



Caltrans Climate Change

Vulnerability and Risk Assessment

Statewide Technical Report

2026

ARUP

Acknowledgements

The work undertaken for this project included coordination with these Caltrans teams and divisions, among others:

- Division of Transportation Planning, Office of Air Quality Conformity and Resiliency Planning
- Division of Design
- Division of Maintenance
- Division of Environmental Analysis
- Division of Data and Digital Services
- Directors Office of Sustainability
- Directors Office of Asset Management
- All 12 Caltrans Districts Statewide

Consultant Team

ARUP



The Cal-Adapt Analytics Engine Team and Eagle Rock Analytics provided support and assistance in working with the latest downscaled climate data that underpins California's Fifth Climate Change Assessment.

Disclaimer

This report offers information on Caltrans' State Highway System exposure to climate hazards, vulnerabilities, and risks. Future conditions are inherently uncertain. Climate models, data, and scenarios have limitations, and regional impacts may vary. Forward-looking statements are based on current assessments and interpretations of available information, which may not reflect how actual events unfold over time. The report's information should be interpreted cautiously and with professional judgment.

Acronyms and Abbreviations

Caltrans	California Department of Transportation
CCA4	California's Fourth Climate Change Assessment
CCA5	California's Fifth Climate Change Assessment
CCVA	2019 Climate Change Vulnerability Assessment
CCVRA	2026 Climate Change Vulnerability and Risk Assessment
CMIP5	Coupled Model Intercomparison Project Phase 5 (Used for GCMs)
CMIP6	Coupled Model Intercomparison Project Phase 6 (Used for GCMs)
CoSMoS	USGS Coastal Storm Modeling System
FEMA	Federal Emergency Management Agency
FHWA	Federal Highway Administration
GCM	Global Climate Model
GIS	Geographic Information System
IPCC	Intergovernmental Panel on Climate Change
LOCA	Localized Constructed Analogs
NOAA	National Oceanic and Atmospheric Administration
OPC	Ocean Protection Council
PROTECT	Promoting Resilient Operations for Transformative, Efficient, and Cost-saving Transportation
RCP	Representative Concentration Pathways
RP	Return Period
SCRIPT	State Climate Resilience Improvement Plan for Transportation
SHS	State Highway System
SHSMP	State Highway System Management Plan
SLR	Sea Level Rise
SSP	Shared Socioeconomic Pathways
USGS	U.S. Geological Survey

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Background

Climate-related natural disasters are increasing in frequency and intensity as the climate continues to warm. This assessment provides a quantified and data-driven framework to assist Caltrans as they make strategic investments to support a more resilient transportation network today and over the coming century.

1.1 Purpose

This report presents the methods and findings of Caltrans' 2026 Statewide Climate Change Vulnerability and Risk Assessment (CCVRA). This assessment serves as a comprehensive, planning-level analysis of climate change impacts on the State Highway System (SHS) while including the latest science, climate hazards, and a robust risk assessment.

This assessment has three objectives:

- **Establish a Risk Assessment Approach:** Previous Caltrans assessments evaluated climate hazard exposure and identified adaptation priorities. This updated assessment takes a climate risk approach that incorporates the physical consequences of climate impacts on Caltrans' infrastructure to better inform decision-making and strategic planning to mitigate climate-related risks. The risk assessment approach is consistent across climate hazards and assets, strengthening Caltrans' understanding of potential system disruption and damage associated with climate hazards across all 12 districts.
- **Provide Actionable Resilience Data:** Deliver current data and comprehensive risk ratings for various asset types (roadways, bridges, culverts, and tunnels) for key climate hazards: riverine and coastal flooding, cliff retreat and shoreline erosion, wildfire, and landslides.
- **Increase Transparency and Support Future Updates:** This assessment provides Caltrans with underlying methods and data that will allow them to update the assessment as new climate data is released or additional asset information becomes available. This approach supports continued risk-informed decision making

The findings will inform planning, design, maintenance, and capital investment decisions to build a more resilient, climate-safe SHS for all Californians.

1.2 Context

The CCVRA is a response to existing policy and funding opportunities at both the federal and state levels. It enables Caltrans to factor climate risk into SHS planning and investment decisions.

1.2.1 Federal Policy and Investment Drivers

Federal regulations, primarily under Title 23, require State Departments of Transportation (DOTs) to formally assess climate-related threats by including climate change and extreme weather risks in infrastructure management plans, evaluating facilities that require repeated emergency repairs, and developing strategies to improve the system's overall resilience and reliability. Title 23 is reinforced by the Federal Highway Administration (FHWA) policy directive to manage climate and extreme weather risks. Recent federal laws, including the Bipartisan Infrastructure Law (IIJA) and the Inflation Reduction Act (IRA), dedicated tens of billions of dollars to climate adaptation, funding key programs such as the Promoting Resilient Operations for Transformative, Efficient and Cost-Saving Transportation (PROTECT) Program.

1.2.2 State Legislative and Executive Mandates

California's policy framework requires state agencies to incorporate climate change into planning and investment decisions. Executive Order B-30-15 (2015) foundationally requires state agencies to consider climate change in all major decisions, prioritize adaptation that reduces greenhouse gases, and focus on protecting vulnerable populations using approaches like natural solutions. Executive Order N-19-19 (2019) builds on this by mandating that the state leverage its \$700 billion investment portfolio and transportation budget to accelerate carbon neutrality and transition to zero-emission vehicles. Assembly Bill (AB) 2800 (Quirk, Statutes of 2016) requires Caltrans to account for climate impacts across the entire infrastructure lifecycle. The Climate Action Plan for Transportation Infrastructure (CAPTI) mandates that Caltrans integrate climate risk and equity into investment decisions. This is executed through the State Climate Resilience Improvement Plan for Transportation (SCRIPT), required by Senate Bill (SB) 198 (Committee on Budget and Fiscal Review, Statutes of 2022).

1.2.3 Caltrans Climate Policies, Procedures, and Guidance Documents

Caltrans continuously updates its policies, procedures, and guidance documents to ensure climate change and its associated impacts are integrated into decision-making. The CCVRA is critical in guiding these updates, providing the technical data necessary to meet state mandates. Key planning documents already updated to incorporate climate considerations include the Project Initiation Guidance Document (PID), the Corridor Planning Process Guide, the Project Initiation Report (PIR) guide, and the Regional Planning Handbook.

1.3 What is New Since the 2019 Assessment

The previous assessment (completed in 2019) identified where climate hazards pose the greatest threat to the SHS. This assessment builds on that foundation. Below are key changes:

- In this update, high-resolution, downscaled climate model data consistent with California's Fifth Climate Change Assessment (CCA5) is used, which provides localized insights into climate stressors. All the climate data from CCA5 was downloaded from Cal-Adapt, which is a web-based platform hosting the latest downscaled climate datasets and climate change tools for California and used by most of the state agencies.
- The assessment now incorporates additional hazards, such as landslides, which are expected to increase in likelihood with the rising intensity and frequency of extreme precipitation events.
- The 2026 CCVRA transitions from the exposure-based mapping (2019) to a statewide risk assessment framework aligned with Caltrans asset management practices. This approach differentiates between broad hazard exposure and the actual consequence of system disruption. While the risk assessment prioritizes hazards most likely to cause immediate damage (such as flooding, wildfire, and landslides), the assessment also produced a comprehensive suite of climate indicators to ensure transparency and longevity. This includes data not yet integrated into the statewide risk score, such as groundwater rise, which remains available to support localized district-level project assessments.

1.3.1 User-Friendly, Transparent Tools

The key lesson learned from the 2019 assessment was the need to empower Caltrans staff with practical, accessible resources. This assessment delivers tools built around user needs that prioritize:

- ✓ **Transparency in Methodology:** Ensuring the underlying calculations and assumptions are clear and replicable.
- ✓ **Elimination of "Black Boxes":** Providing staff with confidence in the data and how risk ratings were generated.
- ✓ **Ease of Use:** Developing analytical tools that are straightforward for staff at both Headquarters and the district level to apply during project planning and decision-making.

1.4 How to Use This Report

This report serves Caltrans audiences across planning, asset management, and project delivery. While the document provides the detailed methodology and the statewide risk results, it also provides a broader suite of actionable data. Users can access the full range of climate indicators and exposure assessments included in this document. By offering these modular datasets alongside the primary risk results, the report supports both high-level strategic prioritization and detailed, project-level analysis:

Headquarters Programs and Leadership

Use the statewide results summary to support agency-wide investment strategies, including State Highway Operation and Protection Program (SHOPP) programming, SCRIPT implementation, PROTECT applications, and CAPTI alignment.

Asset Managers and Maintenance Leads

Use asset-specific vulnerability tables and risk findings to understand how risk was evaluated for roadways, bridges, culverts, and tunnels. These results support SHOPP scoping, four-year work planning, and prioritization of resilience investments.

District Planners and Corridor Teams

Use the risk results by hazard and geospatial data for districts to identify high-risk locations, understand key climate stressors, and inform corridor planning, early alternatives development, and engagement with partner agencies.

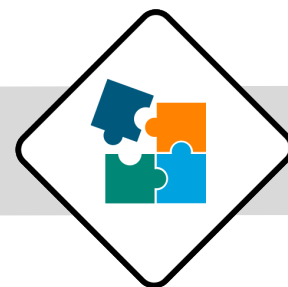
Project Development Teams

Use methods and results to understand how statewide risk ratings should be applied during PID development, alternatives analysis, and early project scoping.

Partner Agencies and Stakeholders

Consult the hazard summaries and interpretive guidance chapters to understand how climate stressors affect the SHS and how the CCVRA supports regional and local resilience planning.

This report also serves as a tool for aligning climate adaptation strategies across the state and provides a ready-made framework for jurisdictions that have not yet developed their own vulnerability assessments. By using these standardized data, partners can ensure their local planning efforts are consistent with statewide climate science and Caltrans' investment priorities.



Caltrans District and Headquarters staff provided technical knowledge and real-world field expertise that helped shape this document.

2.1 Goals, Purpose, and Activities

The engagement process throughout the development of the CCVRA involved Caltrans staff from both Headquarters and all 12 district offices. Engagement activities were designed to incorporate technical knowledge, field expertise, and practical experience from staff directly involved in asset management, planning, and project delivery. This input was essential to ensure the assessment reflects real-world conditions and supports practical application across the agency. The CCVRA project team worked closely with Asset Management, Division of Environmental Analysis, Design, and District offices in the development of deliverables.

To manage input efficiently, Caltrans established two committees:

Steering Committee: The Steering Committee provided overall technical direction for the CCVRA. This group reviewed major deliverables, guided methodological development, and helped ensure appropriate coordination with other committees. Members provided critical input on analytical approaches, metrics, assumptions, and implementation considerations.

District Committee: The District Committee served as the primary conduit for district-level input. Members provided local context, operational perspectives, and ground-truthing of results to ensure the CCVRA outputs are relevant and usable for district planning, scoping, and project development activities.

2.2 What we heard and how it was applied

Input from these committees emphasized the need to build a robust, actionable assessment by significantly advancing the technical and strategic foundation of the previous work from the 2019 CCVA. Specific input included the following topics:

2.2.1 Data, Modeling, and Technical Rigor

Ensure statewide consistency: The Asset Management team emphasized that a single, standardized set of criteria and approaches is needed for assessing needs across the state. There were multiple districts as well that emphasized a clear need for risks from different hazards to be evaluated consistently to improve prioritization efforts. In other words, a High risk from wildfire needs to hold the same meaning and be determined by the same criteria as a High risk from flooding (see Section 3.1 for details on the methodology).

Eliminate “black box” methods: Stakeholders from districts and Headquarters repeatedly emphasized the need for greater transparency in the preparation and presentation of the risk assessment methods and results. Many desired the ability to access the raw data used in the assessment and have access to a procedure that would allow them to recreate the results.

Advance data fidelity and accuracy: Address limitations of the previous input data both for hazards and assets. Specifically, the updated CCVRA must use higher-quality geospatial data to represent complex assets such as bridges to more accurately understand their exposure to flood hazards. To achieve this, this report uses the most recent bridge data collected by the Data and Digital Services Division (DDS) and a sophisticated risk approach integrating the bridge structural condition (see Section 5.4 for details).

Deepen analytical rigor: Ensure the risk assessment methodology has both technical rigor and practical utility by incorporating the physical consequence of climate exposure using a consistent scale and by focusing on hazards that are associated with tangible adaptation solutions. The final prioritized list must be derived from a sophisticated analysis using accurate data to enable funding and guide implementation.

2.2.2 District Issues

Caltrans districts are facing a complex array of interconnected climate challenges that vary significantly by geography but converge on issues of system failure, outdated infrastructure, and the need for localized, cost-effective adaptation strategies. Examples include:

Wildfire and Post-Fire Effects: Widespread issues where wildfires destroy roadside infrastructure and lead to subsequent mudslides, landslides, and clogged/damaged culverts due to lost vegetation and increased runoff.

Coastal and Inland Flooding: Coastal districts deal with storm surge, king tides, and SLR causing inundation and erosion. Inland areas face washouts and surface inundation from major rain events and atmospheric rivers that overwhelm outdated drainage.

Geohazards: Major issues include landslides, rockfalls, and severe subsidence, which causes unexpected holes and structural issues beneath the roadway.

This direction resulted in several areas of focus and application:

Use the best available data

- Consistent datasets and assumptions across districts
- Updated climate datasets aligned with California's Fifth Climate Change Assessment
- Updated transportation asset dataset

Align with Caltrans frameworks

- Alignment with relevant Caltrans plans and programs
- Coordination with Asset Management and DDS Divisions
- Outputs readily integrated into Caltrans tools

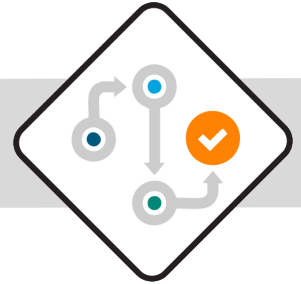
Have data transparency

- Collaboration with DDS
- Clarity in relationship between hazard and risk scores, providing intermediate values

Enhanced Methodology & Outputs

- Statewide maps and reports
- Accessible and user-friendly GIS datasets inclusive of all inputs/outputs for replication

Risk Assessment Methodology



CCVRA's methodology uses the best available data within a standardized framework to objectively compare and evaluate climate risks across the SHS.

This chapter details the methodology used to objectively evaluate and compare the risks posed by multiple climate hazards to Caltrans' assets throughout the state. The assessment considers the variety of impacts these hazards can have and uses a standardized, semi-quantitative framework to ensure comparability across hazards, assets, and locations. This framework is designed to overcome common limitations in risk assessment by ensuring consistent scoring and a level of accuracy that is appropriate for planning-level prioritization efforts. It establishes a state-of-the-art approach to risk evaluation in two fundamental ways:

Consistent risk scoring across hazard types. Many risk assessments will provide outputs like risk scores or risk ratings but will often not ensure that these outputs are consistent across hazards (i.e., High risk may mean something different for flood compared to wildfire). In the CCVRA approach, risk outputs hold the same meaning regardless of hazard. This enables Caltrans to make clear and consistent decisions for prioritizing investments across the state.

Vulnerability and Consequence levels. Risk assessments do not always consider how the impact of a hazard depends on its severity and the vulnerability (i.e., susceptibility to damage) of the specific asset. For example, a couple of inches of minor flooding should lead to very different outcomes compared to six feet of high velocity flooding on a highway. The CCVRA addresses this by considering multiple hazard severities, when data is available to do so, and the varying vulnerability of different assets to inform the potential consequence level of the impact. This provides Caltrans with a richer, more accurate understanding of the true risk to infrastructure from different hazards.

The approach is applied to the latest available climate datasets, including future climate projections from California's Fourth and Fifth Climate Change Assessments, to reflect the most up-to-date understanding of how climate change is impacting California.

3.1 Methodology

The methodology defines the risk to Caltrans' SHS assets as the integration of three components:

Hazard: the likelihood and intensity of a climate event posing a threat to SHS assets.

Exposure: the location of SHS assets relative to specific hazards.

Vulnerability: how susceptible the exposed SHS assets are to damage for a given hazard.



The CCVRA methodology uses a structured, multi-step approach to assess risk for a specific asset and hazard. This process follows five core steps:

- 1. Assess the hazard:** Use the best publicly available data with statewide coverage to evaluate the hazard's footprint, spatial variation, intensity, and likelihood of occurrence (i.e., return period) for existing and future conditions.
- 2. Assess the exposure:** Overlap the Caltrans asset data with each hazard to identify the locations and properties of the assets that could be impacted.
- 3. Assess vulnerability:** Identify the levels of damage likely to occur for different levels of hazard intensity (e.g., flood depth). Damage estimates were developed through the review of scientific literature, analyzing historical damage data, and interviewing subject matter experts. Vulnerability is also dependent on the asset characteristics (e.g., design criteria) and conditions. This assessment considers asset-specific details when available and proceeds with reasonable, large-scale assumptions when the data is less robust.
- 4. Assess consequences:** Once the damage levels are identified, the resulting impact is quantified. The CCVRA measures downtime, defined as the time to fully restore the asset to its original form and function, including completing all necessary repairs.
- 5. Assign risk:** Use risk matrices to assign an appropriate risk rating considering both likelihood and consequence. When supported by the available data, risk can be calculated for multiple hazard events with different likelihoods. In this scenario, the highest risk rating is selected to represent the hazard.

The specific details for implementing each step depend on the format of the datasets available for each hazard. These details are discussed in the subsequent chapters.

When risk is calculated using the components of hazard, exposure, and vulnerability, the resulting metrics are expressed as estimates of **likelihood** and **consequence(s)** of impacting events. These likelihood and consequence estimates are combined into qualitative risk ratings using standardized risk tables (or risk matrices). Risk matrices are hazard agnostic, meaning they provide a consistent framework to evaluate all climate hazards and compare the resulting risk ratings, regardless of whether the hazard is flooding, wildfire, landslides, etc.

		Consequence (Downtime)				
		Temporary Route Loss	Short-Term Route Loss	Medium-Term Route Loss	Long-Term Route Loss	Semi-permanent Route Loss
Likelihood	Permanent Exposure	Extremely High	Extremely High	Extremely High	Extremely High	Extremely High
	Exceptionally Likely	Medium	Medium-High	High	Very High	Very High
	Very Likely	Low-Medium	Medium	Medium-High	High	Very High
	Likely	Low	Low-Medium	Medium	Medium-High	High
	Possible	Very Low	Low	Low-Medium	Medium	Medium-High
	Unlikely	Very Low	Very Low	Low	Low-Medium	Medium

Table 1 The risk matrix adopted for the CCVRA.

The risk matrix used for the CCVRA (shown in Table 1) is adapted from existing risk tables within the 2022 Transportation Asset Management Plan (TAMP) and the draft 2025 State Highway System Management Plan (SHSMP).

While the matrix uses qualitative terms such as “likely” or “medium-term route loss,” each category is designed to correspond to a quantitative range when supported by the underlying data.

Figure 2 below shows how the likelihood and consequence categories map to quantitative ranges of return period (RP) and downtime respectively, where downtime is the time required to fully restore the asset to its original form and function.

Likelihood	Return period (yrs)	Consequence	Downtime
Permanent Exposure	RP < 0.01 yrs	Temporary Route Loss	< 2 days
Exceptionally Likely	$0.01 \leq RP \leq 2$ yrs	Short-Term Route Loss	2 – 10 days
Very Likely	$2 < RP \leq 10$	Medium-Term Route Loss	1.5 – 6 weeks
Likely	$10 < RP \leq 50$	Long-Term Route Loss	1.5 – 18 months
Possible	$50 < RP \leq 250$	Semi-permanent Route Loss	> 18 months
Unlikely	RP > 250		

Figure 2 Likelihood and consequence categories and correspondence with quantitative ranges of RP and downtime respectively.

The methodology is finalized with two specific considerations:

1. The “Permanent Exposure” likelihood category only applies to coastal hazards, due to the permanent nature of future SLR combined with daily tidal (i.e., non-storm) flooding.
2. A “Unlikely” risk rating is automatically assigned to any asset that is not physically exposed to a specific hazard.

This framework defines the **Baseline Risk Analysis**. At the end of this process, each combination of asset, hazard, and climate scenario receives a Baseline Risk Rating for both present-day and future climate scenarios. Risk ratings for future climate scenarios are intended to represent risk under future conditions, rather than being adjusted or discounted to present-day conditions.

The consideration of each asset’s criticality, or importance, to its users or the broader network can be used to adjust the results of the baseline risk analysis and develop enhanced risk scores that can inform mitigation action prioritization. A criticality-weighted approach can provide more robust risk metrics necessary for effective decision-making in specific contexts. While a criticality analysis was not performed within the CCVRA, Chapter 10 discusses potential datasets and future implementation opportunities.

3.2 Climate Science Assumptions

The CCVRA is grounded in the best available climate science at the time each indicator was developed, prioritizing publicly available datasets with the most complete statewide coverage (e.g., FEMA National Flood Hazard Layer) to characterize potential transportation impacts.

The final list of climate indicators and hazards was selected through a collaborative process within Caltrans. While a specific Caltrans district may possess more detailed local data, such as regional or project-level hazard modeling, the CCVRA approach emphasizes consistency and replicability across all districts. However, alternative data sources can be used by individual districts to augment this assessment and support local project planning and design.

The CCVRA incorporates projections from California's Fourth (CCA4) and Fifth (CCA5) Climate Change Assessments, which rely on climate projections from the global climate models (GCMs) developed for the Intergovernmental Panel on Climate Change (IPCC) Coupled Model Intercomparison Project (CMIP).

- **CCA4 Data (CMIP5):** The core risk assessment indicators rely on projections from the earlier CMIP5 GCMs since the technical analysis and modeling have not yet been completed for CCA5. These datasets were statistically downscaled using the Localized Constructed Analogs (LOCAv1) approach to a 6-kilometer (km) resolution. Localized Constructed Analogs is a technique for downscaling climate model projections of the future climate. The term "v1" stands for "version 1," and "v2" stands for "version 2." LOCA was created by the Scripps Institution of Oceanography.
- **CCA5 Data (CMIP6):** Most climate indicators stem from the newer CCA5 work, which uses the latest CMIP6 GCMs. In California, these models were downscaled to a higher 3 km resolution. These climate datasets, referred to as LOCAv2-Hybrid, were approved for CCA5 and are hosted on Cal-Adapt.

Recognizing that no single model simulation can fully characterize existing and future conditions, the assessment uses multi-model ensembles (statistical analysis of results from multiple models). This approach is essential for characterizing the range of uncertainty and providing statistically robust probabilistic information about future climate risks.

A comprehensive description of the climate modeling methods and analysis is provided in Appendix A.

3.2.1 Climate Scenarios and Time Horizons

Since the CCVRA draws from climate modeling across two generations of scientific assessments (CCA4 and CCA5), it requires the consideration of two complementary scenario approaches:

- **Representative Concentration Pathways (RCPs):** Used by CCA4/CMIP5, RCPs describe greenhouse gas emission levels.
- **Shared Socioeconomic Pathways (SSPs):** Used by CCA5/CMIP6, SSPs provide the storylines covering major socioeconomic, policy, and demographic trends that create the world leading to the RCP emission levels (Riahi et al. 2017 and IPCC 2023).

For consistency with previous Caltrans work and across the CCA4/CCA5 frameworks, the CCVRA uses four primary scenarios, which represent the closest possible matches between the RCP and SSP pairings:

Scenario	Assessment	Description
RCP4.5	CCA4	Intermediate Emission: Global GHG emissions decline by 2045.
RCP8.5	CCA4	Very High Emission: Continued rise in GHG emissions, reliant on fossil fuels.
SSP2-4.5	CCA5	Middle of the Road: Social and economic trends follow historical patterns; uneven development globally.
SSP5-8.5	CCA5	Fossil-Fueled Development: High economic growth coupled with reliance on fossil fuels and energy-intensive lifestyles worldwide.

Table 2 Future emission scenarios used in the CCVRA.

Figure 3 shows the potential degree of warming the United States may experience based on projected future global emissions compared to 1951–1980. The figure shows how projected temperatures diverge through 2100 across these pathways. Within this framework, the CCVRA focuses on intermediate and high emissions futures, evaluated across historical, mid-century, and late-century conditions. The colored lines show the modeled historical (1975–2014) and projected (2015–2095) change in surface temperature under different climate scenarios.

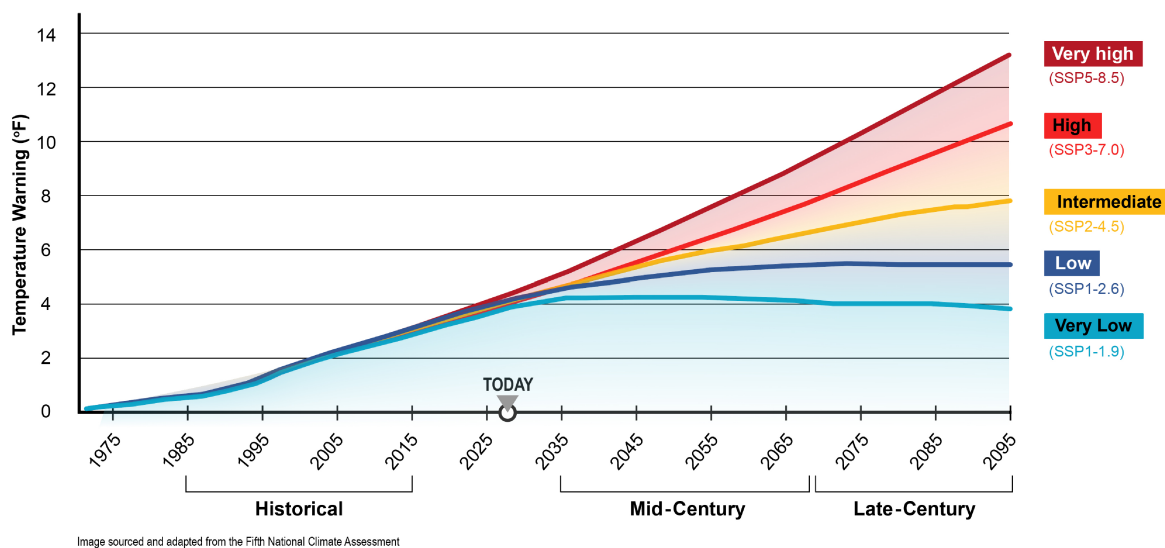


Figure 3 Potential Warming Pathways in the United States (Jay et al. 2023).

Recent literature has questioned the likelihood that future emissions could lead to the warmest scenarios. SSP5-8.5 relies on assumptions of sustained, large-scale fossil fuel (particularly coal) use that may be increasingly inconsistent with observed energy, technology, and policy trends (Hausfather and Peters 2020; Shiogama et al. 2023). As a result, some researchers have suggested that SSP3-7.0 may represent a more plausible high-end emissions pathway for risk assessments (Shiogama et al. 2023).

SSP3-7.0 was not included in the CCVRA for consistency and continuity with the 2019 CCVA. Caltrans can discuss the SSP1-2.6 scenario and other scenarios as valid options in future CCVRA updates or in other phases of project delivery, including project design. However, the SSP1-2.6 scenario and SSP 1-1.9 scenario cannot be incorporated into the 2026 CCVRA maps and risk assessments, since staff used downscaled GCM outputs from the Fifth California Climate Assessment as the basis for the GIS maps in the 2026 CCVRA, and these outputs are not available for SSP1-2.6 or SSP1-1.9.

To reduce the natural year-to-year climate variability while retaining sufficient data to complete extreme value analysis, all climate model output is analyzed relative to three 30-year epochs, or time horizons. The time horizons selected for the CCVRA are defined based on the following time periods:

- Historical, representative of year 2000
- Mid-century, representative of year 2050
- Late-century, representative of year 2085

Caltrans Asset Overview



Caltrans owns and maintains one of the largest highway systems in the world. Effectively understanding and analyzing the assets that comprise this system is a "big data" exercise involving continuous review and updates.

The California SHS encompasses approximately 15,000 centerline roadway miles and includes a vast array of assets that are susceptible to climate-driven hazards. The SHS includes over 13,000 state-owned bridges and numerous tunnels, and the drainage system is comprised of ~100,000 culvert systems and various drainage facilities. Threats to these assets are threats to system integrity and continuity of service, and therefore this assessment analyzes how climate hazards affect the performance, condition, and operational reliability of these assets.

Caltrans' GIS asset data is maintained through a robust and ongoing process involving multiple divisions across the agency. This ensures the data is reliable, accessible, and of high quality for critical functions like asset management, planning, and decision-making. For this assessment, data was pulled from multiple sources and then carefully processed to ensure consistent and standardized outcomes. Known and observed limitations or caveats regarding the source data were documented and considered during the assessment.

Asset	Description	Quantity	Data Source
Roadways 	Represents the length of pavement in each direction, including all lanes, along the SHS	15,000+ centerline roadway miles	State Highway Network Lines California State Geoportal
Bridges 	Bridges along the SHS	13,000+	Bridge Maintenance Division
Tunnels 	Tunnels along the SHS	63	National Bridge Database
Culverts 	Essential for managing water runoff and protecting SHS roadways	275,000+	Culvert Inspection Management System

Table 3 Summary of the asset data used for the CCVRA, including details and data source.

4.1 Roadways

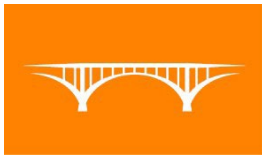


Roadway data was processed to create a standardized network suitable for analysis, focusing exclusively on mainline highway segments. This involved separating each route into distinct directional alignments (e.g., northbound/southbound) and dividing them into standardized 1/10th mile segments based on State Highway Postmile Tenths using the ArcGIS Pro

Postmile tool developed by Caltrans for internal use. This segmentation was introduced to improve the accuracy of the results. All the CCVRA results are presented using centerline miles (based on both alignments) to reflect the geometry of the original dataset.

Ramps and interchange connectors were not originally part of this roadway dataset. However, they were included in the bridge data received from the Caltrans Bridge Maintenance Division. Local ramps were excluded since they are not part of the SHS, and extremely small segments generated during processing were intentionally removed to ensure data consistency and accuracy in the analytical model.

4.2 Bridges



Bridge data from the Bridge Maintenance Division required several manipulations to filter out non-SHS bridges. This included the removal of all non-vehicular structures (including pedestrian overpasses and underpasses) due to many not belonging to the SHS. Bridge alignments were corrected when necessary. The bridge data presented several limitations that impacted the analysis, including

partial alignment availability and missing vertical clearance and height data.

The bridge dataset was integrated with structural details from the National Bridge Inventory (NBI) to better characterize the observed conditions and vulnerability of each structure and improve the accuracy of the risk assessment.

All roadway segments falling within 100 feet of a bridge were identified as possible approaches (i.e., segments of roadway leading to and away from the bridge). Using the route, alignment, and postmile information of the roadway segments, whenever possible, each bridge was associated with its approaches. This information was used to improve the accuracy of the flooding risk assessment, described in detail in Section 5.4.

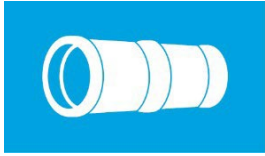
4.3 Tunnels



Tunnel location data was extracted from the National Bridge Inventory (NBI). These data points were filtered and spatially joined to the roadway network. To accurately map the entire alignment, manual verification and tagging using satellite imagery was required to associate all relevant roadway segments with each tunnel. Structures such as underpasses identified in the NBI, which are

technically tunnels but not on the primary network, were included and tracked distinctly. For multi-bore tunnels with more physical bores than roadway alignments (like the four-bore Caldecott Tunnel), the bores were logically assigned to the corresponding directional roadway.

4.4 Culverts



Culvert polyline data, sourced from the Culvert Inspection Management (CIM) database, details nearly 300,000 components on or crossing the SHS and includes information on health status, material, and end treatments. Due to the high density of culverts, the data was aggregated by road segment, providing a list of culvert system numbers for each segment rather than individual culverts.

A detailed description of the asset data sources and manipulations is provided in Appendix C.



Riverine Flooding

When rivers and creeks overflow, the resulting flooding can compromise Caltrans assets. Damage includes roadway washouts, bridge foundations being eroded, tunnel blockage from water and debris, and culvert failure due to clogging and erosion.

This chapter discusses the risks posed by riverine flooding to Caltrans assets. It details which assets are exposed to this hazard and how they are impacted and then combines this information to develop risk ratings across various assets and future climate scenarios.

5.1 Hazard

Riverine, or fluvial, flooding occurs when rivers or creeks overflow their banks, causing water to flow onto the adjacent land.

5.1.1 Present-Day Riverine Flooding

The assessment of present-day riverine flooding uses FEMA's National Flood Hazard Layer (NFHL) (FEMA 2025). This widely used public dataset is available on a statewide scale. The NFHL maps the present-day riverine flood hazard, defining key zones based on their annual probability of flooding:

- 100-Year Floodplain: Represents an area with a 1% chance of flooding annually.
- 500-Year Floodplain: Represents an area with a 0.2% chance of flooding annually.

The CCVRA analysis uses this data to determine if assets are located within either of these floodplain boundaries.

While the NFHL is a standard resource, it has several limitations for a comprehensive risk assessment:

- FEMA analyzes and maps flooding based on historical conditions and does not account for future climate change.
- Data can be incomplete: some remote areas are unmapped, and analysis for certain rivers is outdated.
- Flood depth information is not consistently reported and therefore is not used by the CCVRA.
- FEMA does not map localized stormwater flood hazards, so this hazard is largely excluded.

Figure 4 shows the distribution of the 100-year and 500-year FEMA flood zones across the state.



Figure 4 Locations of the 100-year (blue) and 500-year (yellow) FEMA NFHL flood zones across California.

5.1.2 Adjustment for Future Climate

At present, no publicly available dataset provides projections for how FEMA-designated flood zones (e.g., the 100-year or 500-year floodplains) may shift under future climate conditions. To account for the influence of climate change on riverine flooding, the CCVRA evaluated multiple climate indicators to estimate how the likelihood of present-day FEMA floodplains may plausibly change in the future. The indicator selected for this purpose is Total Runoff, which provides a basin-scale measure of future hydrologic conditions.

Total Runoff, defined as the maximum annual total runoff (surface runoff plus baseflow), is calculated from the LOCAv1 Variable Infiltration Capacity (VIC) Model (LOCAv1-VIC), which uses downscaled precipitation and temperature inputs to estimate grid-scale hydrologic processes (Liang et al. 1994; Hamlet et al. 2005; Das et al. 2009). Total Runoff includes runoff from precipitation events and runoff related to snowmelt in snow-dominated watersheds (He et al. 2019). For each water year, the maximum daily runoff value was identified, and these annual maxima were averaged across each time horizon and climate scenario for each GCM.

Because riverine flood response is typically analyzed at the watershed scale, which is much larger than the LOCAv1 grid (6 km), the Total Runoff indicator was spatially aggregated to HUC-10 (Hydrologic Unit Code) watersheds, representing drainage areas on the order of 40,000-200,000 acres (USGS 2025). This aggregation ensures that projected changes reflect watershed-scale hydrologic shifts relevant to roadway flood exposure.

Figure 5 presents the statewide distribution of the Total Runoff indicator. Historical values are shown for context; however, because LOCAv1 hydrologic outputs are not bias-corrected, the results should be

interpreted as projected trends rather than absolute runoff volumes. Future conditions are expressed as percent change relative to historical baselines. Bias-corrected climate modeling is a post-processing technique used to adjust raw output from global or regional climate models to match observed historical data.

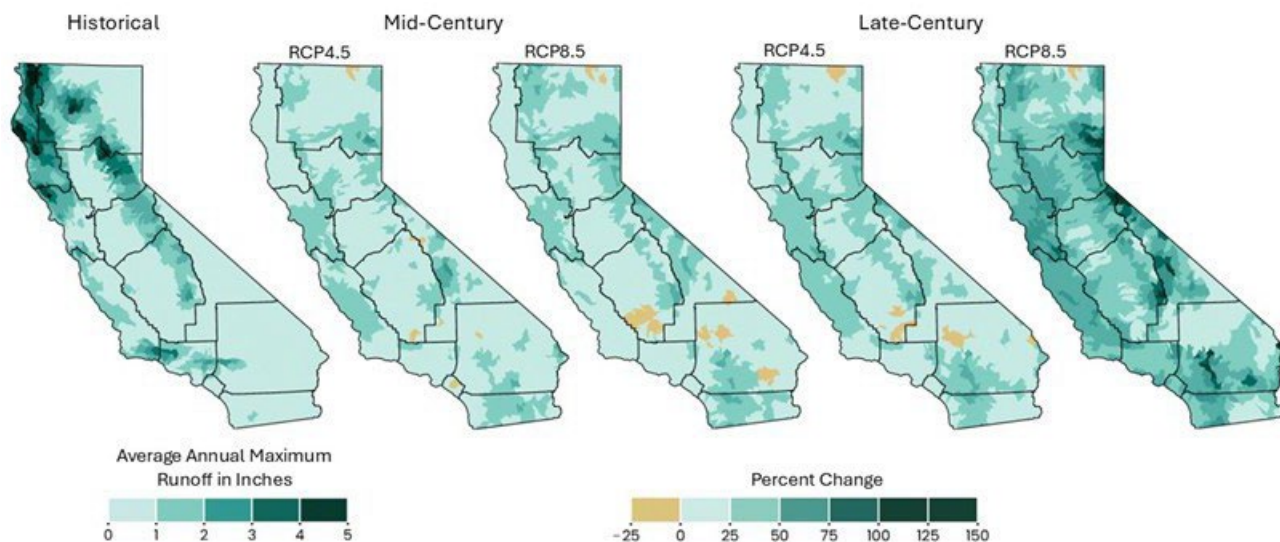


Figure 5 Average annual maximum total runoff (in inches) over time.

The CCVRA adopted Total Runoff as an indicator of the impact of climate change on the future likelihood of flooding for areas that are known to be exposed to riverine flooding under current conditions. To achieve this, it was assumed that increases in basin-scale runoff corresponds to increases in the likelihood of high-flow events on the order of the 100-year or 500-year floods. A simple, non-stationary flood-frequency relationship can be used to illustrate this effect: If flood magnitudes scale approximately with total runoff, then increases in runoff on the order of 20% to 40% can shift a present-day 100-year flow toward a frequency more comparable to a 50-year event. Larger increases in runoff may shift the same flow toward an even more frequent event category (e.g., ~20- to 30-year). While the CCVRA does not attempt to calculate new RPs explicitly, these relationships provide a defensible basis for treating large increases in runoff within a watershed as indicative of higher likelihood of floodplain inundation in the future within the same watershed.

To operationalize this concept within the CCVRA risk matrix methodology, projected Total Runoff values were grouped into ranges reflecting small, moderate, and large hydrologic change. Each range corresponds to an incremental upward shift in the likelihood category assigned to the present-day FEMA 100-year floodplains (representing a “Possible” likelihood). The adjustment framework is as follows:

- If the future total runoff increases by 20% to 40%, the future likelihood is increased by one category to “Likely”
- If the future total runoff increases by 40% to 80%, the future likelihood is increased by two categories to “Very Likely”
- If the future total runoff increases by 80% or more, the future likelihood is increased by three categories to “Exceptionally Likely”
- The likelihood of the historical 500-year flood zone (representing an “Unlikely” likelihood) is increased to “Possible” or 100 years for all future climate scenarios.

This adjustment method is intended as a planning-level screening tool to help identify where flood risk may increase under future climate conditions across the state. It is not intended to delineate future floodplains, nor does it attempt to update or replace FEMA Flood Insurance Rate Maps (FIRMs). This approach should be applied only for planning and prioritization purposes and is not designed to meet the level of technical rigor required for engineering design, regulatory decision-making, or floodplain mapping.

This portion of the CCVRA was finalized prior to the availability of LOCAV2-VIC model simulations. Consequently, these simulations were not integrated into this study but are identified as a primary data source for subsequent updates to the statewide assessment.

5.2 Exposure

After the potential for riverine flooding was identified, the next step was to assess which assets (i.e., roads and bridges) are located within mapped flood hazard areas. Using GIS-based spatial analysis, every asset was evaluated for maximum exposure to present-day FEMA floodplains. Specifically, the analysis checked:

- Is the asset located in a 100-year (1% annual chance) flood zone?
- Is the asset located in a 500-year (0.2% annual chance) flood zone?

Future floodplain extents and depths were not modeled explicitly, as no statewide, climate-adjusted FEMA floodplain dataset currently exists. Instead, assets located within the present-day 100-year or 500-year flood zones were assumed to remain intersecting those areas in the future but with adjusted likelihoods of inundation based on the maximum projected change in Total Runoff as described above. This approach preserves the spatial footprint of vetted floodplain maps while allowing the probability of flooding to be augmented for assigning risk ratings.

Figure 6 and Figure 7 below show the exposure of the SHS to riverine flooding and Total Runoff.



Figure 6 Exposure of the SHS to present-day riverine flooding.

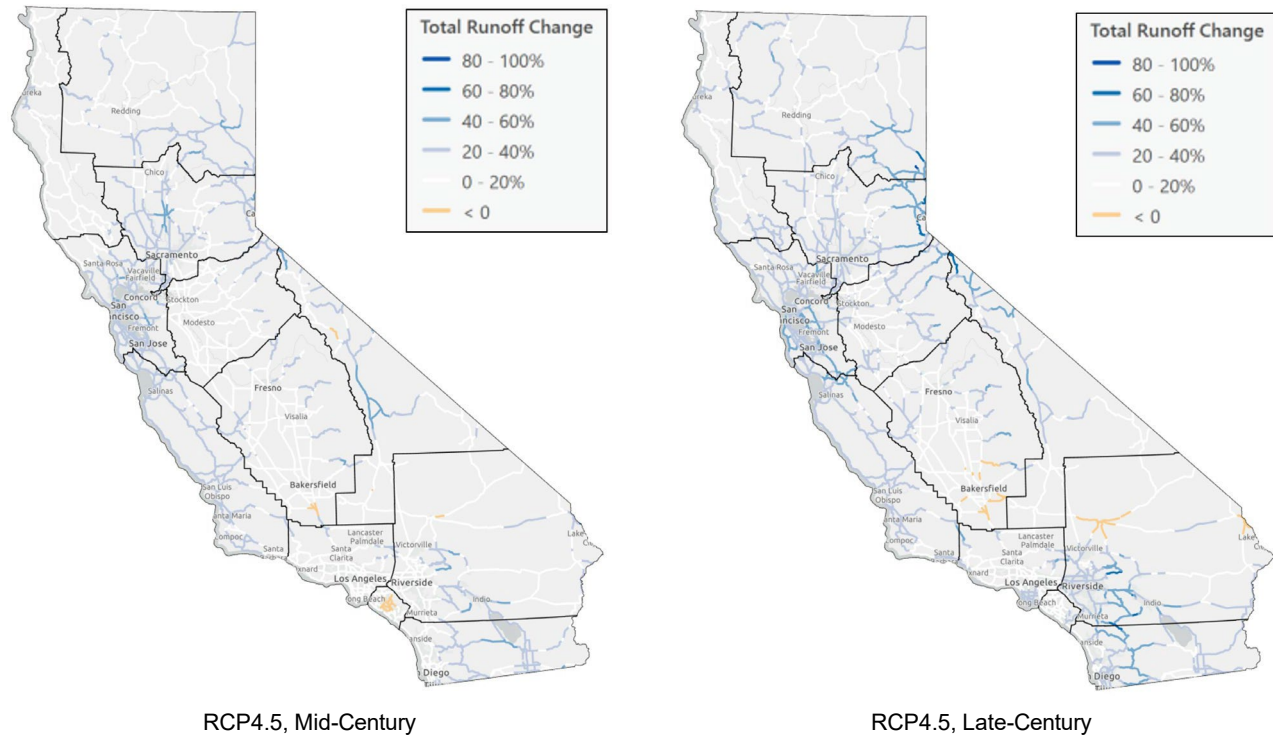


Figure 7 Exposure of the SHS to total runoff, expressed as percent change from historical, for RCP4.5 for mid-century (left) and late-century (right).

Approximately 11% of the SHS is located within the present-day FEMA 100-year floodplain, indicating a meaningful level of statewide exposure to riverine flooding. An additional 4% of the SHS lies within the 500-year floodplain, representing areas with lower but still notable flood potential. All the CCVRA results are presented using centerline miles, including both alignments, to be consistent with the original roadway dataset.

Notably, almost 20% of the SHS is situated in areas not mapped by FEMA, meaning flood exposure in these locations is not well characterized by publicly available data. These unmapped areas represent important data gaps for understanding systemwide vulnerability.

Looking ahead, Total Runoff is projected to increase across much of California, with the largest increases generally occurring in Districts 4, 8, 11, as well as throughout the Sierra Nevada. These trends suggest that the likelihood of inundation within currently mapped floodplains may rise in the future, even if the spatial extent of those floodplains is not explicitly modeled.

All exposure results were integrated directly into the Caltrans asset geodatabase to support tracking, querying, and future updates.

5.3 Vulnerability

This section describes how susceptible the CCVRA assets are to impacts from riverine flooding based on the hazard intensity and asset characteristics.

5.3.1 Roadway Vulnerability to Riverine Flooding

Riverine flooding poses a significant threat to the roadways along our SHS. When flood events occur, they can compromise the safety, quality, and operation of the roadway for several reasons:

Impassable roadways: High floodwaters themselves, or debris carried by the fast-moving water, can block roads and create hazardous conditions, disrupting vehicle operations.

Wash-out: If the flooding is deep, fast, and enduring, it can lead to roadway washout. This involves a combination of the road being submerged (inundation) and the soil/materials underneath being eroded. Washouts often require the road to be completely rebuilt.

Prolonged physical damage: Prolonged exposure to heavy rain or river overflow can damage the structure of the road by eroding base materials, saturating the subgrade (the soil layer beneath the road surface), and washing out surface layers. Even seemingly shallow flooding can cause lasting harm by degrading asphalt and reducing the road's overall service life by softening and eroding the foundation.

In summary, the extent of the disruption and damage to a road largely depends on three factors: water depth, flow velocity, and the duration of inundation. The CCVRA applies three damage states to roads representing downtime-specific impacts from riverine flooding:

1. Temporary: Disruption to vehicle operations due to floodwater on the roadway.
2. Short-term: Disruption to vehicle operations due to debris on the roadway, and the need for minor repairs.
3. Long-term: Road closure due to the need for roadway reconstruction resulting from a wash-out.

Table 4 summarizes the representative damage states and corresponding consequences for roadways affected by riverine flooding used in this study.

In the past, major winter storms have caused flood-related roadway failures along State Route 1, where inundation and erosion led to roadway washouts, as seen in Figure 8, requiring full reconstruction before reopening. Studies also show that flooding can degrade pavement performance and reduce service life by saturating underlying layers and weakening structural support, increasing susceptibility to damage during and after flood events.

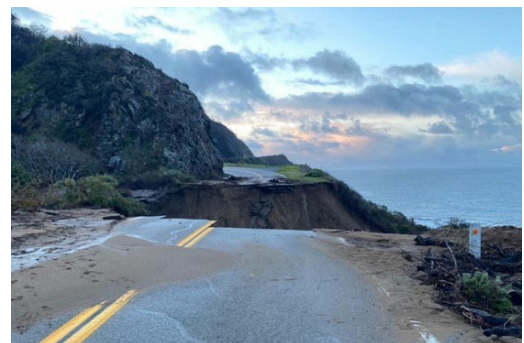


Figure 8 Example washout on State Route 1.

5.3.2 Bridge Vulnerability to Riverine Flooding

Riverine flooding poses a variety of threats to bridges, ranging from temporary closures to structural failure. The damage is driven by four primary factors: water depth, flow velocity, the amount of sediment being carried, and force of debris impacts.

Flooding affects bridges in three main ways:

Impassable Approaches: Floodwaters flow over the roadway approaches, requiring temporary closure even if the bridge deck is intact.

Scour (Foundation Erosion): High-speed, turbulent water around the supporting piers and abutments causes severe scour, the erosion of foundation soil. This scour can expose the foundations, cause abutments to settle, and ultimately lead to a loss of bearing capacity, which is critical for stability.

Physical Damage: Fast-moving water carries debris (like trees), which can strike and damage the main bridge structure, while buoyant forces (water lifting the bridge) can also cause structural harm. These threats may require inspection, repair, and in extreme cases, complete bridge replacement.

This study evaluates three damage states to bridges resulting from riverine flooding:

1. Short-term: The bridge must be closed temporarily due to inundation of the roadway approaches until the floodwaters recede.
2. Medium-term: The bridge foundation requires stabilization or major repair resulting from impacts from high-speed floodwaters.
3. Long-term: Core structural elements of the bridge require replacement due to major damage resulting from extreme flood depths and velocities.

To determine if a bridge is susceptible to more serious damage (damage states 2 or 3), the condition of the substructure and superstructure is extracted from the NBI records and integrated into this assessment.

Table 4 summarizes the representative damage states and corresponding consequences for bridges affected by riverine flooding used in this study.

During the 2017 winter storms, heavy rainfall and associated landslides severely damaged the Pfeiffer Canyon Bridge on State Route 1 near Big Sur, causing Caltrans to close the bridge after ground movement displaced a support column and left the structure beyond repair. Examples of scour impacts on bridges include the Boulder Creek Bridge in Santa Cruz County, where Caltrans accelerated a scour repair project to protect the abutment from continued erosion, and the Redwood Creek Bridge, which received state funding in 2024 to mitigate local scour.



Figure 9 Bridge scour of the Boulder Creek Bridge, Santa Cruz County (District 5).

5.3.3 Tunnel Vulnerability to Riverine Flooding

Riverine flooding can disrupt tunnel functionality by causing water and debris to accumulate both at the entrances (portals) or within the tunnel bore, particularly where slopes are steep or drainage capacity is undersized. Floodwaters can block access, erode approach embankments, and damage drainage and electrical systems. The main factors influencing damage are water depth, slope stability, and the capacity of the drainage system.

When portals are inundated, tunnels may be temporarily closed for safety and inspection. In areas with unstable slopes, combined rainfall and runoff can also trigger shallow slides that obstruct tunnel entrances.

This study evaluates two damage states to tunnels resulting from riverine flooding:

1. Short-term: tunnel closure due to floodwater and debris accumulation at portals.
2. Medium-term: combined flooding and slope instability around portals requiring cleanup and slope stabilization before reopening.

Table 4 summarizes the representative damage states and corresponding consequences for tunnels affected by riverine flooding used in this study.

In California, the combination of intense rainfall and complex terrain has caused multiple tunnel closures from flood-related debris. During the 2017 winter storms, storm-driven debris and slope instability affected approaches near the Tom Lantos / Devil's Slide tunnels on the San Francisco Peninsula (District 4), requiring cleanup and stabilization before reopening (ABC News, 2023).



Figure 10 Slope instability near the Tom Lantos tunnels on the SF Peninsula (District 4). Source: ABC News.

5.3.4 Culvert Vulnerability to Riverine Flooding

Flooding can damage culverts (pipes or tunnels that carry water under a road or embankment) through three main processes:

Blockage: When culverts are clogged by debris or sediment, the water backs up, causing upstream flooding.

Erosion and Washout: High flow velocities can erode the surrounding embankments and cause the pipes to become misaligned. Culverts with open-ended barrels or weak retaining walls are especially vulnerable to scour and complete washout when floodwater exceeds the system's design capacity.

Structural Damage: Culverts can also sustain structural damage from the intense hydraulic pressure of the floodwaters.

The risk and type of damage depend mainly on the flow velocity, the amount of debris being carried, and whether the culverts have protective features like concrete end treatments. Poor structural conditions and delayed maintenance can also increase the impacts of flooding on culverts.

This study evaluates two damage states to culverts resulting from riverine flooding, shown in Table 4:

1. Short-term: blockage due to debris and silt accumulation
2. Long-term: erosion or partial washout requiring replacement and earthworks.

In California, repeated high-intensity rainfall events have caused culvert failures and washouts. The atmospheric river storms in 2023 led to multiple culvert blockages and embankment collapses, including cases where flooding caused culvert failure and roadway closure requiring reconstruction. For example, flooding led to the failure of the Bethany Culvert along West Cliff Drive in Santa Cruz County, resulting in prolonged roadway closure and the need for culvert replacement and associated earthworks before reopening.



Figure 11 Bethany culvert failure in Santa Cruz County, District 5.

Damage State Description			Downtime			
			Temporary (< 2 days)	Short-term (2-10 days)	Medium-term (1.5-6 weeks)	Long-term (1.5-18 months)
Roads						
1	Floodwaters high enough for traffic to be limited for duration of event.	Road or lane closed until floodwaters recede & debris is cleared.	X			
2	Debris on road needs time for clearance & minor pavement repairs.	Road or lane closed until floodwaters recede & debris is cleared.		X		
3	Roadway washout or significant subgrade damage requiring significant repairs or replacement.	Reconstruction of washed-out roadway sections & embankments; slope stabilization & resurfacing required before reopening.				X
Bridges						
1	Approach roads inundated; bridge structure intact, & service resumes after event.	Bridge closed until floodwaters recede & debris/silt is cleaned.		X		
2	Scour or foundation instability at footings, piles, piers, or abutments.	Placement of riprap around piers or abutments, &/or installation of gabions at riverbanks.			X	
3	Structural damage to substructure or superstructure due to high flow velocity or debris impact.	Core structural elements of the bridge (sub/superstructure) need replacement.				X
Tunnels						
1	Floodwaters or debris temporarily block tunnel portals; structure unaffected.	Tunnel closed until floodwaters recede & debris is cleared.		X		
2	Tunnel closed due to floodwaters, debris, or slope instability near portals.	Tunnel closed until floodwaters recede & debris is cleared. Earthworks to ensure slope stability around portals.			X	
Culverts						
1	Clogged culvert due to debris/silt accumulation or backflow; minor flooding of approaches.	Culvert not functional until floodwaters recede & debris/silt is cleaned.		X		
2	Partial washout, embankment erosion, or misalignment of culvert barrel. Possible roadway failure.	Trenching works likely required for replacement of culvert and/or earthworks.				X

Table 4 Damage states for riverine and coastal flooding.

5.4 Baseline Risk Assessment

The final stage of our risk assessment combines all the previous information to determine the baseline risk ratings for each asset. The process combines:

1. **Hazard:** the likelihood and severity of riverine flooding
2. **Exposure:** whether the asset is in the area that may experience flooding
3. **Vulnerability:** how susceptible the asset is to damage if flooded, based on the hazard intensity and asset characteristics, if available.

By combining these factors, which define the likelihood of an event and its expected consequences, a single, easy-to-understand risk rating is derived for every asset and every climate scenario using the risk matrix in Table 1. The CCVRA developed a suite of Python scripts to complete this operation, and the results were then added to the GIS datasets for simplicity, clarity, and completeness.

Redefining the Risk for Bridges

When assessing the risk to roads, bridges, tunnels, and culverts, the risk assigned to bridges is adjusted to prevent overestimating the hazard.

Although all bridges crossing mapped waterways are automatically flagged as exposed to riverine flooding on FEMA flood maps, many were specifically designed to withstand typical flood impacts, meaning severe damage is not necessarily expected.

To avoid being overly cautious when assessing risk, a more detailed check is done for exposed bridges: the assessment includes looking at whether the bridge approaches (the roads leading to the bridge) are also exposed to flooding.

A bridge exposed to riverine flooding is assigned a “Very Low” risk rating when both approaches are confirmed to be outside the flood zone AND the bridge substructure is not flagged as deficient (weak or damaged). For all other scenarios (if either approach is exposed, or the substructure is deficient), the consequences and resulting risk ratings are determined based on the detailed vulnerability assumptions described previously.

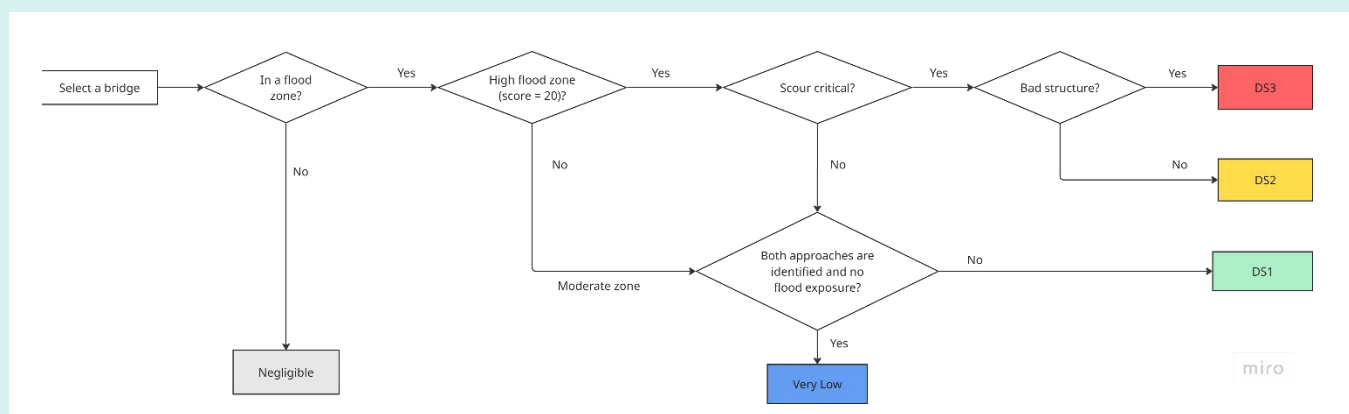


Figure 12 Adjusted damage state assignment for bridges exposed to riverine flooding.

The maps and plots below summarize the statewide risk results for riverine flooding for roadways. Figure 13 shows the geographic distribution of the results for present-day (left) and late-century (right), assuming the RCP4.5 scenario for the total runoff indicator. In these maps, only risk ratings of Medium and above are shown. Based on the possible combinations of hazard and consequences for riverine flooding, the maximum risk rating that a roadway segment can achieve for present-day is Medium, which can increase up to Very High in future scenarios.

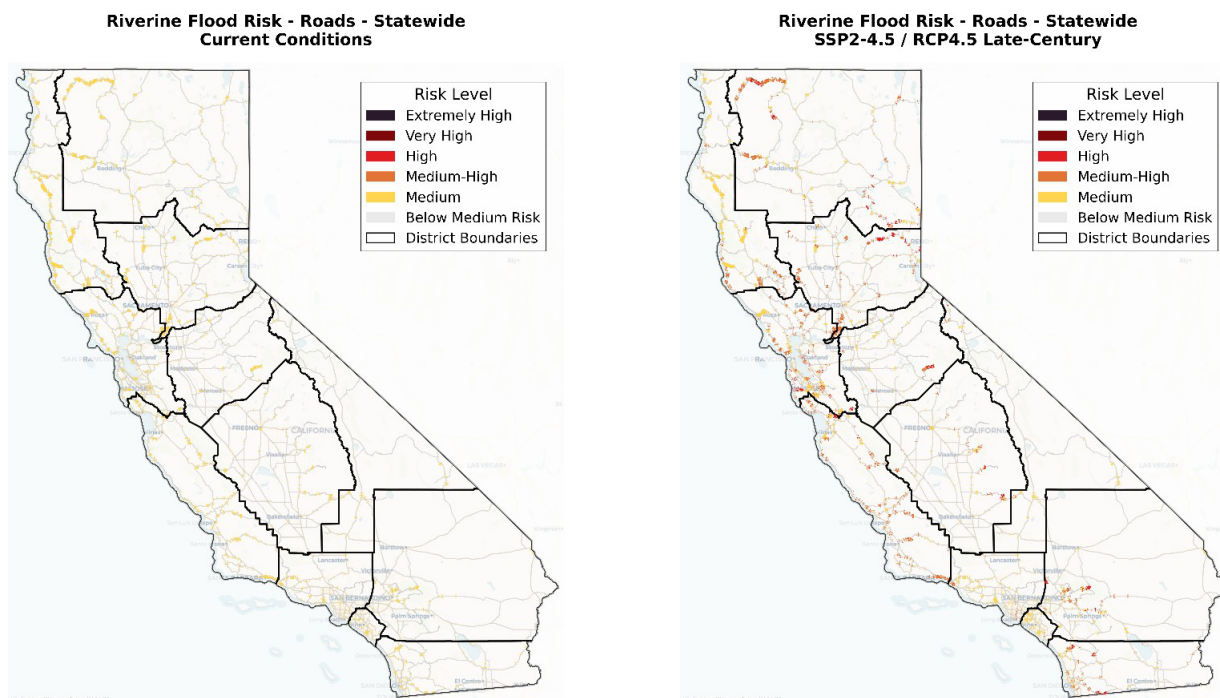


Figure 13 Statewide distribution of the baseline risk ratings for riverine flooding for present-day (left) and late-century for RCP4.5 (right). Only Medium and higher risk ratings are shown.

Figure 14 and Figure 15 summarize the statewide results for roadways and bridges respectively. The results are summarized by climate scenario and by risk rating using the total (left plots) and percentage (right plots) centerline miles.

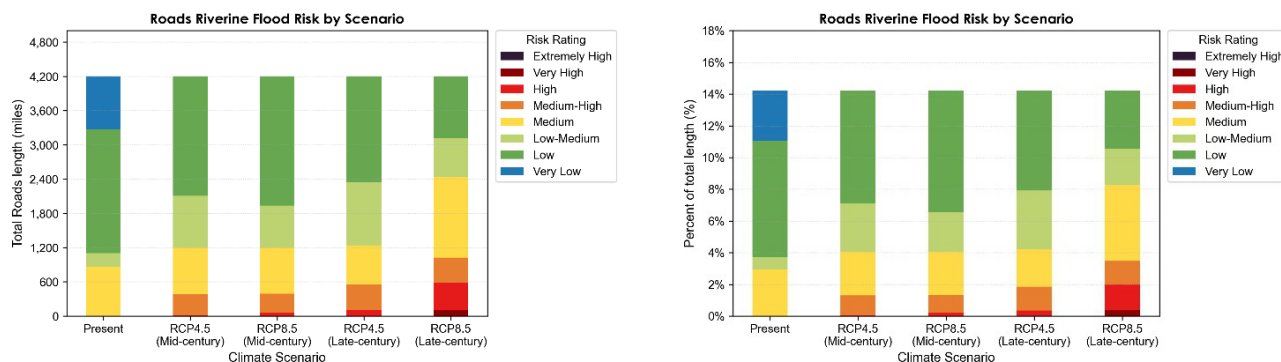


Figure 14 Miles (left) and percentage (right) of roadways assigned to each risk rating for riverine flooding for all climate scenarios.

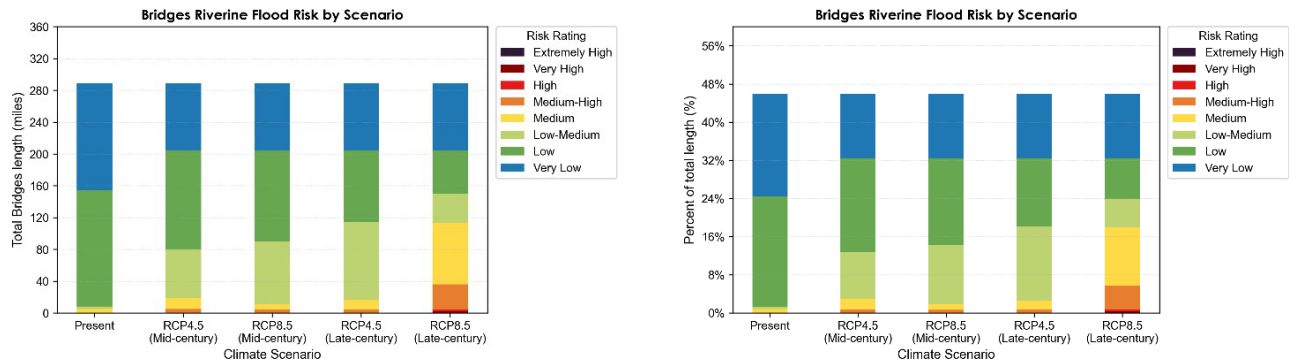


Figure 15 Miles (left) and percentage (right) of bridges assigned to each risk rating for riverine flooding for all climate scenarios.

The figures show that while a substantial portion of the SHS is exposed to riverine flooding (about 15%), most segments are expected to experience limited damage and/or low likelihood, leading to limited risk. This finding is reasonable considering that assets are expected to be designed to withstand the 100-year flood event. The highest risk is experienced by segments that are exposed to frequent flooding and landslide susceptibility simultaneously, which can significantly damage the road.

While the present-day risk ratings are moderate, a portion of the assets is expected to experience more frequent flooding and higher risk in the future due to increased extreme precipitation and runoff. It is therefore important that Caltrans consider including future climate conditions in the design process.

Only a selection of the results is presented within the technical report to support the narrative, but the full suite of statewide and district-wide risk maps is included as an attachment to this report.

5.5 Key Findings

The CCVRA uses the FEMA NFHL maps to characterize the present-day riverine flooding hazard and the LOCAv1-VIC Total Runoff indicator to estimate the increase in future likelihood of flooding.

Based on the analysis of the FEMA NFHL maps, today 11% of the SHS lies within a 100-year flood zone, and 4% is within a 500-year flood zone. Almost 20% of the SHS lies in areas of currently unmapped riverine flooding hazard.

While the impact of flooding on the SHS is generally limited, roadways can be especially vulnerable to riverine flooding when they are also exposed to landslides as the combined effect of these hazards can cause significant damage. In these cases, roadways reach a Medium risk rating, the highest risk rating for present-day riverine flooding. The risk can increase up to Very High for future scenarios for large values of total runoff.

Coastal Flooding

Coastal flooding occurs when seawater moves inland due to high tides, storm surge, and wave-driven processes, and is expected to intensify as sea levels rise due to climate change. Unlike riverine flooding, coastal flooding can result in permanent or near-permanent loss of infrastructure, fundamentally altering the feasibility of asset protection or repair.

This chapter introduces the coastal flooding hazard and associated data sources, discusses which assets are exposed and how they are impacted, and combines this information to develop risk ratings across assets and climate scenarios.

6.1 Hazard

To analyze coastal flooding, the CCVRA uses data from the Coastal Storm Modeling System (CoSMoS), developed by the United States Geological Survey (USGS). CoSMoS analyzes coastal flooding extent and flood depth to make detailed predictions of storm-induced coastal flooding, erosion, and cliff failures over large geographic scales along the California coastline (Barnard et al. 2009; 2014).

SLR refers to the increase in the surface elevation of the world's oceans due to increasing global and local temperatures. As sea levels rise, the frequency of coastal hazards will increase and, in some locations, will trigger permanent inundation. In the CCVRA framework, permanent inundation represents a terminal exposure condition in which conventional repair or protection is no longer viable, necessitating asset abandonment, relocation, or full redesign.

The SLR scenarios selected for the CCVRA align with the latest Ocean Protection Council (OPC) guidance released in 2024 (California Ocean Protection Council, 2024) and are summarized in Table 5 below. Scientists have limited confidence related to how rapidly glaciers and ice sheets will melt in response to a warming climate, particularly after 2050 if climate change continues to accelerate (IPCC 2023c). Therefore, the late-century SLR projections span a wide range of SLR alternatives. Additional details on coastal flooding, the datasets used, and how the climate scenarios relate to the SLR scenarios are provided in Appendix A.

Coastal Hazard Data Gap:

CoSMoS was selected as the coastal flooding data source for the CCVRA; however, CoSMoS data was not available for the northern coastal counties (Del Norte, Humboldt, Mendocino) during this analysis. As a result, NOAA sea level rise inundation mapping was used for District 1. The NOAA data does not consider the breadth of coastal processes considered in the CoSMoS dataset.

Future updates are recommended to incorporate the recently released CoSMoS data specific to District 1.

Climate Scenario	Time Horizon	OPC (2024) Scenario		CoSMoS Scenario	NOAA Scenario (D1 only*)
	Historical		0 ft	0 cm (0 ft)	0 ft
SSP2-4.5	Mid-century	Intermediate	0.8 ft	25 cm (0.8 ft)	1.0 ft
SSP2-4.5	Late-century	Intermediate	3.1 ft	100 cm (3.3 ft)	3.0 ft
SSP5-8.5	Mid-century	High	1.2 ft	50 cm (1.6 ft)	1.5 ft
SSP5-8.5	Late-century	High	6.6 ft	200 cm (6.6 ft)	6.5 ft

* Due to the absence of CoSMoS data for Del Norte, Humboldt, and Mendocino counties during the CCVRA coastal flooding analysis, the District 1 exposure was modeled using the NOAA Sea Level Rise Viewer.

Table 5 CCVRA SLR scenarios and mapping between OPC, CoSMoS, and NOAA.

The CCVRA analyzes two types of coastal flooding, as recommended by the OPC and as shown in Figure 16 below:

- **Permanent inundation (High-Tide Flooding):** This is the flooding that occurs when daily high tides cause water to move inland. High-tide flooding is also referred to as “sunny day” flooding to represent flooding that occurs in the absence of a storm event.
- **Temporary inundation (Storm-related Flooding):** This occurs when extreme tides or storm events cause elevated coastal water levels to overtop the shoreline, resulting in flooding of inland areas. Once the elevated coastal levels subside, the floodwaters recede.

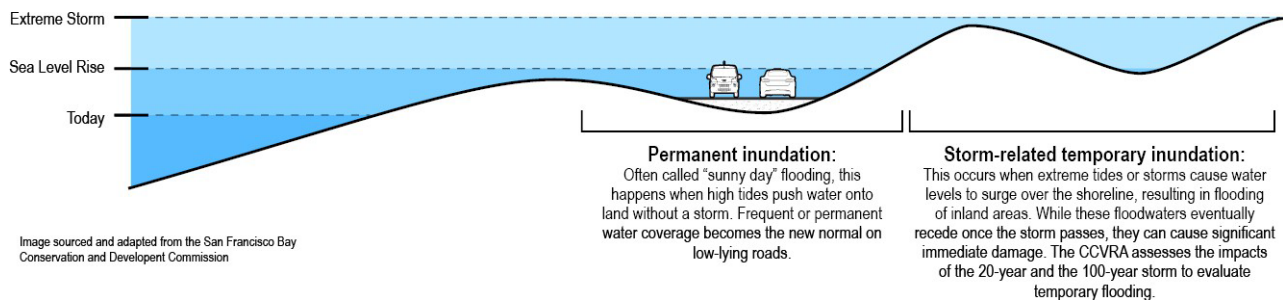


Figure 16 Graphical description of permanent and temporary inundation.
Adapted from the San Francisco Bay Conservation and Development Commission (2017).

For storm-related flooding, the CCVRA uses both the 20-year storm (5% chance of occurring annually) and the 100-year storm (1% chance of occurring annually) from CoSMoS. For District 1, where CoSMoS data was unavailable, three feet were added to each NOAA scenario to represent the associated 100-year storm event, based on an analysis of the CoSMoS data from the adjacent coast.

Figure 17 shows how coastal flooding (both permanent and storm-related) is expected to progress with rising sea levels in San Diego.

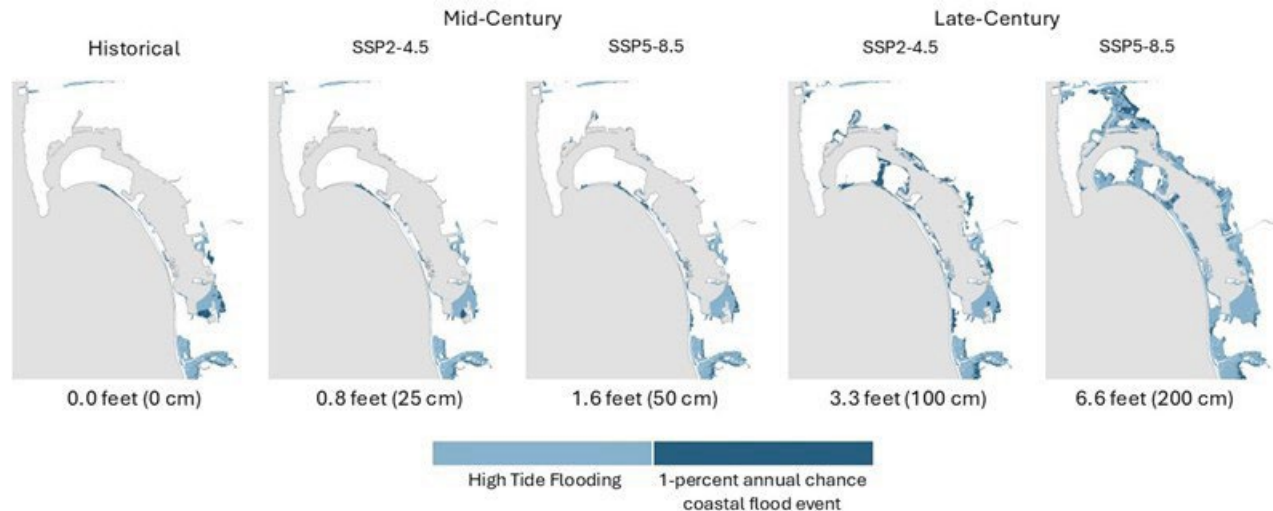


Figure 17 High-tide and storm-based flooding in San Diego with increasing SLR scenarios.

6.2 Exposure

Using GIS-based analysis, the exposure of each asset to coastal flooding was evaluated across all the SLR scenarios and storm events. For each SLR scenario, three storm events are considered:

- **No storm** (equivalent to permanent inundation)
- **20-year storm**: represents temporary flooding caused by a storm event with a 5% chance of occurring in any given year (Note: This was applied to all coastal districts except District 1 due to different data sources)
- **100-year storm**: represents temporary flooding caused by a severe storm event with a 1% chance of occurring in any given year

All exposure results were integrated directly into the Caltrans asset geodatabase to support tracking, querying, and future updates.

Only the six coastal districts (D1, D4, D5, D7, D11, D12) are exposed to coastal hazards. Currently, about 90 miles of roads are exposed to coastal flooding, mainly during storm events. However, as climate change progresses, up to 440 miles of coastal roads could be impacted, and up to 330 miles could be permanently flooded and lost, see Figure 18.

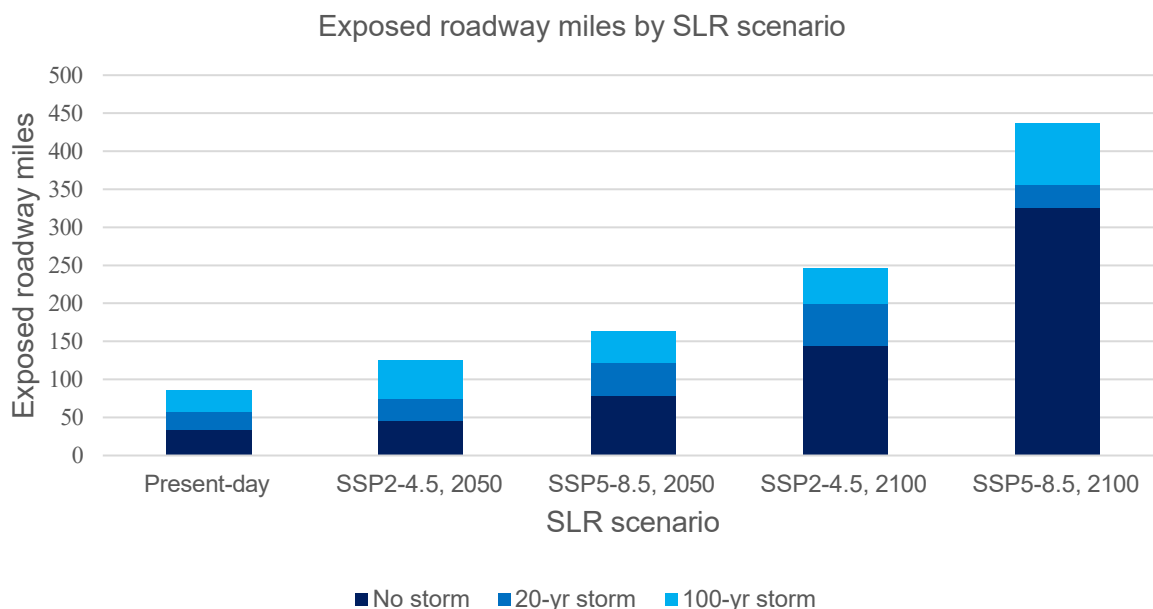


Figure 18 Miles of coastal roads exposed to coastal flooding for each SLR scenario.

6.3 Vulnerability

The vulnerability, or susceptibility to damage, for all Caltrans assets (roadways, bridges, tunnels, and culverts) is analyzed using the same damage states and consequence logic established for riverine flooding.

In essence, whether the asset is impacted by overflowing rivers or rising seawater (coastal flooding), the structural damage mechanisms, severity criteria, and repair downtime categories remain consistent. For a detailed discussion of how floodwaters impact each asset type (e.g., through washout, scour, blockage), please refer to the Riverine Flooding chapter and Table 4.

6.4 Baseline Risk Assessment

The final stage of the risk assessment combines the hazard, exposure, and vulnerability information to determine the baseline risk ratings for each asset. By combining these factors, which define the likelihood of an event and its expected consequences, a single risk rating is derived for every asset and every climate scenario using the risk matrix in Table 1.

While the overall process is similar to the one discussed for riverine flooding in Section 5.4, coastal hazards include the potential for permanent exposure. To account for this severe consequence, the risk rating is adjusted for assets facing permanent inundation. These assets are automatically assigned the highest risk category: "Extremely High," as this level of damage requires asset abandonment, relocation, or complete redesign.

For each SLR scenario, the assessment considers three storm events: no storm (equivalent to permanent inundation), 20-year storm, and 100-year storm. The assessment then calculates a risk rating for each storm scenario and assigns the highest risk rating to each SLR scenario, as described in Figure 19.

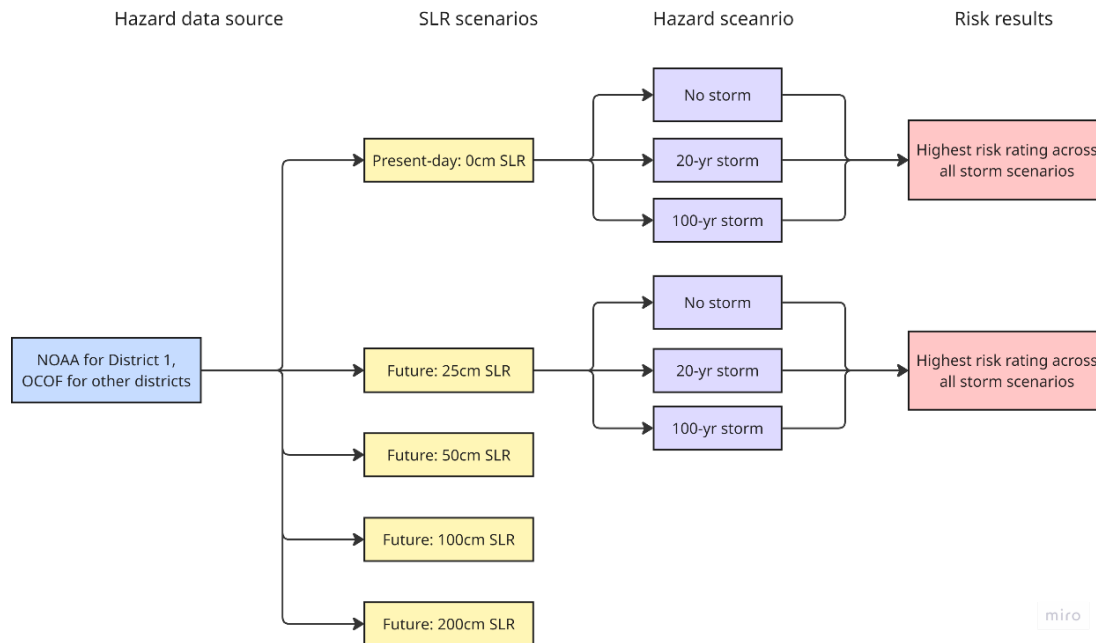


Figure 19 Graphic representation of the SLR and storm scenarios included in the CCVRA, including how they inform the risk assessment.

Also aligned with riverine flooding, the coastal flooding risk assessment was adjusted for bridges to evaluate whether the inundation is contained under the bridge or involves the bridge approaches, as well. This adjustment reflects the functional reality that a bridge can remain operational when inundation is confined to the waterway beneath the structure and does not impair approach access or compromise structural integrity.

While the adjustment is slightly different for the “No storm” and the storm-related scenarios (detailed in Figure 20 and Figure 21 below respectively), a bridge exposed to coastal flooding is assigned a “Very Low” risk rating when both approaches are experiencing minimal or no flooding AND the bridge substructure is not flagged as deficient.

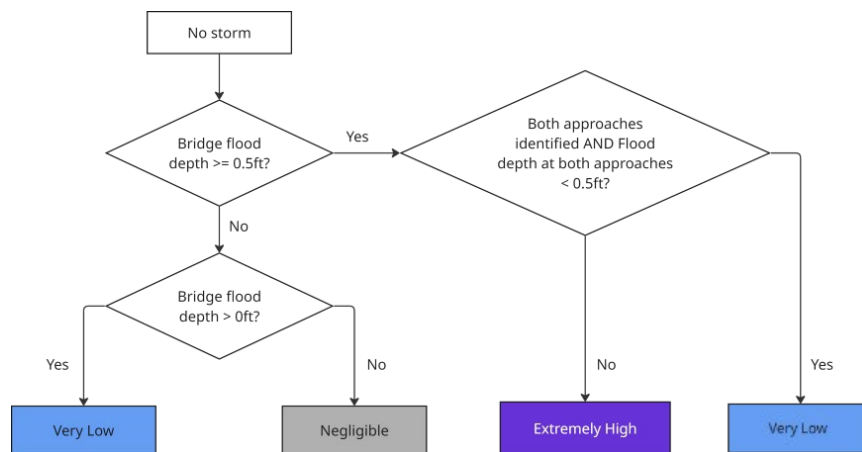


Figure 20 Adjusted damage state assignment for bridges exposed to permanent (i.e., not storm-related) coastal flooding.

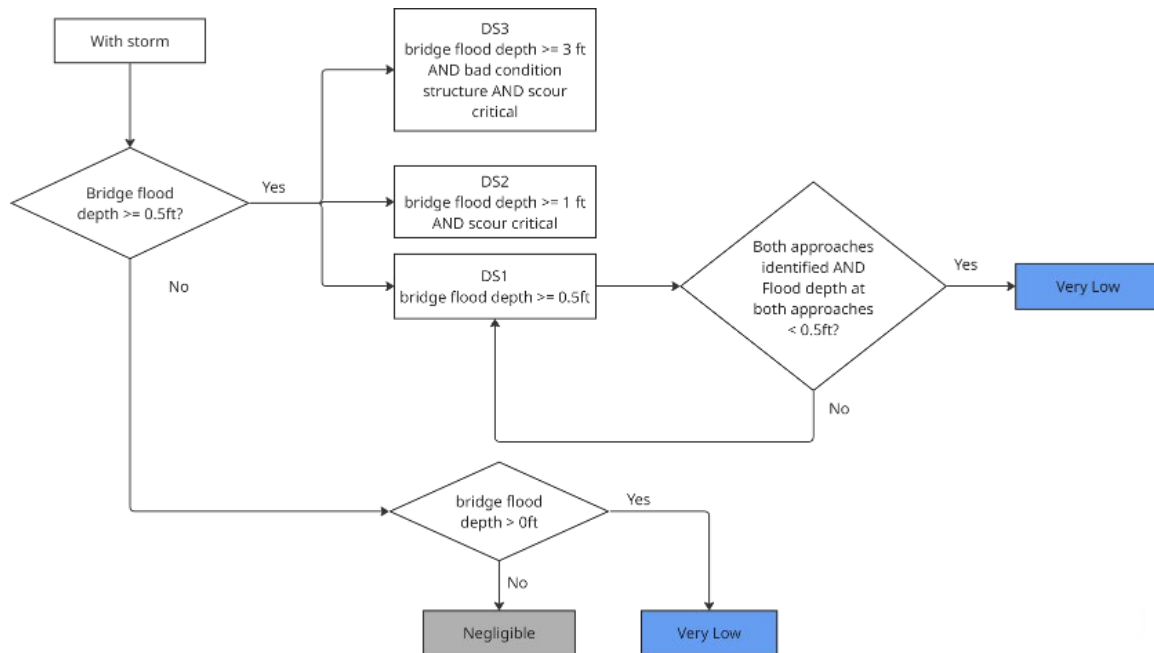


Figure 21 Adjusted damage state assignment for bridges exposed to temporary (i.e., storm-related) coastal flooding.

The plots below summarize the statewide risk results for coastal flooding for roadways and bridges respectively. The results are summarized by climate scenario and by risk rating using the total (left plots) and percentage (right plots) centerline miles. The risk results confirm the findings of the exposure assessment: An increasing portion of coastal roads will be affected by coastal flooding and permanent loss as SLR increases throughout the century.

While the percentage plots show that coastal flooding only affects a minor portion of the Caltrans statewide inventory, coastal hazards can have catastrophic consequences, requiring a full asset redesign or relocation inland, evidenced by the highest risk rating of Extremely High.

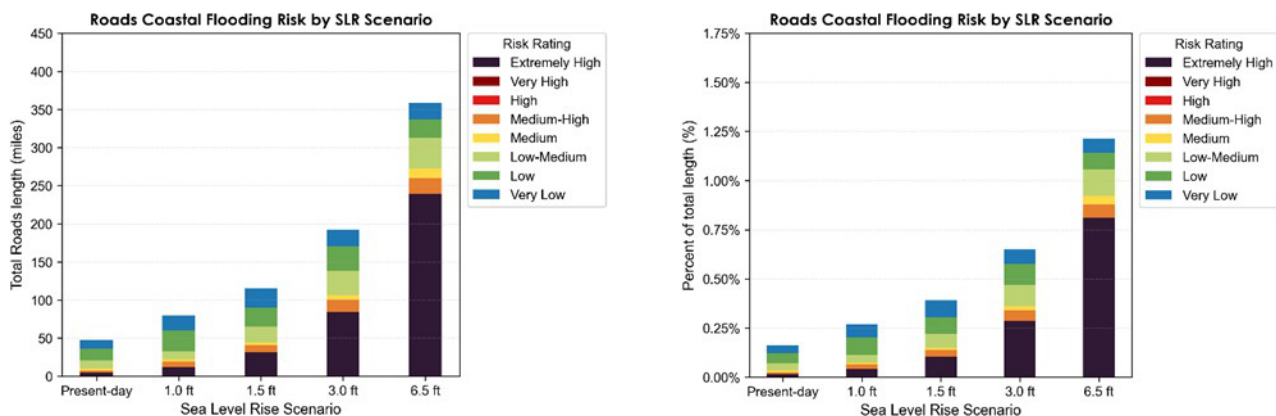


Figure 22 Miles (left) and percentage (right) of roadways assigned to each risk rating for coastal flooding for all climate scenarios.

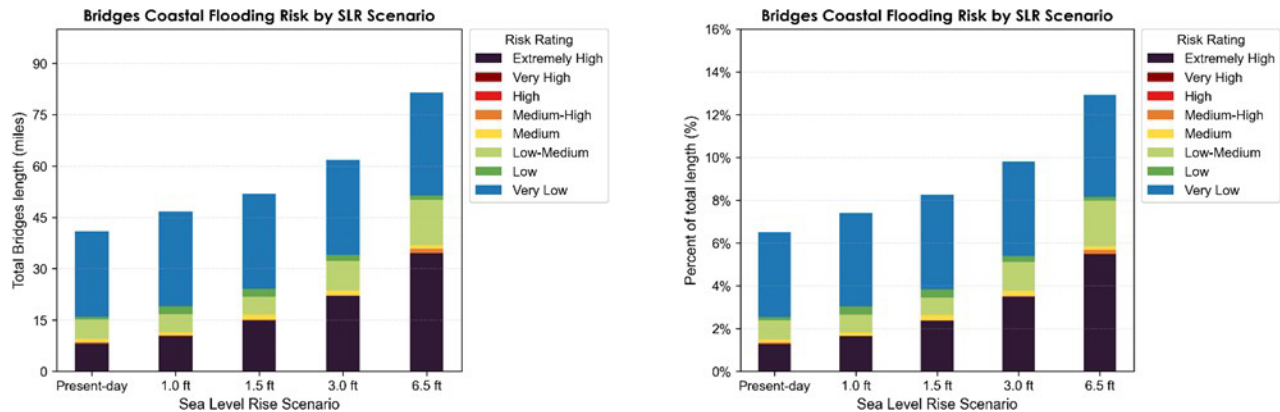


Figure 23 Miles (left) and percentage (right) of bridges assigned to each risk rating for coastal flooding for all climate scenarios.

Finally, the large portion of bridges with a Very Low risk rating confirms the need for the bridge risk adjustment discussed above, which downgrades the bridge risk when the approaches are not affected.

6.5 Key Findings

Among all evaluated hazards, coastal flooding represents the highest potential for permanent asset loss. This risk is primarily driven by sea level rise and regular tidal flooding, which increase over time. While mid-century impacts remain relatively modest, they give way to substantial late-century inundation of critical roadway segments. By late-century, this permanent inundation dominates risk outcomes, triggering automatic "Extremely High" risk ratings because affected assets will likely require total redesign, relocation, or abandonment.

Although coastal flooding affects a small percentage of the SHS, its consequences are disproportionately severe, often necessitating transformational adaptation rather than incremental repairs. This is further complicated by episodic storm flooding, which significantly expands exposure in mid-century scenarios even before permanent inundation sets in.

Notably, while bridge structures generally show lower risk than roadways because they can often keep functioning with rising water beneath them, their risk ratings escalate rapidly when flooding reaches the approaches, cutting off access regardless of the bridge's structural integrity.

Coastal Erosion: Cliff Retreat and Shoreline Change

Coastal erosion is a chronic hazard that causes permanent loss of infrastructure, requiring relocation or redesign rather than simple repair. This poses a significant long-term risk to coastal highways constrained by steep bluffs and narrow shorelines.

This chapter introduces the coastal erosion hazard and data sources, discusses which assets are exposed and how they are impacted, and combines this information to develop risk ratings across assets and climate scenarios.

7.1 Hazard

Coastal erosion is the progressive loss of land along the coast, primarily caused by the erosive force of seawater and waves. This process is expected to accelerate in the future due to rising sea levels caused by climate change.

The CCVRA uses two primary hazard datasets from the CoSMoS model for the coastal erosion analysis: shoreline change and cliff retreat. The future SLR scenarios are the same as for coastal flooding (see Section 6.1).

- **Shoreline change:** This analysis looks at how the shoreline, including beaches, will shift due to changing water levels and erosion and/or sediment deposition. For shoreline change, the CCVRA applies a conservative “hold-the-line” assumption, which assumes that existing shoreline armoring remains in place while beach nourishment is discontinued. This approach reflects the high cost, long-term uncertainty, and regulatory complexity associated with sustained nourishment efforts.
- **Cliff retreat:** This tracks the landward movement of cliff edges caused by erosion from tides, sea level rise, and wave impacts (Limber et al. 2018). For cliff retreat, the CCVRA applies a “let-it-go” assumption, recognizing that even where localized armoring exists, rising sea levels and increasing wave energy are expected to progressively undermine cliff bases over time. This assumption reflects observed retreat patterns along California’s coastline and aligns with the CoSMoS model intent.

It is important to note that the CoSMoS models are designed for broad-brush, regional determination of coastal retreat based on large-scale atmospheric, oceanic, and geological conditions. These models are not ideal for assessing site-specific, individual infrastructure components and hardened coastlines. They provide a general determination of susceptibility to coastal erosion or retreat.

7.2 Exposure

Because coastal erosion results in irreversible loss of land, any asset exposed to this hazard is assumed to experience permanent loss of function within the CCVRA framework. Using GIS-based analysis, the exposure of each asset to coastal erosion was evaluated for all the SLR scenarios previously discussed. All exposure results were integrated directly into the Caltrans asset geodatabase to support tracking, querying, and future updates.

Only the six coastal districts are exposed to coastal hazards (D1, D4, D5, D7, D11, D12). By mid-century, at least 32 miles of roads are expected to be lost to coastal erosion across the state. As climate change progresses and sea levels rise, up to 84 miles could be permanently lost, mostly located in D5, followed by D1, D4, and D7.

Figure 24 shows the coastal erosion progression along the northern coastline of D5 for SLR scenarios increasing from 25 centimeters (cm) (SSP2-4.5, mid-century) to 200 cm (SSP5-8.5, late-century) by mapping the SLR causing the first exposure for each roadway segment (i.e., the segment is not exposed to coastal flooding under sea level rise (SLR) scenarios that are below the mapped threshold scenario).

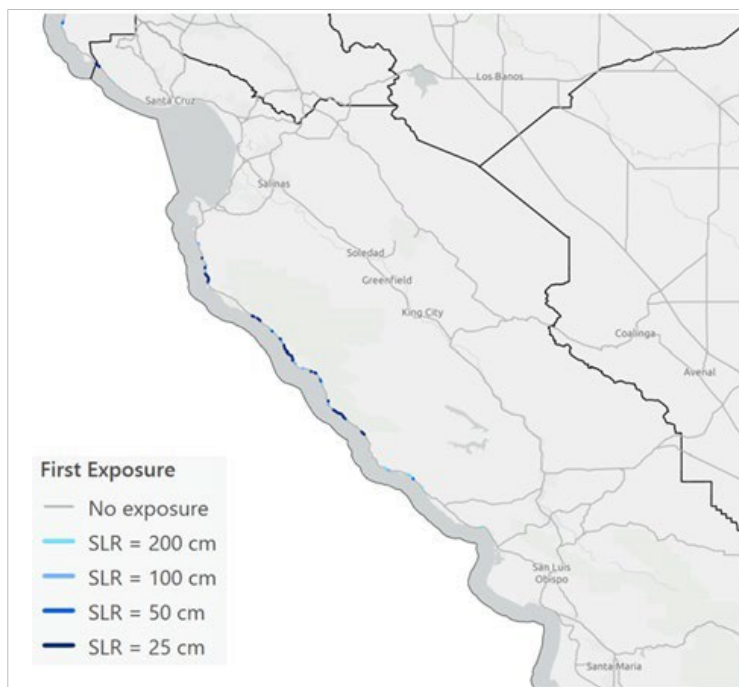


Figure 24 SLR scenario causing the first exposure to coastal erosion for the northern portion of District 5.

Exposure is concentrated along cliff-backed highways and narrow coastal benches, particularly in District 5, where limited setback distances and high retreat rates leave few viable protection options.

7.3 Vulnerability

This section describes how the CCVRA assets can be impacted by coastal erosion. Given the permanent nature of coastal erosion, the CCVRA applies a single terminal damage state across all asset types, representing complete loss of function and the need for relocation or replacement.

7.3.1 Roadway Vulnerability to Coastal Erosion

Coastal erosion can undermine the structural integrity of roadways built along cliffs, dunes, and beaches by progressively removing the ground supporting them. This occurs through three main processes: bluff retreat, beach lowering, and direct wave attack at the road base.

These erosive processes remove the support beneath the road pavement (the subgrade), leading to cracking, shoulder loss, or full pavement collapse. The damage depends heavily on the interaction between the power of the waves, the type of soil or rock in the bluff, and how close the road is to the active shoreline. When the erosion line reaches the road's foundation, major work like stabilization or moving the road inland (realignment) is necessary to keep the road open.

The CCVRA uses a single damage state to describe the impact of coastal erosion on roadways. This damage state represents a roadway washout that requires significant stabilization or relocation inland. Table 6 summarizes the representative damage state for roadways affected by coastal erosion used in this study.

In Sonoma County (District 4), State Route 1 at Gleason Beach has historically suffered from repeated bluff failure and roadway collapse following winter storms. Because coastal erosion and storm damage often lead to recurring closures and eventual alignment failure, Caltrans realigned the roadway and constructed a new bridge to shift State Route 1 approximately 400 feet inland. This realigned segment successfully bypasses the rapidly eroding ocean bluffs to ensure long-term route stability.

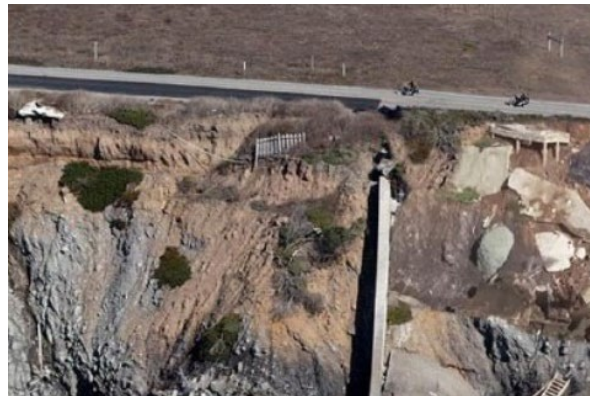


Figure 25 Bluff failure at Gleason Beach in Sonoma County, District 4.

7.3.2 Bridge Vulnerability to Coastal Erosion

Coastal erosion poses a threat to bridges by weakening the soil that supports the bridge ends (abutments and approaches). When cliff retreat or shoreline change removes this supporting soil, it exposes the bridge foundations to direct wave attack. This erosion can lead to settlement, loss of bearing capacity, or complete bridge failure. The risk depends on factors like how deep the foundation is, the type of soil (geotechnical setting), and the bridge's distance from the eroding shoreline.

The CCVRA uses a single damage state to describe the most severe impact of coastal erosion on bridges: bridge failure resulting from the erosion directly hitting the abutments or foundations. This damage requires replacement or relocation further inland. Table 6 summarizes the representative damage state for bridges affected by coastal erosion used in this study.

Coastal erosion is an active threat to California's bridge inventory, specifically where bluff retreat encroaches on structural approaches. Current examples include the Albion River Bridge, which requires stabilization to manage approach erosion, and the Gleason Beach realignment.



Figure 26 Albion River Bridge.

7.3.3 Tunnel Vulnerability to Coastal Erosion

Coastal erosion can destabilize tunnel portals built in retreating bluffs by removing the supporting ground and increasing lateral pressure on portal walls. Loss of toe support or slumping above portals can compromise their stability and make them unsafe for operation. Damage mechanisms for tunnels subject to coastal erosion include bluff retreat, undercutting of portal foundations, and increased rockfall or debris hazards near the entrance.

The CCVRA uses a single damage state to represent tunnels at risk of collapse when cliff retreat or shoreline change undermine portal structures, requiring stabilization, reinforcement, or relocation inland. Table 6 summarizes the representative damage state for tunnels affected by coastal erosion used in this study.

7.3.4 Culvert Vulnerability to Coastal Erosion

Coastal erosion can undermine culverts located at the base of eroding bluffs or near receding shorelines. The erosion removes the surrounding soil, which normally supports the pipe. When this support is lost due to bluff retreat or shoreline lowering, culverts can crack, deform, or collapse entirely. The failure of a culvert has serious consequences, including the collapse of the supporting road embankment, roadway washouts, and the permanent loss of the road's essential drainage function.

The specific failure mechanisms for culverts are governed by several factors, including the rate of bluff retreat, the elevation of the outlet, and the material of the culvert itself.

Research indicates that culverts exposed to coastal erosion often fail due to:

- Loss of backfill support: the surrounding soil is washed away
- Local scour: erosion of the soil directly around the culvert's opening
- Settlement of adjacent embankments: the soil next to the culvert sinks, pulling the culvert out of alignment

This study uses a single damage state to represent complete culvert washout when cliff retreat or shoreline change undermine the surrounding soil, requiring extensive earthworks for slope stabilization and culvert replacement. Table 6 summarizes the representative damage state for culverts affected by coastal erosion used in this assessment.

In California, storm-driven coastal erosion has damaged road embankments and caused culvert failures requiring replacement. For example, at Humboldt Lagoons State Park in Humboldt County, severe winter storms caused erosion beneath the roadway, resulting in culvert failure, roadbed washout, and prolonged road closures, with emergency repairs requiring culvert replacement and associated earthworks to restore access (Underwood, 2025; Redheaded Blackbelt, 2025; California Department of Parks and Recreation, 2025).



Figure 27 Culvert failure. Source: DirtWirx, 2026.

DS	Damage State Description	Repair Description	Downtime
1	<u>Roadway</u> washout	Stabilization with rock armor to protect remaining road sections; re-alignment to move roads inland, away from the eroding coastline; foundation reinforcement using deep pilings or concrete mats.	Permanent loss
1	<u>Bridge</u> failure	Significant bridge repairs, replacement, or relocation further inland.	Permanent loss
1	<u>Tunnel</u> is at risk of collapse	Significant stabilization, reinforcement, or relocation further inland.	Permanent loss
1	Complete washout of <u>culvert</u> , irrespective of end treatments and material	Undermining of soil beneath/surrounding culvert leading to culvert collapse or displacement. Requires extensive earthworks for slope stabilization and culvert replacement.	Permanent loss

Table 6 Damage states to Caltrans assets due to coastal erosion.

7.4 Baseline Risk Assessment

In the final step of the risk assessment, the hazard, exposure, and vulnerability information, which define the likelihood and expected consequences, are combined to return a single, easy-to-understand risk rating for each asset and climate scenario using the risk matrix in Table 1. Although risk ratings for coastal erosion result in the highest risk category once exposure occurs, this framework allows Caltrans to consistently compare erosion risk across scenarios, districts, and hazards.

As is also the case with permanent coastal inundation, coastal erosion has permanent implications for the affected assets, requiring a complete redesign or a relocation away from the eroding shoreline. To account for these severe consequences, for each SLR scenario, exposed assets are flagged with an “Extremely High” risk rating, which is the highest risk category.

The plots below summarize the statewide risk results for coastal erosion for roadways and bridges respectively. The results are summarized by climate scenario using the total (left plots) and percentage (right plots) centerline miles. The risk results mirror the findings of the exposure assessment: an increasing portion of coastal roads will be permanently lost as SLR increases throughout the century.

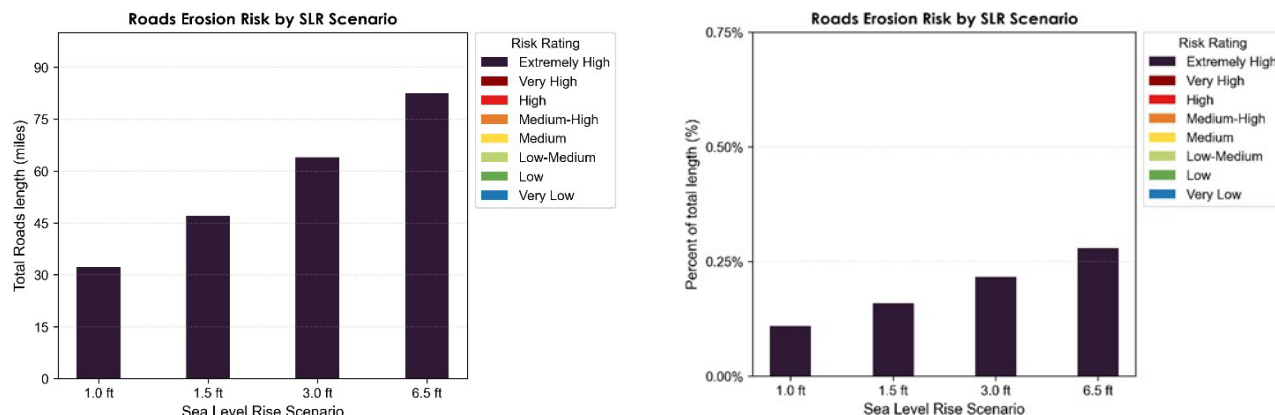


Figure 28 Miles (left) and percentage (right) of roadways assigned to each risk rating for Coastal Erosion for all climate scenarios.

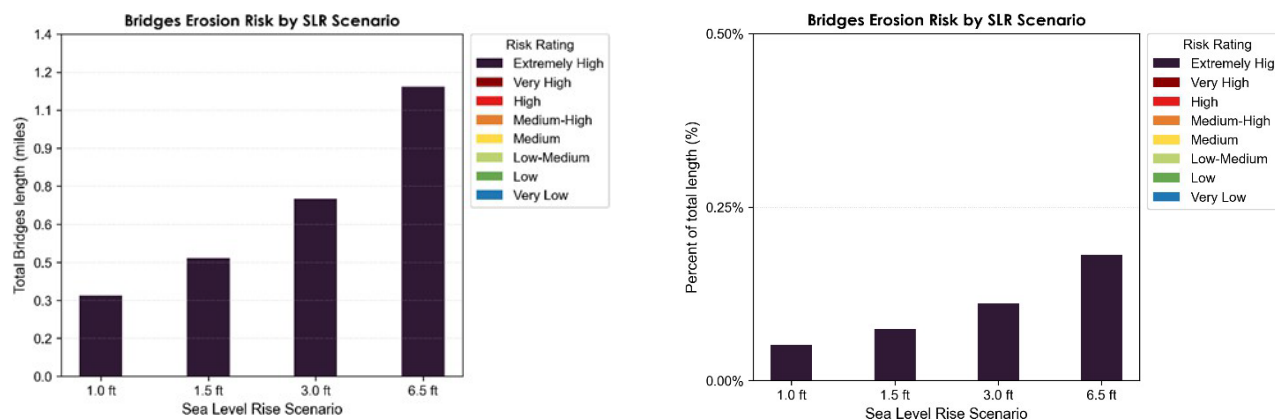


Figure 29 Miles (left) and percentage (right) of bridges assigned to each risk rating for Coastal Erosion for all climate scenarios.

7.5 Key Findings

Coastal erosion is a permanent and irreversible hazard to the SHS, as exposed assets are assumed to face a complete loss of function that necessitates full redesign or relocation. While the total roadway mileage affected by erosion is lower than that of flooding, the consequences are disproportionately more severe because they eliminate the feasibility of conventional repair or recovery. This exposure scales steadily with SLR, leading to substantial permanent losses of coastal roadway segments by late-century, with particularly high impacts in District 5.

Roadways backed by cliffs are the most vulnerable, as high retreat rates and limited inland setbacks leave few viable long-term adaptation options. Consequently, all exposed asset types (roadways, bridges, tunnels, and culverts) transition directly to an “Extremely High” risk rating. This classification underscores a critical shift in asset management: rather than relying on incremental protection, these locations will require transformative adaptation strategies to maintain system operations and connectivity.



Wildfire affects the SHS through direct heat and smoke impacts, damage to roadside and structural components, and post-fire secondary hazards such as debris flows, rockfall, and culvert blockage. These impacts can drive closures, maintenance burdens, and localized structural damage, particularly in forested corridors.

This chapter introduces the wildfire hazard and data sources, discusses which assets are exposed and how they are impacted, and combines this information to develop risk ratings across assets and climate scenarios.

8.1 Hazard

8.1.1 Present-Day

As the prevalence of wildfires increased in recent decades, the California Department of Forestry and Fire Protection's (CAL FIRE) Fire and Resource Assessment Program (FRAP) has produced multiple datasets to increase public awareness of wildfire risks and promote forest management practices that reduce the potential for damaging and intractable wildfires.

In 2018, CAL FIRE released a statewide wildfire threat dataset in support of the 2017 Assessment of California's Forests and Rangelands (CAL FIRE 2018b; 2018a), presented in Figure 30 below. Wildfire threat provides a measure of fuel conditions and fire potential, representing the relative likelihood of a damaging wildfire occurring in each area. Wildfire threat combines the fire probability, or the likelihood of a given area burning, with the potential fire behavior using five threat classes: Low, Moderate, High, Very High, Extreme.

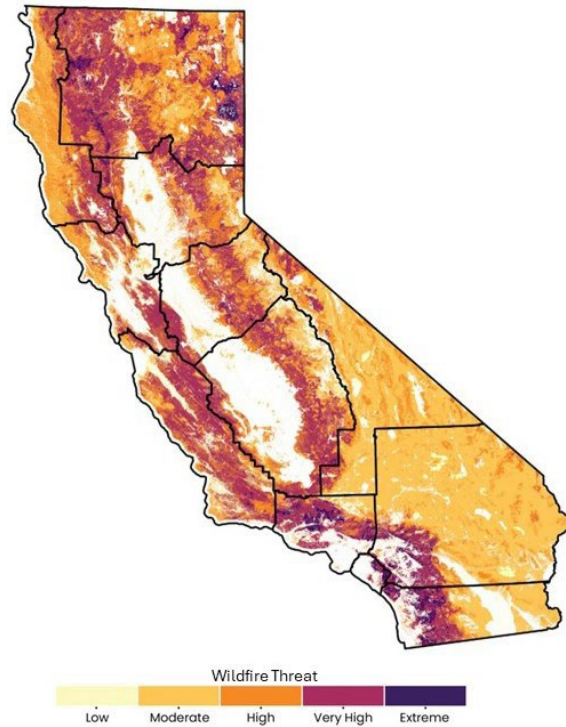


Figure 30 Wildfire threat classes across California.

Over the past two decades, substantial tree deaths occurred in forested lands across California. Trees were stressed from increasing temperatures, decreased water availability, and drought-related insect activity (Keen et al. 2022). The high levels of tree mortality rapidly altered fuel availability, increasing the likelihood of larger and more intense wildfires (Reed et al. 2023). In response, CAL FIRE and the USGS initiated a mapping effort to identify areas of increased tree mortality (CAL FIRE 2022). This dataset is used in the CCVRA to further characterize the likelihood of fire events in combination with the fire threat dataset and is presented in Figure 31.

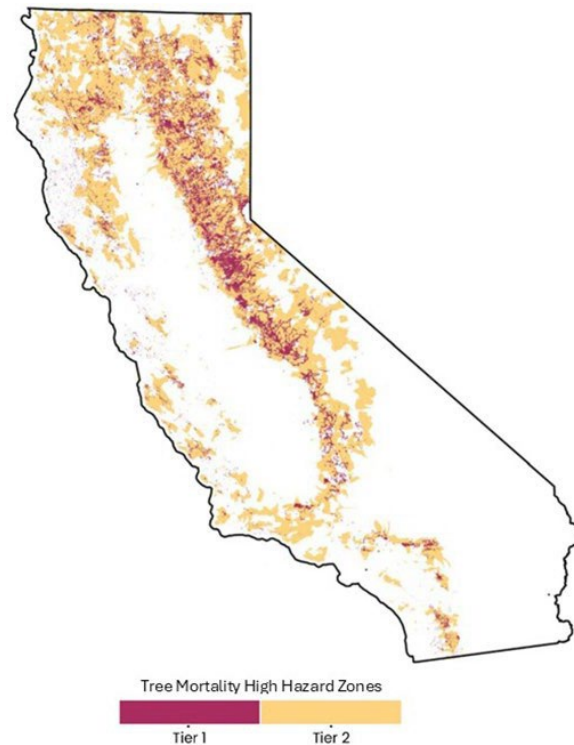


Figure 31 Distribution of the mapped tree mortality high hazard zones across California.

The CCVRA combines these two datasets using the methodology described in the fire threat documentation (CAL FIRE, 2018) to associate specific hazard combinations with likelihood categories, resulting in the mapping presented in Table 7. While this association is somewhat qualitative, it allows for consistent application of the standardized risk approach described in Section 3.1.

The likelihood categories and representative return periods are used as a standardized way to translate hazard class combinations into the CCVRA likelihood scale for consistent cross-hazard comparison. For the purposes of this document, a return period is the average time between fire events. These return periods are not intended to represent precise local fire recurrence intervals at an asset location; rather, they provide a consistent relative likelihood basis aligned with the statewide hazard classification approach.

Fire Threat Class	Fuel Rank	Likelihood Category	Representative Return Period
Low	Moderate	Unlikely	350 years
Low	High	Unlikely	350 years
Moderate	Moderate	Possible	250 years
Moderate	High	Unlikely	350 years
High	Moderate	Likely	50 years
High	High	Likely	50 years
Very High	Moderate	Very Likely	5 years
Very High	High	Likely	25 years
Extreme	Moderate	Very Likely	5 years
Extreme	High	Very Likely	5 years

Table 7 Likelihood category assignment for wildfire for present-day.

8.1.2 Adjustment for Future Climate

Over the past three decades, the number of wildfires and the associated acres burned has increased rapidly on the West Coast (Westerling 2016; Moran et al. 2025; Abatzoglou et al. 2021) due to a variety of factors, including warmer temperatures and more severe periods of drought.

CAL FIRE does not provide future fire threat data; therefore, the CCVRA uses a climate indicator, the change in the decadal (every 10 years) probability of a wildfire occurring, in conjunction with the present-day wildfire threat class data to estimate how the likelihood of a given intensity of wildfire may change in the future. This indicator was developed by the University of California, Berkeley's Geospatial Innovation Facility based on the methods described in Dale et al. (2018) using the wildfire simulations developed by Westerling in 2018. These wildfire simulations were developed for CCA4, and the source datasets are available from Cal-Adapt.

Figure 32 illustrates how the likelihood of wildfires occurring over a ten-year period ("decadal wildfire probability") is expected to shift throughout the state under different future climate conditions or climate change scenarios. Since this indicator is derived from LOCAv1, it is not bias-corrected, so the CCVRA uses the percent change relative to historical events instead of the absolute probabilities.

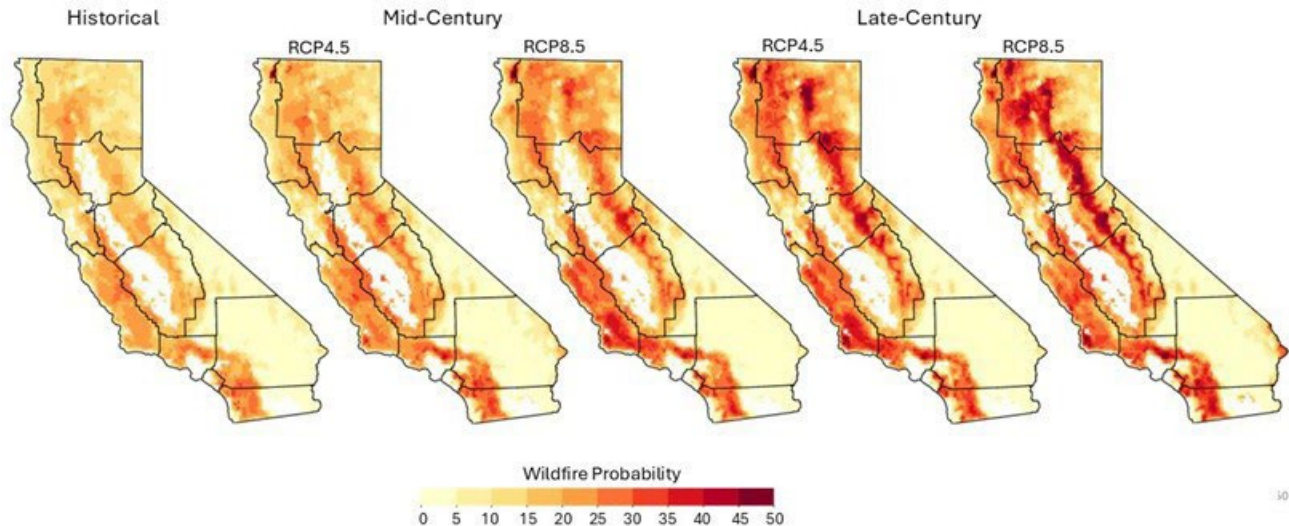


Figure 32 Probability of wildfire occurrence over a 10-year period across California based on historical data.

The percent change in the decadal wildfire probability at each asset's location is used to adjust the present-day wildfire likelihood presented in Table 7 based on the associated return period and the following assumptions:

- **Cap rationale:** Likelihood increases are capped at +600% to limit category inflation from outlier percent-change values and to maintain stability in risk classifications given the uncertainty in downscaled wildfire probability projections.
- **1% threshold rationale:** Adjustments are applied only where the historical decadal wildfire probability exceeds 1% to avoid unstable percent-change results in locations with near-zero baseline probability.
- **No decreases rationale:** Decreases in probability are not applied; future likelihood is held at least equal to present-day likelihood to reflect conservative risk management practices and uncertainty in projecting reductions in wildfire potential.

8.2 Exposure

Using GIS-based analysis, the exposure of each asset to wildfire threat and tree mortality was evaluated.

The boundary of wildfire threat classes often follows roadway corridors without directly intersecting the roadway. The CCVRA examined the hazard intensity within a buffer distance from the asset (250 ft for roadways, bridges, and tunnels and 25 ft for culverts) for both fire threat and tree mortality. Buffer distances were selected to reflect the spatial resolution of hazard datasets and the plausible zone of direct fire effects and radiant heat on transportation assets, with a smaller buffer for culverts due to their localized footprint.

Figure 33 below shows the exposure of the SHS to wildfire hazards. Statewide, almost 75% of the roadways are exposed to some level of wildfire hazard, which increases to 90% and above for D1, D2, D5, and D9.

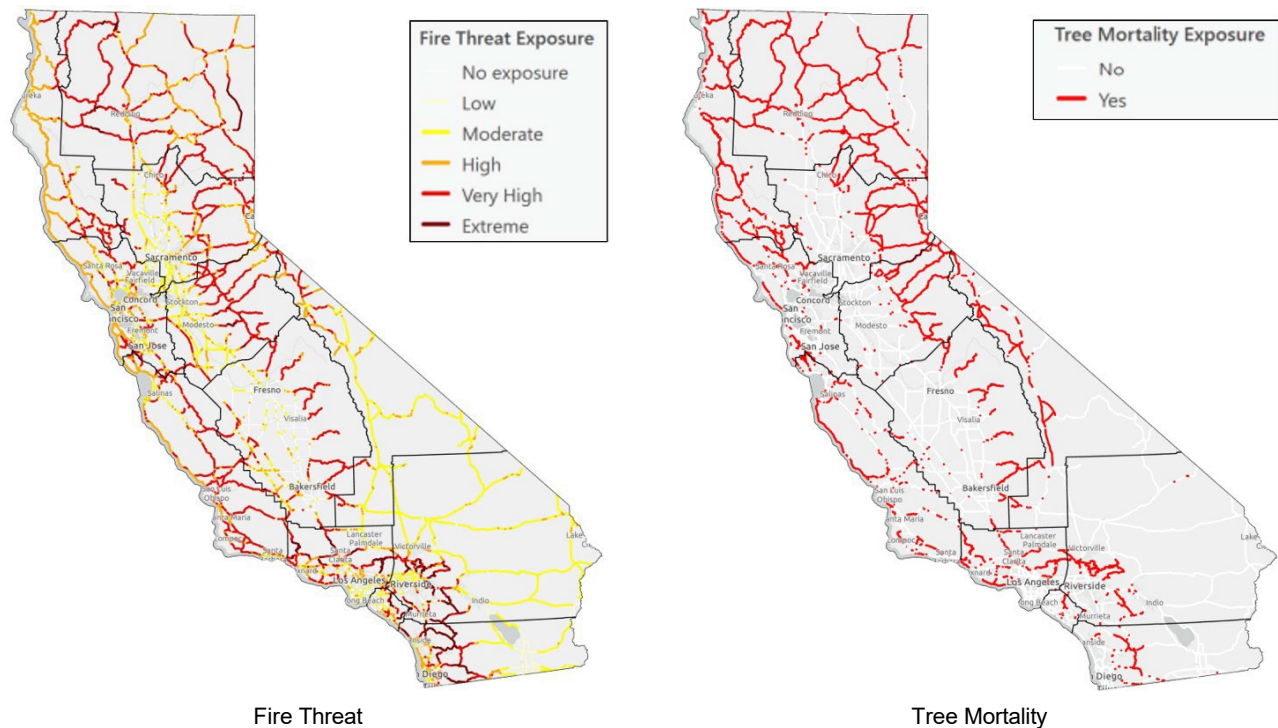


Figure 33 Exposure of the SHS to present-day wildfire hazard: Fire threat (left) and tree mortality (right).

The analysis also extracted the change in future wildfire probability for each asset and climate scenario to adjust the future likelihood within the risk assessment.

All exposure results were integrated directly into the Caltrans asset geodatabase to support tracking, querying, and future updates.

8.3 Vulnerability

This section describes how the CCVRA assets can be impacted by wildfire based on the hazard intensity and asset characteristics.

For transportation infrastructure, wildfire impacts are frequently dominated by secondary hazards during the first rainy seasons following a burn, including debris flows, sediment delivery, rockfall, and drainage system blockage. These effects can cause extended closures and significant maintenance demands even where direct thermal damage to pavement or structures is limited.

8.3.1 Roadway Vulnerability to Wildfire

Wildfire can affect roadway function by generating hazardous driving conditions from smoke, heat, and debris, and by damaging roadside features or pavement edges. Direct flame contact or radiant heat can weaken asphalt binders and cause cracking or surface distress while subsequent rainfall over burned slopes can deposit debris and ash on the roadway. Damage mechanisms for roadways exposed to wildfire are controlled by fire intensity, duration of heat exposure, and proximity of roadside vegetation.

The CCVRA identifies three damage states to roads representing downtime-specific impacts from wildfire:

1. Temporary: Temporary closures due to reduced visibility or surface obstruction. The available hazard datasets do not allow the identification of segments exposed to this first damage state, so it is not implemented in the CCVRA (and conservatively covered by the following damage states).
2. Short-term: Surface scorching and debris cleanup. This damage state is reserved for roadway segments not located in areas of high tree mortality.
3. Medium-term: Severe pavement or shoulder damage from direct flame impingement requiring partial reconstruction. This damage state can be reached by roadway segments exposed to wildfire and located in areas of high tree mortality.

Table 7 summarizes the representative damage states for roadways affected by wildfire used in this assessment.

The 2018 Camp Fire and 2020 Glass Fire caused extensive roadway closures in Northern California, where smoke, ash, and debris made travel unsafe and required cleanup before the road could be reopened (ABC News, 2018; CalOES, 2023). In certain areas, scorched pavement surfaces and burned signage required minor resurfacing, though underlying pavement structures typically remained intact.



Figure 34 Downed power lines after a wildfire in Santa Rosa, District 4. Source: San Francisco Chronicle (2017).

8.3.2 Bridge Vulnerability to Wildfire

Wildfire can impact bridges when heat or debris affect approach roads, abutments, or bridge decks. Smoke and debris can reduce visibility and accessibility, while radiant heat can deform steel members, char timber decks, or compromise bearings and joints. Damage mechanisms for bridges exposed to wildfire depend on fire intensity, duration, and material composition—timber and steel bridges are particularly vulnerable whereas concrete components generally resist short-duration heat exposure.

In this study, the first damage state represents closures for inspection due to smoke and nearby fire activity, the second represents minor surface or railing damage requiring limited repair, and the third reflects direct structural damage to bridge components from high-intensity fire exposure requiring replacement. Table 8 summarizes the representative damage states for bridges affected by wildfire used in this assessment.

The CCVRA applies three damage states to bridges to represent the impacts from wildfire:

1. Temporary: Temporary closures for inspection due to smoke and nearby fire activity. This damage state is reserved for bridges not located in areas of high tree mortality.
2. Short-term: Minor surface or railing damage requiring limited repair. This damage state is reserved for concrete bridges located in areas of high tree mortality.

3. Long-term: Direct structural damage to bridge components from high-intensity fire exposure requiring replacement. This damage state is reserved for bridges located in areas of high tree mortality and made of heat-sensitive materials (e.g., wood, steel).

In California, bridges within burn areas have repeatedly required inspections following major wildfires. During the 2018 Carr Fire, several bridges in Shasta County were closed for inspection and limited repairs due to nearby heat and debris exposure (Aven et al., 2021; United States Department of the Interior Bureau of Land Management, 2018). Similarly, closures of Highway 1 in Big Sur occurred during the breakout of the Colorado Fire. These bridge inspections often precede reopening once debris is cleared and structures are deemed safe.



Figure 35 The Colorado Fire burns along Rocky Creek Bridge on State Route 1, District 5. Source: The Associated Press (2022).

8.3.3 Tunnel Vulnerability to Wildfire

Wildfire can reduce tunnel usability by introducing smoke, soot, and debris, and by creating unsafe air conditions within the bore. While concrete tunnel linings are resistant to short-term heat, portal structures and ventilation systems can be damaged by prolonged exposure. Damage mechanisms for tunnels under wildfire are controlled by proximity to the burn perimeter, fuel loads near portals, and air circulation patterns that determine smoke infiltration.

The CCVRA applies two damage states to tunnels to represent the impacts from wildfire:

1. Temporary: Temporary closure due to smoke infiltration or soot accumulation. This damage state is reserved for tunnels not located in areas of high tree mortality.
2. Short-term: Structural or mechanical impacts at portals requiring ventilation repair and debris removal. This damage state is reserved for tunnels located in areas of high tree mortality.

Table 8 summarizes the representative damage states for tunnels affected by wildfire used in this study.

Fire engineering literature shows that prolonged or intense fire conditions can damage tunnel infrastructure, including spalling of concrete linings and impairment of mechanical and ventilation systems, leading to extended service disruptions and repair needs (Lombardi, 2023). In post-fire settings, slope instability can also obstruct access and require excavation before reopening.

8.3.4 Culvert Vulnerability to Wildfire

Wildfire can damage culverts through heat exposure, melting of plastic components, or clogging by ash and debris. Post-fire hydrologic changes can also accelerate erosion and sediment transport, causing blockage or structural failure. Damage mechanisms for culverts subject to wildfire depend on material type and fire intensity; polymer and High-Density Polyethylene (HDPE) pipes are particularly vulnerable to high heat.

Therefore, if culverts or drainage structures are constructed from polymer or HDPE materials, it is likely these thermoplastic drainage structures will be vulnerable to direct fire contact. However, concrete end treatments provide protection from high temperatures and are considered an appropriate mitigation option for plastic culverts in wildfire-prone areas.

The CCVRA applies two damage states to culverts to represent the impacts from wildfire, where both damage states only apply to culverts without concrete end treatments:

1. Short-term: Functional loss due to blockage from ash or debris. This damage state is reserved for culverts not located in areas of high tree mortality.
2. Medium-term: Structural failure of thermoplastic culverts under high heat, requiring excavation and replacement. This damage state is reserved for culverts located in areas of high tree mortality.

Table 8 summarizes the representative damage states for culverts affected by wildfire used in this assessment.

The “Plastic Culverts in Fire-Prone Areas” study conducted by Caltrans Division of Research, Innovation and System Information found that heat exposure during California wildfires can cause melting and deformation of plastic culvert ends due to high wildfire vulnerability, requiring full replacement (Caltrans Division of Research, Innovation and System Information, 2019).

Therefore, if culverts or drainage structures are constructed from polymer or HDPE materials, it is likely these thermoplastic components will be vulnerable to direct fire contact unless protected by concrete end treatments.



Figure 36 Collapsed melted culvert caused by the 2018 Camp Fire.
(American Concrete Pipe Association, 2021).

Damage State Description			Downtime			
			Temporary (< 2 days)	Short-term (2-10 days)	Medium-term (1.5-6 weeks)	Long-term (1.5-18 months)
Roads						
1	Smoke & ash limit visibility; temporary closure but no structural damage ¹ .	Roadway closed until fire is put out & wildfire debris is removed.	X			
2	Minor surface scorching or obstruction by debris; subbase intact.	Roadway closed until fire is put out & wildfire debris is removed.		X		
3	Severe pavement or shoulder damage due to direct flame impingement or prolonged high heat.	Roadway repairs or shoulder replacement.			X	
Bridges						
1	Approach roads or immediate vicinity impacted by smoke/debris; bridge closed for safety inspections.	Bridge not accessible until fire is put out & wildfire debris is removed.	X			
2	Deck charring, railing damage, or minor structural distress.	Bridge not accessible until fire is put out & wildfire debris is removed.		X		
3	Structural damage to timber, steel, or composite components due to direct flame exposure or heat deformation.	Bridge repairs/replacement.				X
Tunnels						
1	Smoke infiltration, soot accumulation, or temporary closure for safety checks.	Tunnel closed until fire is put out & wildfire debris is removed.	X			
2	Portal infrastructure or lining damaged due to high temperature exposure; ventilation systems impaired.	Tunnel closed until fire is put out, wildfire debris is cleared from tunnel portals, & ventilation systems safely recycle clean air again.		X		
Culverts						
1	Blockage by ash, debris, or sediment post-fire; structure intact.	Culvert does not fully drain water until fire is put out & wildfire debris is removed.		X		
2	Melting or collapse of polymer/plastic culvert material; surrounding soil scorched or destabilized.	Trenching works likely required for replacement of culvert.			X	

¹ This damage state is conservatively not implemented in the CCVRA due to the lack of appropriate hazard data.

Table 8 Damage states for all assets due to wildfire.

8.4 Baseline Risk Assessment

In the final step of the risk assessment, the hazard, exposure, and vulnerability information, defining the likelihood and expected consequences, are combined to return a single, easy-to-understand risk rating for each asset and climate scenario using the risk matrix in Table 1.

The maps and plots below summarize the statewide wildfire risk results. Figure 37 shows the geographic distribution of the results for roadways for present-day (left) and late-century (right), assuming the RCP4.5 scenario for the future probability adjustment. In these maps, only risk ratings of Medium and above are shown. Based on the possible combinations of hazard and consequences for wildfire, the maximum risk rating that a roadway segment can achieve for present-day is Medium-High, which can increase up to High in future scenarios. For both present-day and future conditions, only a limited number of roadway segments reach the highest risk ratings, mostly in the forested areas surrounding Los Angeles, San Bernardino, San Diego, and in parts of D2.

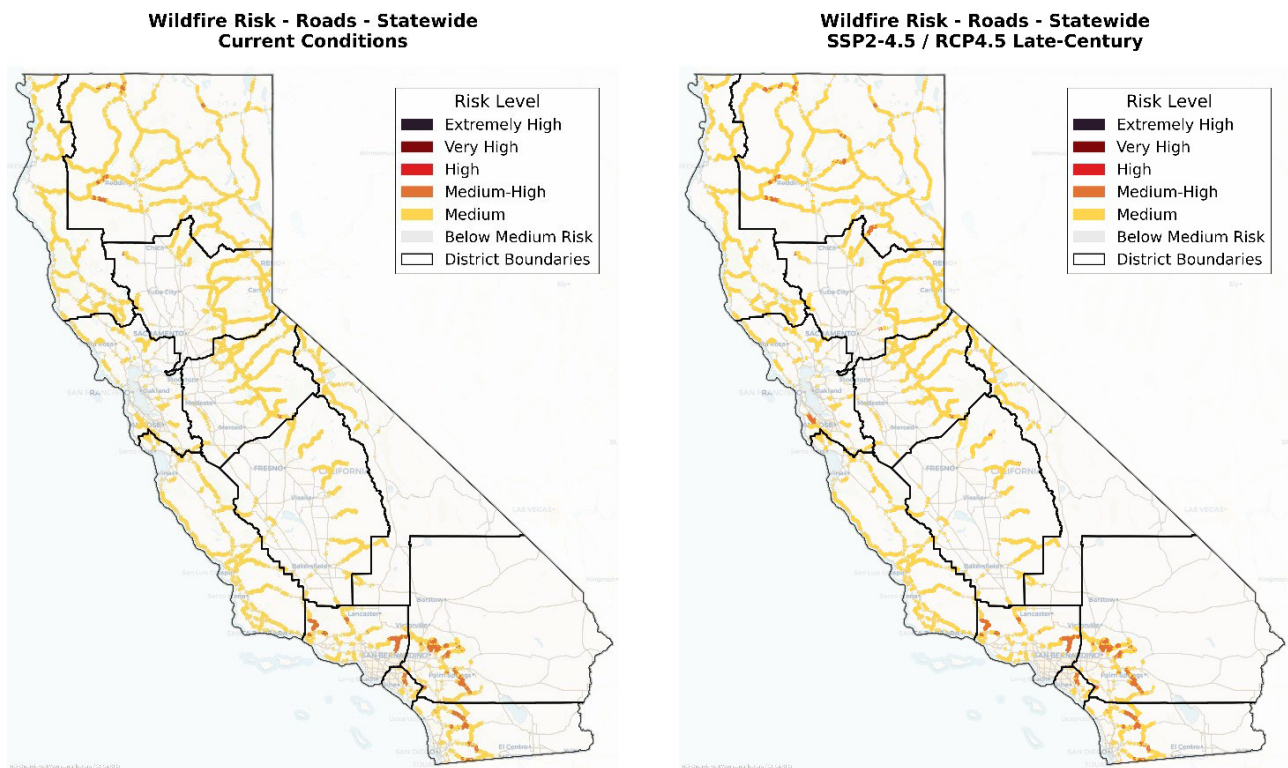


Figure 37 Statewide distribution of the baseline risk ratings for wildfire for present-day (left) and late-century for RCP4.5 (right). Only Medium and higher risk ratings are shown.

Figure 38 and Figure 39 summarize the statewide results for roadways and bridges respectively. The results are summarized by climate scenario and by risk rating using the total (left plots) and percentage (right plots) centerline miles.

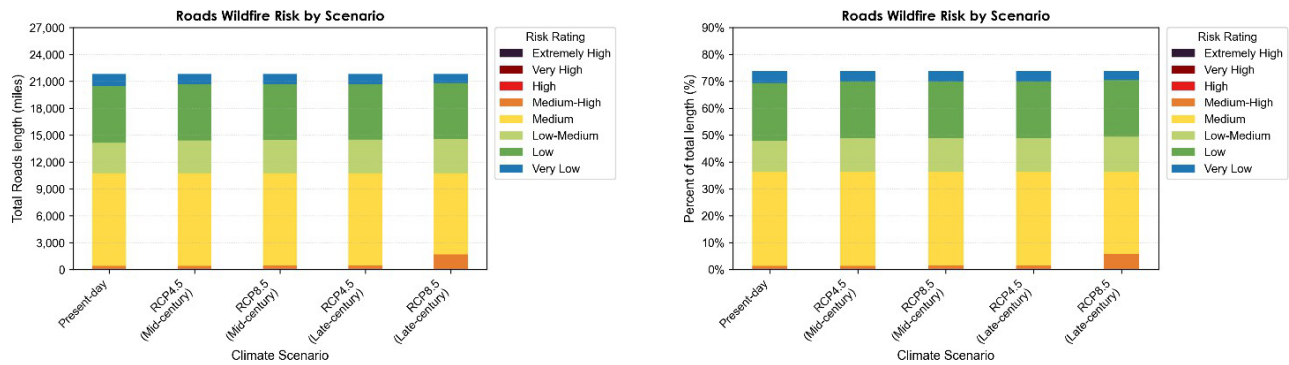


Figure 38 Miles (left) and percentage (right) of roadways assigned to each risk rating for wildfire for all climate scenarios.

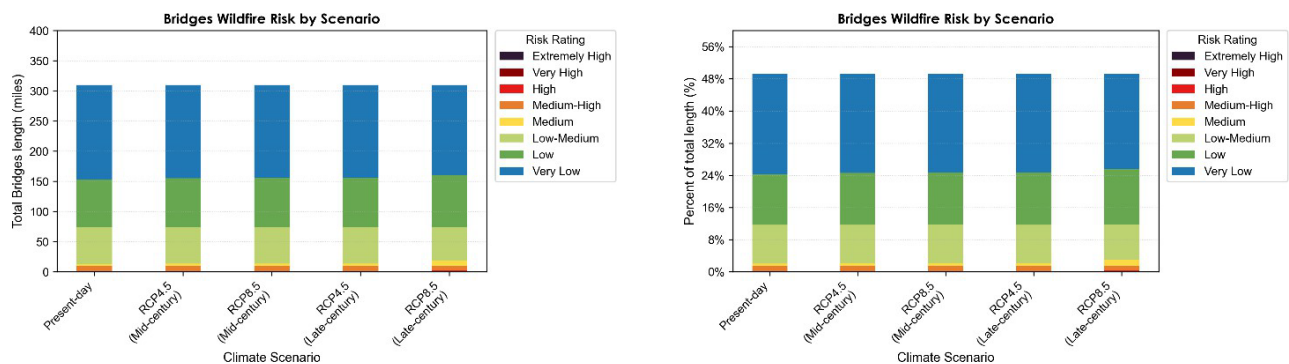


Figure 39 Miles (left) and percentage (right) of bridges assigned to each risk rating for wildfire for all climate scenarios.

The plots confirm the results of the exposure assessment and vulnerability research:

- While a large number of assets are exposed to wildfire across the state, and despite the high likelihood of some fire events, the overall risk to the roadway system remains moderate given the low consequences caused by fires to roads. Very few assets exceed a Medium risk rating.
- Similarly, bridges are also generally resilient against wildfire, with overall risk ratings lower than for roads. Only timber and steel bridges can reach the highest ratings, which represent a minority of the structures in wildfire-prone regions.
- Under the CCVRA framework, future wildfire probability increases generally shift likelihood upward for some assets, but overall risk ratings remain moderate because the assessed direct consequences to core roadway and bridge structures are typically limited relative to other hazards.

8.5 Key Findings

Wildfire is a widespread reality throughout California and a challenge felt most acutely in Districts 1, 2, 5, and 9. While exposure to the SHS is broad, the most severe risk outcomes remain concentrated along specific corridors, particularly within heavily vegetated, mountainous regions and the forested areas of Southern California.

Notably, the primary driver of wildfire risk for most roadways is not structural damage but operational disruption. This includes safety closures necessitated by smoke and active flames, debris and ash cleanup, and post-fire sediment and debris delivery during subsequent storms.

With regard to specific assets, bridge risk is generally lower than roadway risk, owing to the inherent heat resistance of most modern bridge components. However, a subset of timber and steel bridges in high-threat zones remains highly vulnerable to elevated consequences. Culverts and drainage features emerge as a major vulnerability pathway, as thermoplastic materials are susceptible to melting, and post-fire landscapes often trigger heavy debris loads that lead to blockages, scour, and embankment instability.

While future climate scenarios are expected to increase the likelihood of wildfire and elevate risk ratings for certain assets, the statewide risk is still largely low to moderate. The assessed physical consequences for core structures typically remain lower than those posed by flood- or erosion-driven hazards.

Landslides

Landslides compromise the SHS by blocking travel lanes, undermining embankments, and in severe cases removing roadway segments entirely. These events can produce long-duration closures and costly reconstruction, particularly along steep coastal corridors and mountainous terrain.

This chapter introduces the landslide hazard and data sources, discusses which assets are exposed and how they are impacted, and combines this information to develop risk ratings across assets and climate scenarios.

9.1 Hazard

Landslides occur when the stress on the slope exceeds the combined soil, rock, and vegetative cohesion or strength. Triggers for landslides in California can include heavy precipitation, earthquakes, uplift, groundwater flow, riverine erosion, freeze-thaw cycles, or a combination of these factors (Bontemps et al. 2020; Handwerger et al. 2022; Oakley et al. 2024). Landslides can be either deep-seated, initiating with a failure in the subsurface rock, or in the shallow soil layer as a shallow landslide.

9.1.1 Present-Day

To characterize the present-day landslide hazard, the CCVRA uses the deep-seated landslide susceptibility mapping developed by the California Geological Survey (CGS) (Wills et al. 2011; Jones et al. 2008; Wilson et al. 1985), which combines information about local rock strength (informed by the local geology and landslide history) and slope steepness to calculate landslide susceptibility classes, categorized from 0 to X (roman numerals), in order of increased susceptibility. The classifications do not include climatological landslide triggers such as extreme rainfall and earthquakes. Figure 40 below shows the distribution of the landslide susceptibility classes across California.

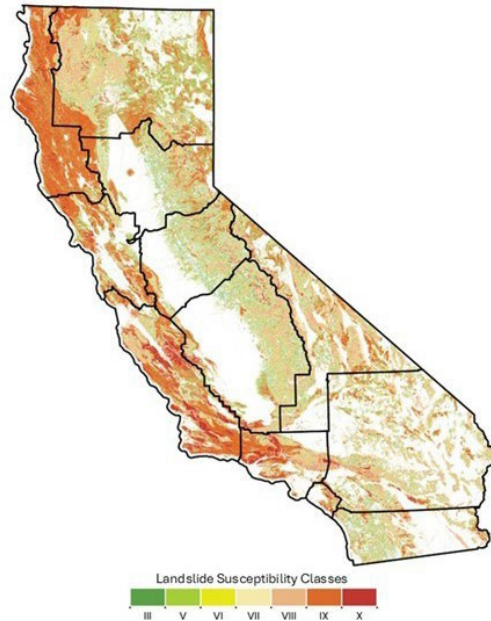


Figure 40 Landslide susceptibility classes across California.

It is not possible to associate the susceptibility classes with a quantitative likelihood or return period (time between events) without a comprehensive review of the landslide history at each location, which is not feasible at the statewide scale of this assessment, and no other data source exists in the literature that better represents the landslide hazard across the entire state. Therefore, the CCVRA adopted a qualitative yet reasonable mapping of susceptibility classes to likelihood categories to consistently apply the standardized risk approach described in Section 3.1 across all hazards. The mapping in Table 9 is a rule-based translation of CGS susceptibility classes into the CCVRA likelihood scale. It preserves the ordinal intent of the susceptibility classes and was selected to support consistent statewide screening and cross-hazard comparison while recognizing that site-specific failure probability depends strongly on local triggers (e.g., rainfall intensity-duration, groundwater conditions, prior disturbance, and seismicity).

Susceptibility Class	Likelihood Category
III	Unlikely
IV	Unlikely
V	Unlikely
VI	Possible
VII	Possible
VIII	Possible
IX	Likely
X	Very Likely

Table 9 Likelihood category assignment for landslides for present-day.

9.1.2 Adjustment for Future Climate

Based on climate model predictions for the next century in California, which include increases in average annual precipitation and increases in the frequency of dry-to-wet extremes, landslide activity is likely to increase (Handwerger et al. 2019). At the time of the completion of the CCVRA, there are no comprehensive studies or data sources quantifying the effect of climate change on the future landslide hazard in the state. However, saturated soils in areas with notable landslide risk can trigger the occurrence of a landslide (Ray and Jacobs 2007). In California specifically, atmospheric rivers and shallow saturated soil conditions are correlated with landslides, including the most-dangerous deep-seated landslides (Handwerger et al. 2022; Cordeira et al. 2019; Iverson et al. 2015; Rutllant et al. 2023). For these reasons, while the science behind future landslide hazards remains an area of active research, the CCVRA adopted soil moisture as a proxy to estimate the change in likelihood of future landslides.

The CCVRA uses a soil moisture indicator derived from LOCAv1-VIC representing average winter-season (Dec-Feb) soil moisture in the upper soil layer (top ~10 cm) as a statewide proxy for wetter antecedent conditions that can contribute to slope instability. This proxy is most directly relevant to shallow landslides and debris flows; for deep-seated landslides, it serves as an indirect indicator of wetter seasonal conditions and is used to flag areas where climate trends may increase landslide susceptibility.

Figure 41 shows the distribution of the resulting indicator across the state. Historical results are included for reference, but since LOCAv1 is not bias-corrected, the projected values should be interpreted as projected trends. Results for future climate scenarios are presented as percent change from historical conditions.

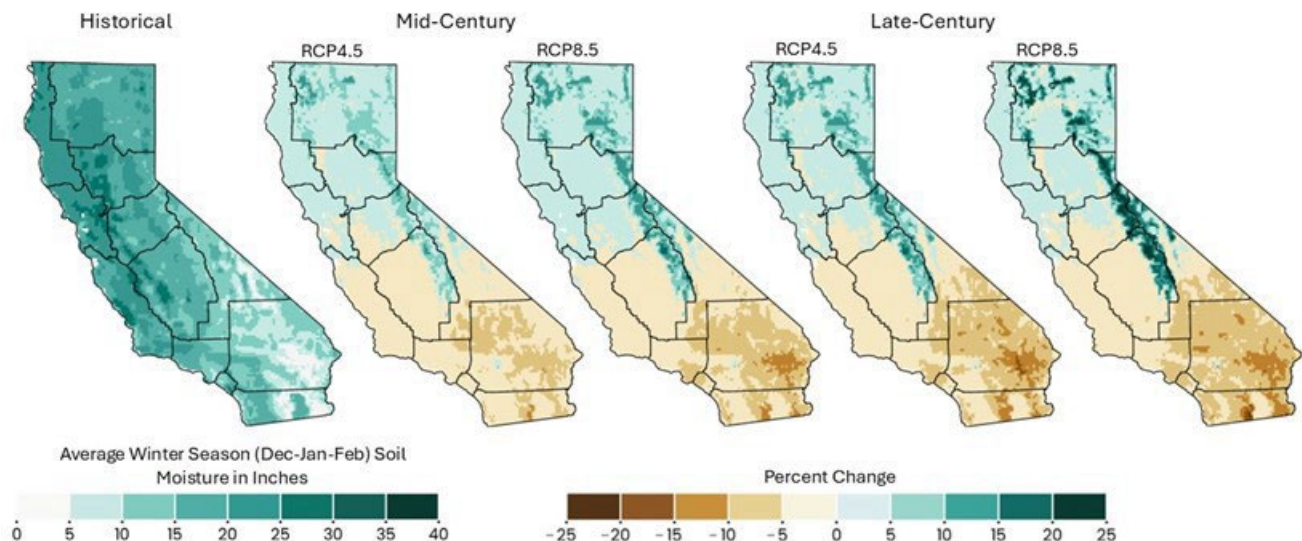


Figure 41 Average winter season (Dec-Jan-Feb) soil moisture in inches.

The soil moisture indicator shows stable trends into the future, with limited variation across the state with the exception of a pronounced increase in the Sierra Nevada and other forested areas in Northern California. Soil moisture is expected to decrease in the southern portion of the state. Likelihood decreases are not applied. Instead, future likelihood is held at least equal to present-day likelihood to reflect conservative risk management practices and uncertainty in projecting reduced landslide occurrence.

Based on the distribution of the results across the SHS assets, a soil moisture increase threshold of 1% was selected as a proxy to increase the future landslide likelihood by one category (e.g., from

“Possible” to “Likely”). The 1% increase threshold was selected to provide a stable, interpretable rule that identifies a meaningful subset of assets for which wetter winter-season conditions may increase landslide likelihood while avoiding widespread likelihood inflation driven by small numerical changes. This threshold implies that about 10% of the roadway segments see an increase in landslide risk in the future. Despite the qualitative nature of this assumption, it is helpful in identifying areas where the risk is expected to increase and which should be flagged for more detailed assessment.

9.2 Exposure

Using GIS-based analysis, the exposure of each asset to landslide susceptibility was evaluated and is reported in Figure 42 below. Statewide, almost 50% of the roadways are exposed to some level of landslide hazard, with the highest exposure (measured in centerline miles) in D6, D8, and D2.

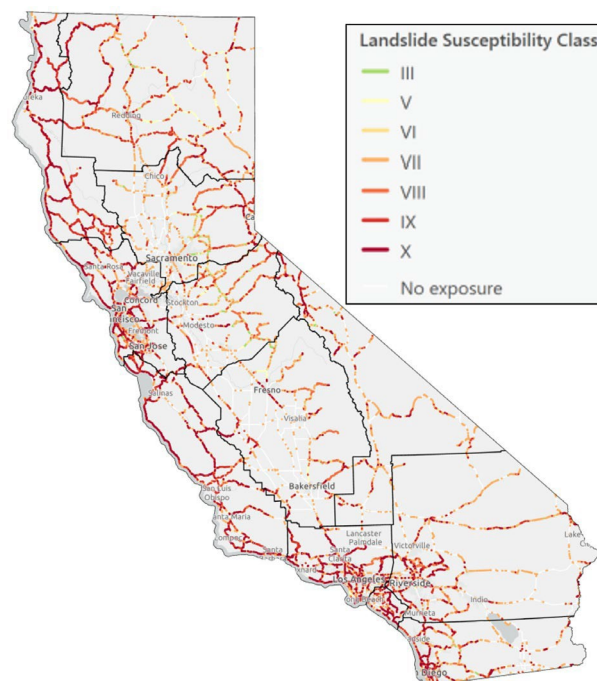


Figure 42 Exposure of the SHS to present-day landslide hazard.

The analysis also extracted the change in future soil moisture for each asset and climate scenario to adjust the future likelihood within the risk assessment, shown in Figure 43 for RCP4.5. The maps clearly indicate that in the future this indicator is expected to increase in the northern portion of the state, especially in the Sierra Nevada, and decrease elsewhere.

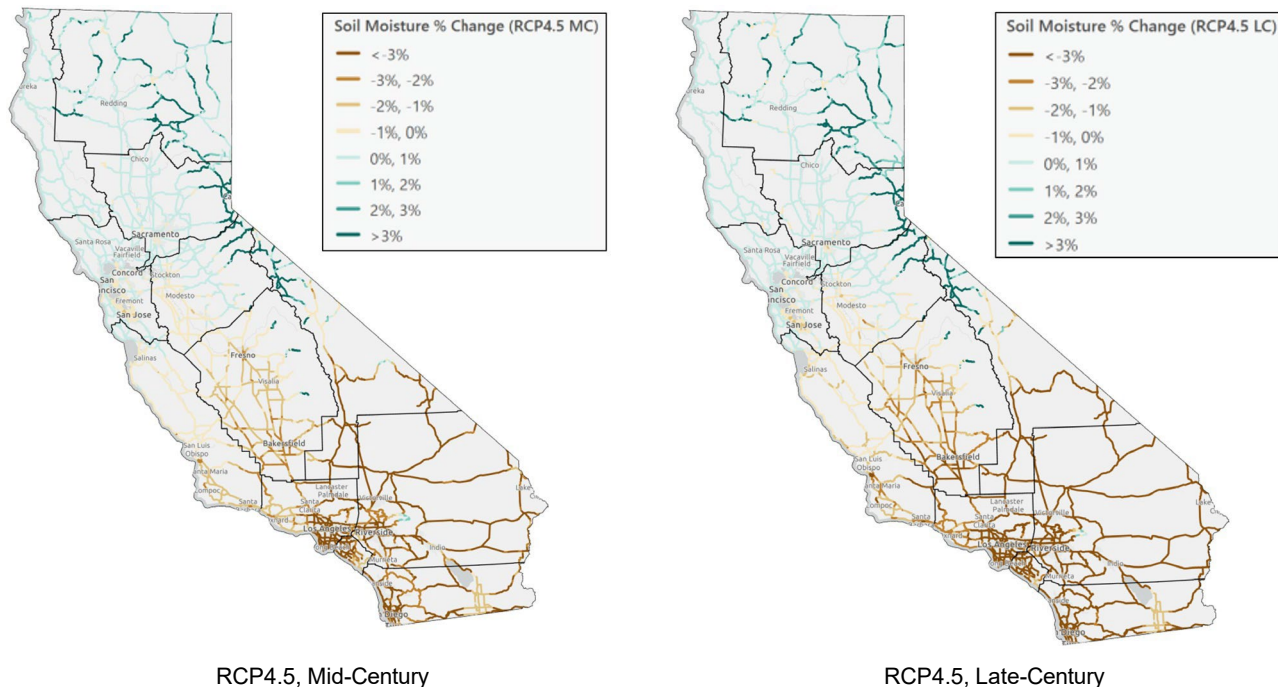


Figure 43 Exposure of the SHS to future change in soil moisture for RCP4.5 for mid-century (left) and late-century (right).

All exposure results were integrated directly into the Caltrans asset geodatabase to support tracking, querying, and future updates.

9.3 Vulnerability

This section describes how the CCVRA assets can be impacted by landslides based on the hazard intensity and asset characteristics.

9.3.1 Roadway Vulnerability to Landslides

Landslides can damage roadway networks by depositing debris onto road surfaces, undermining embankments, or entirely removing sections of the road prism. These events can vary from small rockfalls, or shallow debris slides that cause short-term closures, to large-scale slope failures that result in complete roadway loss. Damage mechanisms for roadways subject to landslides are governed by slope geometry, soil and rock type, saturation levels, and rainfall intensity. When slope instability intersects road corridors, the most common outcomes include blocked lanes, embankment failure, and pavement cracking or collapse.

The CCVRA identifies three damage states to represent impacts to roads from landslides:

1. Short-term: Temporary closures due to debris on the road surface.
2. Medium-term: Partial lane or shoulder failure due to slope movement.
3. Long-term: Total roadway collapse where the roadbed fails entirely. The available hazard dataset does not allow the project team to differentiate the level of damage experienced by the roadway, so this damage state is conservatively assigned to all segments exposed to landslide hazard.

Table 10 summarizes the representative damage states for roadways affected by landslides used in this study.

California's coastal and mountain highways are frequently impacted by slope failures. The 2017 Mud Creek landslide buried more than 0.25 miles of Highway 1 under approximately six million cubic yards of material, requiring over a year of reconstruction before reopening (USGS, 2021; Caltrans, 2018). Numerous smaller slides along Big Sur and Humboldt County corridors cause temporary closures every winter season for debris removal and slope stabilization.



Figure 44 Example of lane failure due to slope movement in Big Sur.

9.3.2 Bridge Vulnerability to Landslides

Landslides can affect bridge structures by destabilizing approaches or abutments and by exerting lateral pressure on foundations when slope movement extends into the bridge footprint. Damage mechanisms for bridges subject to landslides include approach settlement, embankment slippage, and loss of bearing capacity at abutments. While superstructure elements are often unaffected, access can be lost for extended periods if abutments or foundations are compromised.

The CCVRA identifies three damage states to represent impacts to bridges from landslides:

1. Short-term: Minor debris accumulation and inspection needs at abutments.
2. Medium-term: Approach settlement or slope slippage causing functional impairment.
3. Long-term: Foundation or abutment failure requiring reconstruction. The available hazard dataset does not allow the project team to differentiate the level of damage experienced by the bridge, so this damage state is conservatively assigned to all assets exposed to landslide hazard.

Table 10 summarizes the representative damage states for bridges affected by landslides used in this study.

In California, landslides have caused repeated closures and reconstructions where slope failures undermine bridge supports. During the 2017 winter storms, a landslide undermined a support for the Pfeiffer Canyon Bridge on State Route 1 near Big Sur, causing severe damage beyond repair and necessitating emergency bridge replacement to restore access.



Figure 45 Landslide-related bridge failure at Pfeiffer Canyon Bridge. LA Times, 2017

9.3.3 Tunnel Vulnerability to Landslides

Landslides can disrupt tunnel operations by depositing debris at portals, damaging structural elements, or causing slope instability in adjacent cut faces. These effects are most pronounced in steep terrain where prolonged rainfall or seismic activity trigger mass movement near tunnel entrances. Damage mechanisms for tunnels under landslide conditions include blockage by debris, deformation of portal linings, and slope failures that restrict access.

The CCVRA identifies two damage states to represent impacts to tunnels from landslides:

1. Short-term: Debris accumulation near portals requiring short-term cleanup.
2. Long-term: Slope failures that block the portals or damage the tunnel, possibly culminating in tunnel collapse, necessitating excavation and stabilization. The available hazard dataset does not allow the project team to differentiate the level of damage experienced by the tunnel, so this damage state is conservatively assigned to all assets exposed to landslide hazard.

Table 10 summarizes the representative damage states for tunnels affected by landslides used in this assessment.

California's coastal and mountainous tunnels have periodically faced challenges related to landslides. Following heavy rainfall during the 2017 winter storms, small slides near the Tom Lantos / Devil's Slide Tunnels required debris removal and slope stabilization before reopening (ABC News, 2023).

9.3.4 Culvert Vulnerability to Landslides

Landslides can damage culverts by crushing or displacing pipes, burying inlets and outlets, or eroding surrounding embankments. These impacts can block drainage, increase upstream flooding, and destabilize roadway embankments. Damage mechanisms for culverts in landslide-prone areas include ground displacement, differential settlement, and debris blockage. Rigid concrete culverts are particularly vulnerable to fracture when slope movement exceeds structural tolerance while flexible culverts may deform or separate at joints.

The CCVRA identifies two damage states to represent impacts to culverts from landslides:

1. Short-term: Partial blockage or burial of culverts requiring short-term cleaning.
2. Long-term: Barrel displacement or embankment erosion, potentially leading to culvert collapse, requiring excavation and reconstruction. The available hazard dataset does not allow the project team to differentiate the level of damage experienced by the culvert, so this damage state is conservatively assigned to all assets exposed to landslide hazard.

Table 10 summarizes the representative damage states for culverts affected by landslides used in this assessment.

Post-storm landslides along Highway 1 and other steep coastal corridors have frequently damaged drainage structures. Following the 2017 Mud Creek slide, numerous culverts were excavated and replaced as part of full roadway reconstruction. Similar but smaller failures have occurred statewide following heavy rainfall, where debris flows clog inlets or displaces barrels.



Figure 46 Example landslide washout of culvert.

Damage State Description			Downtime			
			Temporary (< 2 days)	Short-term (2-10 days)	Medium-term (1.5-6 weeks)	Long-term (1.5-18 months)
Roads						
1	Debris, soil, or rockfall accumulation on road surface causing temporary closure.	Remove debris & sediment from the roadway surface & reopen once safe for travel.		X		
2	Partial lane blockage or shoulder damage due to minor slope failure or debris flow.	Clear debris, repair shoulder or damaged pavement, & stabilize minor slope failures.			X	
3	Roadway collapse or slope failure resulting in total loss of access; major reconstruction required.	Reconstruct failed roadway sections & embankments, rebuild slopes, & restore full access.				X
Bridges						
1	Minor debris or soil accumulation at abutments or approaches; no structural damage.	Clear debris & inspect abutments & approaches before reopening bridge to traffic.		X		
2	Approach settlement or slope slippage causing functional impairment; structure intact.	Stabilize approach slopes & repair settled pavement or abutment transitions.			X	
3	Bridge foundation or abutment failure due to slope movement or loss of bearing support.	Reconstruct damaged abutments or foundations & stabilize supporting slopes.				X
Tunnels						
1	Small debris or soil accumulation near portal; no structural damage.	Remove loose debris near tunnel portal & confirm structural stability prior to reopening.		X		
2	Tunnel safety undermined due to deep-seated landslide (risk of tunnel collapse).	Excavate landslide material, repair portal lining or entry damage, & stabilize surrounding slopes.			X	
Culverts						
1	Culvert partially buried or inlet blocked by debris; function restored after clearing.	Clear debris & sediment from inlet/outlet & ensure culvert flow is re-established.		X		
2	Culvert barrel displaced or embankment eroded by slope movement; culvert collapse.	Excavate around displaced culvert, repair or replace barrel, & reconstruct eroded embankments.			X	

Table 10 Damage states for all hazards due to landslides.

9.4 Baseline Risk Assessment

In the final step of the risk assessment, the hazard, exposure, and vulnerability information, defining the likelihood and expected consequences, are combined to return a single, easy-to-understand risk rating for each asset and climate scenario using the risk matrix in Table 1.

The maps and plots below summarize the statewide landslide risk results. Figure 47 shows the geographic distribution of the results for roadways for present-day (left) and late-century (right), assuming the RCP4.5 scenario for the future change in soil moisture. In these maps, only risk ratings of Medium and above are shown. Based on the possible combinations of hazard and consequences for landslides, the maximum risk rating that a roadway segment can achieve for present-day is High, which can increase up to Very High in future scenarios. A large portion of the SHS reaches High risk ratings, especially along the coast and the Sierra Nevada, where roads are exposed to the highest landslide susceptibility categories. The higher risk associated with landslides compared to other hazards is evidence of the severe damage and long repair time landslides can cause to roadways.

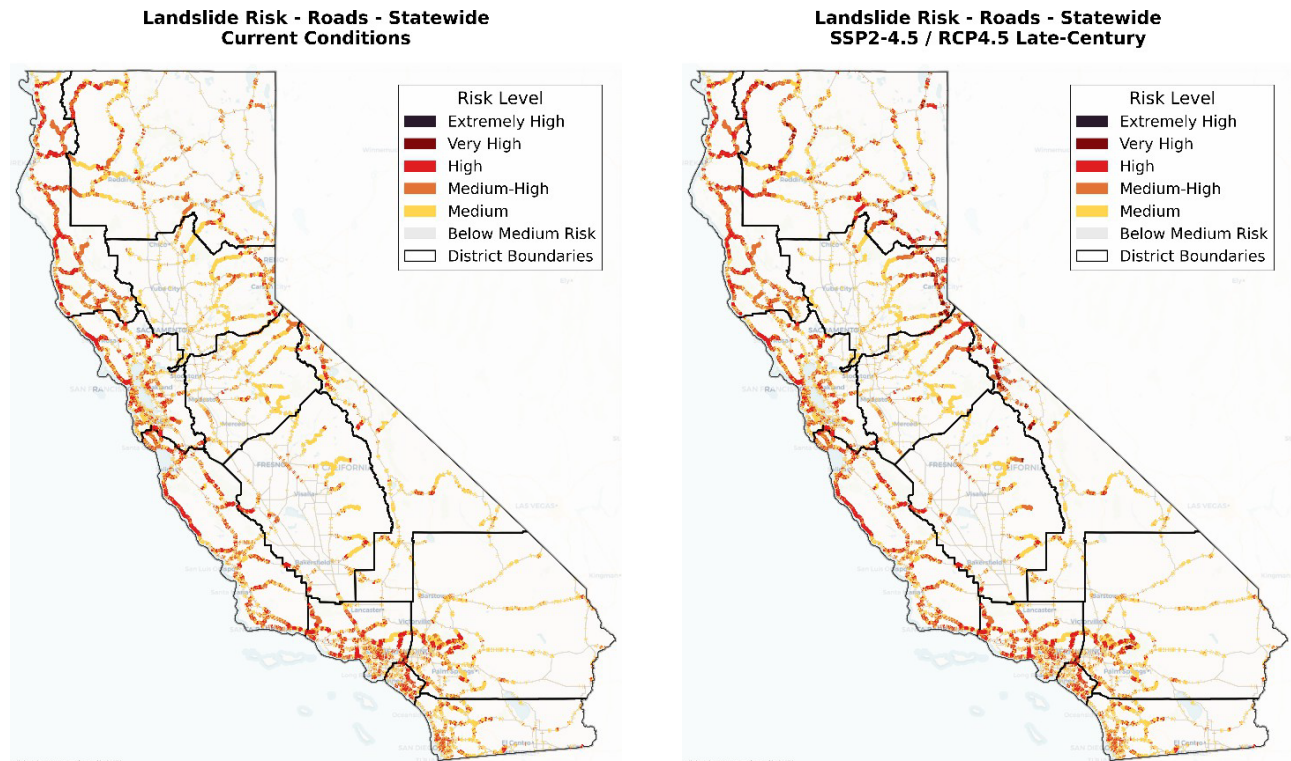


Figure 47 Statewide distribution of the baseline risk ratings for landslides for present-day (left) and late-century for RCP4.5 (right). Only Medium and higher risk ratings are shown.

Figure 48 and Figure 49 summarize the statewide results for roadways and bridges, respectively. The results are summarized by climate scenario and by risk rating using the total (left plots) and percentage (right plots) centerline miles. Overall, the future risk of landslides increases for about 7% of the roadway network.

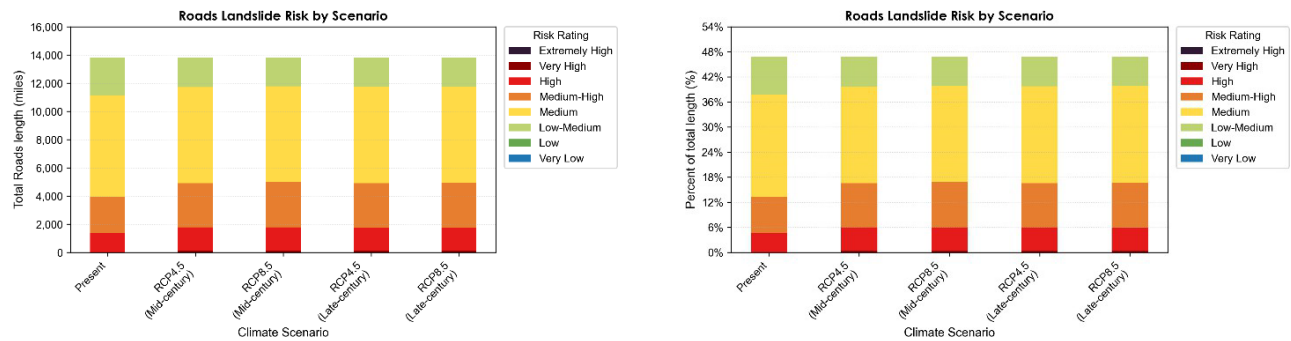


Figure 48 Miles (left) and percentage (right) of roadways assigned to each risk rating for landslides for all climate scenarios.

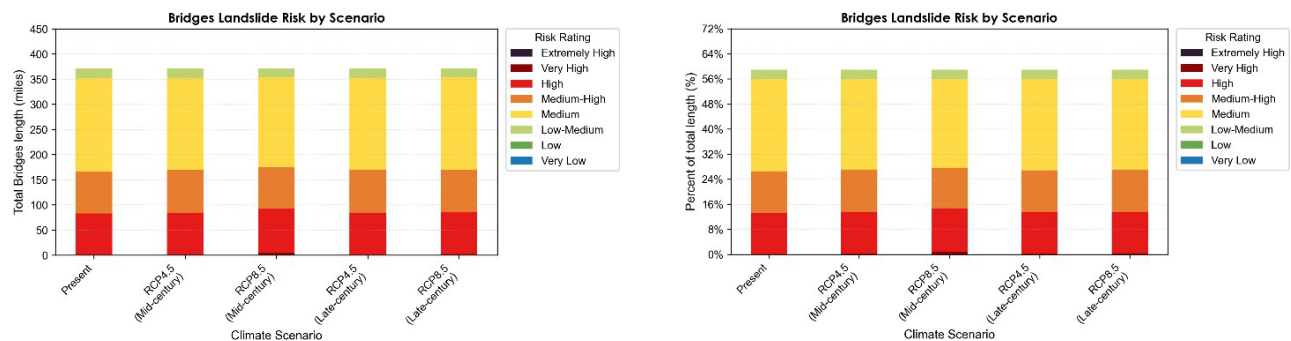


Figure 49 Miles (left) and percentage (right) of bridges assigned to each risk rating for landslides for all climate scenarios.

9.5 Key Findings

Landslide risk poses a significant challenge to the SHS, with approximately half of the network being susceptible. While this susceptibility is broad, the most severe High and Very High risk ratings are spatially clustered in steep coastal corridors and mountainous terrains, most notably along the North Coast and within the Sierra Nevada, where slope gradients and weaker geologic units coincide. Unlike more transient hazards, landslides often result in long-duration closures and necessitate costly reconstruction, positioning them as one of the most disruptive hazards due to their potential for extended downtime and major capital repairs.

Looking ahead, climate change is expected to progressively increase the likelihood of these events in specific regions. By using winter-season soil moisture as a proxy, potential risk increases particularly in the northern portions of the state and across the Sierra Nevada. While this soil moisture analysis serves primarily as a screening tool, it is useful for long-term planning, helping to identify where more frequent wet-season conditions may trigger slides and allowing for the prioritization of detailed geotechnical evaluations and corridor-specific resilience strategies.

Planned Activities



Introduction and Chapter Purpose

- Shifting from Assessment to Action: Defining the objective of this chapter as the bridge between technical findings and strategic implementation.
- Audience and Responsibility: Identifying the primary stakeholders (e.g., Caltrans Planners, Engineers, Maintenance Teams, District Management) responsible for applying the report's insights.

Decoding the Report's Key Findings

- Understanding the Risk Matrix
- Prioritization/ Criticality Enhancement:
 - Definition: Explaining what "criticality enhancement" means in the context of transportation assets (e.g., impact on system network, essential services, regional economy, and equity). Caltrans is currently drafting updated criticality criteria with the California Office of Emergency Services (Cal OES). It is recommended that any implementation of criticality for the CCVRA be aligned with this new framework once it is finalized and that any required information or dataset be developed at a statewide scale to ensure uniform and consistent application across all the 12 districts.
 - Prioritization Metric: How to use criticality to elevate high-risk assets that, if they fail, would result in the most severe cascading consequences.

Integrating CCVRA Findings into Caltrans Processes

- Long-Range Planning and Programming:
 - Incorporating high-risk locations and adaptation costs into the State Highway Operation and Protection Program (SHOPP) and other long-term investment strategies.
 - Using the data to inform updates to the State Transportation Improvement Program (STIP).
 - Using the data to inform the development of Corridor Plans and Project Initiation Documents (PIDs).
- Project Development and Design Standards (PA/ED, PS&E):
 - Screening Tool: Recommending the use of the CCVRA database as a screening tool during the Planning and Environmental (PA/ED) phase for all new projects and major rehabilitations.
 - Climate-Informed Design: Using the CCVRA to inform future updates to Caltrans Design Standards (e.g., storm drain capacity, road elevation, material specifications) if helpful to account for future climate conditions.
- Maintenance and Operations:
 - Targeted Maintenance: Reallocating resources to increase inspection frequency and pre-emptive maintenance in high-criticality, high-risk locations.

- Emergency Response: Using hazard maps to pre-position resources and optimize closure/detour routes during extreme weather events.

Strategic Adaptation Planning and Implementation

- District-level Adaptation Projects
- Securing Funding and Partnerships:
 - Leveraging Data for Grants: Using the quantified risk and criticality scores to strengthen applications for federal grants (e.g., FEMA Hazard Mitigation, USDOT grants).
 - Interagency Collaboration: Establishing partnerships with local, regional, and federal agencies to coordinate adaptation efforts, especially for non-Caltrans assets that impact the transportation system.

Monitoring, Evaluation, and Update

- Performance Tracking:
 - Establishing Key Performance Indicators (KPIs) to measure the effectiveness of adaptation investments (e.g., reduction in closure days, decrease in recurring maintenance costs).
 - Feedback Loop: Creating a formal process for Maintenance and district personnel to provide feedback on the accuracy of the risk scores and the efficacy of implemented solutions.
- Adaptive Management and Review Cycle:
 - Defining a regular schedule (e.g., five-year cycle) for updating the CCVRA report with new climate projections, improved asset data, and lessons learned from extreme events.
 - Ensuring the assessment remains a living document to support long-term climate resilience.

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