Adaptation Strategies for Transportation Infrastructure

EDUCATIONAL RESOURCE

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INTRODUCTION

This educational-only resource describes the types of hazards and/or threats represented by different climate stressors and lists the types of adaptation actions or strategies that could be considered to avoid or minimize impacts. **This document should be used as an educational tool for planners that provides an initial look into how to consider project-level strategies to adapt to more extreme risks.** The document does not consider feasibility for permitting conditions or other site-specific considerations. Any planning of actual projects, for PID phase or other purposes, should be done so in consultation with Design and other relevant district expertise. Furthermore, the document does not include maintenance strategies that could prevent or reduce the impacts of extreme events to the state transportation system. Please reach out to your district's maintenance division to discuss these strategies. DOTP will consider adding a section on maintenance strategies in a future iteration of this document.

The intended users of this document are district planners, and for consultation with Project Development Teams (PDTs) at early project scoping stages. For more information on how the strategies described in this document may be incorporated into the planning process, please refer to the Climate Change Emphasis Area Guidance for Corridor Planning.

The adaptation actions or strategies provided in this guide are generally organized into traditional engineered protection approaches, natural and nature-based solutions, and a hybrid of these approaches. Engineered solutions include the use of constructed structures like levees, armoring, or Rock Slope Protection (RSP). Natural, or nature-based solutions include approaches that work with and enhance nature to build climate resilience and/or contribute to carbon neutrality. A priority emphasized by California's 2022 Climate Adaptation Strategy, the State's commitment to advancing multi-benefit, nature-based solutions seeks to ensure that California's communities and natural systems continue to thrive together in the face of climate change—and also reflects the opportunity to avoid ***maladaptation***—or the concept of constructing protective infrastructure in some of our most hazard-prone areas that can increase vulnerabilities and provide a false sense of security (IPCC AR6, 2022). Natural or nature-based solutions should be prioritized wherever feasible, particularly in areas that could be flooded or eroded from tidal or fluvial processes like riverine or coastal areas. Hybrid approaches are a combination of at least two strategies that are used together on a single site to address different levels of risk, or different strategies may be phased and implemented over time to address changing conditions.

This guide includes strategies to address potential climate change impacts to transportation infrastructure including those analyzed in the Caltrans District Climate Change Vulnerability Assessments, and Adaptation Priority Reports.

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ADDRESSING CHANGES IN PRECIPITATION

Climate-driven changes in precipitation may cause a rapid increase in peak flows along streams, potentially leading to pooling or riverine flooding. Flooding events can heavily impact transportation assets passing nearby or over these streams, whether by disrupting traffic or damaging infrastructure. The section below provides adaptation strategies to address impacts on the transportation system from changes in precipitation.

Although not included in this section, depending on flooding levels, frequency of flooding events, and other drainage features, elevation of the roadway may be needed.

RIVERINE FLOODING

Three main strategies can be pursued to address riverine flooding. They are not exclusive of each other and could be pursued in tandem depending on the project or application and are as follows:

- **Floodplain Conservation and Restoration (Nature Based):** Floodplain creation and restoration can be an effective option for reducing flood risk where the transportation system is protected from riverine floods by levees. As increased flows in waterways are given an opportunity to re-connect with the floodplain and slow down—the risk of levee failures are reduced. Wetland and riparian habitat restoration on the floodplains can further slowdown the flow of floodwaters, enable groundwater recharge, and hold soil in place. Coordination with state, local, and regional partners is an important aspect of use of this strategy.
- **Drainage Improvements:** Drainage improvements may assist in mitigating events where transportation facilities are overwhelmed by high flows from precipitation or runoff. Drainage can be improved through a variety of methods including widening the capacity of culverts, elevating road surfaces, bioswales, retention/detention ponds, and improving permeability. Designing and building with less-permeable surfaces can cause a significant increase in surface runoff, so incorporating permeable surfaces into design may improve the overall drainage capabilities of facilities.
- **Accommodate:** Roadway inundation from flood zones can occur when roadways are built parallel to rivers and streams or transect river floodplains. Elevating roads in at-risk flood zones (taking into account future flood events) above a certain flood level can protect roads from routine flooding.

Sources used for this section:

- California Natural Resources Agency (Resources) California Climate Adaptation Strategy (2022)
- Caltrans Highway Design Manual - Chapter 890
- Caltrans, Hybrid Streambank Revetments: Vegetated Rock Slope Protection (DIB-87-01)
- Caltrans Landscape Architecture Program (Intranet Links)

    - Model Water Efficient Landscape Ordinance
    - Erosion Control Design
    - Low Impact Development
- EPA Wetlands Restoration Definitions and Distinctions
- FHWA Highways in the River Environment-Floodplains, Extreme Events, Risk, and Resilience (2nd Edition, 2016)

Example Strategies for Flooding and Riverine Flooding

Strategy	Project	Project Details
Floodplain Preservation and Restoration	Levee set-back and Wetland/ Riparian Habitat Restoration (Nature Based)	• Restoration of the floodplain and connectivity with the river system increases residence time of flood flows, and reduces the potential of levee failure • Wetland and riparian restoration can further slowdown river flows by restoring habitat through placement of imported sediment, removal of invasive vegetation and other foreign materials, and planting of native marshland vegetation that stabilizes soils, and increases sediment retention. • Re-establishment of wetlands consists of modifying the physical, chemical, or biological characteristics of a site with a goal of returning natural/historic functions to former or degraded wetland.
Drainage Improvements	Bioswales/ Bioretention Basins (Nature Based)	• These strategies mitigate stormwater flooding impacts by serving as an absorbent catchment for the stormwater. Plants act to attenuate water flows and hold soil in place, while the permeable groundcover allows infiltration into the soil. • Can assist with ground water recharge – addressing ground subsidence issues in the area which may help protect the facility. In dry and arid areas, dry swales may be more appropriate. Bioswales can improve water quality of runoff compared to other strategies by catching and breaking down pollutants in stormwater, such as heavy metals. • These facilities require regular upkeep to maintain their beneficial functions over long periods of time.
	Retention Ponds	• Retention ponds consist of a permanent pond area with landscaped banks and serves to control the quantity of runoff discharged to receiving waters.
	Detention Ponds	• Typically, these are engineered with hardened, less permeable shorelines. These ponds act as a temporary water storage to reduce peak flow periods and allow for more gradual runoff when flow levels recede.

Drainage Improvements	Culvert Expansion/ Bridge Elevation	• The redesign of a culvert or bridge to allow for higher peak flow levels. • Current design standards are for 100-year flood standards, however, with projected shorter and more intense wet seasons, this may result in an underestimation for potential flows if climate change projections are not considered in design.
Accommodate	Elevate	• If necessary, given projected flood levels and/or subsidence, roads, bridges, and other transportation facilities can be elevated above a certain flood level (such as through bridge abutment lengthening, increases in bridge freeboard, or a viaduct or causeway), generally to protect against storm conditions or future routine flooding. • Elevating individual components is costly and elevating or constructing new roadways can be both complex and expensive; however, those costs should be balanced against on-going maintenance costs associated with repeated damages from flood events and environmental mitigation costs.

STREAM EROSION & FLOW ALTERATION

Strategies to address stream erosion and stream flow alteration are grouped into the following three categories:

- **Stabilization:** Stabilization by either a nature-based, structural, or hybrid approach may assist in protecting streambanks. These methods include bulkheads made of concrete, masonry or steel, and vegetation which is the most natural method for stabilization of embankments and channel bank protection.
- **Armor Protection:** Armor is the artificial surfacing of bed, banks, shore, or embankment to resist erosion or scour. Armor devices can be flexible (self-adjusting) or rigid. Flexible types include rock slope protection, gabions, and precast concrete articulated blocks. Rigid types include concreted-rock slope protection, sacked concrete slope protection, and concrete filled cellular mats.
- **Training Systems/Redirection of Flows:** Structures, usually within a channel, that act as countermeasures to control the direction, velocity, or depth of flowing water. When training systems are used, they generally straighten the channel, shorten the flow line, and increase the local velocity within the channel. In the case of a stream attack, a new channel can be created, or the stream can be diverted away from the embarkment by the use of baffles, deflectors, or spurs.

Sources used for this section:

- Caltrans Construction Manual – Chapter 4
- Caltrans Highway Design Manual – Chapter 870
- Caltrans Hybrid Streambank Revetments: Vegetated Rock Slope Protection (DIB-87-01)
- Caltrans Standard Plans

Example Strategies for Stream Erosion

Strategy	Project	Project Details
Stabilization	Vegetation Stabilization (Nature Based)	• The most natural method for stabilization of embankments and channel bank protection. It can be relatively easy to maintain, visually attractive and environmentally desirable. • The root system forms a binding network that helps hold the soil. • Grass and woody plants above ground provide resistance to the near bank water flow causing it to lose some of its erosive energy.
	Bulkheads	• A steep or vertical structure supporting a natural slope or constructed embankment which include the following: gravity or pile supported concrete or masonry walls, and sheet piling. • As bank protection structures, bulkheads serve to secure the bank again erosion as well as retaining it against sliding.
Armor Protection (Flexible)	Rock Slope Protection (RSP)	• Streambank Rock Slope Protection, commonly referred to as riprap, consists of rock courses placed upon the embarkment or the natural slope along a stream. • Rock Slope protection has the following advantages: it is flexible, local damage is easily repairable, construction is not complicated, appearance is natural, it is salvageable (may be stockpiled and reused if necessary). • Adding vegetation to create Vegetated Rock Slope Protection has positive attributes on stream integrity such as improving stream ecology, increasing soil strength, and providing flow resistance. However, vegetation can also increase slope failure potential under saturated conditions.
	Gabion	• Consist of rectangular wire mesh baskets filled with stone. • Wall Type: Empty cells are positioned and filled in place to form walls in a stepped fashion. Not fully self-adjusting but has some flexibility. • Mattress Type: Baskets are positioned on the slope and filled. This type is very flexible, and well suited for man-made roadside channels (with uniform flow), and as overside drains that are constructed on steep and unstable slopes.
Armor Protection (Rigid)	Concreted-Rock Slope Protection	• Consists of rock slope protection with interior voids filled with plain cement concrete to form a monolithic armor. • This method has application in areas where rock of sufficient size for ordinary rock slope protection is not economically available.
	Partially Grouted Rock Slope Protection	• A form of smaller rock held together with a cementitious material. • A viable alternative to larger rock or concreted rock slope protection where either the availability of large materials is limited, or there are site limitations regarding the placement of large materials.

Armor Protection (Rigid)	Sacked-Concrete Slope Protection	• Consists of facing the embankment with sacks filled with concrete. • Use of this method is generally limited to replacement or repair of existing sacked concrete facilities, as it is both a cost- and labor-intensive approach.
Training Systems	Bendway Weirs	• Bendway Weirs, also referred to as steam barbs, bank barbs, and reverse sills, are low-elevation stone sills used to improve lateral stream stability and flow alignment problems at river bends and highway crossings on streams and smaller rivers. • They also encourage deposition of bed material and growth of vegetation.
	Spurs	• Can be a pervious or impervious structure projecting from the streambank into the channel. • The main function of spurs is to reduce flow velocities near the bank, which in turn, encourages sediment deposition due to the reduced velocities. Increased protection of banks can be achieved over time, as more sediment is deposited behind the spurs. • Deflectors and Baffles can also be used to control direction and velocity of flow.
	Guide Dikes/Banks	• Guide banks are appendages to the highway embankment at bridge abutments, they are smooth extensions of the fill slope on the upstream side, and can be used on both sand and gravel-bed streams. • The two major enhancements guide banks bring to bridge design are (1) reduce the separation of flow at the upstream abutment face and thereby maximize the use of the total bridge waterway area, and (2) reduce the abutment scout due to lessening turbulence at the abutment face.

ADDRESSING SEA LEVEL RISE

Over the past century, increases of average global temperatures have already caused sea levels to rise from thermal expansion of warming ocean water, as well as through land ice melt. While the California coast already regularly experiences erosion, flooding, and significant storm events, future sea level rise will exacerbate these natural forces, leading to an increase in the potential for flooding and erosion of Caltrans roadways and infrastructure. Adaptation strategies that are most appropriate for a particular asset or segment within a transportation corridor will depend on the specific circumstances for each location. Each type of adaptation strategy—including protection, accommodation, retreat, or a hybrid of these—are associated with benefits and impacts that should be considered in decision-making around when each one should be used.

As a guiding principle when considering which adaptation strategy might be most appropriate to use—as the transportation system generally provides critical infrastructure services for Californians in terms of national or regional economic security, national or regional energy security, and national or regional public health or safety—**accommodation strategies should be prioritized that relocate or elevate transportation infrastructure to safe areas to avoid the need for hard shoreline protection that harms coastal resources and could have expensive ongoing maintenance costs**.

- More specifically, adaptation strategies for *new* transportation infrastructure should seek to avoid areas where sea level rise could affect the infrastructure over the entire expected service life of the asset or project. For transportation infrastructure that is *already established*, a combination of adaptation strategies may be necessary that clearly relate how short, medium, and long-term choices—or a "phased" or "adaptation pathways" approach—will collectively deliver long-term resiliency over time. For example, short-term protection through armoring may be necessary to maintain transportation services while a longer-term solution is planned or constructed which realigns the roadway.
- In general, it is well understood through the Intergovernmental Panel on Climate Change (IPCC) that reliance on traditional engineered protective approaches like sea walls can facilitate long-term commitments that "lock in" vulnerability, asset exposure, and risks that are difficult and costly to change and are "maladaptive" (IPCC AR6, 2022); therefore, use of these approaches should be thoughtfully considered such that options remain open for longer-term adaptation pathways that avoid and relocate transportation infrastructure away from sea level rise risks in the future.

For additional guidance on addressing sea level rise in terms of State policy, guidance, resources, science, and tools, visit the Sea Level Rise and the Transportation System in the Coastal Zone webpage developed by the Division of Environmental Analysis. The section below provides a summary of adaptation strategies to address impacts on the transportation system from changes in sea level rise.

COASTAL FLOODING AND EROSION

Adaptation strategies which address sea level rise hazards for the purposes of this guide can generally be organized into those which address flooding and erosion, while the specific adaptation approach should be selected given the project location (i.e., open coast, beach, or sheltered bay). Examples are organized according to four main adaptation strategies as follows:

- **Retreat:** Retreat strategies are those in which assets are moved out of harm's way. This includes removing or relocating existing structures that are in danger from hazards, as well as siting new development to avoid hazardous areas so that it will be safe over its anticipated lifetime without requiring additional adaptation measures. Examples include highway realignment or deliberate use of detours.

- **Soft Shoreline Protection:** Can be referred to as "green" or "nature-based" strategies and considers features that rely on natural components and processes to provide protection, such as constructed or restored dunes, beach nourishment, vegetation, oyster beds, and the like.

- **Engineered Shoreline Protection:** Strategies in which a physical barrier is constructed to essentially keep water (either from flooding or erosion) away from a structure. Examples include Rock Slope Protection (RSP), secant walls, and seawalls.

- **Accommodate:** Accommodation strategies are those in which the asset itself is designed to accommodate impacts from coastal hazards and enable current and future oceanic hydraulic (stillwater levels, wave run-up, storms, scour, groundwater) processes in conjunction with the companion geological and environmental setting of the project location within the littoral cell. Examples include bridge abutment lengthening, causeways, culvert conversions to bridges, and viaducts.

- **Hybrid Approach:** A solution that combines any of the above strategies for an asset or collection of assets along a transportation corridor including natural (nature-based) and constructed (structural) elements.

Sources used for this section:

- California Coastal Commission Sea Level Rise Policy Guidance: Interpretative Guidelines for Addressing Sea Level Rise in Local Coastal Programs and Coastal Development Permits (2018)
- California Coastal Commission Critical Infrastructure at Risk: Sea Level Rise Planning Guidance for California's Coastal Zone (November 2021)
- California Natural Resources Agency Report for Fourth Climate Change Assessment: Toward Natural Shoreline Infrastructure to Manage Coastal Change in California
- Caltrans Design Manual for Hybrid Coastal Protection Strategies (2022)
- Caltrans Drainage References (intranet link)
- FHWA HEC-25 Highways in the Coastal Environment
- FHWA Nature-Based Solutions for Coastal Highway Resilience: An Implementation Guide
- Governor's Office of Planning and Research (OPR) Planning and Investing for a Resilient California: A Guidebook for State Agencies (2018)
- Ocean Protection Council State of California Sea-Level Rise Guidance: 2018 Update (2018)

Example Strategies for Coastal Flooding and Erosion

Strategy	Project	Project Description	Coastal Flooding	Coastal Erosion
Retreat (Nature Based)	Realignment/ Relocation	• Realignment away from the at-risk location is a potential strategy that may be most appropriately explored as part of long-term adaptation of the transportation system. • Planned retreat can be utilized by predicting sea level rise through scientific models, though this option is often highly costly—however, it is also understood that evidence suggests that in vulnerable areas, the cumulative costs of keeping infrastructure safely in place could eventually outweigh the costs of relocation.	X	X

Soft Shoreline Protection (Nature Based)	Sand Dunes	• Coastal dunes are mounds or hills of sand and native vegetation often situated landward of the wave run-up zone of a beach. • Dunes can act as a sand supply reservoir that helps re-nourish the beach when erosion from coastal storms and waves may deplete the sediment. Coastal dunes provide protection by reducing wave overtopping events and inhibiting saltwater surface intrusion in the backshore environment. • Dunes with plantings are more stable and more resilient and offer important habitat for many rare and unique species.	X	X
	Sand Nourishment	• Sometimes referred to as beach nourishment, sand nourishment is the placement of sand onto a beach. • The additional sediment gets redistributed either by waves and currents or through human manipulation until it reaches an equilibrium profile. • Sand nourishment helps maintain the beach zone, acts as a buffer between upland areas to reduce the impacts of coastal hazards and supports beach ecosystems.	X	X
	Regional Sediment Management	• The systematic approach to addressing sediment supply imbalances at a regional scale. • Includes the restoration of natural processes as much as possible throughout the sediment system and encourages the use of clean sediment as a resource at sediment-starved locations.		X
	Sand Berm	• Often constructed out of existing sand to create temporary flood protection, and a high relief structure that reduces wave overtopping. • Sand berms can be eroded during large storms or regarded into the beach. Sand can also be imported to create berms or "dune embankments" that may have vegetation.	X	
	Oyster Bed	• Low-relief structures that consist of native oyster aggregates located in intertidal and subtidal zones. • They provide protection by buffering storm surges, attenuating waves, reducing shore erosion, and encouraging sediment accretion.	X	X
	Eelgrass Bed	• Communities of eelgrass on soft bottom substrates at lower intertidal and subtidal areas that provide high levels of primary productivity, high biodiversity, and high species density. • Eelgrass beds can provide protection by dissipating wave energy and slowing tidal currents at low tide.	X	X

Soft Shoreline Protection (Nature Based)	Wetland Restoration	• Helps reduce erosion by restoring habitat through placement of imported sediment, removal of invasive vegetation and other foreign materials, and planting of native marshland vegetation that absorbs wave energy, stabilizes soils, increases sediment retention, and dampens incoming waves and coastal turbulence.	**X**	**X**
	Tidal Bench	• Gently sloping benches that typically extend from the mean tide level (MTL) or lower toward the backshore. • Tidal benches are constructed with fill material and vegetation and provide habitat and protection by dissipating wave energy and encouraging sediment accretion.	**X**	**X**
	Native Vegetation Stabilization	• Removal of invasive vegetation like iceplant (carpobrotus edulis) and planting of native vegetation that does not require irrigation can help stabilize the surface of the bluff face and reduce erosion.		**X**
	Artificial / Constructed Reef	• A submerged breakwater that aims to dissipate waves and provide habitat for hard-substrate ecological communities in the surf zone.	**X**	**X**
	Cobble berm	• Sometimes referred to as a dynamic revetment, cobble berms are constructed out of smaller, typically rounded rocks. • The cobble can be moved by larger waves during storms to create berms that dissipate wave energy and stabilize the shoreline.	**X**	**X**
	Ecotone Levee	• Also referred to as horizontal levees, ecotone levees are wide, and have a gently sloped footprint that extends from the subtidal zone to above mean higher high water (MHHW) to include the upland transition zone. • Ecotone levees provide for extended zoning of ecological resources while simultaneously creating textured surfaces through the use of vegetation and substrates that dissipate wave energy.	**X**	
	Marsh Sill	• Shore parallel structures that combine a low-profile stone "sill" with wetland vegetation. • The structural component provides protection to the marsh vegetation, allowing time for the plants to establish as well as the upland environment by dissipating wave energy and reducing shoreline erosion.	**X**	**X**
Engineered Shoreline Protection	Bulkhead	• A structure or partition to retain or prevent sliding of the land, and to protect the upland against erosion from wave action.	**X**	

Engineered Shoreline Protection	Seawall	• A structure, often concrete or stone, built along a portion of a coast to prevent erosion and other damage by wave action. It often retains earth against its shoreward face. • Typically, more capable of resisting greater wave forces than a bulkhead.	**X**	**X**
	Flood Barrier	• Temporary flood barriers may include the use of sandbags, plywood, and/or rubber bladders.	**X**	**X**
	Rock Slope Protection (RSP)	• Commonly referred to as riprap, RSP consists of rock courses placed upon the embankment or shore to prevent erosion.	**X**	**X**
Accommodate (Nature-based)	Elevate	• Roads, bridges, and other transportation facilities can be elevated above a certain flood level (such as through bridge abutment lengthening, increases in bridge freeboard, or a viaduct or causeway), generally to protect against storm conditions or extreme tides. • Elevating individual components is costly and elevating or constructing new roadways can be both complex and expensive; however, those costs should be balanced against on-going maintenance costs associated with repeated damages from wave exposure and environmental mitigation costs.	**X**	**X**
Hybrid Approach	Combination of nature-based and structural solutions	• A solution that combines any of the above strategies for an asset or collection of assets along a transportation corridor including natural (nature-based) and constructed (structural) elements. Additional guidance on hybrid approaches can be found in the Caltrans Design Manual for Hybrid Coastal Protection Strategies (2022)	**X**	**X**

ADDRESSING CHANGES IN TEMPERATURES

Extreme heat events are projected to become more frequent and severe in the future, affecting both the transportation infrastructure and its users. In hot weather, unshaded roofs and pavements in urban and heavily paved locations can be heated to temperatures far above that of the surrounding air, creating what is called a "heat island." Heat islands increase summertime peak energy demands, air conditioning costs, GHG emissions, and heat related illnesses. Wherever feasible, planners should consider these conditions when planning for streetscapes at a human scale.

High and low temperatures can cause pavements to buckle or crack. However, *pavement heat considerations are not included in this document; planners should consult the Division of Maintenance to consider the types of pavements that may be necessary to maintain efficiency of the roadway*. For more information, please review and reach out to the Caltrans Pavement Program.

Increases in snowpack coupled with warmer temperatures later in the year can result in rapid runoff events to communities along rivers and streams, as well as contribute to debris on the roadway and drainage facilities, please refer to the section on "Change in Precipitation" for strategies related to flooding, erosion, and flood alteration.

The section below provides adaptation strategies to address impacts on the transportation system other than pavements from changes in temperatures.

EXTREME HEAT EVENTS

Complete Streets and Improved Transit: Designing transportation facilities that remain usable for a variety of modes of transportation events would be an equitable approach for addressing impacts to non-auto users. Extreme heat is known to contribute to a variety of health risks that can affect non-vehicular travelers who have limited access to travel options that feature air conditioning. When considering complete streets projects, coordinate with active transportation representatives and partner agencies to consider complete street options that incorporate strategies for extreme temperatures.

Sources used for this section

- Caltrans Complete Streets Elements Toolbox Version 2.0

Example Strategies for Extreme Heat Events

Strategy	Project	Project Description
Complete Streets	Street Trees	• Trees shade pavement and rooftops, which helps maintain more comfortable summertime temperatures. • Trees also cool the air via evaporation, which alone or in combination with shading, can help reduce peak summer air temperatures and heat islands.
	Cooling Pavements	• Cooling Pavements reflect more solar radiation (thereby absorbing less heat) and are used in lieu of conventional black asphalt. • Decreasing the amount of heat absorbed by pavements can be achieved by using lighter materials such as concrete or using a lighter colored aggregate in asphalt paving mixes.
	Improved Active Transportation Safety	• Protected active transportation infrastructure that allows cyclists to move at slower, safer speeds during extreme heat events rather than higher speeds when sharing the road with cars. • Reduces the potential risk of exhaustion during extreme heat events.
Improved Transit	Transit Shelters	• Shaded areas where transit users can wait for transit in more comfortable conditions during extreme hear events.

Improved Transit	Increased Transit Service	• Reducing wait times for transit service to reduce exposure to extreme heat conditions and provide improved service.

ADDRESSING DROUGHT

Drought is a constant issue for the State, warmer temperatures, variable snowpack and precipitation, and earlier snowmelt caused by climate change make for longer and more intense dry seasons. Moisture loss from soils and vegetation contribute to drier conditions overall. This may lead to increased plant mortality, shifts in habitat, and increased wildfire risk. Using drought-tolerant plants not only contribute to water conservation, but also benefit fire-resistant landscaping, as plants that are drought-tolerant natives are also fire-resistant. This section provides adaptation strategies to address impacts on the transportation system from drought.

DROUGHT

Strategies to address drought are as follows:

- **Drought Resistant Landscaping:** This strategy involves the use of regionally appropriate, drought tolerant, and/or native plant material that may provide aesthetic, safety, environmental mitigation, stormwater pollution prevention, and erosion control benefits.

Sources used for this section

- Caltrans Division of Design – Highway Planting webpage
- Caltrans Climate Change Adaptation Strategy Report

Example Strategies for Drought

Strategy	Project	Project Description
Drought Resistant Landscaping	Highway Planting	• Good planting design provides functional and aesthetic benefits, require little supplemental potable water, and requires minimal resources to maintain. • Functionally, highway planting provides safety benefits such as headlight glare reduction and windbreaks. • Aesthetically, planning helps integrate the highway within its natural or guild environment to provide human scale and maintain an area’s unique visual context.

ADDRESSING INCREASED WILDFIRE RISK

Wildfire is a very rapidly and costly climate-driven hazard affecting Californians every year. While many fires are preventable all together, project increases in temperature coupled with decreased in precipitation will likely generate more sever annual wildfire seasons in California in the future. Some measures can be taken to prevent the generation and uncontrollable spread of wildfire and mitigate potential damage to transportation facilities and their surrounding communities. This section provides adaptation strategies to address impacts on the transportation system from increased wildfire risk.

Caltrans Maintenance Division runs a robust Vegetation and Wildfire Management Program. Information on the needs identified and projects planned can be found here. Please reach out to Lisa Worthington (lisa.worthington@dot.ca.gov) with questions on vegetation management in your district.

INCREASED WILDFIRE RISK

Strategies to address increased wildfire around transportation infrastructure are grouped into the following three categories:

Defensible Space: Defensible space is a buffer that is created between a building and vegetation surrounding it. This space slows or stops the spread of wildfire and additionally protects the building from reactive heat impacts.

Fire-Resistant Landscaping: Fire-Resistant landscaping may prevent fire ignition, and slow or stop the spread of an existing wildfire.

Hardening: The use of ember- and heat-resistant materials may assist in preventing ignition and damage to Caltrans buildings and assets.

Sources used for this section:

- CALFIRE – Defensible Space webpage
- Caltrans Climate Change Adaptation Strategy Report
- Caltrans Roadside Design Strategies for Fire Suppression: Survey of Practice

Example Strategies for Wildfires

Strategy	Project	Project Description
Defensible Space	Fuels Reduction	• Clearing of vegetation long the SHS to protect SHS users from approaching wildfire, as well as protection from the ignition of fuels by SHS activity. • Allows for the SHS to act as a firebreak in wildfire events, potentially slowing the advance of wildfire and improving conditions for fire suppression in such wildfire events. *FYI: Caltrans runs a statewide Vegetation and Wildfire Management Program in the Maintenance Division.*

Fire-Resistant Landscaping	Landscape Management	• Planning and maintaining vegetation that is known to be tolerant to fire, or less likely to die off from higher projected temperatures, and prolonged period of drought. • Use of concrete weed mats (for example in center median) to reduce fuels/vegetation • Water conservation is another benefit to using fire-resistant landscaping, as plants that are fire-resistant are typically drought-tolerant natives.
Hardening	Culvert Replacement	• Replacement plastic culverts with culverts made from inert materials such as corrugated steel pipe (CSP). • Culverts made from inert materials are more resistant to wildfire conditions and can be expected to maintain intended function both during, and after wildfires take place. • In hilly areas that are prone to wildfires, replacement culverts should be wider to help accommodate for landslides that may block drainage systems.
	Guardrail and Signpost Replacement	• Replacement of wooden guardrail posts and signposts with metal or other inert material thar are less likely to be affected by wildfire. • Guardrail posts and signposts made from inert materials are more resistant to wildfire conditions can be expected to maintain intended function both during and after wildfires take place.

DEBRIS FLOW/EROSION

Debris flow generally occur during periods of intense rainfall or rapid snowmelt. Areas recently burned by a wildfire are especially susceptible to debris flow, including the areas downslope and outside of the burned area. Erosion may cause the loosening of soil, plant debris, rocks, and boulders, which can intensify the effects of debris flows. Keeping an area free of excess fuel for fires can also help in the mitigation of debris flows, as burned slopes become more vulnerable to the effects of debris-flow initiation and erosion. Loss of vegetation that holds soil in place and physical and chemical changes to the soil that result from intense heat and burning by fires make this soil more prone to debris flows.

Debris flow/erosion strategies are grouped into the following two categories:

- **Fire-Resistant Landscaping:** Fire-Resistant landscaping may prevent fire ignition, and slow or stop the spread of an existing wildfire.
- **Protection:** Involves measures such as debris-flow basins and retaining walls to protect travelers and highway features from the collateral damage resulting from landslide processes. Protection measures typically are used where the debris must be contained so that soil and debris are stopped from flowing to areas that are vulnerable to debris-flow damage.

Sources used for this section:

- USGS Appendix C. Introduction to Landslide Stabilization and Mitigation

Example Strategies for Debris Flow

Strategy	Project	Project Description
Fire-Resistant Landscaping	Landscape Management	• Keeping an area free of excess fuel for fires can help in the mitigation of debris flows, as burned slopes become more vulnerable to the effects of debris-flow initiation and erosion.
Protection	Debris-Flow Basins	• These catchment basins are commonly built at the base of slopes where debris flows are frequent. • Used especially in areas where debris must be contained so that soil and debris are stopped from flowing into sensitive ocean or river shoreline areas or where there are structures at the base of the slope that are vulnerable to debris-flow damage. • These basins will eventually fill with debris-flow deposits and must be emptied periodically, or they will overflow.
	Retaining Walls	• Designed to stop the progress or debris fall, either by blocking the flow or diverting it around a vulnerable area. • Retaining walls can be made out of steel, concrete, timbers, or other materials. • These structures should be carefully designed as any deflection of material may be unintentionally redirected into additional vulnerable areas.

ADDRESSING LANDSLIDE RISK

Landslides are a hazard that is typically driven by a combination of climate stressors. Precipitation, temperatures, and the occurrence of wildfire all have an influence on the probability that landslides may occur. This section provides adaptation strategies to address impacts on the transportation system from landslides.

LANDSLIDES

Landslide mitigation strategies are grouped into the following four categories:

- **Stabilization:** To be effective in stabilizing a slope, first one must identify the most important controlling process that is affecting the stability of the slope; secondly, one must determine the appropriate technique to be sufficiently applied to reduce the influence of that process. Stabilization involves measures such as earthwork, buttresses, dewatering, retaining walls, shoreline armor, anchor bolts, slope contouring, and drainage systems to preclude of minimize further landslide movement.

- **Protection/Mitigation:** Involves measures such as rock sheds, rockfall barriers, draperies, rockfall fences, and catchment ditches to protect travelers and highway features from the collateral damage resulting from landslide processes. Protection measures typically control rock and soil emanating from a landslide.
- **Avoidance/Relocation:** This strategy involves measures such as roadway realignments, bridges, viaducts, retaining walls, and tunnels to separate the highway from adverse impacts of a landslide. Avoidance allows the landslide movements to continue following mitigation, but those movements no longer affect the highway.
- **Slope Management:** Involves measures such as monitoring systems, patrols, planned road closures, signing, periodic maintenance, and minor rebuilding to allow operation of the highway within a tolerable amount movement and disruption. Management measures are often practical for large, slow-moving slides when the obstacles to other mitigation strategies prove insurmountable.

Sources used for this section:

- Caltrans Geotechnical Manual - Landslides
- USGS Appendix C. Introduction to Landslide Stabilization and Mitigation

Example Strategies for Landslide Risk

Strategy	Project	Project Details
Stabilization	Vegetation Stabilization (Nature Based)	• Seeding with grasses and legumes reduces surface erosion, planting with shrubs adds vegetative cover and stronger root systems will in turn enhance slope stability. • Dry seeding is usually less costly than hydraulic seeding but are limited to rough soil surfaces and gentler slopes. • Hydraulic seeding (hydroseeding) is more costly than dry seeding but is more effective for seeding steeper slopes.
	Bioengineered Stabilization (Hybrid)	• This type of slope protection is used to reduce the environmental consequences of landslide-mitigation. • Consists of two elements: o Biotechnical Stabilization: uses a combination of structures and plants to prevent and arrest slope failures and erosion. o Soil Biotechnical Slope-Protection Systems: emphasize the use of natural, locally available materials such as soil, rock, timber, and vegetation, in contrast to manufactured materials such as steel and concrete.

Stabilization	Surface/Subsurface Drainage	• Surface draining can be implemented through either surface ditches or shallow subsurface drains. • Drainage is effective because it increases the stability of the soil and reduces the weight of the sliding mass.
	Earthwork	• The disturbance of soils associated with clearing, grading, or excavation activities such as removal of soil from the head of a slide, reducing the height of a slope, backfilling with lightweight material, benches, or flattening/reducing/other slope modification. • This strategy can be both costly and environmentally harmful if done incorrectly.
	Scaling and Trimming	• The removal or loose, unstable, and/or overhanging blocks of rock that includes the use of hand-held pry bars, drilling, and small explosive charges. • These operations can be time-consuming and expensive, and on active slopes may need to be repeated every few years, or as needed.
	Rock-fill Buttress/ Berm	• A berm or buttress of earthfill is deposited at the toe of a slope to increase its toe. This creates a counterforce that resists failure. • Broken rock or riprap instead of soil is preferable due to their greater frictional resistance to shear forces and easy draining, which reduced the problem of impeding ground-water flow.
	Plastic Mesh Reinforcement	• Reinforcement of plastic polymer stretched to form a lightweight, high-tensile-strength grid. This grid acts similarly to reinforcing mesh in concrete, adding strength to the shear strength of the soil. • This type of grid has a number of possible applications in slope stabilization, including soil strength reinforcement, soil drainage, improvement, and retaining-wall construction.
	Retaining Wall/Bulkhead	• A strong solid barrier that supports soil laterally, these structures are designed to harness soil to a slope that would otherwise naturally not exist. • Can be made from steel, concrete, timbers, or other materials. • Retaining walls used to separate water from land are called bulkheads.
	Reinforced Earth Wall	• A patented system for constructing fills at very steep vertical angles without the use of supporting structures at the face of the fill. • The system uses horizontal layers of flexible metal strips within the fill to form a composite earth-metal system with high strength.
	Shoreline Armor	• The use of physical structures to protect shorelines including seawalls, breakwaters, and riprap. • Armored shorelines can prevent sandy beaches, wetlands, and other intertidal areas from moving inland as the land erodes, but they also have the potential to eliminate habitat for marine organisms and beach front for the public by restricting the natural movement of sediments.

Stabilization	Anchor Bolts	• Composed of steel rods or cables that reinforce and tie together a rock face to • Anchors are post-tensioned members used to support large blocks of rock, whereas bolts are shorter and support surface rock.
Protection/Mitigation	Rock Sheds	• These shelters are built over roads, railways, and sometimes structures to shield the area from landslide activity such as rockfalls or rock avalanches. • Shed structures are either open ended or completely envelope the rockfall area in a concrete or steel structure that will deflect rockfall away.
	Barriers/Draperies/ Catchment Ditches	• Proactive mitigation method based on topographic contours to catch debris lifted and transported during an increased precipitation event. • Debris flow catchments can be implemented in burn scars that are susceptible to high amounts of runoff. These catchments prevent clogged culverts and subsequent damage to roads from water overflow. • Debris-flow retaining walls can also be used to stop the progress of debris fall either by blocking the flow or diverting it around a vulnerable area.
Avoidance/ Relocation	Roadway Realignments	• Rerouting the roadway to alignments that are less at risk from landslide or other geotechnical hazards.
	Bridge/Viaduct	• Separating a roadway from adverse impacts of potential landslides by raising or moving roadway to another location, allow landslide movements to continue but without affecting the highway.
	Tunnels	• Rerouting the roadway to travel below where the landslide movements may potentials affect the roadway. Known to be a very cost and labor-intensive project that would only be considered if there is no other strategy available.