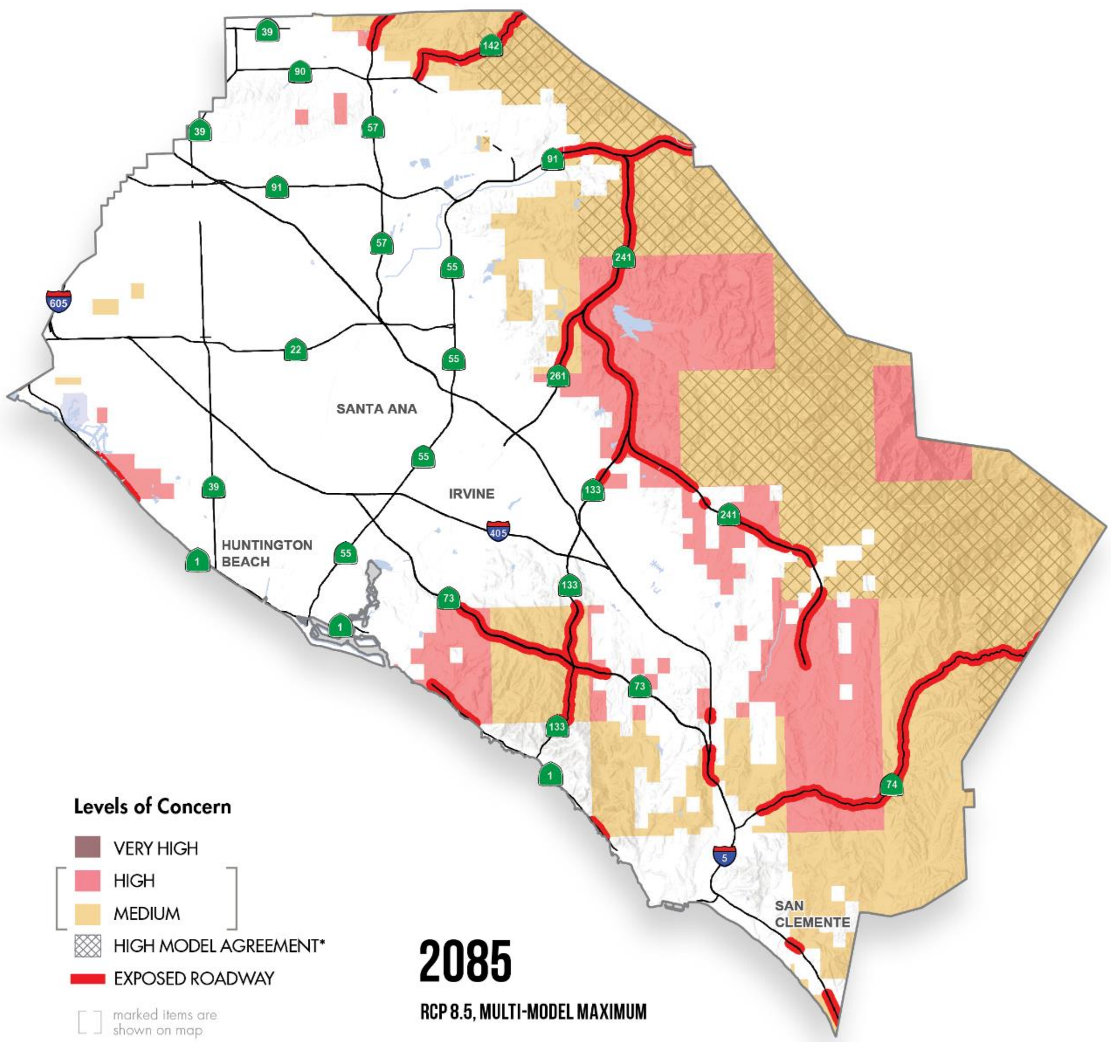
The fire model composite summaries shown are based on wildfire projections from three models: (1) MC2 - EPA Climate Impacts Risk Assessment, developed by John Kim, USFS; (2) MC2 - Applied Climate Science Lab at the University of Idaho, developed by Dominque Bachelet, University of Idaho; and (3) University of California Merced model, developed by Leroy Westerling, University of California Merced. For each of these wildfire models, climate inputs were used from three Global Climate Models: (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.

Areas in white do not necessarily mean there is no wildfire risk, only that the risk classification is below moderate. More information on models used and the classifications for levels of concern can be found in the associated Technical Report.

* 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 2085

LEVEL OF WILDFIRE CONCERN



Future Level of Wildfire Concern for the Caltrans State Highway System within District 12, 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 Global Climate Models: (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.

Areas in white do not necessarily mean there is no wildfire risk, only that the risk classification is below moderate. More information on models used and the classifications for levels of concern can be found in the associated Technical Report.

* 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.

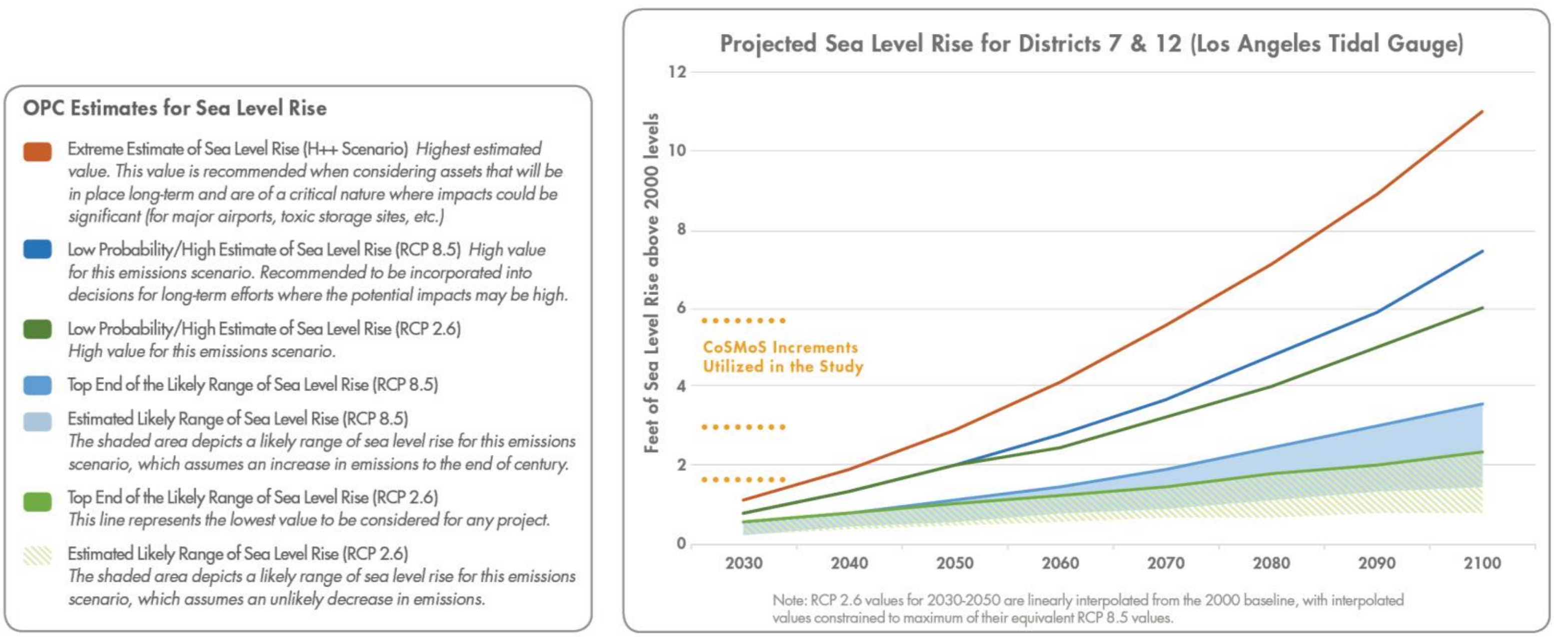
8. SEA LEVEL RISE

The data sets considered for this analysis came from new state projections prepared by the Ocean Protection Council (OPC). The SLR scenarios chosen for this analysis were consistent with these projections in order to follow state guidance on SLR planning. These projections are paired with a model that includes SLR and storm surge to identify approximately when potential impacts to the SHS might occur in District 12.

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

The OPC and California Natural Resources Agency released a 2018 update to the *California Sea Level Rise Guidanc*e while the District 12 assessment was underway. The OPC estimates of SLR, developed by a scientific panel, are based upon various projections of variables that drive SLR, such as thermal expansion, melting land ice, and differences in geography (e.g., areas where there might be land subsidence). Research on these variables will continually be updated long after the completion of this District 12 report, and thus SLR assessment is likely to be one of the climate change impact areas where Caltrans itself will have to update its own analysis approaches. The SLR projections use a base year of 2000 that incorporate average SLR from 1991 to 2009.

FIGURE 18: OPC GUIDANCE ON SEA LEVEL RISE PROJECTIONS FOR LOS ANGELES, 2018



8.2. Model Used

The CoSMoS model was developed by the US Geological Survey (USGS). Data can be viewed and downloaded from the *Our Coast Our Future* site.[58] The model was funded by stakeholders interested in understanding the associated impacts of various storm events combined with future SLR 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 assuming a maximum water level scenario for simulated storm events.

CoSMoS data, available in GIS shapefiles, were developed for SLR levels from 0.00 to 2.00 meters, in quarter-meter increments, and for 5.00 meters to reflect longer-term change. Analysis of the SHS in the District 12 study was completed for all CoSMoS increments. However, the analysis presented in this report is specific to three increments of SLR from the model: 1.64, 3.28, and 5.75 feet (0.50, 1.00, and 1.75 meters, respectively). See Figure 18 to identify approximately when the OPC SLR scenarios will reach the CoSMoS heights and the range between projections.

In addition to considering each increment of SLR, the effects of an annual storm event (a storm that happens on average once a year) were also analyzed. This one-year return period storm event was used to identify when the initial effects of SLR may begin to impact the District 12 SHS.

SHS centerline miles exposed to the three SLR increments along with an annual storm are summarized in Table 4. This information and the location of expected roadway exposure to SLR is an important consideration when establishing investment priorities, especially on SHS roads most affected. It is important to note that these centerline miles include bridges, which may not necessarily be inundated under these SLR increments depending upon their freeboard.

TABLE 4: DISTRICT 12 ROADWAY CENTERLINE MILES EXPOSED TO SEA LEVEL RISE AND AN ANNUAL STORM

	Sea Level Rise		
District 12	**1.64 ft (0.50 m)**	**3.28 ft (1.00 m)**	**5.75 ft (1.75 m)**
Orange	2.8 miles	5.2 miles	8.7 miles

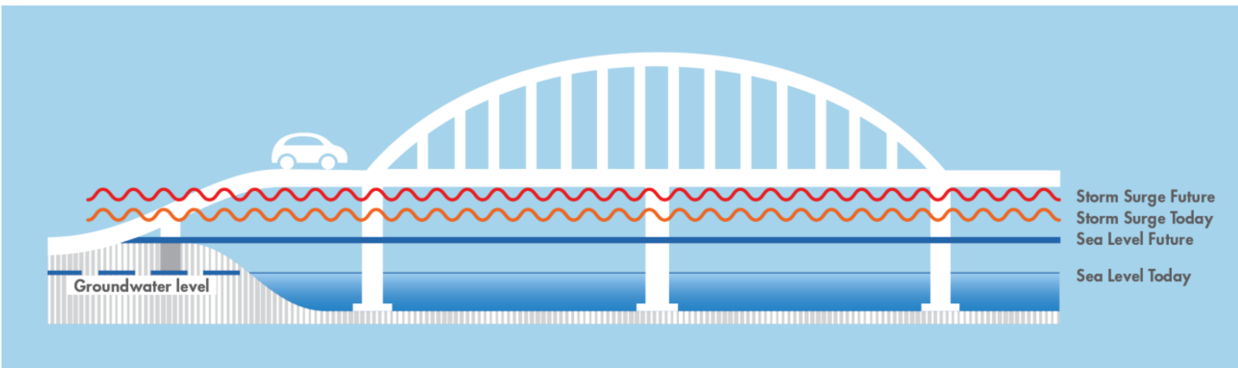
8.3. Bridge Exposure

When considering bridge exposure to SLR, it is important to note that facilities were often designed based on historical data as projected into the future. Changes due to SLR or storm surge may make a facility more vulnerable to damage given future events. Figure 19 shows potential concerns for a bridge associated with water overtopping the bridge deck. They are presented to help set a broader context for the definition of "facility risk" when considering SLR. 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:

[58] Our Coast Our Future can be accessed here: http://ourcoastourfuture.org/

- 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 19: BRIDGE EXPOSURE



The figures on the following pages depict the 1.64, 3.28, and 5.74 feet (0.50, 1.00, and 1.75 meter, respectively) CoSMoS increments for SLR, and indicate District 12 roadways at risk of permanent inundation or exposure from higher sea levels. As noted, more detailed, site-specific analysis will be necessary to determine if bridges will be overtopped.

FIGURE 20: INUNDATION FROM 1.64 FEET (0.50 M) OF SEA LEVEL RISE

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 21: INUNDATION FROM 3.28 FEET (1.00 M) OF SEA LEVEL RISE

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.

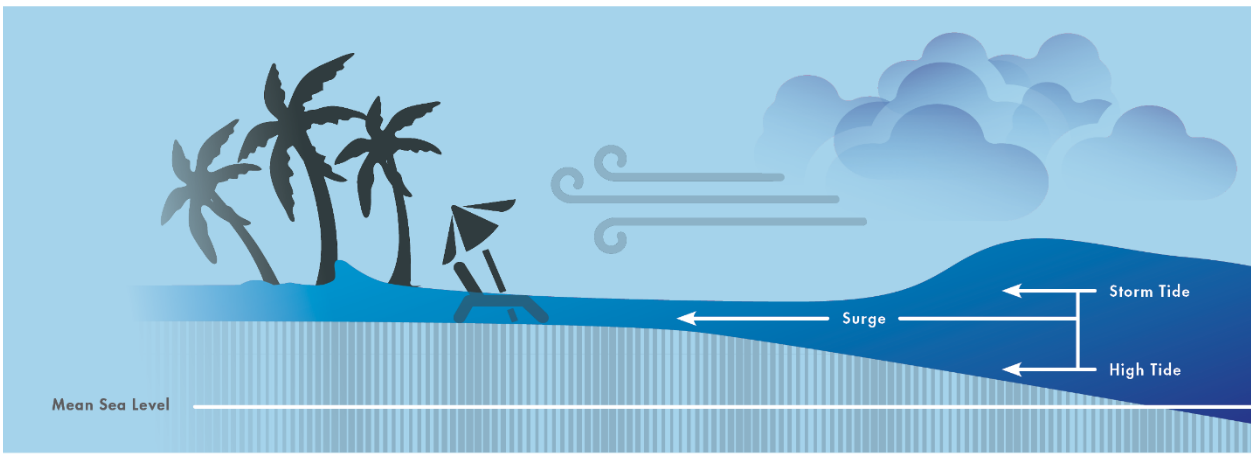
FIGURE 22: INUNDATION FROM 5.74 FEET (1.75 M) OF SEA LEVEL RISE

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.

9. STORM SURGE

Rising seas translate into more water in motion during storm surge events that potentially increase long-term risks to infrastructure. Estimates of future storm surge must consider the impact of new storm types resulting from climate change, that is, the possible effect on storm intensities from a warming ocean or atmosphere. Figure 23 identifies the basic elements of storm surge and how it is different from normal tidal conditions. The graphic, supplied by the National Oceanic and Atmospheric Administration (NOAA) and edited for this study, shows the effect and movement of surge over the land and the additional concern of waves at the shoreline.

FIGURE 23: ELEMENTS OF STORM SURGE



SOURCE: NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

The USGS has developed estimates of flooding extent from storm surge combined with SLR using the CoSMoS model. As noted earlier, CoSMoS estimates the effects of SLR combined with storm surge events for coastal California. For the purposes of this study, estimates for storm surge exposure on Caltrans District 12 highways and bridges are displayed for 1.64, 3.28, and 5.74 feet (0.50, 1.00, and 1.75 meters, respectively) of SLR combined with the 100-year storm event (see Figure 24 to Figure 26).

Table 5 summarizes the centerline miles of the Caltrans District 12 SHS that could flood with SLR and during a 100-year storm event. With 5.74 feet of SLR (the high end of plausible values for the end of the century per the latest science), the 100-year storm could affect almost 12 miles of Caltrans roadways in Orange County. The roadway most vulnerable to sea level rise impacts in District 12 is SR 1 (Pacific Coast Highway). The most vulnerable area in the district is the northern half of the coast, from the Los Angeles County border to Corona Del Mar.

TABLE 5: DISTRICT 12 HIGHWAY CENTERLINE MILES EXPOSED TO SEA LEVEL RISE AND THE 100-YEAR STORM EVENT

	Sea Level Rise		
District 12	**1.64 ft (0.50 m)**	**3.28 ft (1.00 m)**	**5.74 ft (1.75 m)**
Orange	3.7 miles	6.2 miles	11.9 miles

FIGURE 24: FLOODING FROM 1.64 FEET (0.50 M) OF SEA LEVEL RISE AND A 100-YEAR STORM EVENT

SEA LEVEL RISE AND STORM SURGE IMPACTS IN DISTRICT 12

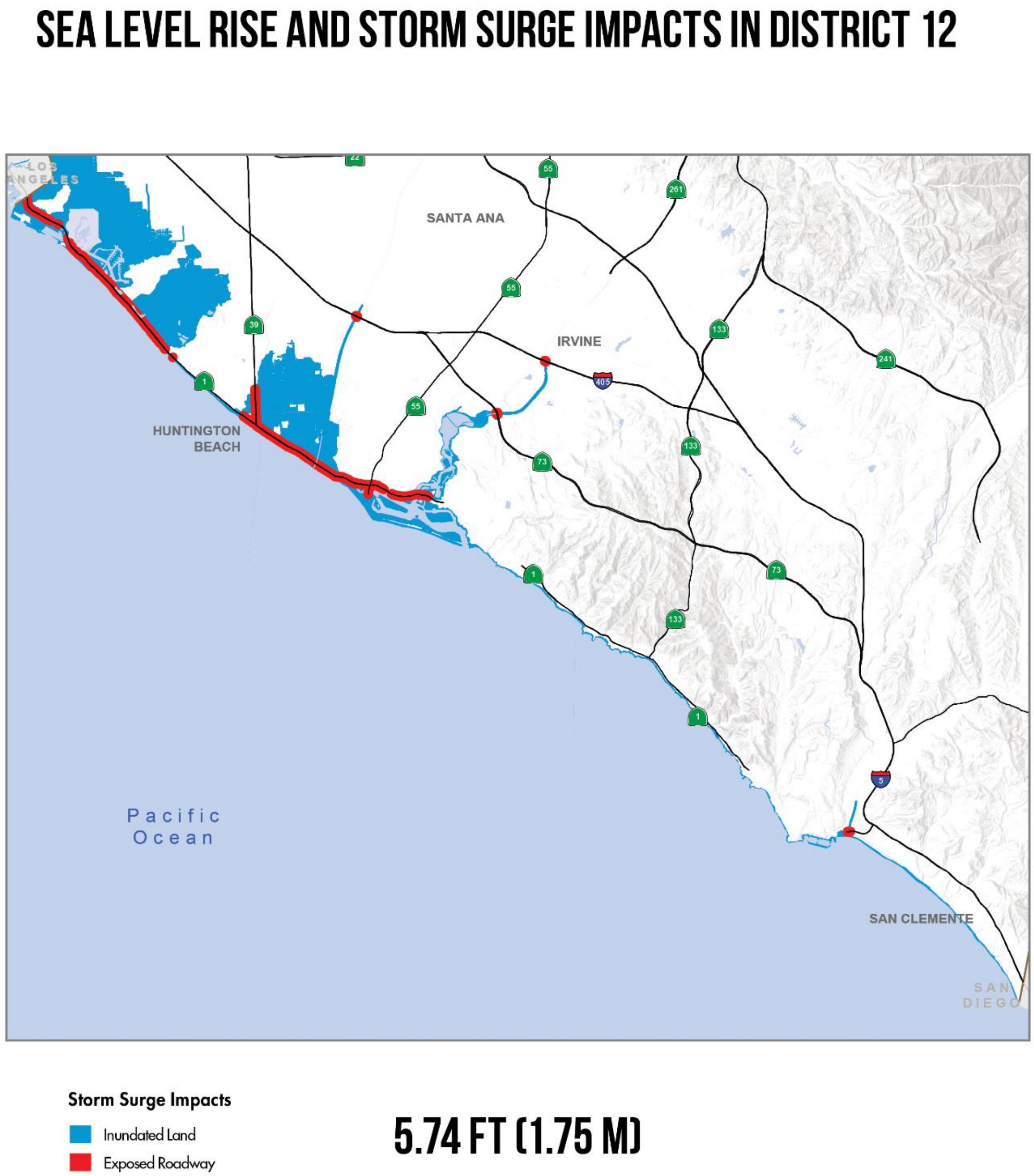
1.64 FT (0.5 M)

SEA LEVEL RISE AND 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 25: FLOODING FROM 3.28 FEET (1.00 M) OF SEA LEVEL RISE AND A 100-YEAR STORM EVENT

SEA LEVEL RISE AND 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: FLOODING FROM 5.74 FEET (1.75 M) OF SEA LEVEL RISE AND A 100-YEAR STORM EVENT



SEA LEVEL RISE AND 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.

10. CLIFF RETREAT

The 1,100-mile California coastline, shaped by various forces over time, is well known for its active areas of erosion, landslides, and cliff retreat. Estimates from a recent coastline study estimated that approximately 72 percent of the California coast has eroding coastal cliffs[59] due to the various forces at play in these areas, including the effects of ocean wave energy on beaches and cliffs. 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.[60]

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.

As noted in earlier sections, climate change is anticipated to result in higher sea levels, resulting in more regular inundation, higher tides, and an increase in wave forces during coastal storms. The effects of these tidal and storm events are anticipated to stretch farther inland, with greater water and wave penetration than what has been observed and planned for in the past.

The impact of erosion and cliff retreat on transportation infrastructure is a significant concern given the potential of the erosion of the soil foundation 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, requiring actions to protect infrastructure from further encroachment.

Research has been conducted on the implications of climate change and the higher water levels on the California coastal environment, including a preliminary assessment of the potential effect on shorelines and cliffs. The US Geological Survey (USGS) 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 SLR and how tidal and storm surge forces may reshape the coastline. One outcome of this effort was the development of the CoSMoS model 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 SLR 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."[61] The USGS effort

[59] 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, last accessed June 20, 2019. https://pubs.usgs.gov/of/2007/1133/of2007-1133.pdf

[60] University of California San Diego, "Study Identifies California Cliffs at Risk of Collapse," December 20, 2017, last accessed June 30, 2019. https://phys.org/news/2017-12-california-cliffs-collapse.html

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

developed two estimates of the future assuming two different conditions – one which included armoring the coast (known as ”hold the line”), and one which assumed that cliff retreat continues unimpeded (known as ”do not hold the line”).[62]

An analysis was conducted to identify which District 12 SHS highways might be impacted by shoreline change and cliff retreat. The analysis was conducted using GIS tools for all SLR scenarios provided by USGS. The heights presented in this report match the increments used in the sea level and storm surge sections – SLR 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 erode from SLR if not protected and/or hardened. Figures 27 to 29 show the results of this analysis. Table 6 summarizes the mileage of the District 12 SHS that may be eroded or otherwise affected by cliff retreat.

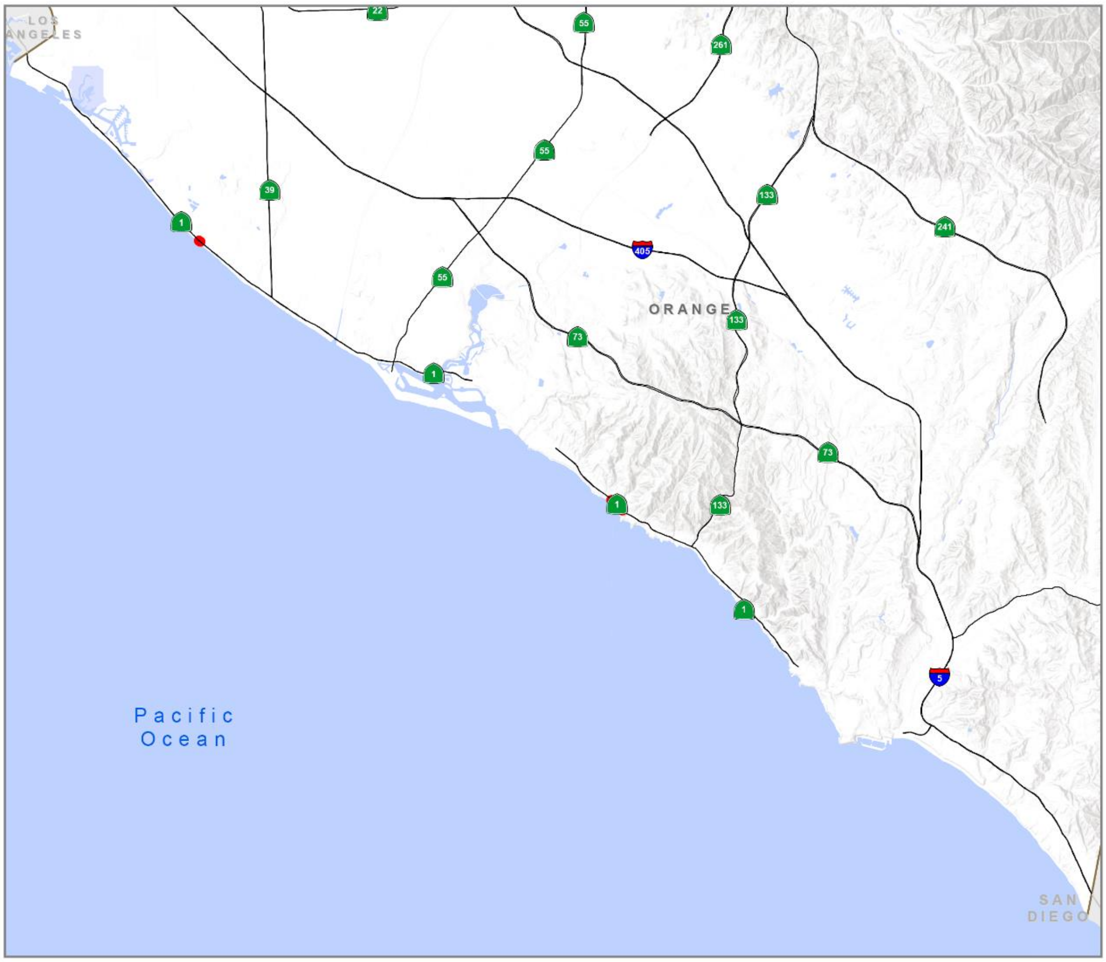
TABLE 6: DISTRICT 12 HIGHWAY CENTERLINE MILES EXPOSED TO CLIFF RETREAT

	Sea Level Rise		
District 12	**1.64 ft (0.50 m)**	**3.28 ft (1.00 m)**	**5.74 ft (1.75 m)**
Orange	0.3 mile	0.7 mile	1.0 miles

[62] Ibid.

FIGURE 27: CLIFF RETREAT FROM 1.64 FT (0.50 METERS) OF SEA LEVEL RISE

CLIFF RETREAT IMPACTS IN DISTRICT 12

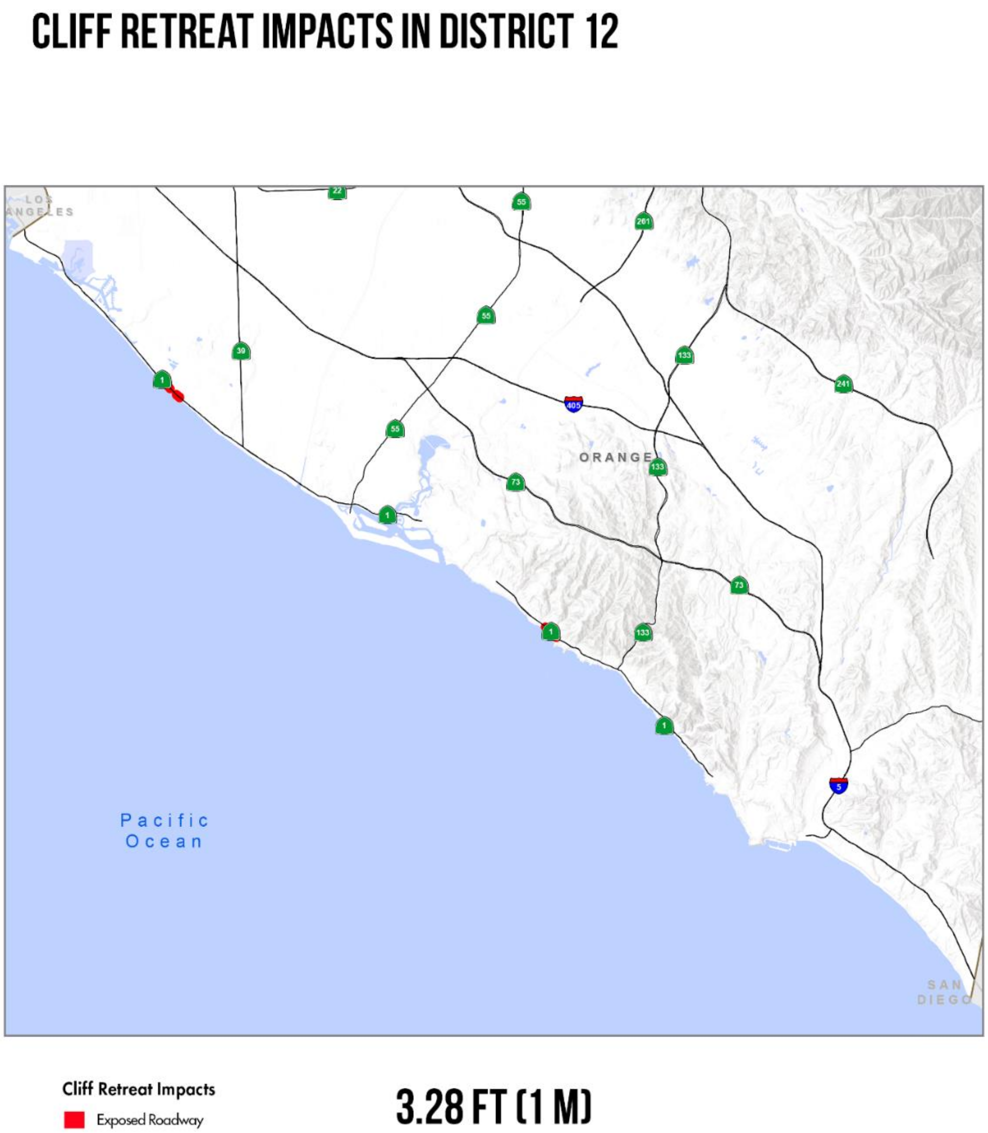


Cliff Retreat Impacts
Exposed Roadway

1.64 FT (0.5 M)

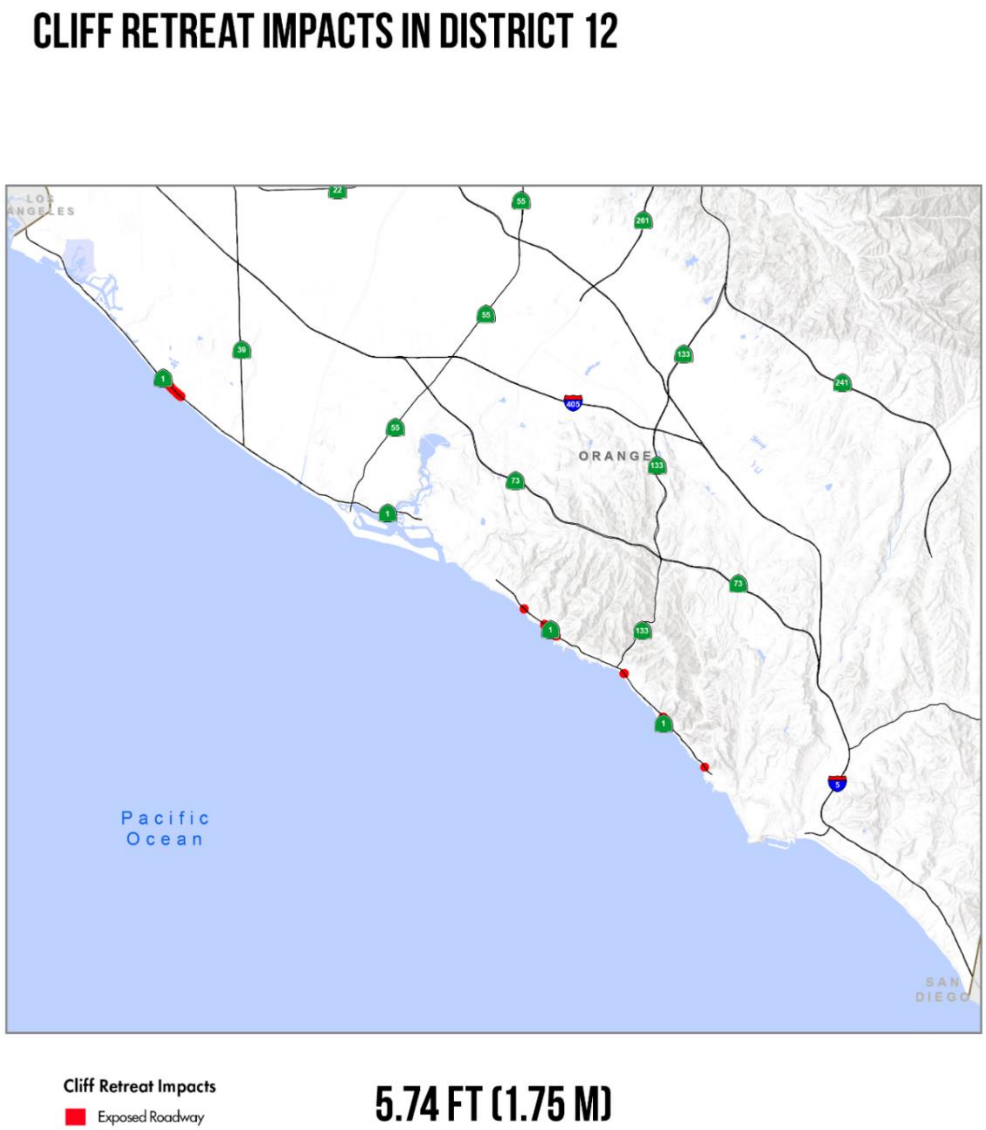
CLIFF RETREAT DATA ARE FROM THE US GEOLOGICAL SURVEY, COASTAL STORM MODELING SYSTEM (COSMOS). THIS DATA APPLIES THE "DO NOT HOLD THE LINE" MANAGEMENT OPTION, WHICH ASSUMES THAT CLIFF RETREAT CONTINUES UNIMPEDED. SEE Our Coast, Our Future AND THE USGS CoSMoS WEBPAGE FOR MORE INFORMATION ON THE MODEL

FIGURE 28: CLIFF RETREAT FROM 3.28 FT (1.00 METERS) 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 5.74 FEET (1.75 METERS) 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

11. INCORPORATING CLIMATE CHANGE INTO DECISION-MAKING

11.1. Risk-Based Design and Decision-Making

A risk-based decision-making approach considers the broader implications of damage and economic loss in determining appropriate design concepts. Climate change is a risk factor that is often omitted from design considerations but reflects the types of stresses and conditions an asset might face over its design life. Incorporating climate change factors into asset-level decision-making has been a subject of research over the past decade, much of it led or funded by the Federal Highway Administration (FHWA). The FHWA undertook some projects to assess climate change and facility design – including the Gulf Coast II 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 changing environmental conditions.

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),[63] 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 30.

The first five steps of the ADAP process cover the characteristics of the project and the situational context. This District 12 Vulnerability Assessment has worked through these first steps and the data used in the assessment have 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 5 focuses on conducting a more detailed assessment of the performance of the facility. When analyzing one facility, it 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 which scenarios will have the greatest impacts 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 proceeds to develop 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. They then proceed to the final steps of the process. These last three steps are critical to implementing adaptive designs. Step 9 involves considering other factors that may influence adaptation design and implementation. For example, California Executive Order B-30-15 requires consideration of:

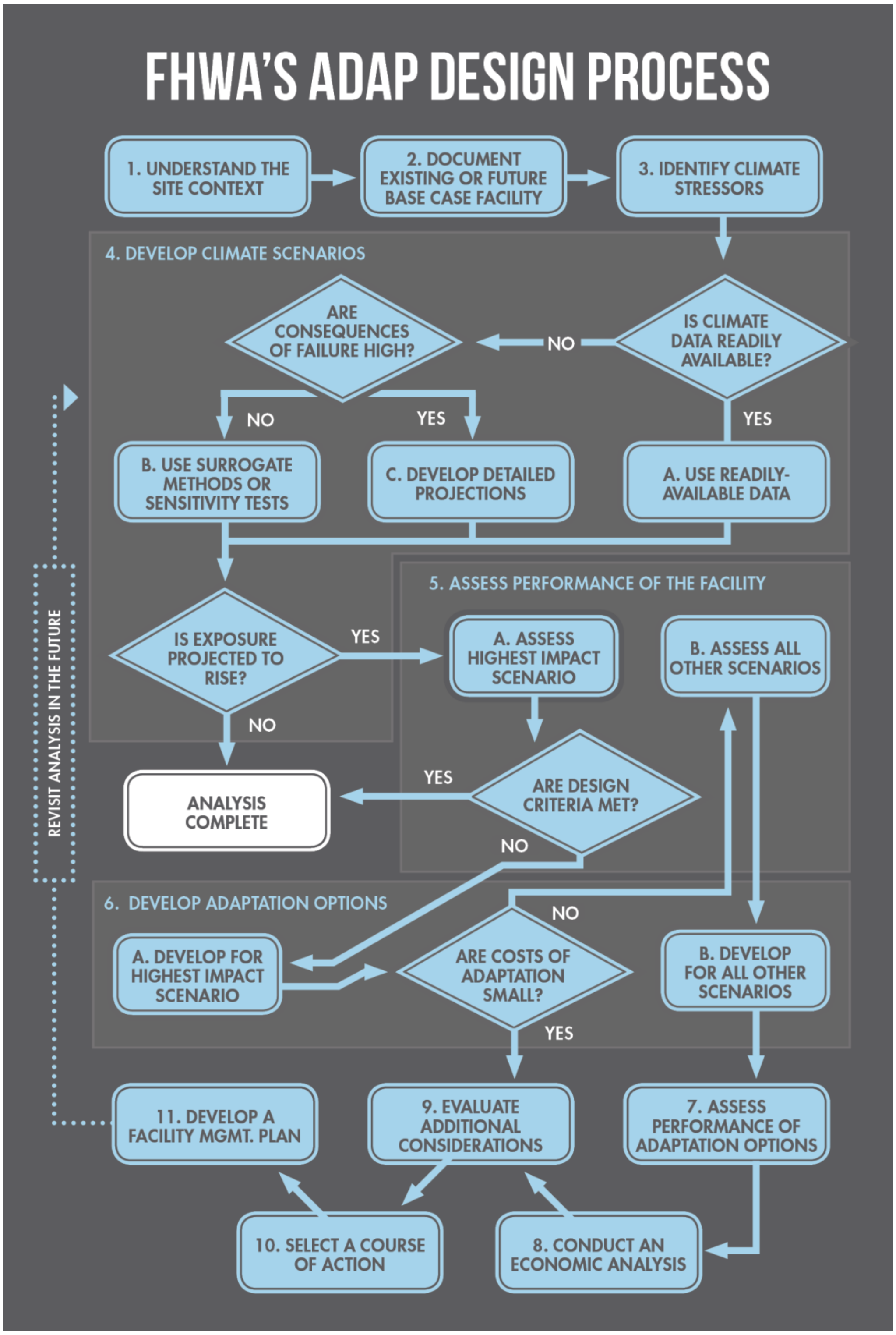
- Full life cycle cost accounting,

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

- Maladaptation,
- Vulnerable populations,
- Natural infrastructure,
- Adaptation options that also mitigate greenhouse gases, and
- 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 is selected and a facility management plan implemented.

FIGURE 30: 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. Prioritization of Adaptive Response Projects

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 transportation agencies in other states—address long-term climate risks and are intended to inform project priorities across the range of diverse project needs. This prioritization approach is specific to climate change effects and only provides one possible process by which to guide decisions. It is not intended as the sole factor in agency prioritization, which includes broader measures, but instead illustrates a method for choosing among projects that are identified as having potential climate change risks. 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.

Guiding principles for the development of the prioritization method included the following:

- It should be straightforward in application, easily discernable, describable, and it should be relatively straightforward to implement with common software applications (Excel, etc.).
- It should be based on best practices in the climate adaptation field.
- It should avoid weighting schemes and multi-criteria scoring, since those processes tend to be difficult to explain and are open to interpretation among professionals with varying perspectives.
- It should be focused on how departments of transportation do business, reflect priorities for program delivery to stakeholders, and recognize the relative importance of various assets.
- It should have the ability to differentiate between projects that may have different implications of risk—like near-term minor impacts and long-term major impacts—to set project priorities.
- It should facilitate decisions among different project types, for example, projects for repairs or for continuous minor damage as compared to one-time major damage events.
- It should enable the comparison among all types of projects, regardless of the stressor causing impacts.

The prioritization method requires the following information:

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

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

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

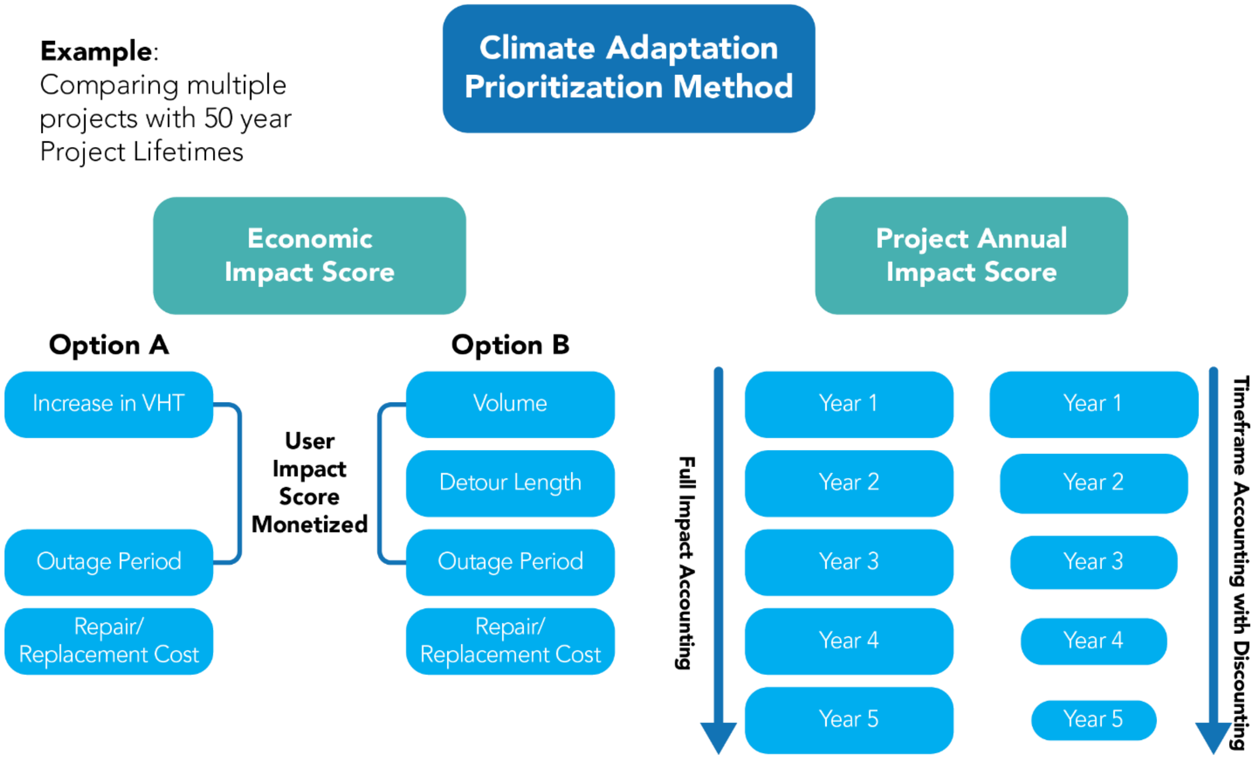
- System impacts (supplied by Caltrans planning staff) – the impacts of the loss of the facility on the broader system. This could be in terms of increase in Vehicle Hours Traveled (VHT) if using a traffic model, or an estimated value using volume and detour length as surrogates.
- Probability of occurrence (supplied by Caltrans climate change staff through coordination with state climate experts) – the probability of events occurring as estimated from the climate data for chosen climate scenarios. Estimated for each year out to the end of the facility lifetime.

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

- The expected cumulative loss estimated for the project over the project lifetime (full impact accounting).
- A method of discounting losses over years– to enable prioritization based on nearer term or longer-term expected impacts (timeframe accounting).

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

FIGURE 31: APPROACH FOR PRIORITIZATION METHOD



The two side-by-side charts represent various approaches to calculating values that can be used for prioritization. The left side (Economic Impact Score) shows two methods for determining costs to the system user. The right-side shows 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 to indicate optional approaches 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 from Caltrans to define the parameters for the approach to inform decisions.

The prioritization method would need estimates, at a minimum, of 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 to the broader SHS 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 systems perspective is that it determines the impacts of multiple loss/failure assessments consecutively and is not confined to only the assessment of each 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 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 in selecting projects. The identification of an annual cost metric, which includes discounting, enables a decision 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 reflects one way of considering climate change impacts in project prioritization. Climate change, with its uncertain timing and non-stationary weather/climate impacts, needs to be considered systematically in transportation agency decision-making, especially in those agencies facing significant climate change risks to their assets in the future.

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 12. 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 the district. The study distilled the larger context of climate change down to a more localized understanding of what such change might mean to District 12 functions and operations, district employees, and the users of the transportation system. It is intended, in part, as a transportation practitioner's guide on how to include climate change into transportation decision-making.

Much of today's engineering design is based on historical conditions, and it is emphasized throughout this report that this perspective should change. A review of climate data analyzed for this study shows that, for those stressors analyzed (SLR, storm surge, wildfire, temperature, and precipitation), there are clear indications that future conditions will be very different from today's, with likely higher risks to highway infrastructure. These likely future conditions vary in terms of when threshold values will occur (that is, when sea levels or precipitation and temperature values exceed a point at which risks will increase for assets) and on the potential impact to the SHS. 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 12 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 12 and where project development efforts for projects in these areas should consider changing future environmental conditions. There are several steps that can be taken to transition from a traditional project development process based on historical environmental conditions to one that incorporates a greater consideration for facility and system resiliency. This process can incorporate the benefits associated with climate change adaptation strategies and use climate data as a primary decision factor. District 12 staff, with its recent history of assessing long-term risks associated with climate change, has the capacity to adopt such an approach and ensure that travelers in the region are provided with a resilient system over the coming years.

The following section provides some context as to what the next steps for Caltrans and District 12 may be in order to build upon this work and create a more resilient SHS.

12.1. Next Steps

The work completed for this effort answers a few questions and raises many more. The scope of this work was focused on determining what is expected in the future and how that may affect the SHS. This analysis has shown that climate data from many sources indicates an expanded set of future risks – from increased extreme precipitation, to higher temperatures, and an increase in wildfires – all concerns that will need to be considered by District 12.

There are a few steps that will be required to improve decision-making and help Caltrans achieve a more resilient SHS in District 12. 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.
    - The changing elements of climate change require the risk-based 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 Risk-Based Design and Decision-Making).
- Acquisition of Improved Data for Improved Decision-Making
    - Determining potential impacts of precipitation on the SHS will require additional system/environmental data to complete a system-wide assessment. This includes:
        - Improved topographic data across District 12 (and the state).
        - Improved asset data – including accurate location of assets (bridges and culverts) and information on waterway openings at these locations.
    - The assessment of wildfire potential is an ongoing effort in the state. New research and updated models are likely to present new capabilities to Caltrans in identifying further wildfire risks as these new capabilities are incorporated into Caltrans analysis approaches.
    - The precipitation and temperature data presented in this report are based on the most recent data available in California. Methods to summarize this data across many climate models is ongoing and the conclusions of that work may yield information that could more precisely define expected future changes for different stressors.
    - Efforts are underway to refine the understanding of other stressors, including landslide risks and a better understanding of coastal erosion. Further refinements of those efforts will require additional investment and coordination. 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 best to 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.

This report should be considered a first step in Caltrans' journey toward a more adaptive and resilient SHS. The focus of this study was to identify and estimate the level exposure of the District 12 SHS to future climate change stressors. Locations where the SHS were likely to be exposed to future climate stresses were identified and the general exposure of the entire district's SHS (most often measured in SHS miles exposed) was estimated. Caltrans should use this information as a point-of-departure for examining what these risks to SHS performance mean in terms of the many different responsibilities it has in planning, delivering, operating, and maintaining the SHS.

Although this study has only examined Caltrans highways, it represents and approach and methodology that others in the District can emulate. District 12 is unique in that it includes only one county, so many of the climate change challenges facing Caltrans will also be faced by the county and cities as well, in fact in many of the same places where the assessment shows SHS vulnerability. As noted in the above paragraph, just as this report can act as a point-of-departure for Caltrans itself to become more sensitive to climate change risks, so too does it represent an important opportunity for reaching out to district communities to discuss mutual concerns and issues. Especially in the context of an areawide disaster, it would be beneficial to account for other jurisdictional transportation systems and modal networks such as passenger and freight rail. Another opportunity would be to discuss alternate routes for major corridors in the event of a significant system disruption.

13. GLOSSARY

50th percentile downscaled model outputs (for temperature and precipitation projections) – 50th percentile results represent the median of downscaled climate model outputs under RCP 8.5 for the metric shown, as calculated across the state using the area weighted mean.

100-year design standard: Design criterion for highway projects that addresses 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.

King Tide: The highest high tide of the year.

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

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

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

Scour (Bridge): Typically, a result of swiftly moving water removing soil/sediment from around structural elements like abutments or piers. It can increase risk of failure for the structure.

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

Storm surge: Refers to elevated sea levels during a storm event due to a combination of onshore wind and reduced atmospheric pressure. Higher than normal waves during the storm, themselves the results of high winds, can contribute to the storm surge impacts.

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

Tidal flooding: As sea level rises, tides will get progressively higher and lead to longer periods of inundation at high tide. Eventually rising sea levels will lead to permanent inundation.

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.

Vulnerable populations: “Vulnerable populations include, but are not limited to women; racial or ethnic groups; low-income individuals and families; individuals who are incarcerated or have been incarcerated; individuals with disabilities; individuals with mental health conditions; children; youth and young adults; seniors; immigrants and refugees; individuals who are limited English proficient (LEP); and Lesbian, Gay, Bisexual, Transgender, Queer, and Questioning (LGBTQQ) communities, or combinations of these populations.”[64]

[64] Governor’s Office of Planning and Research, “Planning and Investing for a Resilient California: A Guidebook for State Agencies,” March 13th, 2018, last accessed June 20, 2019. http://opr.ca.gov/planning/icarp/resilient-ca.html

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