SACRAMENTO REGION TRANSPORTATION CLIMATE ADAPTATION PLAN

ABSTRACT

Many state, regional, and local governments are beginning to explore how potential climate change impacts could affect their natural and man-made resources. Damage to transportation infrastructure from extreme weather events can be physically and fiscally difficult to repair. This plan outlines key strategies and actions the Sacramento region can take to ensure its transportation assets are adaptable to potential climate related events.

Sacramento Area Council of Governments & CivicSpark

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Sacramento Region Transportation Climate Adaptation Plan

Executive Summary

Climate adaptation can be defined as: adjusting to changing climate conditions in a way that minimizes negative effects and takes advantage of new opportunities. Through adaptation planning, the Sacramento Area Council of Governments (SACOG) can identify how climate change is likely to impact the region's ability to achieve its mission, operate efficiently, and meet its policy and program objectives. By integrating climate change adaptation strategies into planning, SACOG can ensure that resources are invested wisely, operations remain effective in current and future climate conditions, and the region is well positioned for any forthcoming regulations or incentives related to climate change.

In conjunction with CivicSpark, SACOG has authored a plan to address how potential climate change impacts affect the region's transportation infrastructure. The plan discusses:

- potential impacts the region could face over the next 100 years due to climate change,
- how different climate related events impact transportation and supporting infrastructure,
- how managing agencies can begin to prepare for these impacts through the planning, design, and maintenance phases of a project,
- and outlines the steps necessary to help make the region's transportation infrastructure more adaptable to climate risks.

Target Audience

This plan is intended to be a framework to inform subsequent climate adaptation work on the region's transportation investments. This work will help inform the SACOG Board of Directors about the potential impacts from climate related events, and how the region can best prepare its transportation assets to be adaptable to a changing environment. As outlined in the next steps portion of the plan, subsequent work includes: working with identified stakeholders to conduct asset criticality and vulnerability assessments, and further refining climate adaptation policies.

Climate Risks and Vulnerabilities

A climate related risk is the combination of the likelihood that an event will happen and the consequences of that event. These events have the potential to cause injuries or fatalities, environmental damage, property damage, infrastructure damage, and interruption of operations. Climate risks have their own characteristics, like geographic extent, impacts and severity, and seasonality. A climate related event also has the potential to create multiple hazards: heat is a factor in increased wildfires and wildfires can lead to landslides. Therefore, it is necessary to identify the potential primary and secondary hazards from climate risks.

	Extreme Temperature	Precipitation	Wildfire	Landslides
Roadways	Asphalt-concrete cracking and curling, rutting/softening	Asphalt stripping, concrete corrosion, subbase erosion, washouts	Rutting/softening	Washouts, slope destabilization
Railways	Rail track buckling, expansion of catenary wires, slower speeds and forced delays, derailments	Substructure erosion, forced delays, inundation	Blocked routes, forced delays	Washouts, blocked routes
Bridges	Expansion joint buckling, increased maintenance	Increased scour, decreased safety (visibility, traction), possible inundation	Weakening of steel bridge material	Washouts, slope destabilization
Walking & Biking	Decreased comfort, health risks	Decreased safety (visibility, traction), decreased comfort	Decreased air quality, health hazards	Loss of life, injury
Drainage	Little/No consequence	Drainage overflows, clog drains with leaves	Increased debris flow and clogged drainage systems	Clogged/blocked drainage systems
Traffic Flow	Vehicles overheating, congestion and network delays	Slowdowns, increased accidents	Reduced visibility and whiteouts, route closures, slowdowns and congestion	Slowdowns, congestion
Public Transit	Decreased comfort, transit vehicles overheating, network delays	Decreased comfort, delays	Route closures, trip delays	Route closures
Buildings & Facilities	Load shedding and power outages, construction and maintenance forced to halt or slow down	Inundation of electrical boxes/equipment	Construction forced to halt	Buildings/facilities buried or washed out, maintenance crews diverted for landslide cleanup
Traffic Controls	Power outages to signals	Power outages to signals, reduced sign visibility	Power outages to signals, reduced sign visibility	Damage to infrastructure

Legend	
(dark blue)	High likelihood or Damage
(medium blue)	Moderate likelihood or Deterioration
(light blue)	Medium likelihood or Disruption
(white)	Low likelihood or No Consequences

For this plan, members of the Sacramento CivicSpark team worked to disaggregate international climate change scenarios into regional climate risks in order to identify particular climate trends and the likelihood of their occurrence in the Sacramento region throughout the horizon years of the Metropolitan Transportation Plan/Sustainable Communities Strategies (MTP/SCS) and beyond. This effort identified the following major climate related risks to our region: extreme heat; precipitation, runoff and flooding; increased wildfires; and landslides.

Four categories of consequences cover most eventual impacts to transportation assets. Some events may have multiple possible consequences, while some may not have any notable consequences at all. The four categories of consequences are: No Impact, Disruption of Services or Operation, Deterioration of Infrastructure or Property, and Damage to Infrastructure or Property.

Figure 1 outlines the likelihood and consequences of the identified climate risks and how they may impact vulnerable transportation assets.

Adaptation Approaches

Actions toward climate change adaptation range widely, from relatively low-effort infrastructure management policy changes to expensive and disruptive asset retrofits and replacements. These actions can be broadly categorized into three sectors: Planning, Design, and Maintenance.

Within each of these sectors, actions can be taken toward four types of adaptation strategies: maintain and manage, strengthen and protect, enhance redundancy, and retreat.

Figure 2 provides an overview of these strategies and how they address the different climate related impacts.

Actions

In order to implement this plan, SACOG is proposing a series of action steps.

Action 1. Engage Stakeholders
Create a Technical Advisory Committee (TAC) made up of private, public, non-profit, and research entities. This group will be involved in all aspects of implementation of the climate adaptation plan, including additional analysis of climate impacts, identifying the most critical transportation assets, and overseeing the ongoing monitoring of infrastructure.

Action 2. Conduct Asset Level Assessment
With input from the TAC, carry out an asset level vulnerability assessment on the region's most critical transportation investments. Determine impacts and best possible adaptation strategies.

Action 3. Set Policy for Future Funding Rounds
Work with the SACOG Board of Directors to determine how climate adaptation should be addressed in the biennial regional funding round given the outputs from the asset level assessment.

Action 4. Monitor
Continue to track how the region's transportation investments are adapting to potential climate risks, and define which components are critical and vulnerable.

ADAPTATION STRATEGIES

Maintain and manage: Enhance maintenance and repair policies to improve severe event preparedness and response. Manage procedures for monitoring infrastructure and create/update emergency action plans.

Strengthen and protect: Retrofit existing infrastructure and build new structures that better withstand extreme climate events.

Enhance redundancy: Identify and create alternatives to vulnerable routes. Utilize different modes of transportation to enhance redundancy.

Retreat: Relocate or abandon infrastructure located in highly vulnerable areas. Avoid building new infrastructure in vulnerable locations.

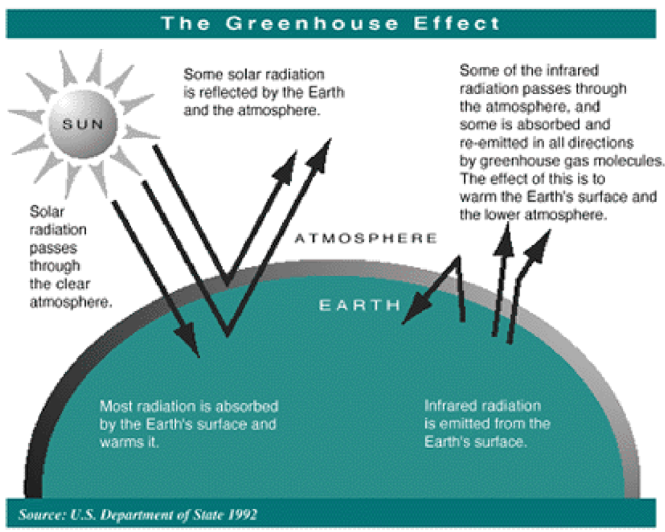
	Extreme Temperature			Precipitation, Runoff, Flooding			Wildfire			Landslides		
	plan	design	maintenance	plan	design	maintenance	plan	design	maintenance	plan	design	maintenance
Roadways	Change design standards on maximum temperatures	Use heat and rut-resistant materials	Implement asset management system, increase monitoring and maintenance schedules	Identify alternative routes to vulnerable and critical routes, limit development in floodplains, conduct risk assesments	Protect evacuation routes, use different asphalt/concrete mixtures, pavement grooving and sloping	Implement asset management system, increase monitoring and maintenance schedules	Identify alternative to vulnerable and critical routes, update emergency improvement plans,	Use heat resistant materials, protect electrical equipment	increase monitoring and maintenance schedules, repair damage as needed	Identify alternative to vulnerable and critical routes, update emergency improvement plans	Protect evacuation routes, ensure adequate drainage on roadbed surfaces and shoulders, incorporate rock fall protection, implement slope hardening	Implement asset management system, increase monitoring and maintenance schedules, ensure roadway is clear of rocks, debris, vegetation, minimize repair backlogs
Railways		Design joints for higher maximum temperatures	Increase monitoring and maintenance schedules, lighten train loads and reduce speeds		Upgrade drainage system and increase culvert capacity							
Bridges		Design joints for higher maximum temperatures, use heat and rut-resistant materials	Implement asset management system, increase monitoring and maintenance schedules	Identify alternative routes to vulnerable and critical routes, limit development in floodplains, conduct risk assessments	Protect bridge piers and abutments, protect evacuation routes, use different asphalt/concrete mixtures, pavement grooving and sloping	Implement asset management system, increase monitoring and maintenance schedules	Identify alternative to vulnerable and critical routes, update emergency improvement plans,	Use heat resistant materials, protect electrical equipment				
Walking & Biking	Provide shade, create safe alternative routes											Identify alternative to vulnerable and critical routes
Drainage				Restrict development in floodplains, conduct risk assessments	Upgrade drainage systems/ increase standard drainage capacity, increase water storage systems	Increase monitoring and maintenance schdules, ensure systems are clear during extreme precipitation, increase capacity of pumps, minimize repair backlogs		Use heat resistant materials				Implement asset management system, increase monitoring and maintenance schedules, minimize repair backlogs
Traffic Flow	Incentivize alternative modes and teleworking			Identify alternative to vulnerable and critical route			Identify alternatives to vulnerable and critical routes			Identify alternative to vulnerable and critical routes, update emergency improvement plans	Protect evacuation routes	
Public Transit	Provide shade, use alternative fuels, encourage carpools											
Buildings & Facilities			Increase monitoring schedule, shift to evening work schedules		Weatherproof equipment and install higher	Increase monitoring and maintenance						
Traffic Controls	Plan alternative traffic control measures			Plan alternative traffic control measures								

FIGURE 2 POSSIBLE ADAPTATION STRATEGIES TO ADDRESS POTENTIAL CLIMATE CHANGE IMPACTS

Section 1

Climate Science

Climate change is a measurable shift in normal weather conditions over time, usually decades or longer[1]. A growing body of scientific research has linked climate change to an increase in the concentration of Greenhouse Gas emissions (GHGs) in the Earth's atmosphere. Concentrations of atmospheric GHGs has remained relatively constant up until the last two hundred years at between 260 and 285 parts per million[2]. Current levels of atmospheric GHGs exceed 400 parts per million[3]. Part of this fluctuation is caused by the natural carbon cycle. Absorption and release of GHGs by the oceans, plants, and the atmosphere is a natural occurrence. However, the Energy Information Administration (EIA) estimates that there are 6 billion metric tons of GHG emissions annually from human activity, and while some of this is absorbed by the carbon cycle, roughly 3 billion metric tons are released into the atmosphere each year[4].



In the United States, roughly 80 percent of all GHG emissions come from the use of petroleum and natural gas[5]. This equals about 25 percent of global emissions. According to an EIA report, world energy consumption will increase by 47 percent from 2007 to 2035. This increase will be led by the use of liquid fuels, including petroleum and natural gas. Worldwide demand for oil is growing steadily. Current world oil usage is about 90 million barrels per day, with demand rising to around 111 million barrels per day by 2035[6].

The impacts from a change in global climate can be felt throughout the state and region. California has adopted the public policy position that global climate change is "a serious threat to the economic well-being, public health, natural resources, and the environment of California." Health and Safety Code § 38501 states that:

> *the potential adverse impacts of global warming include the exacerbation of air quality problems, a reduction in the quality and supply of water to the state from the*

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[1] Intergovernmental Panel on Climate Change, Annex I – Glossary, http://www.ipcc.ch/pdf/glossary/ar4-wg1.pdf

[2] California Climate Change Portal, http://www.climatechange.ca.gov/background/index.html

[3] Dr. Pieter Tans, NOAA/ESRL (www.esrl.noaa.gov/gmd/ccgg/trends/) and Dr. Ralph Keeling, Scripps Institution of Oceanography (scrippsco2.ucsd.edu/).

[4] Energy Information Administration, http://www.eia.gov/oiaf/1605/ggccebro/chapter1.html

[5] Environmental Protection Agency, http://www.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2015-Main-Text.pdf

[6] Energy Information Administration, http://www.eia.gov/oiaf/1605/ggccebro/chapter1.html

Sierra snowpack, a rise in sea levels resulting in the displacement of thousands of coastal businesses and residences, damage to marine ecosystems and the natural environment, and an increase in the incidences of infectious disease, asthma, and other human health-related problems … [and that] … global warming will have detrimental effects on some of California's largest industries, including agriculture, wine, tourism, skiing, recreational and commercial fishing, and forestry (and)…will also increase the strain on electricity supplies necessary to meet the demand for summer air-conditioning in the hottest parts of the State.

CLIMATE RISKS

General Circulation Models (GCMs), also referred to as Global Climate Models, are numerical models that are used to simulate the Earth's physical processes through atmospheric and oceanic circulation patterns. These models are derived from complex mathematical equations that account for how the atmosphere, oceans, ice, land surface, and natural and anthropogenic emissions of greenhouse gases interact globally in the climate system over the next centuries. Because different models account for atmospheric feedbacks to determine climate sensitivity in various ways, four GCMs were selected for this analysis. These GCMs have been shown to model climate change in California with relative reliability, and are therefore widely used for climate impact analyses within the state:

- The NCAR Parallel Climate Model (PCM1)
- The NOAA Geophysical Fluids Dynamics Laboratory, Version 2.1 (GFDL)
- The NCAR Community Climate System Model, Version 3.0 (CCSM3)
- The French Centre National de Recherches Météorologiques, CM 2.1 (CNRM)

EMISSION SCENARIOS

A critical organization involved in climate analysis and publication is the Intergovernmental Panel on Climate Change (IPCC), a scientific intergovernmental body established in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP). The IPCC produces technical literature that supports scientific research to inform the international community of the ongoing environmental and socio-economic impacts of climate change, and offers appropriate strategies for mitigation and adaptation.

IPCC 4[7]

The IPCC Fourth Assessment Report (AR4), Climate Change 2007, is the fourth in a series of scientific reports to assess climate change impacts. In this report, the IPCC developed a Special Report on Emission Scenarios (SRES) which utilized different modeling approaches and a range of GHG emission assumptions to define six plausible global emission scenarios. Each of these scenarios represents a hypothetical storyline about alternative energies, global population, gross domestic product, and the resulting energy consumption. Two of such – the A2 and B1 scenarios,

[7] Intergovernmental Panel on Climate Change (IPCC). 2007: IPCC Special Report: Emission Scenarios. https://www.ipcc.ch/pdf/special-reports/spm/sres-en.pdf

representing medium-high and low emission projections, respectively – are the most widely used scenarios to compare theoretically opposite narratives of international development.

A2 scenario assumes a "business-as-usual" scenario with continuous rapid population growth and unparalleled agricultural productivity, compounded by a widening disparity in economic and technological growth between developed and less-developed nations. The slow development of renewable energy and other energy-efficient improvements will result in continuous increase in emissions over the next century.

B1 scenario assumes a "best-case" scenario with population growth peaking at mid-century and declining thereafter. Rapid socioeconomic growth and technological achievements will promote more equitable and democratic developments and efficient utilization of resources. Developments for more non-fossil fuel options will be available, diverting energy supply and demand from conventional oil and gas venues.

To provide a sense of the variance in climate sensitivity measured under the two SRES emission scenarios, Figure 1 below compares the rise in annual temperature (˚C) by 2070-2099 from the historical average of 1961-1990 between four different GCMs under the A2 and B1 scenarios.

	Global Climate Models			
	PCM1	**CNRM**	**CCSM3**	**GFDL**
A2 (medium-high)	2.6 ˚C	3.9 ˚C	4.2 ˚C	4.5 ˚C
B1 (low)	1.6 ˚C	2.2 ˚C	2.4 ˚C	2.7 ˚C

TABLE 1. ANNUAL TEMPERATURE DIFFERENCE BETWEEN GLOBAL CLIMATE MODELS AND SRES EMISSIONS SCENARIOS. SOURCE: CAL-ADAPT 2013.

IPCC 5

In November 2014, the IPCC released a Fifth Assessment Report (AR5), which addresses some of the ambiguities of SRES by employing a third generation of emission futures, called Representative Concentration Pathways (RCPs). Rather than using presumed storylines about development scenarios, RCPs present emission projections utilizing baseline levels of radiative forcing* from all natural and anthropogenic sources (expressed in Watts per square meter). RCPs are thus not contingent upon any particular socioeconomic futures, and thereby allow for greater flexibility to incorporate different economic, technology, policy, and institutional features[8]. Four main pathways were presented in the report: RCP8.5, RCP6, RCP4.5, and RCP2.6 (or RCP3-PD). As outlined in Figure 2, projections using SRES B1 are analogous to RCP4, and SRES A2 sits somewhere between RCP6 and RCP8.5[9].

[8] Intergovernmental Panel on Climate Change (IPCC). 2014: Scenario Process for AR5. http://sedac.ipcc-data.org/ddc/ar5_scenario_process/RCPs.html

[9] Rogelj, J., Meinshausen, M., Knutti, R., (2012). "Global warming under old and new scenarios using IPCC climate sensitivity range estimates." Nature Climate Change 2, 248-253. Online.

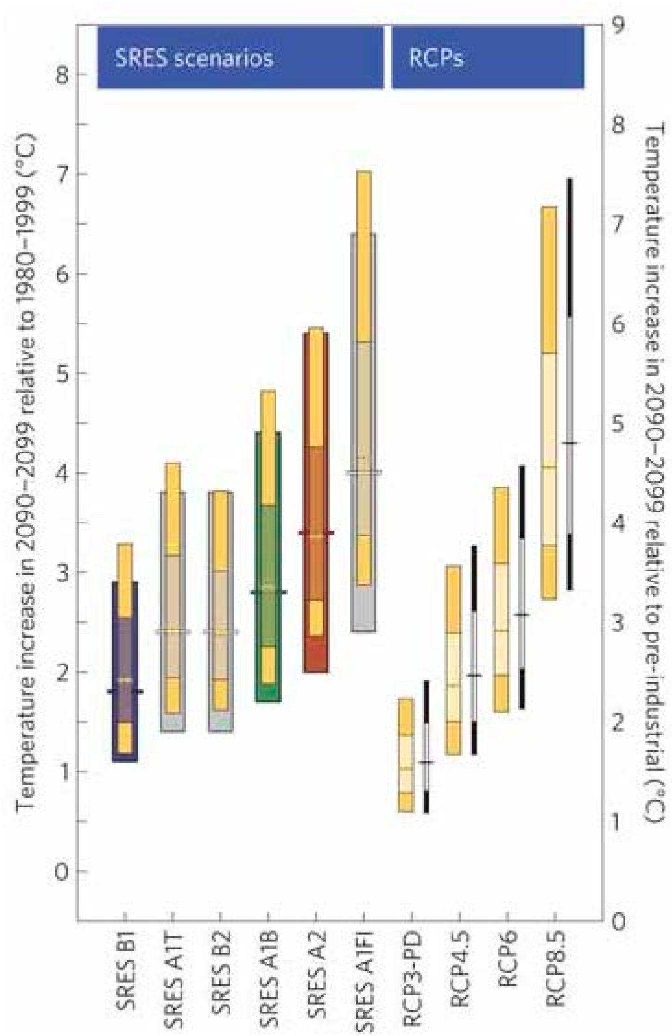

FIGURE 3 COMPARISON OF TEMPERATURE INCREASES PROJECTED BY SRES EMISSIONS SCENARIOS AND RCPS. SOURCE: ROGELJ ET AL. (2012).

Because of the relatively recent release of AR5 and the lack of available data evaluated under these pathways, RCPs were not used in this particular analysis in favor of using existing methods that are more widely used in California and other transportation agencies.

**Radiative forcing is essentially a measure of energy balance on Earth, indicating how much energy is flowing in and out of the planet (Chandler, 2010). It is calculated as the difference of sunlight absorbed by the Earth and the energy that is radiated back into space.*

Types of Impacts

In this report, a distinction is made between primary, secondary, and tertiary impacts of climate change. Primary effects are direct large-scale changes in climate factors, such as increased temperature, that will drive the secondary consequences on a natural resource or asset. The compounding effect of these factors may then increase the potential for a tertiary hazard. For example, higher temperatures will increase the rate of evapotranspiration in plants, resulting in greater presence of dry fuels in forests and create a higher potential for wildfire risks. Precipitation pattern changes in the season may increase the magnitude of surface runoff, which may trigger landslides. The primary climate factors most relevant to the SACOG region, and therefore evaluated in this report, are changes in temperature and precipitation patterns. These primary changes will affect the secondary impact of changing runoff patterns, which may increase the tertiary risks of increasing wildfires, landslides, flooding, and drought in the region. Temperature, precipitation, runoff and wildfires have been quantitatively projected by global climate models and are analyzed in detail in this work. Landslides, drought, and flooding are difficult to quantitatively project, but are included in this analysis due to their potential impacts to the transportation system.

A plethora of other factors may be, in some way, affected by climate change, ranging from seismic risks to large-scale ground subsidence, as well as social, economic, and land-use issues related to the transportation system. However, the necessity to keep a focused and reasonable scope prevents this analysis from considering all ancillary factors that could be related to

climate adaptation in the transportation system. Instead, the plan focuses primarily on transportation infrastructure and directly related planning issues.

It is also important to note that the consequences of climate change will manifest at different timescales and intensities. Some impacts will occur gradually over time, such as average temperatures increasing over the next 100 years. Other climate changes will trigger sudden events, such as extreme precipitation events that intensify landslides and debris flow. The resulting impacts on the transportation network may be low-urgency, such as the reduced lifespan of a road segment; or they may be catastrophic, as in the structural collapse of a bridge or roadway. When planning for climate change, consequences all along this spectrum of timing and intensity should be considered. More sudden and severe events may require partnering with emergency and hazard mitigation services, while gradual changes may be mitigated through cooperation among long-term planning agencies.

Climate change is a complex science that continues to evolve as improved research, methods, and data are introduced. There are no perfect reproductions of climate processes, as there are high levels of uncertainties, natural fluctuations, and competing effects that are difficult to capture within model algorithms. Different climate models also give varying weights to physical variables, like the interactions between atmospheric pressure, ocean circulation, and water vapor. Furthermore, the SRES scenarios evaluate GHG emissions based on presumptions about socioeconomic parameters, demographic changes, technological innovations, and policy initiatives that are virtually impossible to accurately predict.

Additional problems are introduced when applying these data at the regional scale. GCMs are designed to model climate change on a global continental scale; the spatial resolution per grid cell used in the 2007 IPCC report is roughly 120 by 180 miles[10]. The coarse cell size neglects much of the topological and ecological nuances that impact climate processes at the local level. It is important to remember that these are projections, not predictions or forecasts, of climate consequences based on plausible social and economic scenarios in the next century.

Regional Climate Risks

Methodology

Cal-Adapt is an online tool developed by the California Energy Commission under a key recommendation of the 2009 California Climate Adaptation Strategy to synthesize and share existing climate science research that can inform local decision-making and adaptation planning[11]. The site provides access to a wealth of scientific data from well-established institutions such as Scripps Institute of Oceanography, Pacific Institute, U.S Geological Survey, UC Berkeley, UC Merced, and Santa Clara University. Cal-Adapt produces climate projections for the entire state of California, ensuring that the regional climate data extracted for this report takes into account relevant environmental factors that are outside of the SACOG jurisdictional boundary (for instance, regional runoff values will reflect wider watershed behavior). The data uses IPCC SRES emission scenarios that are downscaled to California's geography through two

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[10] Intergovernmental Panel on Climate Change (IPCC). 2007: IPCC Special Report: Emission Scenarios. https://www.ipcc.ch/pdf/special-reports/spm/sres-en.pdf
[11] http://cal-adapt.org/page/about-caladapt/

downscaling methods: bias correction spatial downscaling (BCSD) and bias correction constructed analogues (BCCA).

Data Processing

Tabular and raster data were obtained from Cal-Adapt to analyze projected trends for maximum temperature, precipitation, runoff, and fire. Datasets were extracted between January 1980 and December 2099 from PCM1, GFDL, CCSM3, and CNRM models under A2 and B1 emission scenarios, when available. Due to the temporal variability in climate impacts projected under each climate model, the GCMs were averaged across 30-year time periods:

- 1980 – 2010: Historical
- 2011 – 2040: Near-Term
- 2041 – 2070: Mid-Century
- 2071 – 2099: Far-Term

Tabular data were accessed on Cal-Adapt by selecting grid cells in the approximate shape of the SACOG region, using designated latitude and longitude values associated with each cell. Excel was then used to process the monthly data and produce desired data summaries. These calculations included averaging the data for the historical and projected periods, creating regional averages for each of these datasets, and calculating the change in values over time.

Raster data were obtained in the form of GeoTIFF files and were processed through ArcGIS 10.1. Datasets are georeferenced to World Geodetic System of 1984 (WGS 1984). Based on the tabular data summaries, specific months were selected for their criticality within each climate impact evaluation. The GeoTIFF rasters were averaged across each respective time period, clipped to the SACOG counties boundary, and then averaged across all four GCMs. Calculations of absolute and relative change are calculated using the baseline projections of the Historical Period (1980-2010).

Maximum Temperature

Daily maximum temperature data were available in tabular form on Cal-Adapt, which allowed for the evaluation of extreme heat events. Monthly average raster data were also processed, to display the spatial variation of the temperature changes.

Fire

Fire data were only available on Cal-Adapt in raster form, and in 30-year intervals with years ending in 2020, 2050, and 2085. They were archived in A2 and B1 emissions scenarios under three GCMs: PCM1, GFDL, and CNRM.

Precipitation, Runoff and Flooding

Ideally, extreme precipitation events would be analyzed using daily precipitation data, since extreme events have the greatest impacts on transportation infrastructure. However, because monthly intervals were the smallest time-steps available on Cal-Adapt, precipitation and runoff

trends were evaluated under monthly sums. It is assumed that increases in monthly precipitation and runoff also indicate increases in extreme events in the projected years (through greater storm intensity, frequency, and/or duration).

Precipitation and runoff changes in the Sierras will impact flooding in the Central Valley. However, flooding in the Sacramento region involves complex interactions between Sierra precipitation, snowmelt, and runoff, local precipitation levels, and sea level rise approaching from the Delta. There is little available data that identifies the relationship between climate changes in the Sierra Mountains and flooding in the Valley, so this section does not draw conclusions regarding changes in downstream flooding due to high elevation precipitation and snowmelt. The section on adaptation policies does consider flooding risks when making recommendations.

Climate Change Effects

Expected Climate Projections

EXTREME HEAT

An important indicator of heat levels that affect transportation systems is the number of extreme heat days per year. "Extreme Heat" was set at the threshold of 95ºF, as is consistent with numerous statewide climate[12]. As seen in Figure 4, all counties in SACOG demonstrate a significant increase in the number of days over 95ºF, although Placer and El Dorado exhibit a slightly less dramatic increase due to the cooling effect of the Sierra Nevada Mountains.

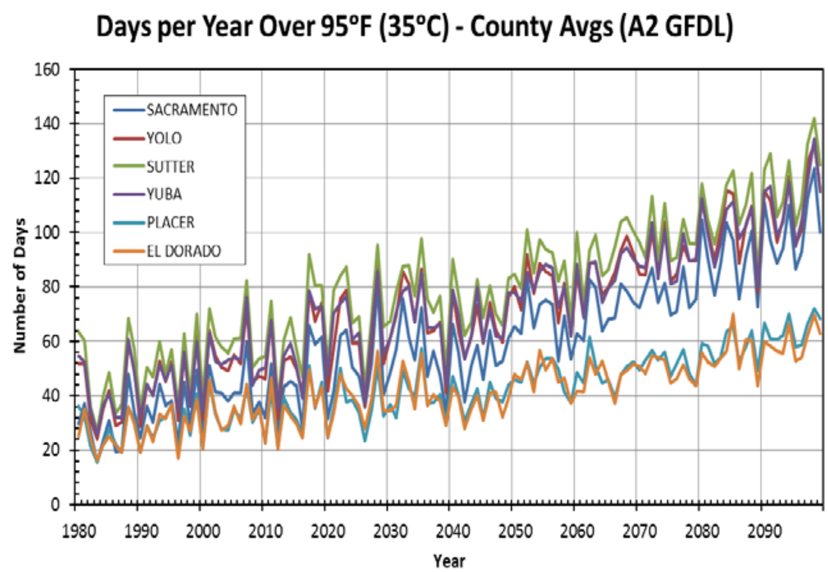


FIGURE 4. NUMBER OF DAYS PER YEAR ABOVE 95□F, AVERAGED BY COUNTY, USING THE GFDL MODEL UNDER A2 EMISSIONS SCENARIO.

While all the models are in relative agreement regarding the trends of increasing temperatures over the century, they exhibit some variation on the magnitude of increase. Figure 5 compares the spread of model results from the Historical period (1980-2010) to the Far-Term period (2071-2099). Overall, the models show a spread of approximately 8ºF in their projected rise in summer

[12] California Department of Transportation (Caltrans) and Humboldt County Association of Governments (HCOG). 2014: *District 1 Climate Change Vulnerability Assessment and Pilot Studies: FHWA Climate Resilience Pilot Final Report*. Prepared by GHD. Online.

temperatures, with the "least hot" model, B1 PCM1, predicting an increase of about 2ºF and the "hottest" model, A2 GFDL, projecting an increase close to 10ºF. The highest maximum temperatures tend to occur in the summer months from June to September, and lower temperatures are generally projected for the B1 emissions scenario than for the A2 scenario (with the exception of A2 PCM1).

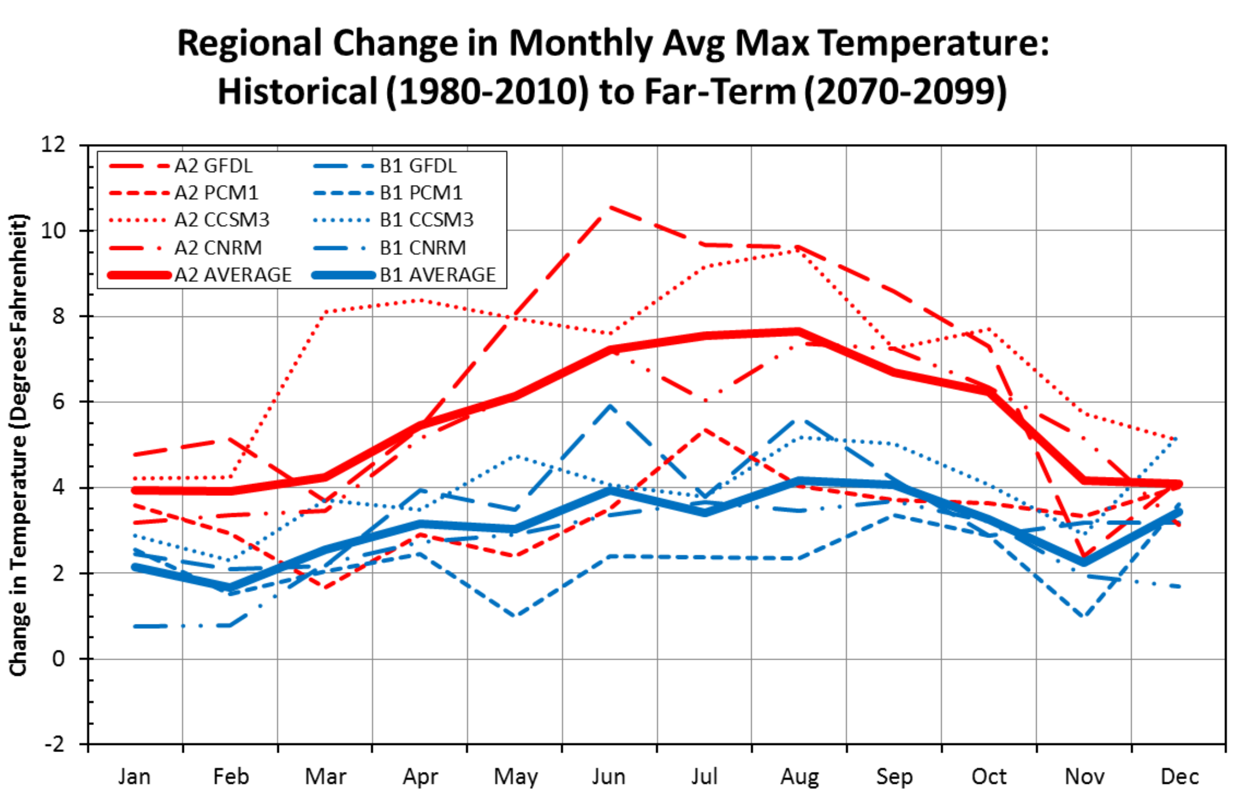


FIGURE 5. CHANGE IN AVERAGE MAXIMUM TEMPERATURE EACH MONTH, AVERAGED ACROSS SACOG, COMPARING FOUR MODELS (GFDL, PCM1, CNRM, CSSM3) AND TWO EMISSIONS SCENARIOS (A2 AND B1).

When averaged across all four GCMs, July and August are identified as the most critical months for increased temperature effects for the entire SACOG region (see Figure 6). These months experience the highest temperatures historically and are projected to undergo the largest increase in temperatures during the 21st century. Under an A2 scenario, the average monthly maximum temperature may reach as high as 95ºF in July and August, showing a drastic increase from the current climate, where 95ºF is considered the threshold for an extreme heat day.

Map Sets 1 and 2 illustrate the locations of the most dramatic increases of average monthly maximum temperatures. All six counties within the SACOG region are expected to gradually warm over the next century under both A2 and B1 emission scenarios. The Central Valley counties (Sacramento, Yolo, Sutter, Yuba) will anticipate the most frequent extreme heat events in the summer months, as average monthly temperatures are projected to reach as high as 105˚F by 2099.

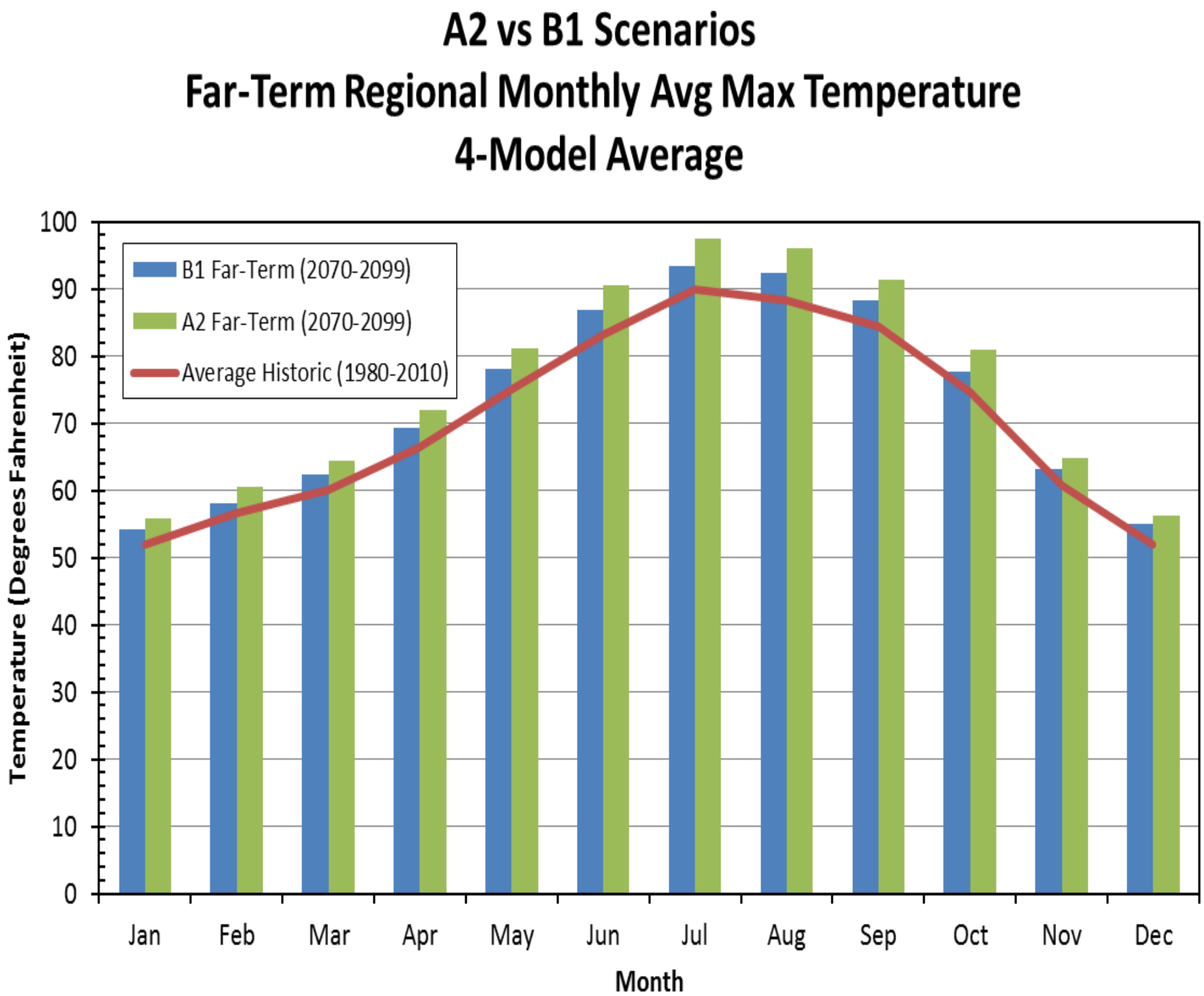
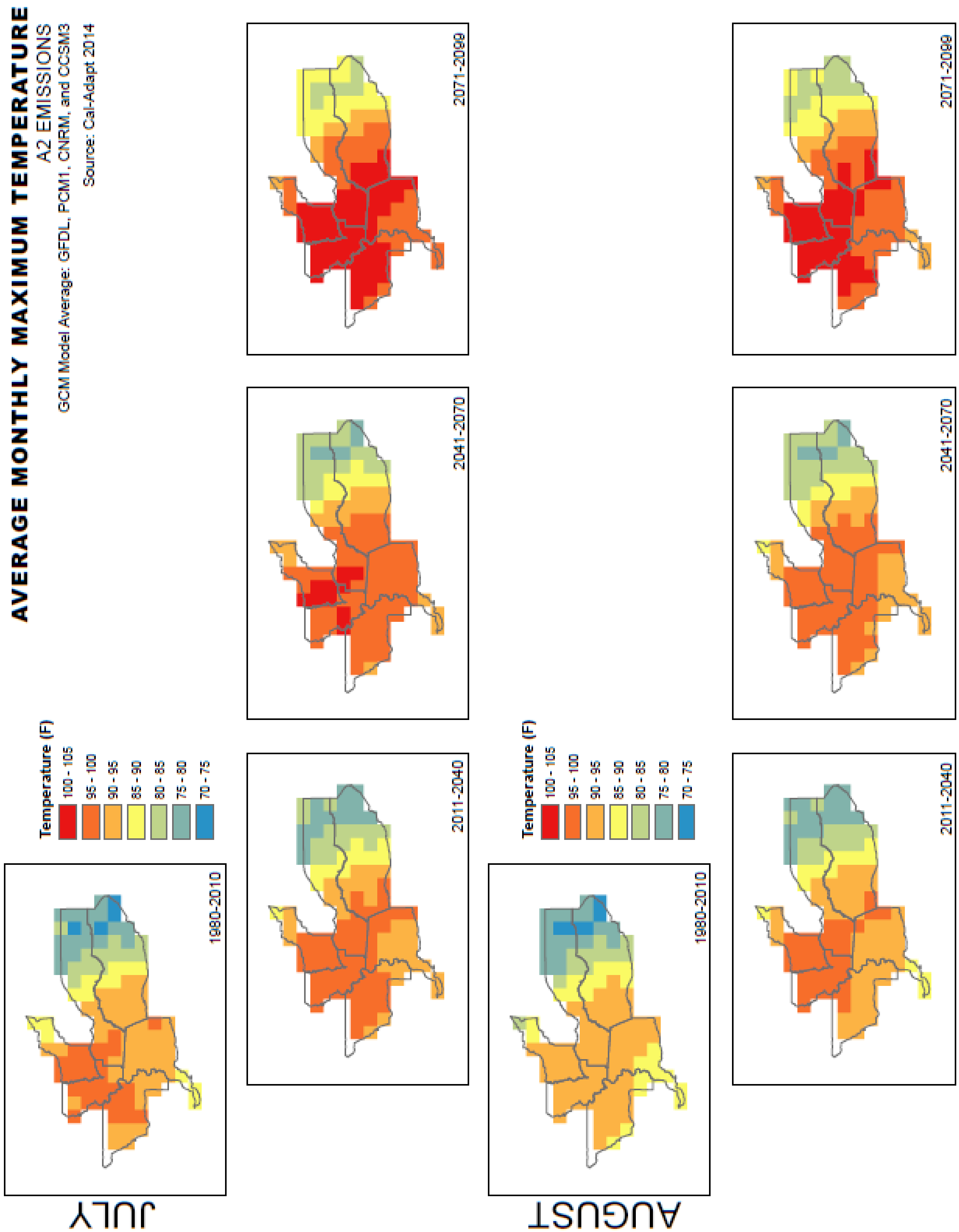
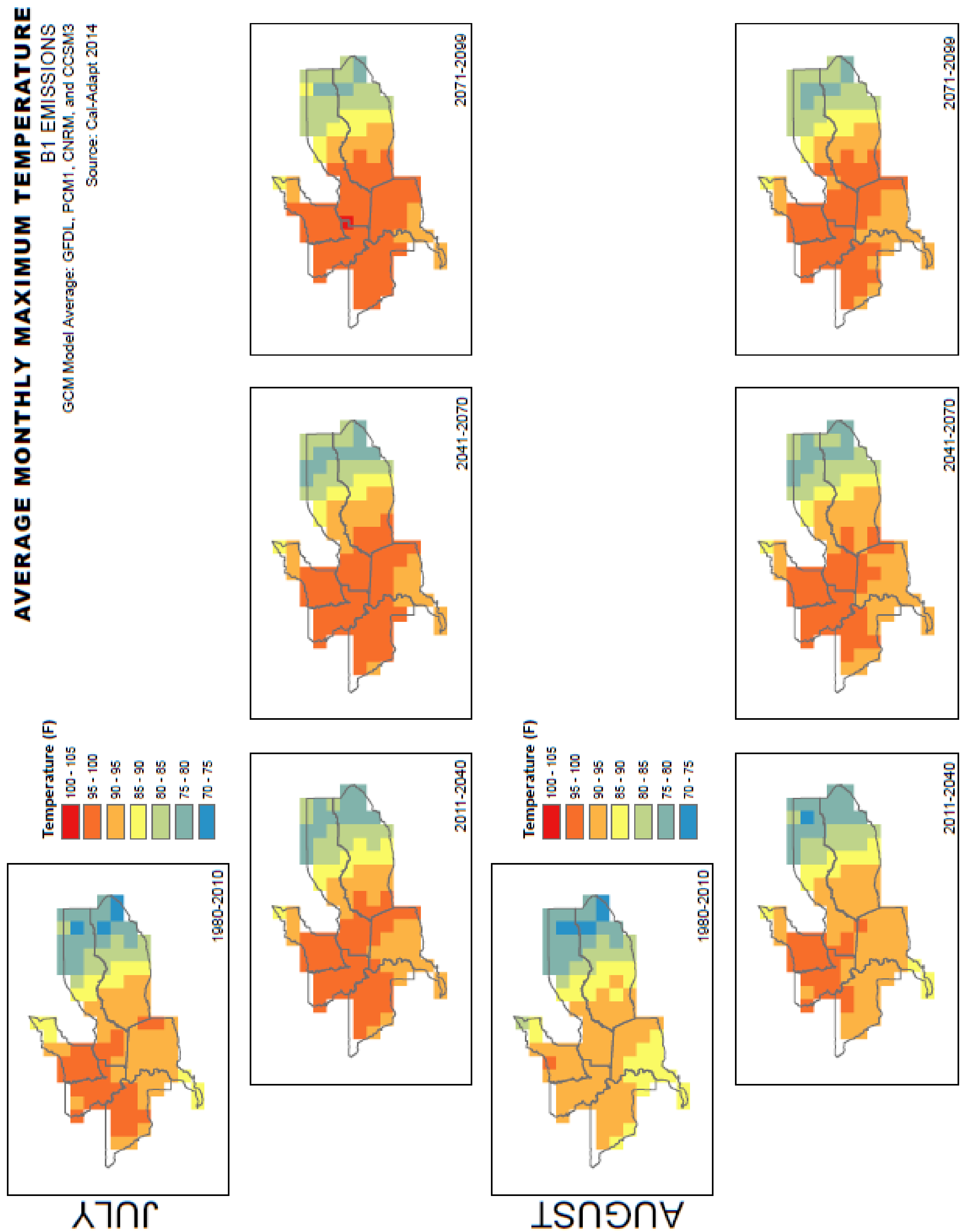


FIGURE 6. AVERAGE MAXIMUM TEMPERATURE EACH MONTH, AVERAGED ACROSS SACOG, USING A FOUR-MODEL AVERAGE (GFDL, PCM1, CNRM, CSSM3), UNDER A2 AND B1 EMISSIONS SCENARIOS.

The warming in the Sierra Nevada mountain regions carries strong implications for earlier snowmelt in the spring, precipitation falling as rain instead of snow, and consequently the winter snowpack decreasing as much as 70 to 90 percent (CCCC 2012).



MAP SET 1. A2 EMISSIONS SCENARIO PROJECTIONS OF AVERAGE MONTHLY MAXIMUM TEMPERATURE OVER FOUR TIME PERIODS, TAKEN AS A GCM AVERAGE.



MAP SET 2. B1 EMISSIONS SCENARIO PROJECTIONS OF AVERAGE MONTHLY MAXIMUM TEMPERATURE OVER FOUR TIME PERIODS, TAKEN AS A GCM AVERAGE

PRECIPITATION, RUNOFF, AND FLOODING

Working with precipitation and runoff data presented a major challenge, due to the wide variability in model projections. Precipitation and runoff are notoriously difficult to predict, and the processes only become more convoluted when accounting for climate change effects projected many years into the future. Yearly precipitation values fluctuate drastically, as shown in Figure 7, which tracks January precipitation levels each year from 1950 to 2099 for one model and scenario.

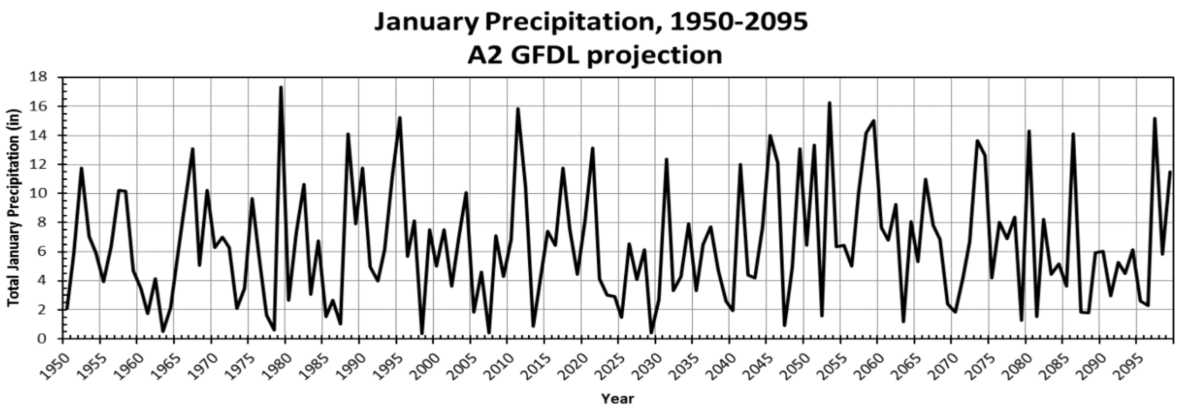


FIGURE 7. JANUARY PRECIPITATION, PLOTTED EACH YEAR FOR THE YEARS 1950-2099, USING THE GFDL PROJECTION FOR AN A2 EMISSIONS SCENARIO.

Each model and emission scenario projects these fluctuations in a different way. This model variability is demonstrated in Figures 6 and 7, where projections drastically vary between the months of December to March regarding both the volume of precipitation and runoff in a given month and the general trends over the course of the year. Averaging the GCMs becomes problematic, since the high positive and low negative projections virtually cancel out and result in near-zero averages.

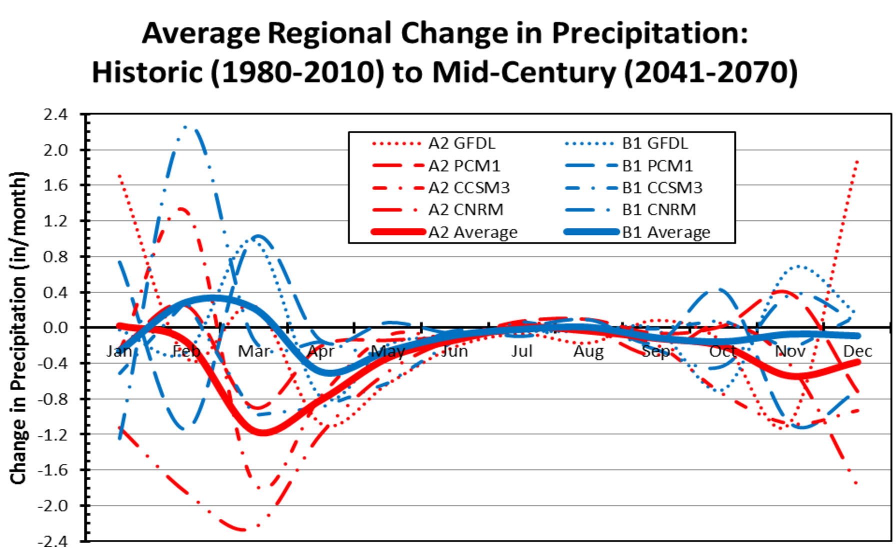


FIGURE 8. COMPARISON OF CHANGE IN PRECIPITATION, AVERAGED ACROSS SACOG, BETWEEN FOUR MODELS (GFDL, PCM1, CNRM, CCSM3) AND TWO EMISSIONS SCENARIOS (A2 AND B1).

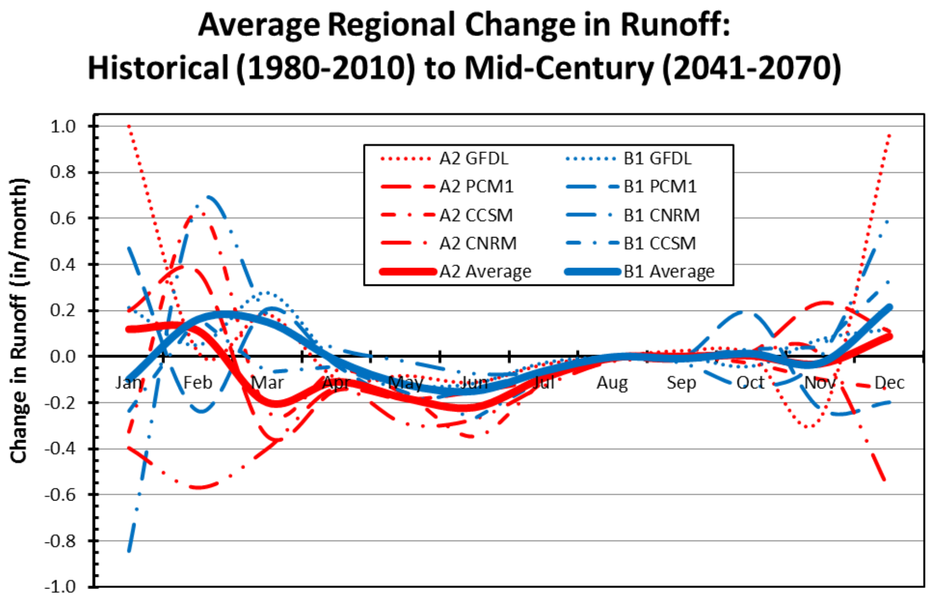


FIGURE 9. COMPARISON OF CHANGE IN RUNOFF, AVERAGED ACROSS SACOG, BETWEEN FOUR MODELS (GFDL, PCM1, CNRM, CCSM3) AND TWO EMISSIONS SCENARIOS (A2 AND B1).

Because taking model averages of precipitation and runoff data minimized the impacts of the climate stressors, the datasets were also screened to select a “worst-case” scenario. January is the most critical month for analysis, showing highest total volume of precipitation and runoff in historical trends, and is expected to increase significantly during this century (see Figures 8 and 9). Within the month of January, A2 GFDL is the “extreme worst case”, based on the highest increases from historical precipitation and runoff trends to mid-century (2041-2070). According to the A2 GFDL model, in January there will be an approximately 28% increase in precipitation from historical (1980-2010) to projected (2041-2070), averaged across the region. This will cause runoff to increase as much as 117%.

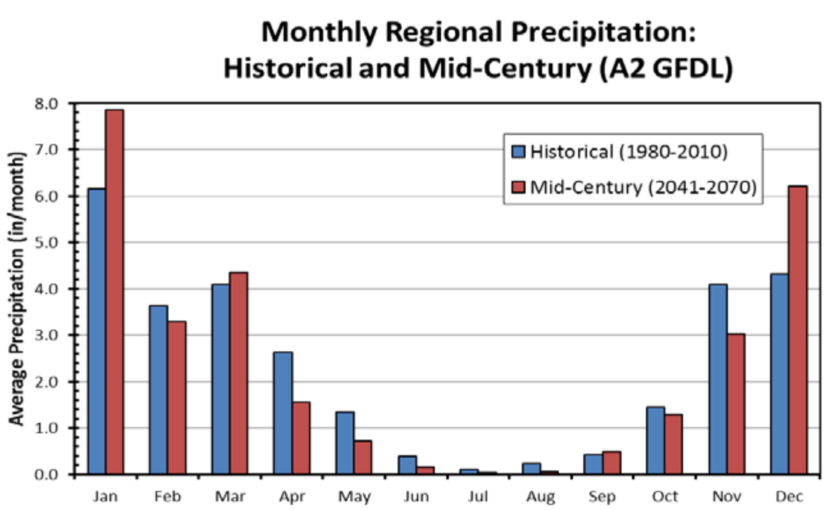


FIGURE 10. HISTORICAL AND MID-CENTURY MONTHLY PRECIPITATION, AVERAGED ACROSS THE SACOG REGION UNDER AN A2 GFDL PROJECTION.

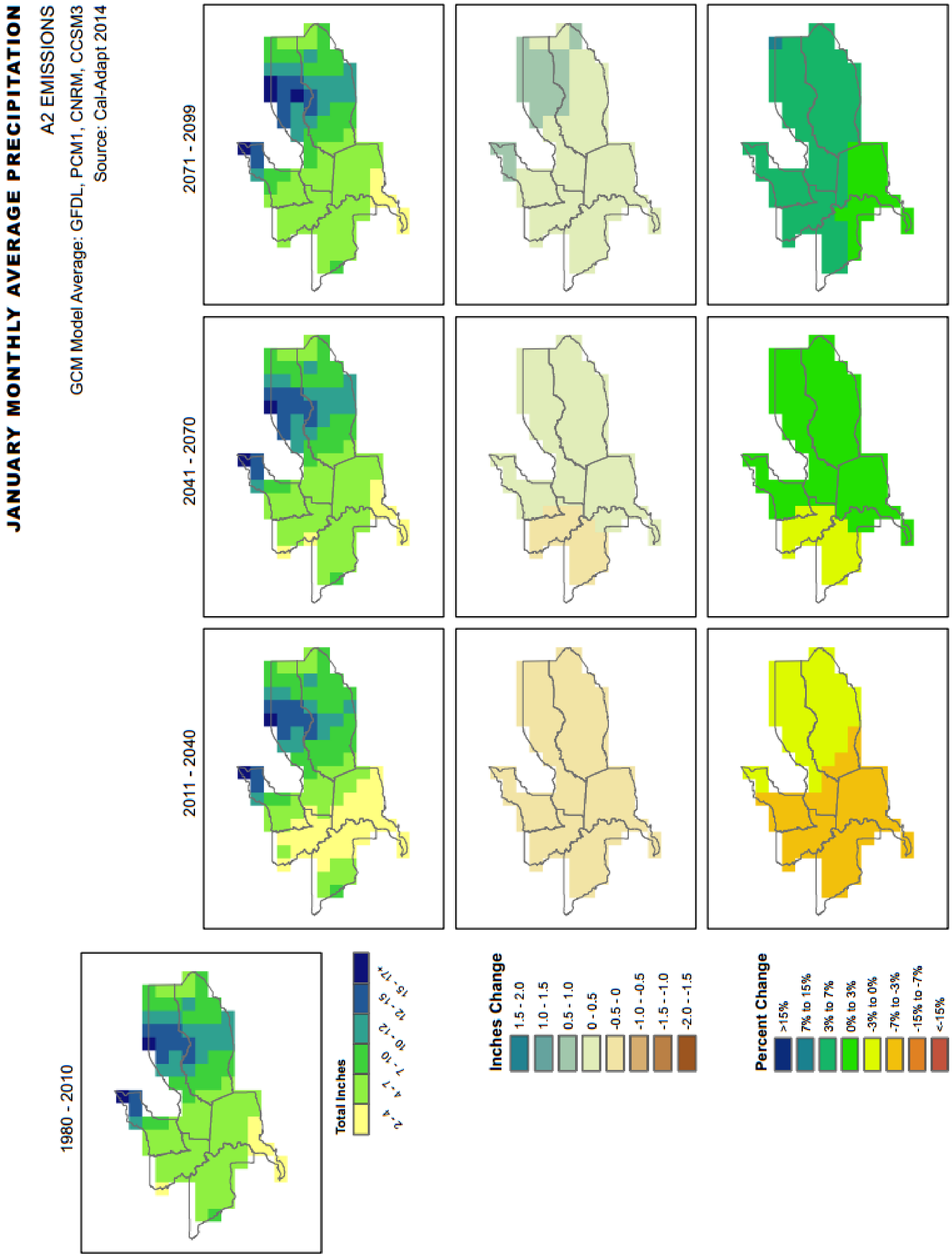
Although precipitation and runoff changes are relatively small for model average analysis, the average trends were still examined for methodological consistency. Precipitation and runoff trends follow very similar trajectories [Map Set 3 - 6]. When averaged across all four GCMs, the A2 emissions scenario projects a progressive increase that will peak by the Far-Term of the century, while B1 emissions scenario will project a high increase in the Near-Term period and then gradually decrease by 2099.

The highest increases in precipitation are projected in the Placer and El Dorado Counties, with up to a 1 inch increase of precipitation near the Sierras, translating to a 7% increase from the Historical Period. Under the B1 emissions scenario, the region will expect a 10% increase in precipitation, about 1.5 inches, in the Near-Term Period (2011-2040). However, the B1 scenario also projects a drastic decrease towards the end of the century, showing a 12% precipitation decrease across the region by 2099.

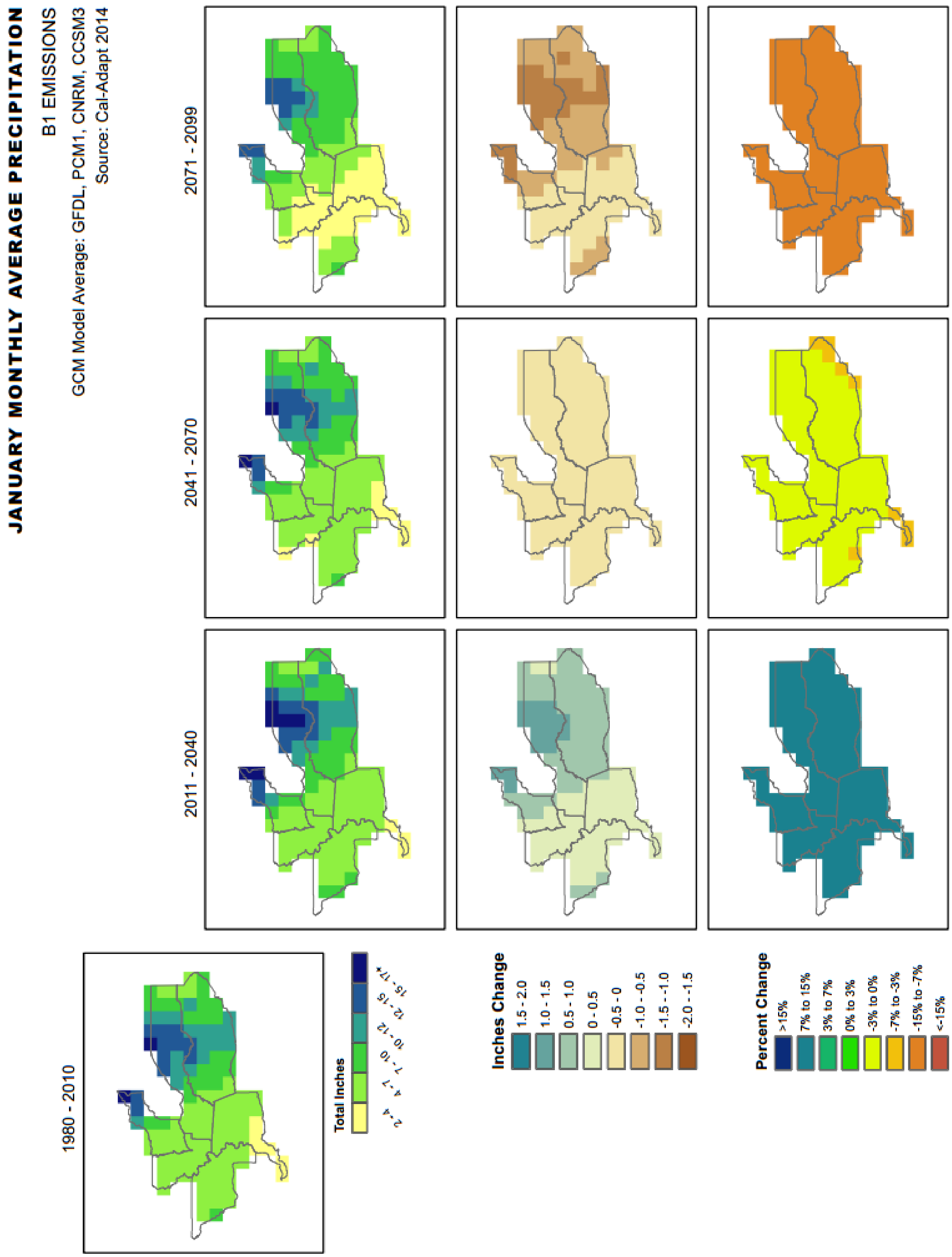
The greatest impacts of runoff occur in the Sierra regions of Placer and El Dorado counties. In the A2 scenario, Placer County will likely experience up to 2 inches of increase by the end of the century. Under the B1 emissions scenario, runoff in the Sierras will also see up to 2 inches increase in the mountainous regions, but will be paired with up to a 1 inch decrease in the foothills. The percent change in runoff ranges up to an increase of 100-600% and decrease of 1-40% in certain grids.

Under an A2 emissions scenario, the GFDL model projects high increases in precipitation and runoff that peak around mid-century [Map Set 7 - 8]. Placer and El Dorado Counties will be the most impacted regions, with up to a 4 inch precipitation increase near the Sierras, a 20-30% increase from the Historical Period. Sacramento, Yolo, and Sutter Counties are expected to experience up to 2 more inches of precipitation, also a 20-30% increase from historical. By the end of the century, precipitation is projected to return to approximately historical levels.

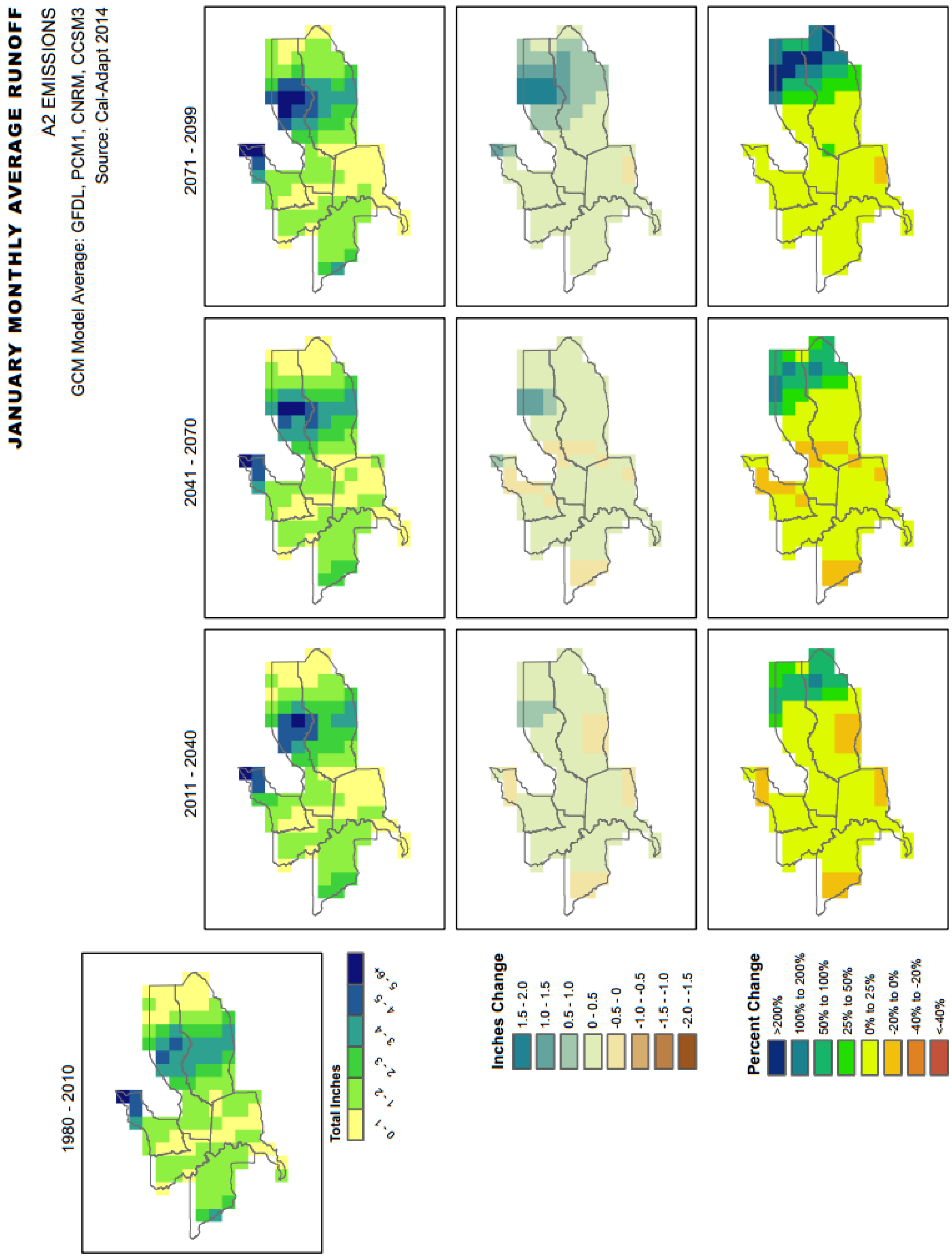
Runoff in the Sierras may increase by up to 4 inches (as much as 600% from historical), accompanied by increases of 0.5-1 inch across the Valley (100-200% from historical). These increases are expected to persist in the Sierras through the end of the century at slightly lower levels, remaining 0.5-3 inches, or 50-600%, above historical during the far-term (2071-2099). The Central Valley is projected to return to approximately historical levels by 2099.



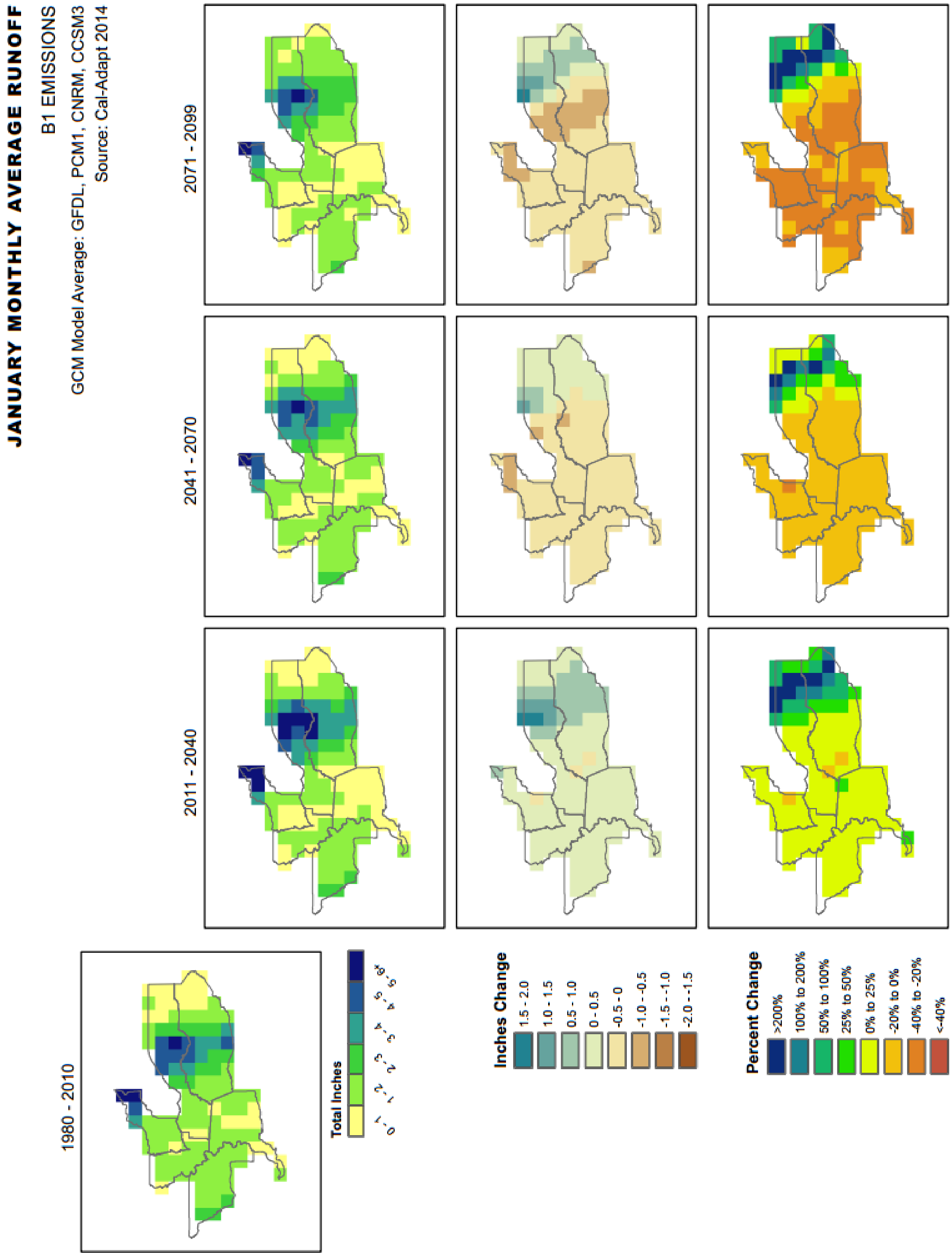
MAP SET 3. A2 EMISSIONS SCENARIO, MODEL AVERAGE PROJECTIONS FOR JANUARY MONTHLY AVERAGE PRECIPITATION OVER TIME, ALONG WITH INCHES CHANGE AND PERCENT CHANGE FROM HISTORICAL.



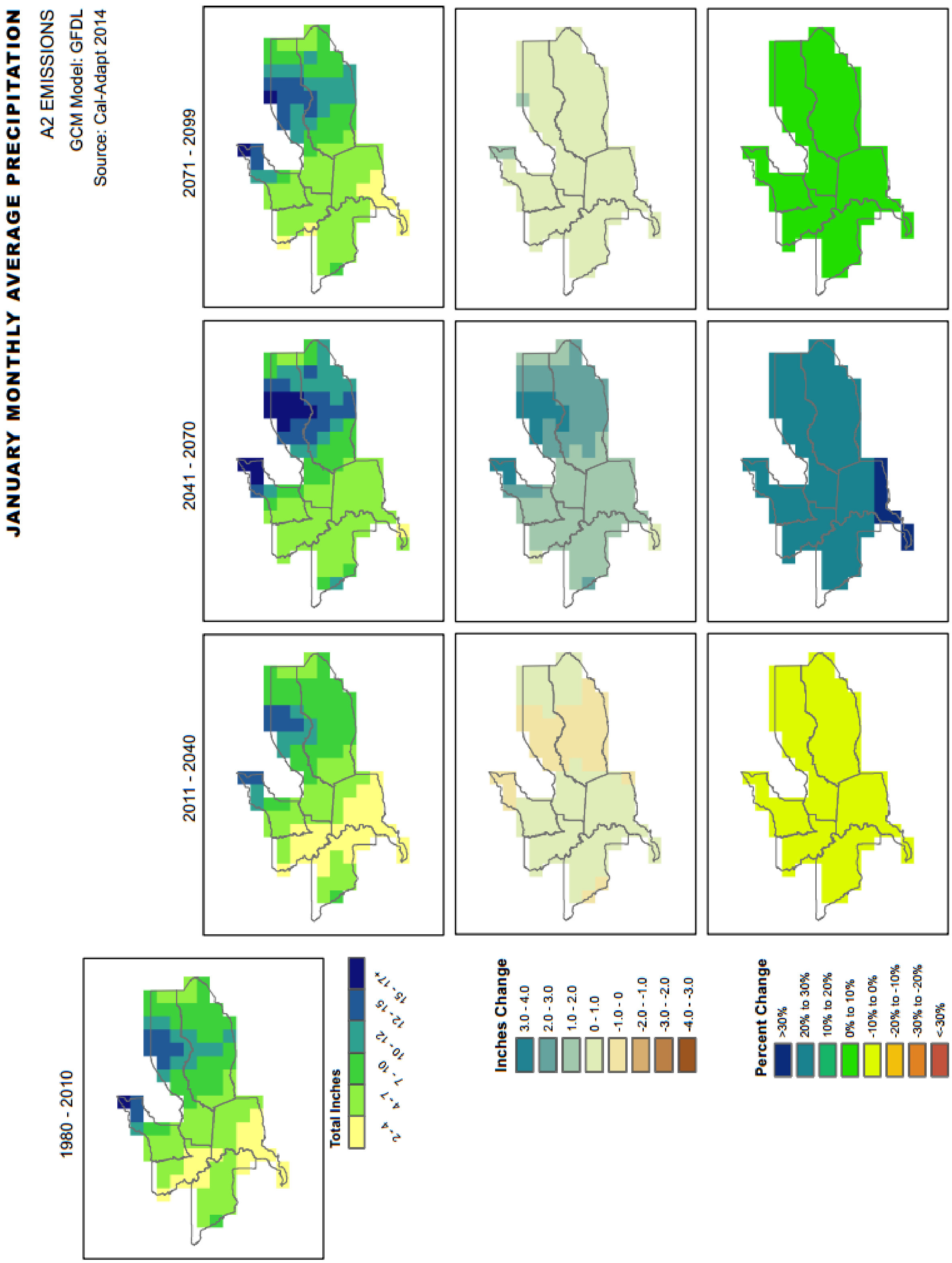
MAP SET 4. B1 EMISSIONS SCENARIO, MODEL AVERAGE PROJECTIONS FOR JANUARY MONTHLY AVERAGE PRECIPITATION OVER TIME, ALONG WITH INCHES CHANGE AND PERCENT CHANGE FROM HISTORICAL.



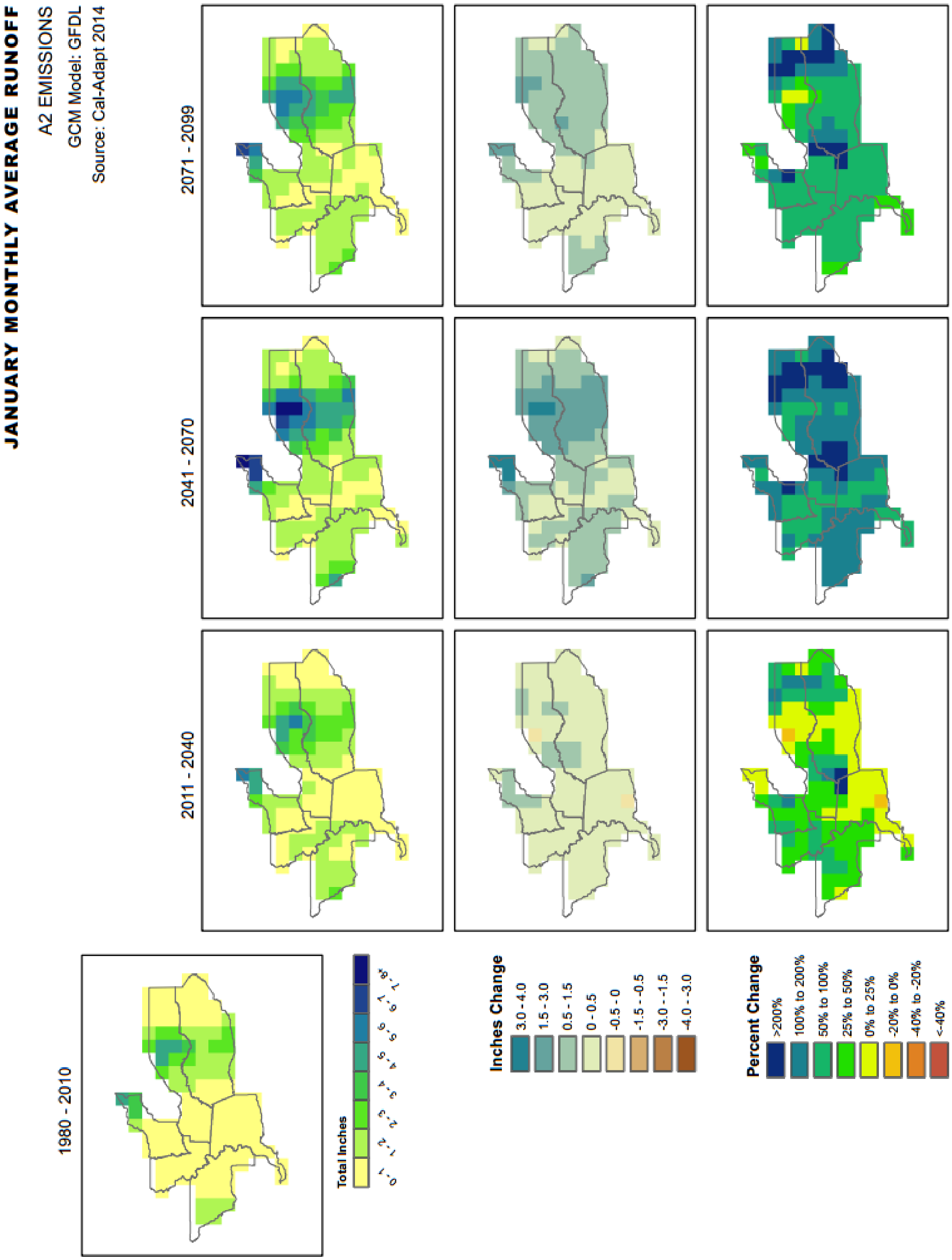
MAP SET 5 A2 EMISSIONS SCENARIO, MODEL AVERAGE PROJECTIONS FOR JANUARY MONTHLY AVERAGE RUNOFF OVER TIME, ALONG WITH INCHES CHANGE AND PERCENT CHANGE FROM HISTORICAL.



MAP SET 6 . B1 EMISSIONS SCENARIO PROJECTIONS OF AVERAGE MONTHLY RUNOFF OVER FOUR TIME PERIODS, TAKEN AS A GCM AVERAGE



MAP SET 7 . A2 EMISSIONS SCENARIO, GFDL MODEL PROJECTIONS FOR JANUARY MONTHLY AVERAGE PRECIPITATION OVER TIME, ALONG WITH INCHES CHANGE AND PERCENT CHANGE FROM HISTORICAL.

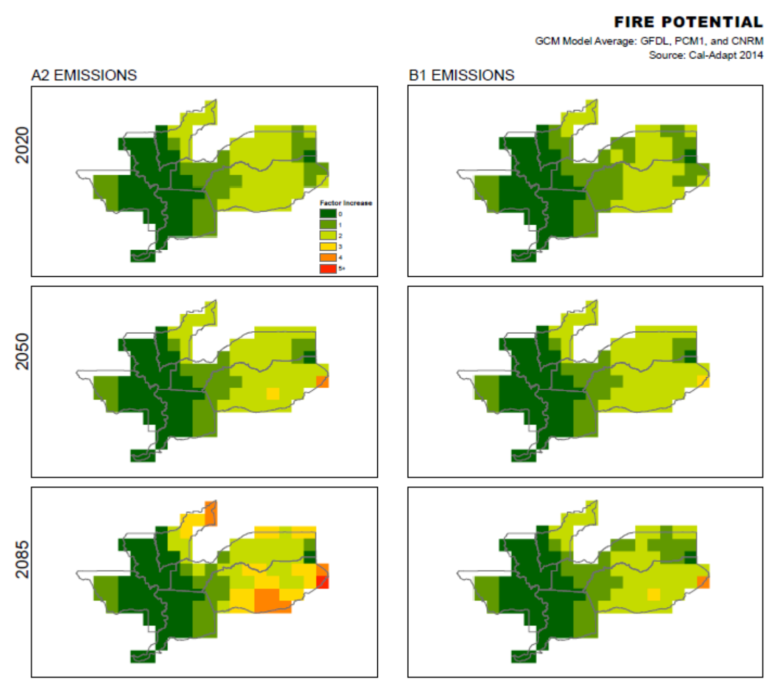


MAP SET 8. A2 EMISSIONS SCENARIO, GFDL MODEL PROJECTIONS FOR JANUARY MONTHLY AVERAGE RUNOFF OVER TIME, ALONG WITH INCHES CHANGE AND PERCENT CHANGE FROM HISTORICAL.

WILDFIRES

Fire potential was assessed based on the ratio of projected increase in fire risk relative to the expected burned area per grid cell. The data, retrieved from Cal-Adapt, uses a probability model[13] to evaluate fire potentials based on factors of precipitation, temperature, soil moisture, snow cover, and elevation (factors that impacted fire frequencies observed between 1980-1999). The projected risk was averaged under three GCMs (PCM1, GFDL, CNRM) within 30-year intervals with years ending in 2020, 2050, and 2085. In some areas of SACOG, fire burn risk is expected to increase 3 to 4-fold by 2085, under the A2 emissions scenario. The locations most vulnerable to fire risk are observed in the forested regions of El Dorado County, Placer County, and northern Yuba County.

It should be noted that climate impacts wildfire risks primarily through its effects on moisture availability, which depends on the cumulative function of temperature and precipitation[14]. Higher temperatures increase the rate of evapotranspiration, reduce winter snowpack that fall as rain instead of snow, and prompt earlier snowmelt into the year – which will subsequently lead to longer and drier summers in forests regions vulnerable to wildfires[15]. Fuel source or vegetation type, size, crown coverage, soil content, and wind speed will also influence the intensity and spread of the fires. For example, dead timber litter (common in spruce habitats around higher altitudes of the Sierras) has higher fuel loads and burn at a greater intensity compared to hardwood forest litter[16].



MAP SET 9 FIRE POTENTIAL OVER TIME FOR A2 AND B1 EMISSIONS SCENARIOS, USING A GCM AVERAGE.

LANDSLIDES

Individual climate change events not only impact transportation infrastructure directly, but also interact with other climate change effects to create additional consequences for the transportation system. An important example of this is the exacerbation of landslide risks caused by the combination of more intense wildfires, larger precipitation events, and altered soil moisture. This will likely impact

[13] Westerling, A. L., Bryant, B. P., 2008. Climate Change and Wildfire in California. Climatic Change (2008) 87 (Suppl 1): s231-s249

[14] Ibid.
[15] Ibid.
[16] Cal Fire. Surface Fuel Maps and Data. http://frap.fire.ca.gov/data/firedata-fuels-fuelsfr.php

regions that already experience landslide susceptibility, regions which are illustrated in Figure 11. The most vulnerable areas include parts of Placer, El Dorado, and Yolo counties, where there are significant enough slopes and weak enough bedrock to potentially induce a landslide.

Landslides involve a combination of complex processes, making it difficult to project landslide susceptibility in the future. Factors that affect the formation of landslides include slope angle, soil type, bedrock strength, soil saturation, and vegetation cover. But while it is extremely challenging to predict landslides accurately, certain key mechanisms are relatively well documented. As early as 1998, studies on landslide susceptibility were performed on the sections of Highway 50 that are located in El Dorado County. These studies showed that the likelihood of landslides increased after heavy rainfalls and wet winters, and specifically pointed out that "rapid melting of major snowpacks and high intensity and duration storms will also trigger new or accelerated failures, especially when the ground is saturated"[17]. Both rapid snowmelt and high intensity storms are projected to occur more frequently due to climate change, and since these are shown to be important landslide mechanisms for the Sierra Nevada Mountains, there is expected to be an increase in landslide frequency and magnitude as a result of climate change.

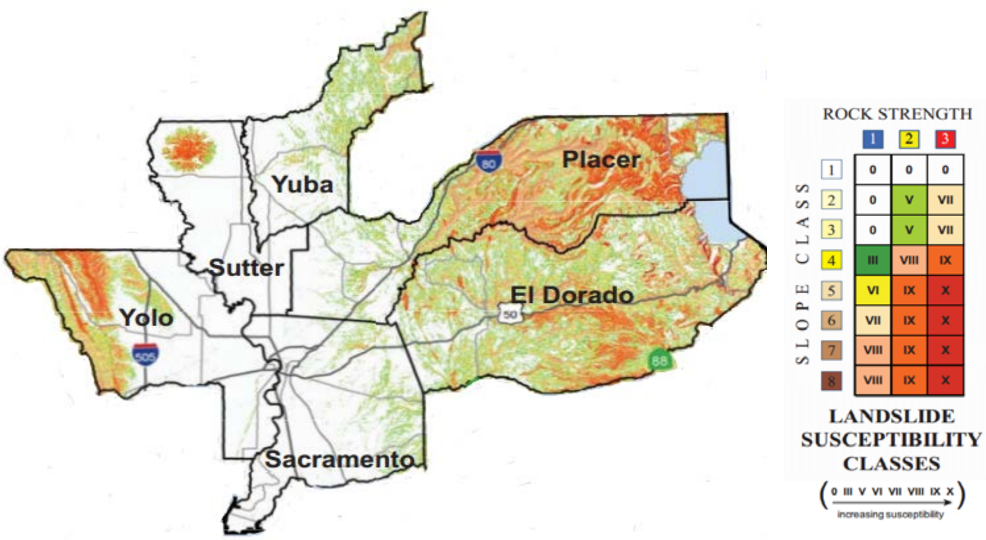


FIGURE 11. LANDSLIDE SUSCEPTIBILITY IN THE SACOG REGION. EXTRACTED FROM A 2011 STUDY PERFORMED BY CALIFORNIA GEOLOGICAL SOCIETY (WILLIS, PEREZ, AND GUTIERREZ 2011).

The connection between landslides and climate change in the high mountains was examined in more detail by a collaborative study performed in 2011. The most important mechanisms linking climate change and landslides were found to be: climatic stimulus of positive feedbacks on

[17] Spittler, Thomas E and Wagner, David L. 1998: "Geology and Slope Stability Along Highway 50: El Dorado County": *California Geology* . Online.

mass movement effects, geomorphic system exceedance of thresholds or tipping points, and the alteration of lag-time effects on sediment and ice storage[18].

Transportation Impacts

Each type of climate change effect may disrupt the transportation system in a number of ways. This section describes the possible consequences of each climate impact, which are summarized below in Figure 12. The assets evaluated in this report are primarily related to ground transportation, which encompasses road and railway infrastructure that supports the transport of people and goods via walking, biking, and land vehicles. However, there are a variety of transportation and human assets that are not evaluated in this report, but will be under consideration for future asset-level analysis, including but not exclusive to: airports, seaports, energy infrastructure, land use types, and community resources. In the next phase of the vulnerability assessment, SACOG plans to launch a stakeholder engagement process with technical and community stakeholders to refine the asset selection process and leverage local expert knowledge to identify critical infrastructure that should be evaluated within the region.

Extreme Heat

Prolonged exposure to extreme heat can exacerbate roadway degradation, as asphalt and concrete can deform at a faster rate under high temperatures, which results in pavement rutting and cracking that may present unsafe road conditions for motorists[19]. Bridges experience expansion and contraction as temperatures fluctuate, impacting the way expansion joints absorb movement and vibration over time. Extreme heat events may increase the risk of rail track buckling, which prompt many transit agencies to issue slow orders that can create bottlenecks or chokepoints within the network[20]. Overhead lines or catenary wires that supply power to lightrail, tram, and streetcar systems will experience thermal expansion and lose tension, which will significantly reduce speeds. All of these infrastructure vulnerabilities will increase the frequency of maintenance and the associated costs for rehabilitation.

Extreme temperatures also cause significant health impacts. Biking and walking becomes more strenuous during extreme heat days, posing health risks and a possible deterrent for biking and walking. During periods of extreme heat, maintenance and construction is forced to stop or slow down due to health risk exposures for workers, and because many materials for transportation infrastructure cannot be properly installed above certain temperatures.

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[18] Huggel, Christian; Clague, John; and Korup, Oliver. 2011: “Is climate change responsible for changing landslide activity in high mountains?” *Earth Surface Processes and Landforms*: 37 (1), 77-91. Online.

[19] ibid

[20] Federal Transit Administration. 2011. Flooded Bus Barns and Buckled Rails: Public Transportation and Climate Change Adaptation. Online.

	Extreme Temperature	Precipitation	Wildfire	Landslides
Roadways	Asphalt-concrete cracking and curling, rutting/softening	Asphalt stripping, concrete corrosion, subbase erosion, washouts	Rutting/softening	Washouts, slope destabilization
Railways	Rail track buckling, expansion of catenary wires, slower speeds and forced delays, derailments	Substructure erosion, forced delays, inundation	Blocked routes, forced delays	Washouts, blocked routes
Bridges	Expansion joint buckling, increased maintenance	Increased scour, decreased safety (visibility, traction), possible inundation	Weakening of steel bridge material	Washouts, slope destabilization
Walking & Biking	Decreased comfort, health risks	Decreased safety (visibility, traction), decreased comfort	Decreased air quality, health hazards	Loss of life, injury
Drainage	Little/No consequence	Drainage overflows, clog drains with leaves	Increased debris flow and clogged drainage systems	Clogged/blocked drainage systems
Traffic Flow	Vehicles overheating, congestion and network delays	Slowdowns, increased accidents	Reduced visibility and whiteouts, route closures, slowdowns and congestion	Slowdowns, congestion
Public Transit	Decreased comfort, transit vehicles overheating, network delays	Decreased comfort, delays	Route closures, trip delays	Route closures
Buildings & Facilities	Load shedding and power outages, construction and maintenance forced to halt or slow down	Inundation of electrical boxes/equipment	Construction forced to halt	Buildings/facilities buried or washed out, maintenance crews diverted for landslide cleanup
Traffic Controls	Power outages to signals	Power outages to signals, reduced sign visibility	Power outages to signals, reduced sign visibility	Damage to infrastructure

Legend: High likelihood or Damage; Moderate likelihood or Deterioration; Medium likelihood or Disruption; Low likelihood or No Consequences

FIGURE 12 LIKELIHOOD AND CONSEQUENCES FROM CLIMATE RELATED EVENTS

A secondary effect of extreme heat is the greater risk of power outages and blackouts. High temperatures decrease the efficiency of power transmission lines, while at the same time demand for electricity is increased for the operation of air conditioners and cooling equipment. The result is a higher risk of blackouts, which in turn shuts down traffic signals and some train operations.

PRECIPITATION, RUNOFF AND FLOODING

Increases in the intensity of precipitation and runoff events will likely lead to increases in localized flooding risks. As the roadways are exposed to a higher volume of water, their pavement materials are susceptible to damage from the excess moisture. The most common form of pavement damage due to water is stripping, a process that separates the aggregates in pavement from the asphalt binder that holds them together. Another potential source of damage occurs when water infiltrates the pavement, either through voids or through cracks in the surface, then becomes trapped between two layers of asphalt. The forces that occur when traffic passes over these areas create intense hydraulic pressures that physically scour the asphalt from the aggregate. The trapped water, combined with traffic forces, may also cause differential vertical

movement of the roadway, leading to stepping.

Detritus from runoff may also accumulate in the joints, impairing thermal movement and ultimately leading to compression failure of the concrete. Additionally, water penetration at expansion joints or surface cracks may cause loss of subbase support. Once saturated, subgrade soils lose a significant amount of strength, which results in rapid deterioration of the upper pavement layers. Without proper drainage, fine material in the subgrade may be washed away, causing settlement and premature road failure. Railways may face a similar problem through the erosion of ballast or subgrade material, causing instability and possible shifting and failure of the rails.

Furthermore, floods can lead to or exacerbate bridge scour. Scour makes the bridge weaker and less safe, and may lead to a need for repairs or replacement. Electrical boxes and other facilities may also be inundated, disrupting service to infrastructure like traffic signals and light rail systems. During fall storms, leaves will likely wash into the drainage systems, further aggravating localized flooding throughout the region. Lastly, more severe precipitation has the potential to increase risks of levee failure, which would lead to more widespread inundation of infrastructure.

Wildfire

Wildfires cause network disruptions including road and airport blockages, closures, and reduced road visibility. Fires may also disrupt power supplies, which impacts the electricity used for rail lines and traffic signals. The smoke and haze created by wildfires decreases air quality, reducing visibility on the road and creating unpleasant and unhealthy conditions for bikers and pedestrians. Fires that cause extremely high temperatures near infrastructure will damage and weaken the infrastructure materials. Burned areas will lose vegetation needed to stabilize the soil, increasing its susceptibility to flash floods and landslides in the event of a rainstorm.

Landslides

Landslides pose immediate hazards for vehicles on roadways and railways. Large or deep-seated landslides can wash out entire sections of road and rail, while smaller landslides may destabilize the subbase or cause cracking and shifting. Even surface-level landslides can cause a substantial amount of mud and debris to flow across roads and railways, blocking traffic or clogging drainage and causing flooding.

General Adaptation Approaches

A robust approach to climate change response should involve both mitigation and adaptation measures. The adopted MTP/SCS primarily addresses mitigation of GHG emissions. The following section addresses adaptation options that will be incorporate into the 2016 MTP/SCS Update.

Guiding Principles

There are many state-of-the-practice guidelines related to climate adaptation planning. These principles can be helpful when setting strategies and actions. For this plan, the Guiding Principles for Adaptation to Climate Change, adapted from a 2010 report by The White House Council on

Environmental Quality[21] were used as they relate to many of principles and practices currently underway at SACOG. They include the following:

- **Adopt integrated approaches**: Incorporate climate change into existing processes and programs.
- **Prioritize the most vulnerable**: Help the people, places, and infrastructure that are most at risk.
- **Use best-available science**: Ground adaptation in scientific understanding.
- **Build strong partnerships**: Coordinate across multiple sectors, scales, and stakeholders.
- **Apply risk-management methods and tools**: Use risk-management tools to prioritize options for reducing vulnerability.
- **Apply ecosystem-based approaches**: Incorporate ecosystem resilience and protection of ecosystem services.
- **Maximize mutual benefits:** Support other initiatives where possible, such as disaster preparedness or sustainable resource management.
- **Continuously evaluate performance:** Determine quantifiable goals and metrics and track progress, adjusting strategies as needed.

KEY ELEMENTS AND STRATEGIES FOR SUCCESSFUL ADAPTATION

Some strategies have proven more effective than others in the creation of climate change adaptation plans. This plan has used the lessons learned from the experiences of other agencies when developing its plan. In a 2011 Report, the Federal Transit Administration outlined the following *Key Elements of Successful Adaptation Efforts*[22]:

- **Flexibility**: Uncertainties surrounding climate change, development, and human response require flexible adaptation strategies. Actions must be continually evaluated and reassessed to ensure positive progress toward resiliency.
- **Broad, cross-disciplinary involvement and buy-in**: Involve staff from across the agency, to facilitate both information sharing and buy-in from those who are involved in the implementation of adaptation actions.
- **Embed climate change into work streams rather than developing a special system**: Improve effectiveness of the plans by mainstreaming policies into existing procedures and policies, leveraging existing knowledge and resources.
- **Prioritize "no regrets" strategies and meet multiple goals**: Whenever possible, incorporate non-climate related goals into climate policies, creating additional benefits that improve the system regardless of climate change results.

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[21] White House Council on Environmental Quality. 2010: *Progress Report of the Interagency Climate Change Adaptation Task Force: Recommended Actions in Support of a National Climate Change Adaptation Strategy*.

[22] FTA Office of Budget and Policy. 2011: "Flooded Bus Barns and Buckled Rails: Public Transportation and Climate Change Adaptation". Prepared for Federal Transit Administration. Online.

- **Plan for communication with customers**: The capacity to quickly communicate with customers is vital for the success of transportation efforts, especially in the case of emergencies.
- **Top level external push**: Climate adaptation plans may depend on an executive push to carry them from idea to implementation.
- **Central point of coordination**: As with any large interdisciplinary effort, a central contact is needed to coordinate efforts and ensure information sharing and accountability.
- **Interdisciplinary seminars with engaging narratives**: Effective information sharing involves more than disseminating raw data. Agencies should organize seminars and discussions in order to effectively move strategies forward and create robust dialogues surrounding climate change adaptation.
- **Coordination with other infrastructure and service providers**: Transportation agencies must also work with entities outside the transportation industry (e.g. telecommunications companies and stormwater management agencies) to create more holistic adaptation plans.

APPROACHES

When implementing the specific actions of the climate adaptation plan, there are four broad categories of adaptation strategies that can be incorporated. In order for the transportation system to remain adaptable to climate impacts, a combination of the following strategies should be used in carrying out policies and actions:

- **Maintain and manage**: Enhance maintenance and repair policies to improve severe event preparedness and response. Manage procedures for monitoring infrastructure and create/update emergency action plans.
- **Strengthen and protect**: Retrofit existing infrastructure and build new structures that better withstand extreme climate events.
- **Enhance redundancy**: Identify and create alternatives to vulnerable routes. Utilize different modes of transportation to enhance redundancy.
- **Retreat**: Relocate or abandon infrastructure located in highly vulnerable areas. Avoid building new infrastructure in vulnerable locations.

ADAPTATION OPTIONS

Actions toward climate change adaptation range widely, from relatively low-effort management policy changes to expensive and disruptive infrastructure retrofits and replacements. These actions can be broadly categorized into three sectors: Planning, Design, and Maintenance. Within each of these sectors, actions can be taken toward each of the four previously listed types of adaptation strategies (maintain and manage, strengthen and protect, enhance redundancy, retreat). Figure 13 below summarizes potential adaptation options in each sector for the climate change effects expected to occur in the SACOG region. These adaptation options reflect current best practices and technologies; however, SACOG will continue to encourage innovation and incorporate emerging technologies as the region improves its climate adaptation planning process over the years. The summary of adaptation options presented here is not an exhaustive list and simply acts as a starting point for determining the best available actions for any given adaptation need. Instead of providing detail in the

body of the plan on strategies related to each risk, a separate report has been created and is presented as an attachment to the plan. These reports are:

Extreme Heat: Appendix A - As the number of extreme heat events is expected to increase in the Sacramento Region over the next century, there will be strong implications on our energy supply and demand, the weakening of transportation infrastructure, and changes in travel behaviors. This report outlines how transportation infrastructure is affected by potential climate risks, and provides best practices in dealing with these impacts.

Precipitation, Runoff, and Flooding: Appendix B - Climate change will likely increase precipitation and runoff which will introduce or exacerbate flood risks in many parts of the world[23]. This report provides an understanding of the impact of these risks, and how to evaluate drainage and flood management systems on a site-specific basis for adequate strength and capacity.

Wildfires and Landslides: Appendix C - With projected increases in runoff and wildfires, the probability of landslides in areas with higher slope increases. This report outlines adaptive strategies in the planning, design, and maintenance phases that can help minimize the impacts from landslides.

Although not specifically covered in the plan, additional reports on **Drought** (Appendix D), adaptation in **Environmental Justice Areas** (Appendix E), and ongoing **Governance** issues (Appendix F) are provided in the Appendices.

[23] IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

	Extreme Temperature			Precipitation, Runoff, Flooding			Wildfire			Landslides		
	plan	design	maintenance	plan	design	maintenance	plan	design	maintenance	plan	design	maintenance
Roadways		Use heat and rut-resistant materials	Implement asset management system, increase monitoring and maintenance schedules	Identify alternative routes to vulnerable and critical routes, limit development in floodplains, conduct risk assesments	Protect evacuation routes, use different asphalt/concrete mixtures, pavement grooving and sloping	Implement asset management system, increase monitoring and maintenance schedules	Identify alternative to vulnerable and critical routes, update emergency improvement plans,	Use heat resistant materials, protect electrical equipment		Identify alternative to vulnerable and critical routes, update emergency improvement plans		
Railways	Change design standards on maximum temperatures	Design joints for higher maximum temperatures	Increase monitoring and maintenance schedules, lighten train loads and reduce speeds		Upgrade drainage system and increase culvert capacity				increase monitoring and maintenance schedules, repair damage as needed		Protect evacuation routes, ensure adequate drainage on roadbed surfaces and shoulders, incorporate rock fall protection, implement slope hardening	Implement asset management system, increase monitoring and maintenance schedules, ensure roadway is clear of rocks, debris, vegetation, minimize repair backlogs
Bridges		Design joints for higher maximum temperatures, use heat and rut-resistant materials	Implement asset management system, increase monitoring and maintenance schedules	Identify alternative routes to vulnerable and critical routes, limit development in floodplains, conduct risk assessments	Protect bridge piers and abutments, protect evacuation routes, use different asphalt/concrete mixtures, pavement grooving and sloping	Implement asset management system, increase monitoring and maintenance schedules	Identify alternative to vulnerable and critical routes, update emergency improvement plans,	Use heat resistant materials, protect electrical equipment				
Walking & Biking	Provide shade, create safe alternative routes											Identify alternative to vulnerable and critical routes
Drainage				Restrict development in floodplains, conduct risk assessments	Upgrade drainage systems/ increase standard drainage capacity, increase water storage systems	Increase monitoring and maintenance schdules, ensure systems are clear during extreme precipitation, increase capacity of pumps, minimize repair backlogs		Use heat resistant materials				Implement asset management system, increase monitoring and maintenance schedules, minimize repair backlogs
Traffic Flow	Incentivize alternative modes and teleworking			Identify alternative to vulnerable and critical route			Identify alternatives to vulnerable and critical routes			Identify alternative to vulnerable and critical routes, update emergency improvement plans	Protect evacuation routes	
Public Transit	Provide shade, use alternative fuels, encourage carpools											
Buildings & Facilities			Increase monitoring schedule, shift to evening work schedules		Weatherproof equipment and install higher	Increase monitoring and maintenance						
Traffic Controls	Plan alternative traffic control measures			Plan alternative traffic control measures								

FIGURE 13 GENERAL CLIMATE ADAPATION STRATEGIES

SECTION 2

ACTION PLAN

GUIDING PRINCIPLES

The MTP/SCS is guided by six principles adopted in 2005 by the SACOG Board of Directors. These principles lead to compact development and mixed-use communities, a better balance of jobs and housing in communities, and a variety of housing types and prices in all communities to match an evolving market and provide a range of housing and transportation choices. These principles can also be used to guide how the region thinks about climate adaptation. The principles are:

Smart Land Use- By identifying climate-impacted areas, the region can expand transportation choices and promote growth patterns that allow the system to become more adaptable and resilient to a changing environment.

Environmental Quality and Stewardship- In order to properly steward the region's natural resources, SACOG must develop knowledge of the region's changing environment, which then informs effective strategies for the protection of climate-impacted areas.

Financial Stewardship- By recognizing the economic effects of climate change on the region's transportation network, SACOG can implement cost-effective strategies for asset planning and resource management.

Economic Vitality- To ensure the continued movement of goods, services, and people across the region in face of climate change, SACOG must evaluate and increase adaptability of the transportation system.

Access and Mobility- As extreme weather events will likely increase due to climate change, SACOG must maintain access by supporting all forms of transportation modes and encouraging a flexible travel network.

Equity and Choice- Climate change often disproportionately impacts socioeconomically vulnerable populations, who lack the appropriate resources to respond to these environmental hazards. It is important to recognize the risks on such populations as climate change begins to take effect, and adopt appropriate plans and regulatory approaches that can mitigate their exposure to these impacts.

From the work outlined in Section 1 of this plan, and based on the guiding principles described above, this climate adaptation plan recommends four unique policies be implemented. Each policy has a specific action to ensure the region's transportation system becomes adaptable to potential climate related risks, and maintains that adaptability throughout the horizon year of MTP/SCS and beyond. The four areas are: Stakeholder Engagement, Asset Level Assessments, Climate Adaptation in Transportation Funding, and Monitoring. The rest of this document describes these policies in detail, with specific recommended actions.

Stakeholder Engagement

As communities are already starting to experience climate and environmental shifts, the need for adaptation response is becoming more pressing. Governments are beginning to take on adaptation planning; however faced with limited resources and political constraints, climate action will require the concerted efforts of private, public, non-profit, and research entities to carry out effective change.

Following best practices described in previous sections of this report, engaging with stakeholders is best addressed through existing channels and groups. Working with SACOG's Regional Planners Committee, Regional Manager's Committee, and Regional Planning Partnership along with the Capital Regional Climate Readiness Collaborative will bring the appropriate people into the climate adaptation planning and implementation process. Part of this process will also involve developing a targeted communications strategy that ensures that SACOG will effectively engage a variety of stakeholder groups with different priorities, values, and political cultures. Attachment G, which discusses governance issues in climate adaptation planning, details more information and best practices for this action.

Action: Form a Technical Advisory Committee to help guide ongoing climate adaptation planning, implementation and monitoring efforts.

Asset Level Assessments

The development future in the MTP/SCS yields shorter overall commutes based on where people live, work, and recreate. This creates more local trips within communities for which walking, bicycling, and transit become a more attractive options compared to driving, thus lowering VMT and congestion, and increasing transit service and use.

In order for that future to be realized throughout the plan, the underlying transportation infrastructure needs to withstand pressure from use, neglect, and nature. With potential increased environmental stressors on the system over time, infrastructure that is more vulnerable to these impacts needs to be identified and prioritized for action.

Assessing the impact for every transportation related asset in the region would be difficult and costly. Conducting that assessment on just assets that are determined to be more critical for the efficient operation of the larger system will capture the most important assets and be completed in a more efficient manner.

Action: Work with stakeholders to conduct an asset level criticality and climate change vulnerability assessment on the region's transportation network.

Climate Adaptation in Transportation Funding

The region must plan on strategic expansions to meet the current and future needs of residents. However, these expansions can be constrained environmentally when the timing and location of projects are limited, and fiscally as transportation resources become scarcer. This makes it

increasingly important to make all transportation investments in a way that addresses environmental barriers and uses transportation dollars efficiently.

Addressing climate adaptability when determining how to allocate transportation funds could help alleviate concerns related to a project's timing and location, and has the possibility of lowering longer term maintenance costs thus preserving funds for additional strategic expansions.

Action: Based on asset level criticality and climate change vulnerability assessments, work with the SACOG Board of Directors to determine how climate adaptation should be addressed in the biennial regional funding round.

MONITORING

Transportation agencies should keep existing facilities in a state of good repair and continue operation of current services. SACOG has committed to support strategies that will make road rehabilitation projects more resilient to climate events that might otherwise shorten the life of a facility, and keep the transportation system updated to comply with climate adaptation findings in order to reduce costly repairs related to climate impacts. Creating systems to monitor and manage the region's climate data and transportation assets will ensure the system is more equipped to adapt to the wide range of climate-related exposures that the region may foresee into the future, and will be able to function as efficiently as possible under these changing conditions.

Action: Work with stakeholders on long term monitoring of climate conditions and transportation infrastructure adaptability.

ACKNOWLEDGEMENTS

This report was co-written with members of CivicSpark. CivicSpark is a Governor's Initiative AmeriCorps program dedicated to building capacity for local governments to address climate change. CivicSpark is managed by the Local Government Commission in partnership with the Governor's Office of Planning and Research. More details on CivicSpark can be found by visiting their website at http://civicspark.lgc.org/.

Specifically SACOG would like to thank CivicSpark members Melanie Chu and Laura Moser for their dedication and hard work in helping to put this plan together. This work would not have been possible without their efforts during their CivicSpark year.

APPENDICES

APPENDIX A – EXTREME HEAT

APPENDIX B – PRECIPITATION, RUNOFF, AND FLOODING

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APPENDIX D – DROUGHT

APPENDIX E – ENVIRONMENTAL JUSTICE

APPENDIX F - GOVERNANCE

APPENDIX A - EXTREME HEAT

Adaptation Actions to Mitigate Extreme Heat

Planning	Design	Operations & Maintenance
• Adjust maximum temperature thresholds for design standards • Identify roadway segments, bridges, railways affected by past extreme heat events • Address vulnerabilities in transportation plans	• Use heat-resistant or rut-resistant asphalt/concrete mixtures • Ensure that bridge joints can accommodate anticipated thermal expansion • Design for higher maximum temperatures in replacement or new rail infrastructure • Upgrade to constant-tension catenary wires where necessary	• Increase monitoring of critical infrastructure during extreme heat events • Increase maintenance • Shift to morning or evening construction schedules • Use shorter trains, lighten train loads, and reduce speeds to reduce track stress

Preventing Infrastructure Overheating

Road Deterioration

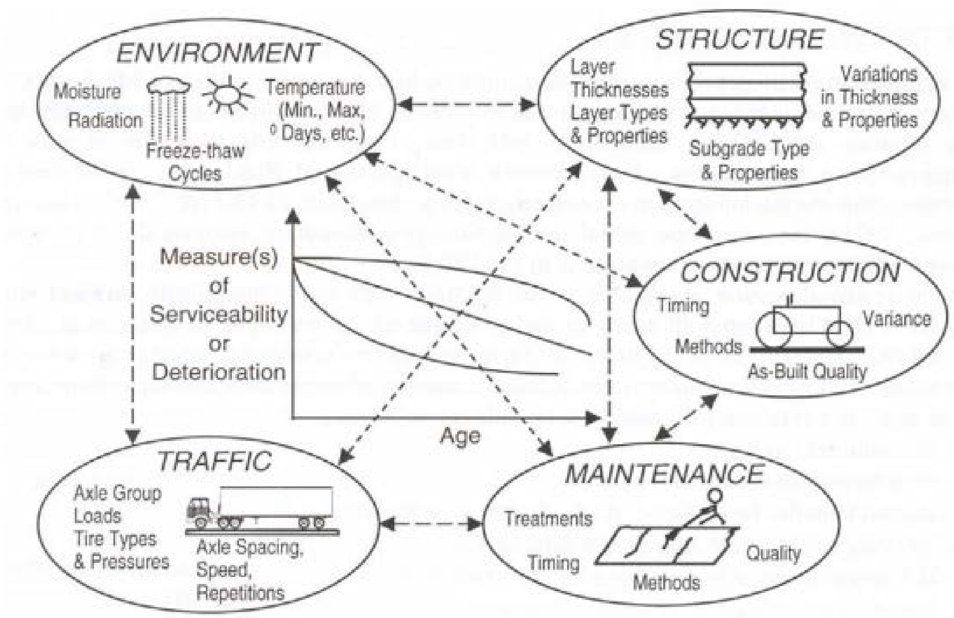

Figure 1 Factors affecting road performance. **Source:** Li et al. (2011)

Pavement life is influenced by numerous factors such as traffic loading cycles, traffic volume and mix, environmental exposures, material properties, subgrade conditions, initial design and construction methods, and maintenance and rehabilitation routines[1]. Initial pavement designs accommodate for small amounts of expansion and contraction; however prolonged exposure to extreme heat causes thermal expansion of the pavement material beyond design thresholds, further exacerbating road degradation and threatening the integrity of the

[1] American Public Works Association (APWA). 2013. Pothole Fact Sheet.

pavements. Changing precipitation patterns and flooding will also influence moisture content in the subbase properties and binder film, and further aggravate pavement structure. Under various climatic exposures throughout its design life, pavements will experience rutting, corrugation, excessive deflection, cracking, bleeding, potholes, and reduced load bearing capacity[2].

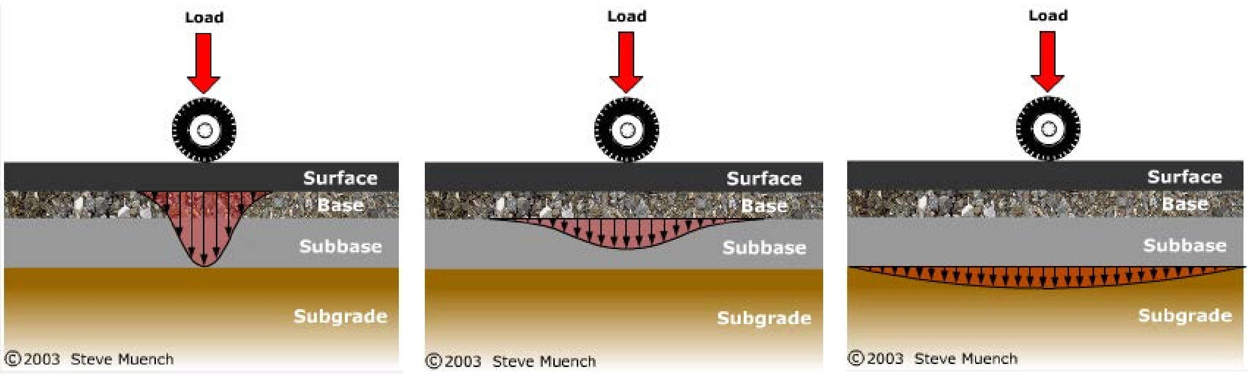

Figure 2 Vehicle loading distribution on each flexible pavement layer. **Source:** pavementinteractive.org (2003)

There are three fundamental pavement structures: flexible, rigid, and composites of the two[3]; and their vulnerability to climate will be determined by both the materials and design structure. Flexible pavements are composed of an asphalt surface layer and a base consisting of aggregate materials like lime, gypsum, granulated blast-furnace slag, and/or steel slag, which may be bound with asphalt or cement. As asphalt pavements age throughout their service life, the bitumen binder hardens due to oxidation – and higher average temperatures will increase the rate of oxidative hardening[4]. Depending on the thickness of the layer, the hardening may interfere with their load spreading ability and reduce the degree of flexing, which may increase the risk of fatigue cracking and escalate structural deformation on subsequent layers. Under high temperatures, the surface layer may also lose its functional characteristics such as skid resistance, texture depth, rut resistance, and (for

Image 1 Asphalt melting in New Delhi during the 2015 Indian Heatwave. **Source:** Kim (2015)

[2] Li, Q., Mills, L., McNeil, S. 2011. The Implications of Climate Change on Pavement Performance and Design. University of Delaware – University Transportation Center.
[3] Willway et al. 2008. *The effects of climate change on highway pavements and how to minimise them: Technical report*.
[4] Ibid.

non-porous asphalt) waterproof protection for underlying layers. In the recent 2015 heatwave that overtook India, air temperatures reached almost 48°C (118.4°F) causing black asphalt surface layers to melt and disintegrate[5]. In California, Rubberized Hot Mix Asphalt (RHMA) is a popular choice for asphalt pavement, which is formulated by mixing granulated rubber from recycled tires with hot asphalt aggregate to form an elastic binder that is less susceptible to temperature changes[6].

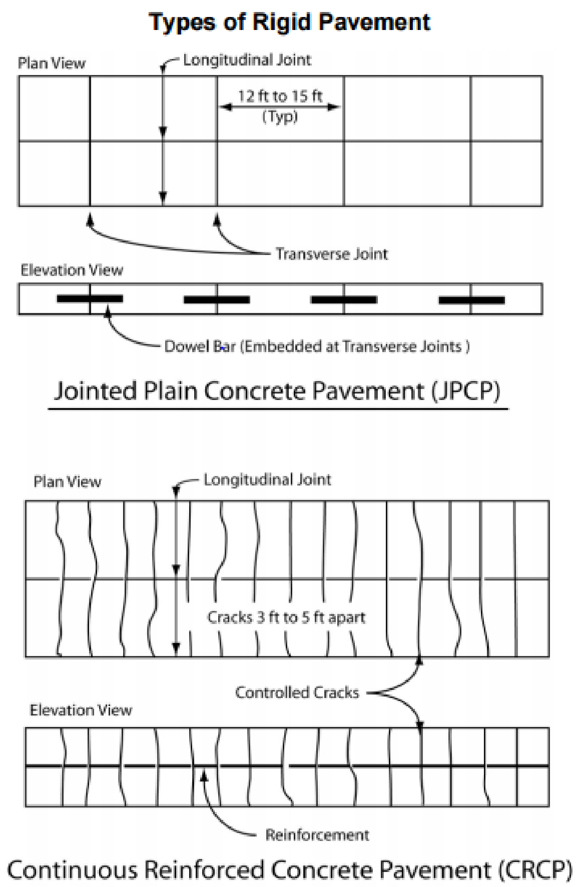

Image 2 JPCP vs. CRCP. **Source:** Caltrans (2012)

Rigid pavements are composed of Portland Cement Concrete as their primary load spreader. Rigid Concrete can withstand high temperatures and liquid penetration, and is widely used for pavements in hot climatic regions[7]. However, thermal gradients within the material, compounded by traffic loads, contribute to internal stresses that give rise to curling or warping of the slabs. Environmental factors also exacerbate curling as slabs will expand when hot, and contract when cool – which may be problematic in regions that experience a wider range of temperatures throughout the day. Jointed Plain Concrete Pavement (JPCP) is the most common type of rigid pavement on California highways, which is engineered with longitudinal and transverse joints to control where cracking occurs[8]. Gaining popularity in the US in recent years, Continuous Reinforced Concrete Pavement (CRCP) has continuous longitudinal steel reinforcement with no immediate transverse expansion or contraction joints, which allows the pavement to form natural, tight transverse cracks to evenly transfer loads and reduce water penetration. CRCP is also favorable as it can sustain heavier traffic volumes and adverse environmental conditions, provide smoother ride quality, require minimal maintenance, and has a lower long-term life cycle cost (despite higher upfront costs).

Due to its life-cycle deterioration over time, pavements are usually a composite of asphalt and concrete mixtures in order to rehabilitate the structural integrity of the pavement. Typically, flexible layers are overlaid above rigid layers to increase the performance of the rigid layer, and act as a thermal or

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[5] Kim, Susanna. 2015. "India's Deadly Heatwave Melting Roads." ABC News International.
[6] Caltrans. 2008. Chapter 630 – Flexible Pavement. *California Highway Design Manual*.
[7] Willway et al. 2008. *The effects of climate change on highway pavements and how to minimise them: Technical report*.
[8] Caltrans. 2012. Chapter 620 – Rigid Pavement. *California Highway Design Manual*.

moisture blanket to prevent curling of the concrete slabs[9]. However because of the complicated nature of pavement engineering, it is difficult to pinpoint a universal method for dealing with pavement heat distress. Caltrans is currently working to adapt to high temperatures by developing new heat-resistant asphalt-concrete mixtures, overlaying with new rut-resistant asphalt, and increasing monitoring and maintenance during extreme heat events[10].

Expansion of Bridge Joints

Bridges also experience expansion and contraction as temperatures fluctuate. In standard practice, the magnitude and direction of thermal movements are estimated and calculated during the design process to reinforce the concrete and steel structure to reduce the risk of deformation and girder deflection. These movements are accommodated through bearings or expansion joints supported by abutments at the end of the bridge[11]. However, expansion joint devices are highly susceptible to vehicular and environmental impacts, causing leakage from the bridge deck that permit salt-laden runoff to deteriorate the substructures[12]. The installation, maintenance, and replacement costs associated with expansion joints are high, and often require close monitoring to support the bridge's structural integrity.

To combat the continual maintenance and cost issues inherent in joints and bearings, many states are transitioning to Fully and/or Semi-Integral Abutment approaches. The Fully Integral Abutment approach directly connects the superstructure with the substructure, allowing the whole structure to move together into and away from the backfill during thermal expansion and contraction. The Semi-Integration Abutment method aims to eliminate expansion joints from the bridge deck with an approach or link slab, and allows only the backwall portion of the substructure to be directly connected with the superstructure[13]. Many bridge designers and engineers around the world are adopting jointless bridges for its long-term serviceability, minimal maintenance requirements, economical savings, and improved overall performance[14] .

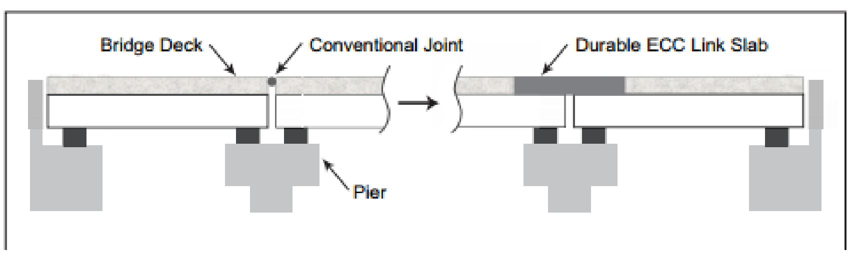

Image 3 Traditional bridge joints vs. Durable link slabs. **Source:** MDOT (2005)

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[9] Caltrans. 2012. *Chapter 640 – Composite Pavement*. California Highway Design Manual.
[10] Caltrans. 2013. *Caltrans Activities to Address Climate Change: Reducing Greenhouse Gas Emissions and Adapting to Impacts*.
[11] Roeder, C. 2002. *Thermal Movement Design Procedure for Steel and Concrete Bridges*. National Cooperative Highway Research Program.
[12] Mistry et al. 2005. *Integral Abutment and Jointless Bridges*. 2005 FHWA Conference.
[13] White, H. 2007. *Integral Abutment Bridges: Comparison of Current Practice Between European Countries and the United States of America*.
[14] Michigan Department of Transportation (MDOT). 2005. Bridge Decks Going Jointless. *Construction and Technology Research Record*, Issue 100.

Heat Kinks and Rail Buckling

Image 4 Rail kinks in the 2009 heatwave in Melbourne, Australia. **Source:** The Telegraph UK (2009)

During the design and installation process, a rail-neutral temperature is generally set between the range of 95-110°F in the U.S[15], allowing the tracks to expand up to a certain temperature before compressive forces induce rail buckling and misalignments. When rail temperatures reach below the neutral temperature, tensile forces begin to develop and the rail may be prone to breaking in cold weather. Rail-neutral temperatures can also change over time due to operational use and environmental factors, and the actual rail-neutral temperature may be lower than the initial installation temperature[16]. On warm days under direct sunlight, rail temperatures can reach as much as 30°F above air temperatures[17]. On these hot days, agencies typically issue slow or heat orders to minimize stress on rail tracks and reduce the risk of track buckling. However, this practice is not the best predictor of all the buckling risks, and it can create network bottlenecks and chokepoints that cause mass system delays. Thus it is important to design the tracks to the anticipated range of temperatures, and implement innovative IT systems to monitor and predict rail temperatures in order to reduce the level of maintenance, and prevent track failure and derailments in the future.

Amtrak has approximately 20 wayside weather stations that directly monitor and record actual rail temperatures, and use these measurements as their primary indicator for issuing slow orders[18]. They have also partnered with Federal Rail Administration to develop a rail temperature prediction model based on the heat transfer process of a rail exposed to the sun. According to the research group, "the model has proven to be able to predict maximum rail temperature within a few degrees and within 30 minutes of the actual time when the maximum rail temperature occurs during the day"[19]. A web-based software application called Track Buckling Warning System, is currently being developed and tested by Amtrak[20].

[15] Volpe (USDOT). 2014. Track Buckling Research.
[16] Federal Transit Administration (FTA). 2011. Flooded Bus Barns and Buckled Rails: Public Transportation and Climate Change Adaptation.
[17] Bruzek, R., Al-Nazer, L., Biess, L., Kreisel, L.. 2014. Rail Temperature Prediction Model as a Tool to Issue Advance Heat Slow Orders.
[18] Federal Transit Administration (FTA). 2011. Flooded Bus Barns and Buckled Rails.
[19] Federal Railroad Administration (FRA). 2008. Development of Rail Temperature Prediction Model.
[20] Ibid.

When temperatures reach over 90°F in Portland, TriMet issues slow orders to reduce train speeds by 10 mph for all areas with a speed limit of 35 mph and above; for days above 100°F or higher, all train speeds must not exceed a cap of 35 miles per hour[21]. However to combat schedule disruptions and customer dissatisfaction, TriMet implemented a concerted strategy with the ultimate goal of no slow orders. The agency identified vulnerable areas with frequent rail buckling, many of which were adjacent to curves or in direct sunlight[22]. Then the Maintenance of Way division broke up the continuously welded rail in 8-9 key areas and installed expansion joints that could expand up to 1.5-2 inches. The costs were estimated to be about $100,000 to $150,000, but reduced slow orders from 10 in 2008 to 3 in 2011[23]. TriMet is also looking into rail attachment systems that can accommodate thermal expansion, and designing buckling resistance at focus sections for new rail construction.

Expansion of Catenary Wires

The overhead line or catenary suspension wires that supply electrical power for much of the light rail, tram, and streetcar systems across the United States experience thermal expansion during hot days. Catenary wires must maintain mechanical tension in order for the pantograph (the electricity transmitting apparatus between the vessel and catenary wire) to guarantee continuous contact for a smooth and swift run. Extreme high temperatures cause the copper wires to expand and lose tension, producing an arch that can significantly reduce train speeds.

Image 5 New Haven Catenary Replacement Project. **Source:** MTA (2005)

In 2011, Amtrak received a $450 million grant to replace direct-fixation catenary with constant-tension catenary upgrades in the Northeast Corridor between Trenton and New Brunswick, New Jersey. This new 16-mile wiring system relies on counterweights to maintain proper tension, and will allow the trains to operate at a fast speed of 160 miles per hour[24]. Connecticut DOT has also initiated a project to replace 10.5 miles of old overhead lines in Metro-North's New Haven Line with constant-tension catenary wires, which is expected to complete in 2017[25]. Portland has also incorporated in

[21] Murphy, Angela. 2014. "It's heating up! Plan ahead for hot weather." TriMet News & Media Releases.
[22] Federal Transit Administration (FTA). 2011. Flooded Bus Barns and Buckled Rails.
[23] Ibid.
[24] Northeast Corridor Commission. 2015. Northeast Corridor Five-Year Capital Plan: Fiscal Years 2016-2020.
[25] Metropolitan Transportation Authority (MTA). 2015. New Haven Catenary Replacement Project Update.

counterweight pulleys into their MAX lines – however TriMet officials say that when temperatures get too hot, the counterweights touch the ground and the wire will begin to sag anyway[26].

Catenary-free streetcar systems are gaining more popularity in recent years with the first modern system being launched in Bordeaux, France in 2003. Power sources can come from either a ground-level power supply imbedded in the track, or by an on-board power-storage device like capacitors or batteries. Other added benefits include reduced visual intrusion, design flexibility, reduced costs for overhead infrastructure, potential energy savings, and better adaptability to varying weather conditions[27]. Several other cities across the world are proposing the use of catenary-free APS ground power supply in several tram systems in Barcelona, Florence, Rio de Janeiro, Beijing, Hong Kong, and Dubai. However due to the relatively new developments of these technologies, the installations are still significantly more costly than traditional rail systems.

Image 6 Alstom's APS catenary-free tram line in Bordeaux, France. **Source:** Alstom Press Centre (2015)

Cooling Capacity in Maintenance/Power Grids/Vehicle Fleets

Electrical equipment, power grids, and fleets are vulnerable to extreme heat days, which can cause significant disruptions and damage to the transportation system. High temperatures will also increase frequency of vehicle breakdowns and reduce service lifetimes on transit fleets. For example, Portland TriMet's substations, ticket vending machines, and the electrical equipment housed on the roofs of low floor vehicles overheated during high heat days because most of their ventilation systems were designed for the Pacific Northwest's mild climate that goes up to 90˚F on average[28].

[26] Murphy, Angela. 2014. "It's heating up! Plan ahead for hot weather." TriMet News & Media Releases.
[27] Global Mass Transit. 2014. Catenary-free trams: Technology and recent developments.
[28] Federal Transit Administration (FTA). 2011. Flooded Bus Barns and Buckled Rails.

New York MTA's Corona Maintenance Shop and Car Wash Facility is the first U.S transit facility to install a number of sustainable state-of-the-art maintenance features that garnered a LEED-Certified rating. The facility features a reflective roof using white-colored EDPM paint that reduces the heat gain of the structure and thereby reducing energy cooling demand[29]. The extensive use of windows and skylights maximizes natural lighting, while the shading from the concrete cantilevers help minimize excess heat gain[30]. Instead of using air conditioners or fans, louvers were used to create a natural air circulation path. The photovoltaic panels and fuel cells generate 300 Kw of power to help sustain the building's energy needs and reduce load on the local utility[31].

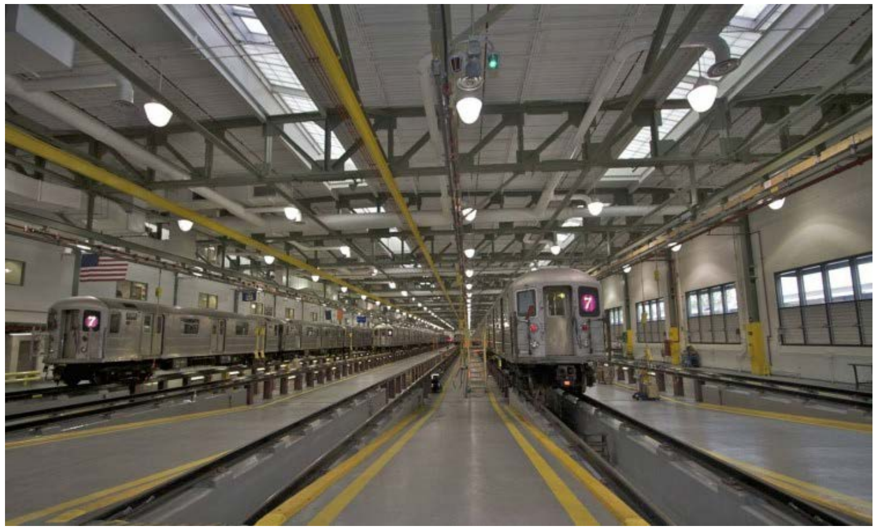

Image 7 New York MTA's Corona Maintenance Facility. **Source:** Epoch Times (2012)

Portland's TriMet is making investments in state-of-the-art hybrid bus fleets that will use a NASCAR-inspired electronic cooling system that will reduce engine load and improve fuel economy by 5-10%[32]. The biodiesel fuel blend and electric motors are expected to produce 95% less emissions than traditional transmissions, leaving a longer a life span and requiring less upkeep[33].

Image 8 Portland TriMet's new hybrid buses. **Source:** Fox 12 Oregon (2013)

[29] Ibid.
[30] Kanthan, Rama. 2007. "Setting a Green Standard for Rail Facilities." Metro Magazine.
[31] Ibid.
[32] Altstadt, Roberta. 2012. "TriMet receives $7.5 million in federal grants to buy 18 buses, including 14 hybrids." TriMet News & Media Releases.
[33] Fetsch, Mary. 2013. "TriMet launches new state-of-the-art hybrid buses." TriMet News & Media Releases.

Power Outage and Blackouts

Image 9 LED traffic signals in Bauru, Brazil. **Source:** LEDinside (2014)

Warming temperatures will also increase our demand for cooling and air conditioning facilities in homes, buildings, and public infrastructure, putting a strain on our power distribution systems and increasing our vulnerabilities power outages and blackouts. A 2009 heatwave that overtook southern Australia created havoc, as a minor explosion in the power supply along three transmission lines caused traffic controls to lose power and lengthy delays and cancellations on rail services[34]. When Melbourne experienced three consecutive days over 43°C (109°F) toward the end of January, traffic controls at 124 intersections were reported to be malfunctioning primarily due to failed electrical supply; and train cancellations peaked when more than 24% of services could not run due to a lack of air conditioning, buckling, and power failures[35]. Since then, transportation departments and transit agencies have adopted new measures, such as purchasing new train fleets with higher heat tolerance level, resetting carriage temperature to higher level to reduce AC load, and deploying standby and portable generators around train network for power and signal restoration[36].

Another strategy to combat traffic control loss during a power outage is to lower electric system strain using LED lights (rather than incandescent bulbs) for critical signaling infrastructure. Sacramento County received a grant in 2004 to retrofit many of its traffic signals to LED lights with back-up batteries, which not only use less power but also prevent signal outages even in the event of a blackout[37]. Such systems are widely-used and generally regarded as safe, practical, economic solutions.

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[34] ABC News Australia. 2009. "Melbourne blackout causes chaos."
[35] National Climate Change Research Facility (NCCARF). 2010. Case Study: Impacts and adaptation responses of infrastructure and communities to heatwaves.
[36] Ibid.
[37] California Energy Commission (CEC). 2004: *Senate Bill 84 XX: Battery Backup Program for Light Emitting Diode (LED) Traffic Signals.*

Safety and Comfort

Heat waves have become a frequent phenomenon in the past 50 years. The 2006 North American heat wave swept across United States and Canada – an estimate of over 140 fatalities were reported in California for the month of July alone, making it the most severe heat-related death toll in 2006[38] .

Transit Shelters

Transit stations are key infrastructures in a transit system as poor design can be a big disincentive for passengers to use your service. For disabled passengers, comfort and accessibility provide positive encourage for riders to take advantage of a fixed-route transit service, thus relying less on paratransit providers. Bus shelters and transit stops are key infrastructures to help cool passengers while waiting to board during the hot summers.

In Phoenix, Arizona, the METRO Light Rail partnered with NRG Energy, Inc. and designed an innovative solar-powered cooling system at their busy 3rd Street/Washington Station that is operational between May through September where temperatures frequently reach over 100°F. The station will allow travelers to push a button near each seating area to release cool air, which utilizes NRG's chilled-water plant that supplies the existing downtown district cooling system. The solar panels help power a set of fans to blow the cool air right above the seats[39].

Image 10 METRO Light Rail cooling stations designed by NRG in Phoenix, AZ. **Source:** Rail Gazette (2011), Hunt Construction

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[38] Trent, Roger. 2007. Review of July 2006 Heat Wave Related Fatalities in California. California Department of Health Services.
[39] Valley Metro. 2011. "Cool Off at 3rd/Washington Light Rail Station." Valley Metro Press Releases.

The Tucson Department of Transportation also began addressing passenger comfort and accessibility by developing an inventory of shading availability in all of their bus stations and sponsored design studies of transit shelters that account for the climatic conditions in the region. The Tucson DOT collaborated with University of Arizona's Drachman Institute of the College of Architecture and Landscape Architecture to design and build four bus shelter prototypes for Pima County that are sensitive to the sunlight orientations throughout the day. One such design regulates eastern-western-southern light entrance through slanted vertical and horizontal surface of a louvered screen structure, while remaining visible to the bus driver[40]. Sun Link, Tucson's modern all-electric streetcar system, incorporated a double-tiered shade station design that provides protection from the sun at all times of the day, and lower temperatures to 10-15°F within the structure[41] .

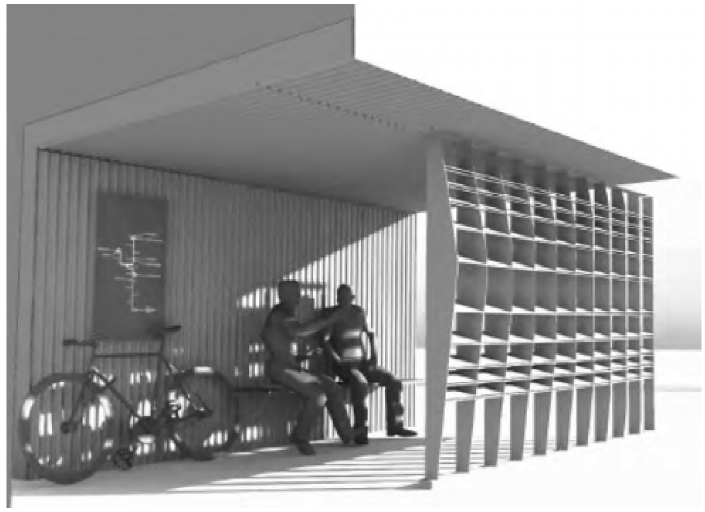

Image 11 University of Arizona Drachman Design Build Coalition, Bus Shelter Prototypes. **Source:** FTA (2011)

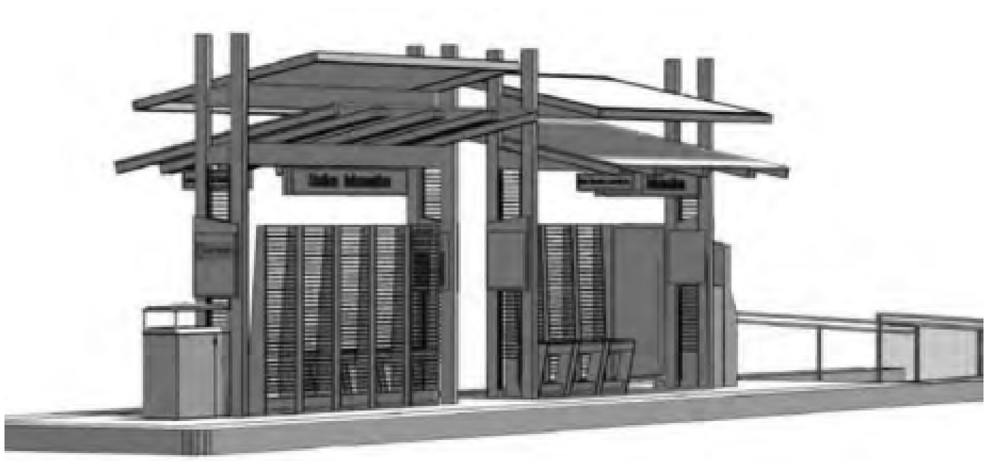

Image 12 Tucson's Sun Link double-tier shade station. **Source:** FTA (2011)

[40] Federal Transit Administration (FTA). 2011. Flooded Bus Barns and Buckled Rails.

[41] Ibid.

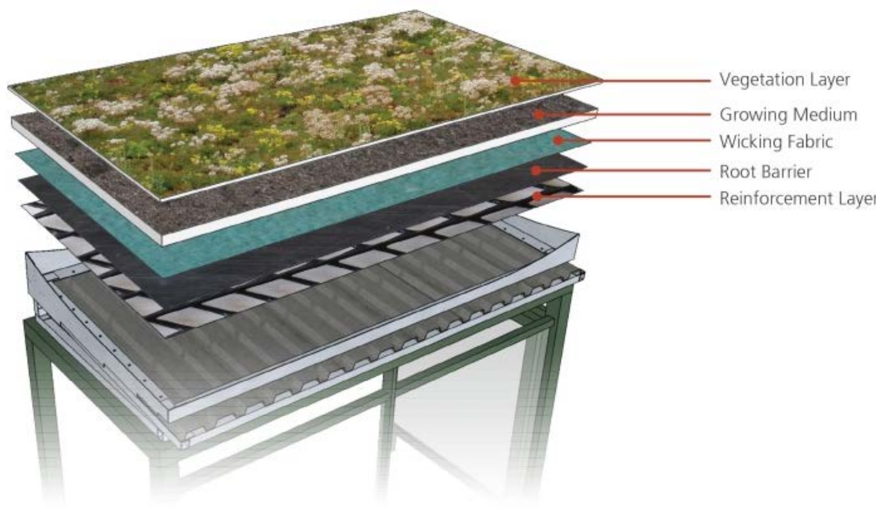

Image 14 Concept design for Philadelphia. **Source:** Philadelphia Water Department

Green or living roofs can also provide cooling, ecological, and educational benefits that can make stations more comfortable for travelers. In Boston, the Ecological Landscape Alliance initiated the Fairmount Line Bus Shelter Living Roof Initiative that retrofitted three bus shelters with soil, mixed sedums, and mosses that were designed to absorb rainfall, improve air quality, educate the community about green roofs, and beautify the urban environment[42]. Similar demonstration efforts have been undertaken in Philadelphia, San Francisco, Austin, and Buffalo.

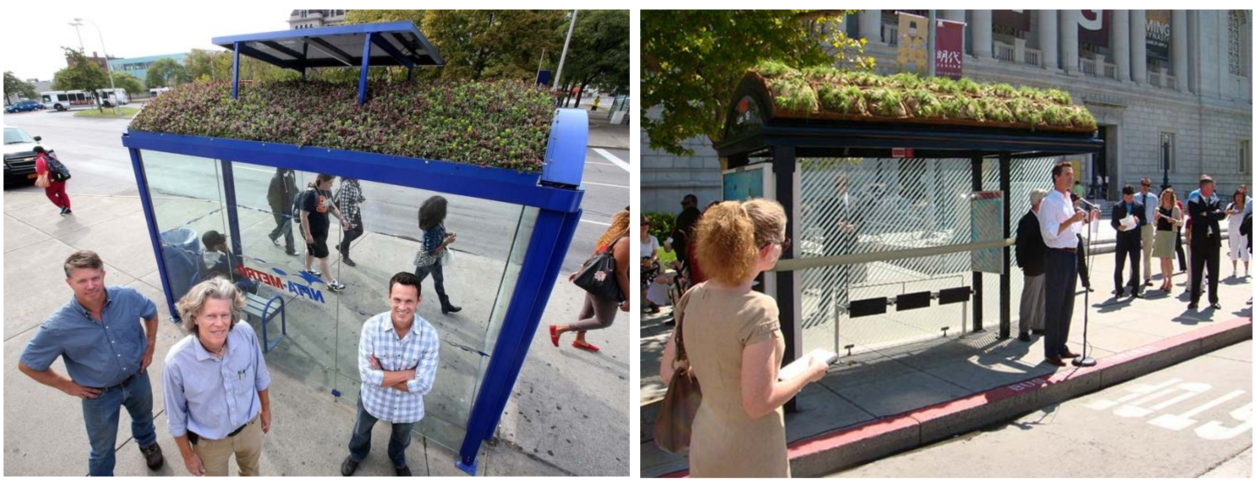

Image 13 Living roof bus shelter with a solar panel in Buffalo, NY (left); Green roof bus shelter in San Francisco, CA (right). **Source:** Buffalo News (2012); 450 Architects

[42] http://www.ecolandscaping.org/fairmount-line-bus-shelter-living-roof-initiative/

Maintenance and Operations

Heat waves can also pose serious health and safety risks for maintenance and construction workers. Hot weather affects both air temperature and humidity, which makes it more difficult for sweat to evaporate and cool the skin. As climate change accelerates the onset of hot weather sooner in the year, it will also shorten the time frame for workers to adapt to warmer temperatures. Several transportation agencies have adjusted their maintenance schedules to work during early hours or evening times during the summer – i.e. Alabama DOT and Caltrans.

The Occupational Safety & Health Administration (OSHA) launched a campaign to prevent heat illness for outdoor workers, and produced various training resources for employers and employees to safeguard heat-related emergencies. Some of the recommendations for employers include: provide workers with water, rest and shade; gradually increase workloads and allow more frequent breaks for new workers or workers who have been away for a week or more to build a tolerance for working in the heat (acclimatization); modify work schedules; plan and train workers on symptoms of heat-related illnesses and preventive methods; and monitor for signs of illnesses[43].

Impacts on Air Travel

Image 15 A US Airways Boeing 737, the most common aircraft for medium-range flights, at takeoff. **Source:** Decoded Science (2011)

Periods of extreme heat will also generate impacts on aircraft performance. When temperatures get warmer, the air becomes less dense – meaning that aircrafts must reach higher speeds before generating enough lift for take-off[44]. Under such circumstances, fully loaded planes can't get up to speed before they run out of runway, and thus weight restrictions – removing passengers or cargo – are imposed to lighten their loads[45]. Under the latest CMIP5 worst case GHG emissions scenario, the number of weight-restricted days at four major U.S airports is expected to increase from 50-200% by 2050[46]. These weather-related responses account for 70-80% of passenger delays, and airlines hundreds of millions of dollars per year[47].

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[43] Occupational Safety & Health Administration (OSHA). 2015. Prevent Heat Illness in Outdoor Workers.
[44] Sumner, Thomas. 2015. "Warming climate will force airlines to shed weight, increase costs." Science News.
[45] Kahn, Brian. 2015. "Hot, Unfriendly Skies Could Alter Flights." Climate Central News.
[46] Coffel, E., Horton, R. 2014. Climate Change and the Impact of Extreme Temperatures on Aviation. American Meteorological Society. Vol 7, Issue 1.
[47] Ibid.

A 2013 research study at University of Reading reveals that warming temperatures will also increase aviation risks associated with clear-air turbulence. Warmer temperatures in the Arctic is causing a rapid loss of reflective sea ice which in turn increases the temperatures at higher altitudes, leading to stronger jet streams and greater turbulence for carriers[48]. Evidence shows that clear-air turbulence has already risen by 40-90% over Europe and North America since 1958, and will likely increase in intensity by 10-40% in the North Atlantic by 2050[49]. Because clear-air turbulence occurs above clouds at cruise altitudes, it cannot be seen by pilots or detected by satellites or on-board radar[50], so pilots can only rely on past travel logs to avoid troublesome routes. The National Center for Atmospheric Research (NCAR) cites that turbulence is the leading cause of weather-related injuries for passengers and crews on commercial aircrafts, and cause delays that can cost airlines millions of dollars every year[51].

Although climate impacts on air travel is still being explored within the scientific and aviation community, the changes that we are currently seeing will have serious implications on the way we move people and goods over the next century.

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[48] Carrington, Damian. 2013 "Climate change will lead to bumpier flights, say scientists." The Guardian.
[49] Ibid.
[50] Williams, P., Joshi, M. 2013. Intensification of winter transatlantic aviation turbulence in response to climate change. Nature Climate Change.
[51] University Corporation for Atmospheric Research (UCAR). 2013. "Triggering Turbulence in Clean Air." AtmosNews.

APPENDIX B - PRECIPITATION, RUNOFF AND FLOODING

Adaptation Actions to Mitigate Flooding

Planning	Design	Operations & Maintenance
• Identify alternatives to vulnerable routes • Restrict Development in floodplains • Perform increased risk assessments for new roads	• Protect evacuation routes • Upgrade drainage systems/ increase standard drainage capacity • Increase culvert capacity • Protect bridge piers and abutments • Use stronger or permeable asphalt/concrete mixtures • Increase water storage systems • Increase strength of levees and seawalls • Levee setbacks & living levees	• Increase infrastructure monitoring • Prepare for service delays • Repair damage as needed • Ensure drainage systems are clear, esp. during extreme precipitation • Increase capacity & maintenance of pump plants • Minimize repair backlogs • Implement emergency operations response procedures • Use pavement grooving and sloping • Improve levee resiliency during maintenance

Adaptation Actions and Case Studies

Road Deterioration

An increase in the intensity of precipitation events will likely lead to increases in localized flooding risks. As the roadways are exposed to a higher volume of water, their pavement materials are susceptible to damage from the excess moisture. The most common form of pavement damage due to water is stripping, a process that separates the aggregates in pavement from the asphalt binder that holds them together. Stripping is highly related to the void content of pavements, since the higher the void content, the higher the volume of water that can seep into the road and separate the aggregates from the binder. Ensuring proper compaction of pavements can help prevent premature stripping. Selecting pavement mixtures with lower void contents can also help adapt the system to increased exposure to moisture[1].

[1] Transportation Research Board (TRB). 2003. *Moisture Sensitivity of Asphalt Pavements: A National Seminar*.

Image 1 Stages of asphalt stripping (left); Stripped binder mix (right). **Source:** Kandhal & Richards (2001)

Another potential source of damage occurs when water infiltrates the pavement, either through voids or through cracks in the surface, then becomes trapped between two layers of asphalt. The forces that occur when traffic passes over these areas create intense hydraulic pressures that physically scour the asphalt from the aggregate. The trapped water, combined with traffic forces, may also cause differential vertical movement of the roadway, leading to stepping. Areas of roadway adjacent to longitudinal construction joints or asphalt layer interfaces are most susceptible to trapping water. Detritus from runoff may also accumulate in the joints, impairing thermal movement and ultimately leading to compression failure of the concrete. Spalling (damage and loss of pavement material) along expansion joints provides an early indication of high stresses that might lead to failure. To prevent excessive water penetration, joint sealants must be selected that perform adequately under the expected amount of thermal joint movement, taking into account projected increases in temperature due to climate change[2].

[2] Willway et al. 2008. *The effects of climate change on highway pavements and how to minimise them: Technical report*.

Additionally, water penetration at expansion joints or surface cracks may cause loss of subbase support. Once saturated, subgrade soils lose a significant amount of strength, which results in rapid deterioration of the upper pavement layers. Without proper drainage, fine material in the subgrade may be washed away, causing settlement and premature road failure. To avoid this type of damage, underlying layers should be resistant to water damage, water should be prevented from permeating the roads, and adequate drainage systems should be utilized to reduce exposure of materials to moisture (see the following section, "Improving Drainage Systems")[3].

MIX DESIGN	• Binder and aggregate chemistry • Binder content • Air voids • Additives
PRODUCTION	• Percent aggregate coating and quality of passing the No. 200 sieve • Temperature at plant • Excess aggregate moisture content • Presence of clay
CONSTRUCTION	• Compaction—high in-place air voids • Permeability—high values • Mix segregation • Changes from mix design to field production (field variability)
CLIMATE	• High-rainfall areas • Freeze–thaw cycles • Desert issues (steam stripping)
OTHER FACTORS	• Surface drainage • Subsurface drainage • Rehab strategies—chip seals over marginal HMA materials • High truck ADTs.

Table 1 Factors that can contribute to moisture-related distress. **Source:** TRB (2003)

Although less likely, water infiltration might also worsen or initiate damaging chemical reactions. One instance of this is the exacerbation of corrosion of steel reinforcing materials in concrete. Corrosion rates are dependent on the temperature and the availability of oxygen and water. With an adequate supply of these factors, rust forms, which occupies a much greater volume than the original steel. The internal pressure from the rust then causes cracks to form in the material, weakening the road. Another less common form of damage may occur through alkali-silica reaction, a chemical reaction between the cement paste and silica present in the aggregate. The reaction dissolves siliceous aggregate particles, forming a gel product that expands in moisture and creates cracks from the internal pressure. This damage most often occurs with the use of recycled concrete aggregate[4]. Sulphate attack is an additional chemical reaction that may be exacerbated by increased rainfall. Sulphate attack occurs when sulfate salts, originating from groundwater or contaminated aggregate, react with hydrated cement and create

[3] Ibid.

[4] FHWA (Federal Highway Administration). 2006. *Interim Recommendations for The Use of Lithium to Mitigate Or Prevent Alkali-Silica Reaction (ASR)*.

expansive products that expand further under exposure to moisture and high temperatures. This leads to cracking and loss of cohesion and strength of the concrete. To minimize damage from the various chemical reactions listed above, constituent materials should be appropriately selected for the local conditions and projected exposure to increased temperatures and moisture[5].

Image 2 Map-cracking in all directions in unrestrained concrete. **Source:** FHWA (2006)

Improving Drainage Systems

Another approach to adapting to localized flooding risks is to improve drainage of the roads, which both minimizes the length of time the material is exposed to water and makes the roadways safer by preventing water ponding and flooding. The first step for this approach is to develop a robust understanding of the existing drainage network and capacity performance of the infrastructure. This typically entails a site-specific analysis of stormwater management practices to identify vulnerabilities within the system.

Once the street sections most prone to localized flooding have been identified, appropriate solutions can be implemented to mitigate the risks. These solutions may include: increasing the capacity of culverts and drainage, expanding pump plants, increasing infiltration via green infrastructure (such as permeable pavements, rain gardens, and green roofs), expanding water storage systems, improving pavement grooving and sloping, or clearing debris from storm drains before and during storms.

When the Vienna metro system experienced climate-change-related flooding for the first time since its 1978 construction, the agency decided to retrofit the system for better flood response. They increased

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[5] Willway et al. 2008. *The effects of climate change on highway pavements and how to minimise them: Technical report*.

drainage capacity and installed aluminum and concrete barriers that can be erected to protect lines that run parallel to nearby rivers[6]. In Taiwan, Typhoon Nari catalyzed the implementation of enhanced design standards for all stations in the Taipei Rapid Transit System. The new standards included requiring station entrances to be 43 inches above the 200-yr flood level[7].

Image 3 Rain Garden construction in Brooklyn that can process thousands of gallons of stormwater each year. **Source:** FTA (2011)

Whenever possible, drainage solutions should be combined with low-impact development strategies and sustainable urban drainage techniques to promote resiliency and maximize co-benefits to the community. Sustainable urban drainage solutions include bioretention, rain gardens, rain capture, permeable pavement, and green rooftops. These methods cause natural infiltration and processing of stormwater, reducing the volume of water collected through gray infrastructure facilities and thereby reducing flooding risks. The U.S. EPA created a comprehensive website on green infrastructure that collects data, best practices and case studies to assist agencies in incorporating low impact development: http://water.epa.gov/infrastructure/greeninfrastructure/gi_design.cfm.

Putting this technology into practice, New York City designed creative solutions for their urban flooding risks through their 2011 Green Infrastructure Plan. In their analysis, the city found that they can reduce combined sewer overflow by 2 billion gallons by 2030 using green stormwater practices, at a cost $1.5 billion cheaper than traditional strategies. Green infrastructure chosen for the plan includes green roofs, bioswales, green streets, rain barrels, and bioretention[8]. A number of other transportation agencies have also installed green roofs at their facilities, including New York MTA, San Francisco MTA, and US DOT[9].

Image 4 Green roof on New York MTA Crew Headquarters. **Source:** FTA (2011)

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[6] Federal Transit Administration (FTA). 2011. Flooded Bus Barns and Buckled Rails: Public Transportation and Climate Change Adaptation.
[7] Ibid.
[8] NYC Environmental Protection. 2011: *NYC Green Infrastructure Plan*.
[9] Federal Transit Administration (FTA). 2011. Flooded Bus Barns and Buckled Rails: Public Transportation and Climate Change Adaptation.

Kansas City recently updated its Bus Rapid Transit (BRT) System to include 30 stations with bump-out rain gardens that will collect and process runoff from surrounding roads and sidewalks. Besides preventing flood and erosion, the gardens also decrease the level of pollutants entering rivers and streams from the roadways[10]. Additionally, permeable parking lots contribute to the new system, allowing for better stormwater infiltration[11].

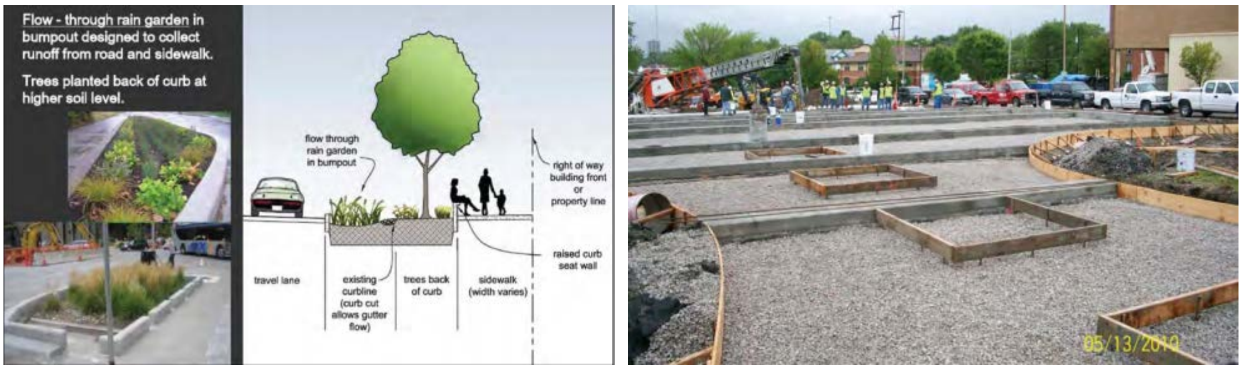

Image 5 Streetscape of Kansas City Rain garden bumpouts (left); Kansas City pervious pavement park-and-ride lot (right). **Source:** FTA (2011)

Strengthening Levees

Climate change will likely introduce or exacerbate flood risks in many parts of the world[12]. To understand the impact of these risks on local flood control levees, it is useful to obtain local projections for extreme rainfall and evaluate levees on a site-specific basis for adequate strength and capacity. To adapt the flood control system, levees can then be strengthened and/or reinforced to provide the needed level of protection.

Figure 1 Traditional vs Living Levee approach. **Source:** MTC (2014)

Retrofitting levees provides an opportunity for introducing sustainable infrastructure through "Living Levees". These levees incorporate vegetation and marsh habitat to create more natural flood protection infrastructure. Living levees are typically designed by expanding and flattening the riverside slope, which

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[10] Kansas City Board of Parks Commissioners. 2009: "Troost BRT Streetscape."
[11] KCATA (Kansas City Area Transportation Authority). "MAX Fact Sheet."
[12] Intergovernmental Panel on Climate Change (IPCC). 2014. *Climate Change 2014: Synthesis Report*. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

provides room for marsh habitat, better dissipates the energy exerted on the levee by the water, allows flexibility for adaptive management in the future, and adds greenspace to the community[13].

As part of their FHWA climate change pilot project, MTC created a conceptual design for two living levees: one at the Bay Bridge touchdown and one at Damon Slough. The living levees would protect against inundation and flooding from both sea level rise and storm surge, while providing marsh habitat and preserving the natural aesthetic of the shoreline[14].

Image 6 MTC's Living Levees at Bay Bridge Touchdown (left) and Damon Slough (right). **Source:** MTC (2014)

Levee setbacks have also been proposed as a method for resilient flood protection, through the incorporation of natural floodplains in hydrologic management. The figure below illustrates the difference between a traditional levee (top) and a setback levee (bottom). Levee setbacks not only decrease stress on the levees and provide additional wetland habitat, but they also increase groundwater recharge due to the wider, slower path of the river. A study of Consumnes River by researchers at UC Davis confirmed that setting levees back from a river measurably contributes to local groundwater storage[15]. By providing multiple functions, setback levees help resolve conflicts between environmental, flood control, and water supply interests.

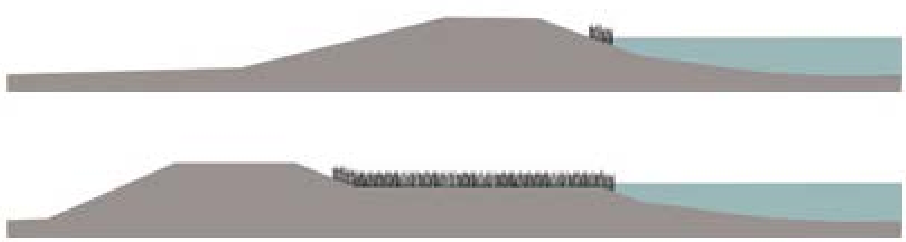

Figure 2 Typical levee (top) vs. setback levee (bottom). **Source:** Delta National Park

[13] Metropolitan Transportation Commission (MTC). 2014: *Climate Change and Extreme Weather Adaptation Options: for Transportation Assets in the Bay Area Pilot Project*.
[14] Ibid.
[15] Fleckenstein, J., M. Anderson, G. Fogg, and J. Mount. 2004. "Managing surface water-groundwater to restore fall flows in the Consumnes River." *Journal of Water Resources Planning and Management* 130, pp. 301-31

Strengthening Bridges


Image 7 Bearing and shear key on MTC's new Bay Bridge. **Source:** CADOT (2014)

Bridges provide critical connections within transportation networks. Increased intensity of storms increases the possibility of bridge overtopping, scour, damage, or failure. Adaptation actions typically involve strengthening protection around piers, using more resilient materials in bridge construction, or building or expanding roadway protections. Other adaptation options include improving the drainage system or increasing bridge height. These actions may be implemented on a case-by-case basis, or it may be prudent to update local/regional design codes to better reflect the changing climactic conditions.

Proactively implementing adaptation measures for bridges can save significant sums of money in the event of a disaster. Following Hurricane Katrina, the costs to repair or replace bridges alone was estimated at over $1 billion[16]. By examining the nature of the bridge damage in the hurricane-impacted areas, researchers found that relatively simple steps could be taken to mitigate future bridge damage. They determined that the most critical features of resilient bridges are: designing to higher elevations and implementing robust design details such as shear keys[17].

Planning and Relocating Infrastructure

Restricting development in floodplains, especially the development of new transportation infrastructure and facilities, helps remove the risk of system disruption due to flooding. Often, bus and rail storage and maintenance facilities are located on low-lying land that is subject to flooding. Moving assets to a less vulnerable location can be a relatively simple way to significantly decrease damage costs in the event of a flood. If new infrastructure must be built in a floodplain, adequate protection (such as levees, retention ponds, and/or pump stations) should be included to prevent disaster under increased levels of precipitation[18].

Moving transportation assets out of harm's way is nationally recognized as a necessary protection against climate change. On January 30, 2015, The President signed into law a Federal Flood Risk Management Standard (Executive Order 13690) that limits the development of federally funded

[16] Padgett et al. 2008. Bridge Damage and Repair Costs from Hurricane Katrina. *Journal of Bridge Engineering*.
[17] Ibid.
[18] Federal Transit Administration (FTA). 2011. Flooded Bus Barns and Buckled Rails: Public Transportation and Climate Change Adaptation.

projects, including transportation infrastructure, in areas prone to flooding. The order updates an existing EO from 1977 by requiring that a "climate-informed science approach" be used when determining the extent of floodplains and flood risk areas[19].

The EPA emphasized a land use approach to adaptation in a 2014 Report, *Planning for Flood Recovery and Long-Term Resilience in Vermont: Smart-Growth Approaches for Disaster-Resilient Communities*. This plan emphasizes the importance of restrictive development policies and conservation of land for sustainable adaptation in the face of increased flood risks[20].

[19] Exec. Order No. 13690, 3 C.F.R. (2015).

[20] Environmental Protection Agency (EPA). 2014. Planning for Flood Recovery and Long-Term Resilience in Vermont: Smart Growth Approaches for Disaster-Resilient Communities.

APPENDIX C - WILDFIRES & LANDSLIDES

Adaptation Actions to Mitigate Wildfires and Landslides

Planning	Design	Operations & Maintenance
• Identify alternatives to vulnerable routes • Perform increased risk assessments for new roads • Prepare to provide alternate route information • Improve emergency action plans	• Protect evacuation routes • Use heat-resistant infrastructure near fire-prone regions • Incorporate landslide mitigation measures for vulnerable projects • Ensure adequate drainage on roadbed surfaces and shoulders • Incorporate rock fall protection • Implement slope hardening	• Repair damage as needed • Increase monitoring of infrastructure • Ensure roadway is clear of rocks, debris, vegetation • Monitor drainage systems • Minimize repair backlogs

Wildfires

High temperatures and wildfire risks are inextricably linked – as the rate of evaporation increases, the hydrologic cycle will intensify over both land and water. Studies suggest that warming of 1.8°F will produce 200-400% increases in median area burned[1]. As California is currently experiencing one of the most severe droughts on record, wildfires have also seen a dramatic increase in frequency. The intensity and extent of area burned will depend largely on the type of fuel or vegetation, moisture content, and wind speeds[2].

Slope Stability and Route Closures

Wildfires burn off vegetation necessary to stabilize soil, thereby increasing the risk of erosion around critical infrastructure and increasing their susceptibility to debris flow and landslides during intense rainstorms. These hazards will prompt road closures, so advanced planning for detour routes will be necessary to ensure safety for motorists while minimizing disruptions in the mobility of people, goods, and services. Fire crews will also need emergency access to roadways for staging, dispatching, and evacuating.

In the summer of 2014, Washington State experienced one of its worst wildfire season burning over 363,000 acres, or 550 square miles of land – which encompassed private, federal, state, and tribal

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[1] National Research Council (NRC). 2010. *Climate Stabilization Targets: Emissions, Concentrations, and Impacts over Decades to Millennia*.
[2] Westerling, A. & Bryant, B. 2007. *Climate change and wildfire in California*. Climate Change, 87.

lands[3]. Active wildfires prompted the closure of several highways, and the smoke and ashes after the fire produced whiteout conditions that slowed down traffic on I-90[4].

Shortly after the devastating fire, rainstorms came and unleashed flash floods, mudslides, debris flow, and other erosion risks that destabilized homes and blocked highways downslope[5]. The mud and debris prompted temporary closure of at least three highways in Okanogan and Douglas Counties.

Image 1 The 2014 mudslides damaged a road east of Twisp, WA. **Source:** CBS News (2014)

Oregon DOT is working to improve their involvement with fighting wildfires to protect highway assets. In the 2012 Climate Adaptation Strategy, they developed three potential actions for adaptation:

- **Research heat impacts on infrastructure** – Investigate how heat from more frequent and intense wildfires impact transportation structures.
- **Develop mitigation and stabilization plans for slopes and road bases** – Identify areas that are both vulnerable to slide activity and are located in the wildfire prone or vulnerable areas. Plan and develop guidelines for conducting assessments of slopes immediately following a wildfire event.
- **Implement more aggressive forest and vegetation management** – More aggressive forest management is needed to reduce fuel next to the highway or other critical transportation routes[6].

Landslides

As both wildfires and precipitation events become more frequent and intense, slope stability correspondingly decreases. Transportation infrastructure located in hilly areas or on constructed slopes will then become more vulnerable to landslides, and adaptation options should be considered to prevent severe disruptions to the system due to the slides.

[3] Atkin, Emily. 2014. "In Washington State, the 2014 wildfire season has been 6 times worse than normal." Think Progress.
[4] Washington State Department of Transportation (WSDOT). 2014. "Wildfire Road Closure Roundup." WSDOT Blog.
[5] CBS News. 2014. "Rain after wildfires triggers mudslides in Washington state."
[6] Oregon Department of Transportation (ODOT). 2012. *ODOT's Climate Change Adaptation Strategy Report*.

Slope Stabilization

One way to lower the chances of a landslide occurring is to provide physical stabilization to the at-risk slope. Three basic approaches can be implemented to stabilize a slope: mechanical methods, hydrogeologic methods, and geometric methods[7].

Mechanical Methods

Mechanical slope stabilization requires increasing the shear strength of the slope or using external forces to counter destabilizing forces. The shear strength of a slope can be increased through technologies such as geosynthetic reinforced soil systems or in-situ soil reinforcement[8]. External stabilization can be achieved through the use of active forces, like anchors and ground nailing, or passive forces, like piles or structural wells[9].

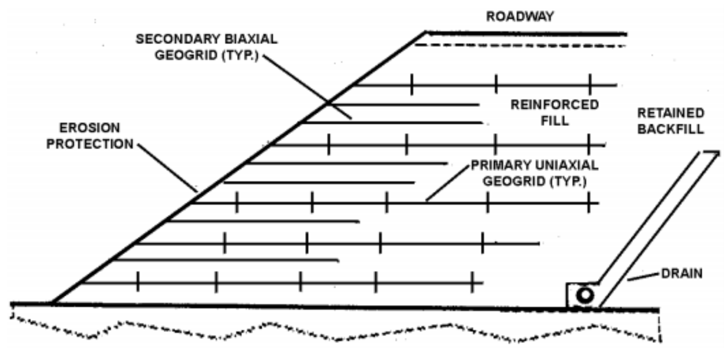
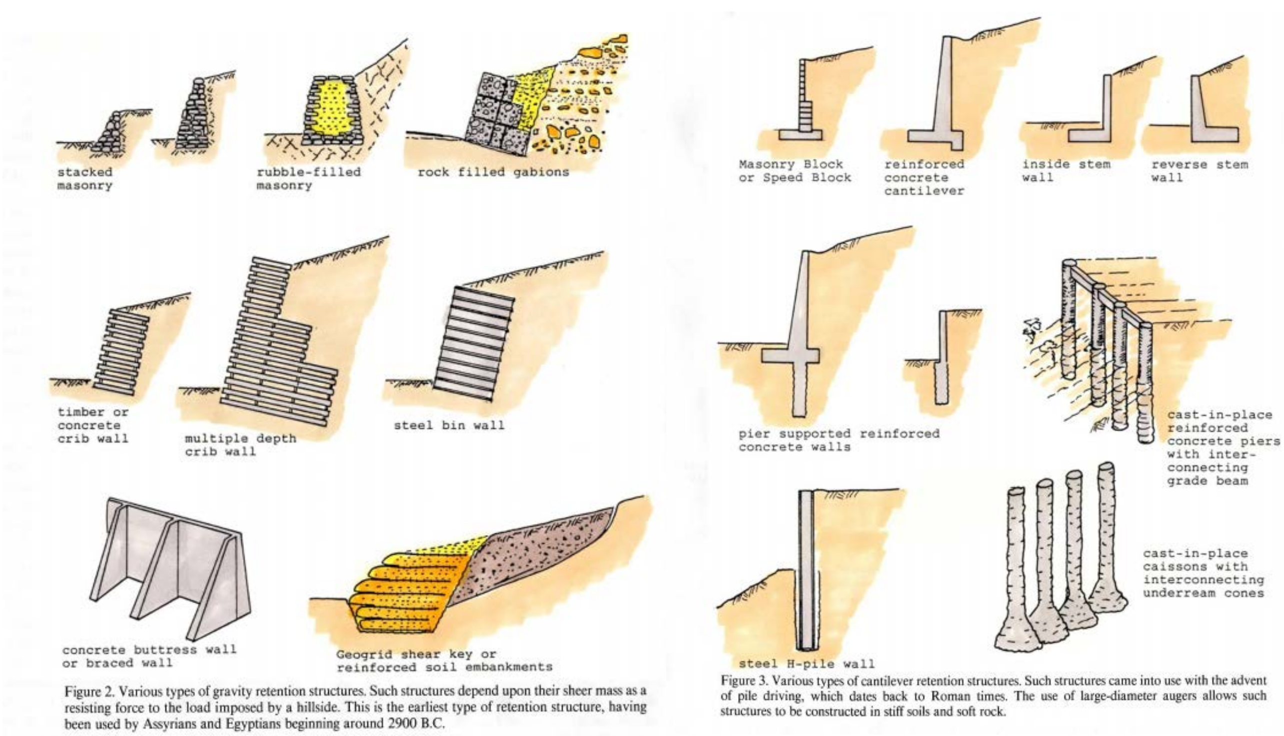


Figure 1 Material and structural components of a typical, reinforced steepened slope. **Source:** Gray & Sotir (1995)



[8] **Figure 2** Examples of gravity and cantilever retention structures. **Source:** Rogers, D. (1992)

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[9] ICSU ROAP. 2008. *Science Plan on Hazards and Disasters: Earthquakes, Floods, and Landslides*

Hydrogeologic Methods

Soil saturation plays a critical role in landslide susceptibility. In 1996, Portland, Oregon experienced a devastating series of landslides that were caused by a combination of heavy snow in upper elevations followed by intense rain, which saturated hillsides and led to approximately 750 individual landslides. Studies found that 76% of the landslides were exacerbated by human activity (such as cut slopes and artificial fill) and about 9% of the landslides could have been reduced simply with better stormwater control measures[10]. Well-designed stormwater management systems may therefore play a significant role in adapting the transportation system to climate change.

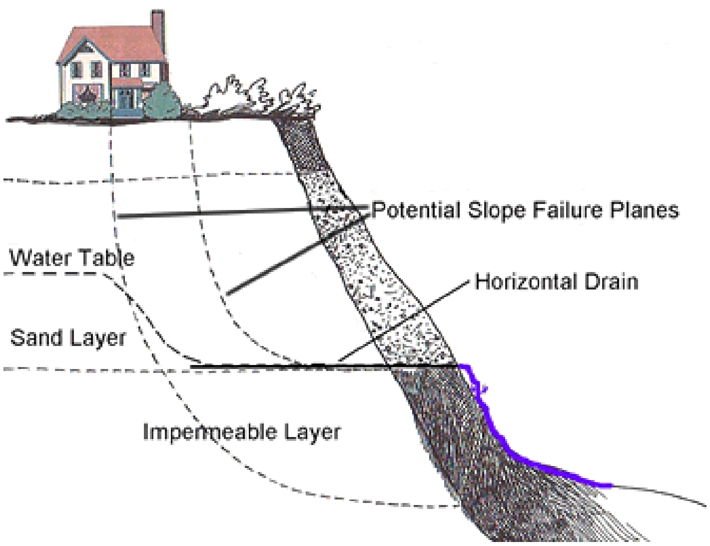

Figure 3 Slope failures from horizontal drains.

Horizontal drains are often used in hillsides to achieve better drainage and reduce porewater pressure. Below is a schematic illustrating the role of a horizontal drain in reducing landslide risk, by decreasing soil saturation above the potential slope failure planes. Generally, the lower the elevation of a horizontal drain, the more effectively it will lower the groundwater table. However, many geotechnical and hydrogeologic factors must be taken into account when designing proper drainage, including soil characteristics (unit weight, cohesion, friction angle), site specific precipitation projections, vegetation type, and watershed delineation[11].

Other drainage improvement options include blanket drains, strategic grading and sloping, and vertical wells and pumps[12] (WA Dept of Ecology). Typically, using a combination of different drainage strategies provides the best overall landslide protection. As part of a recent highway improvement project, for example, the Oregon Department of Transportation (ODOT) implemented a variety of landslide mitigation measures. They installed over 55 miles of horizontal drains to relieve porewater pressure in the slopes, constructed blanket drains to carry water away from vulnerable hillsides, and placed ground anchors for tracking movement and monitoring the mitigation efforts[13]. As landslide risks are exacerbated by climate change, vigilant monitoring of such systems will be necessary to ensure adequate slope stabilization. As more data is gathered, more robust standard practices for drainage

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[10] Walker, L., M. Figliozzi, A. Haire, & J. MacArthur. 2010. *Identifying Surface Transportation Vulnerabilities and Risk Assessment Opportunities under Climate Change: Case Study in Portland, Oregon*.

[11] Washington State Department of Transportation (WSDOT). 2013. *Design Guidelines for Horizontal Drains used for Slope Stabilization*.

[12] http://www.ecy.wa.gov/programs/sea/landslides/help/drainage.html

[13] http://www.oregon.gov/ODOT/HWY/REGION2/Pages/US20-PME-UPRR-to-Eddyville.aspx

improvements can be developed, reducing the amount of ad-hoc planning that tends to be used on such projects.

Image 2 L to R: Horizontal drains, blanket drain, and ground anchors installed by ODOT for U.S. Hwy 20 project. **Source:** ODOT

Geometric Methods

Geometric slope stabilization involves reforming the physical shape of the slope to be more resistant to gravity's pull. This usually requires flattening the angle of the hillside to an inclination that is stable for the soil type and conditions of that particular location. This may also necessitate excavation and recompaction of the existing soil. Geometric methods likely represent some of the oldest techniques of landslide mitigation[14].

COMMON STABLE SLOPE RATIOS
FOR VARYING SOIL/ROCK CONDITIONS

Soil/Rock Condition	Slope Ratio (Hor:Vert)
Most rock	¼:1 to ½:1
Very well cemented soils	¼:1 to ½:1
Most in-place soils	¾:1 to 1:1
Very fractured rock	1:1 to 1 ½:1
Loose coarse granular soils	1 ½:1
Heavy clay soils	2:1 to 3:1
Soft clay rich zones or wet seepage areas	2:1 to 3:1
Fills of most soils	1 ½:1 to 2:1
Fills of hard, angular rock	1 1/3:1
Low cuts and fills (<2-3 m. high)	2:1 or flatter (for revegetation)

Table 1 Slope ratio recommendations for low-volume roads. **Source:** BLM

Biotechnical Slope Protection

Traditional slope stabilization methods typically use "gray" infrastructure (consisting mostly of hard materials like concrete and steel) that is rigid, bulky, expensive, and aesthetically undesirable. Biotechnical methods can be used to stabilize slopes in a more subtle and sustainable manner. Biotechnical stabilization can be exclusively vegetative, or used in combination with gray infrastructure to maximize both the engineering results and ecological design. Vegetating a slope can be one of the most inexpensive and effective ways to provide a significant amount of protection, through improved

[14] Rogers, J. David. 1992. "Recent Developments in landslide mitigation techniques". *Reviews in Engineering Geology, vIX*. Geological Society of America.

drainage (plants slow down infiltration and prevent runoff) and soil reinforcement (root systems provide structural support to the topsoil)[15].

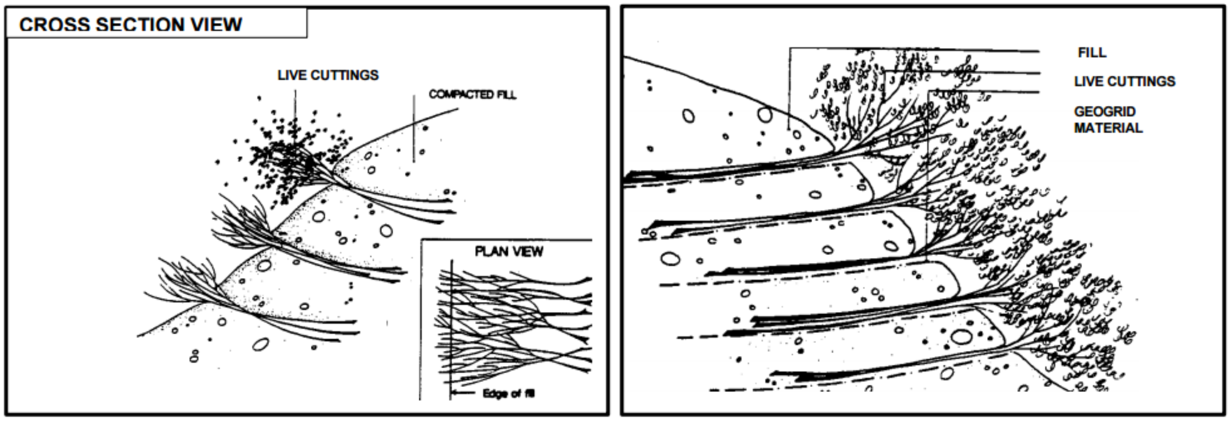

Figure 4 Schematic illustration of fill slope stabilization using live brushlayers (left); schematic illustration of live brushlayers used in combination with geogrids or geotextiles (right). **Source:** Gray & Sotir (1995)

Image 3 A well-stabilized cut slope, with about a 1:1 slope, that is well covered with vegetation. **Source:** BLM

Avoidance & Planning

The most certain way to prevent landslide impacts is to locate transportation infrastructure in low- or non-risk areas. Wherever possible, unstable slopes should be avoided. To accurately determine at-risk areas, landslide potential must be evaluated according to expected climate change, so that future conditions are taken into account and the vulnerable slopes are identified correctly.

[15] Gray, D. & Sotir, R. 1995. *Biotechnical Stabilization of Steepened Slopes*.

If infrastructure must be located within landslide zones, mitigation of that risk should not only include engineering strategies, but also include a comprehensive plan involving aspects like monitoring, emergency management, public outreach, and research.

The Rail Division of Washington State's Department of Transportation, for instance, recently completed a Landslide Mitigation Action Plan that explores options for the prevention and mitigation of landslides that impact the state railway system. The plan identifies key strategies for the agency, including providing drainage improvement incentives, researching and implementing a landslide assessment model, developing education and outreach materials to landowners, and constructing a number of high-priority mitigation projects[16].

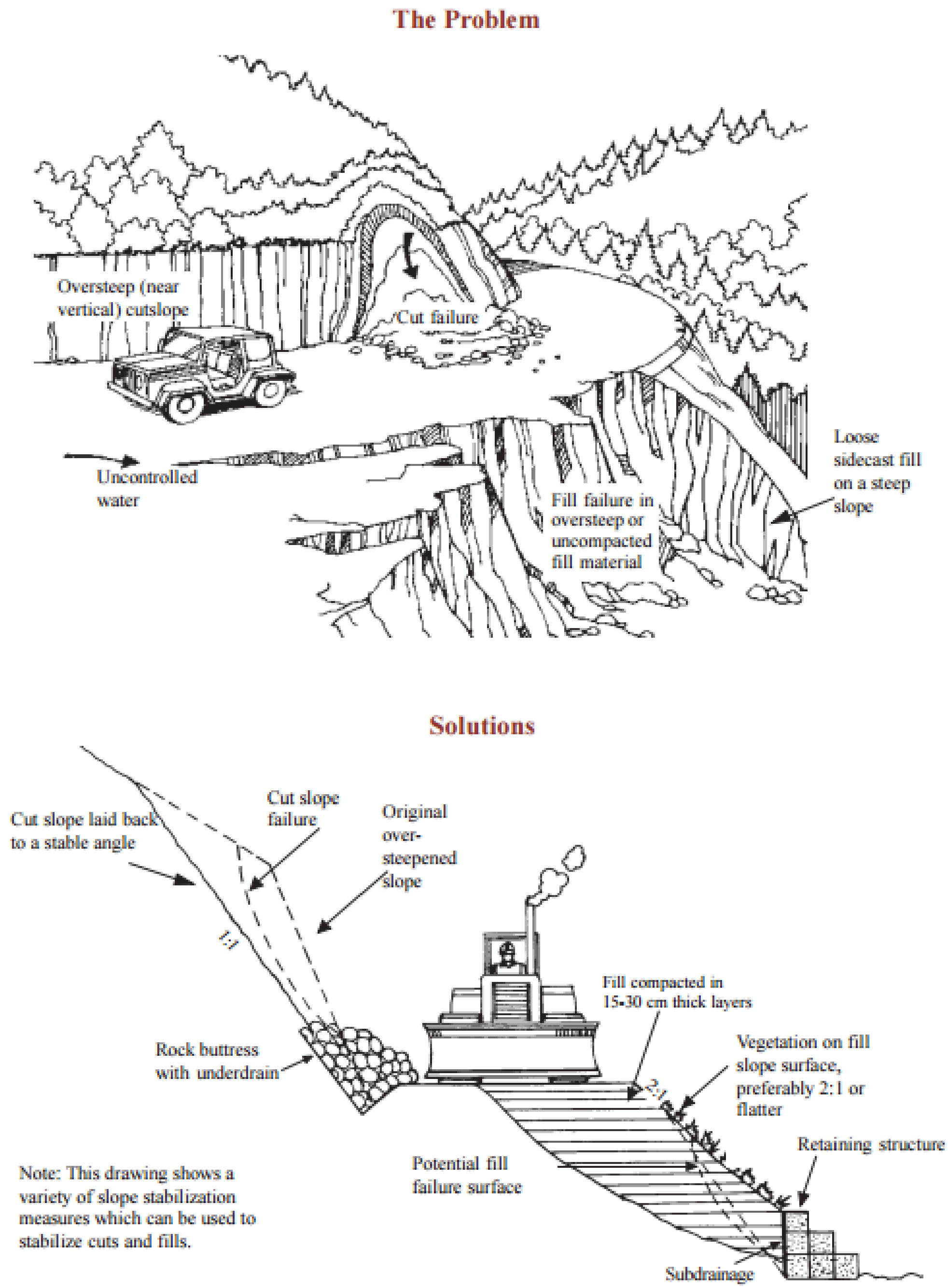

Figure 5 A variety of landslide issues and solutions. **Source:** BLM

[16] Washington State Department of Transportation (WSDOT). 2014. *Landslide Mitigation Action Plan.*

APPENDIX D - DROUGHT

Although the causes of drought have not yet been explicitly tied to climate change, it is known that increased temperatures from the changing climate will prolong and exacerbate droughts that occur throughout the next century. The Sacramento region is particularly prone to droughts; it is therefore important to consider the effects of drought on transportation infrastructure when considering adaptation options for the region.

Adaptation Actions to Mitigate Drought & Power Loss

Planning	Design	Operations & Maintenance
• Adhere to GHG emission goals, decreasing petroleum production • Create policies to shift from fresh water sources for energy production • Improve emergency action plans • Improve outage management systems	• Incorporate backup power for critical systems • Add non-electric signs and signals at vulnerable & important locations • Advocate/implement smart-grid technology	• Adjust maintenance schedules according to change in truck traffic • Implement emergency response plans/shuttles for transit outages • Ensure crews have backup/non-electric methods for communication

Adaptation Actions and Case Studies

Road Deterioration

Severe droughts tend to be associated with extreme temperature impacts on roads; however, drought may also directly damage pavements. The most common type of damage results from soil shrinkage due to the loss moisture from the soil underlying or adjacent to the road. The soil on the outside edge of the road dries first, and as it starts to compress, the edge of the pavement begins to bend. A longitudinal crack then forms on the roadway due to the stresses from the bending pavement. Typically, a series of several longitudinal cracks are formed as the drying advances from the outside of the road towards the middle[1].

Image 1 Severe crack that formed during the 2011 Texas drought. **Source:** Texas Tribune (2011)

Texas experienced this effect firsthand during a severe drought in the summer of 2011. The multitude of cracks that appeared due to soil shrinkage kept around 100 employees working full-time to repair the

[1] Schwab, James C., ed. 2013. *Planning and Drought.* American Planning Association, Report #574.

roads and bridges[2]. In total, the drought forced the Texas Department of Transportation to expend $32.4 million towards infrastructure repair, primarily on pavement maintenance[3].

Shrinkage risk varies significantly depending upon the type of soil beneath the roadway. The presence of underlying peat or clay soils, for instance, increases the vulnerability of pavement to drought conditions. Cambridgeshire's peat roads experienced widespread damage during a prolonged dry period in the summer of 2003, costing upwards of £1.1 million in emergency repairs[4]. Lancashire regularly contends with soil shrinkage on moss roads that were developed over hundreds of years without proper foundation construction. Each year, repairs on these roadways cost £2,000 to £3,000 per km to fill in potholes, provide emergency repairs, fix cracks, and remove badly damaged areas[5].

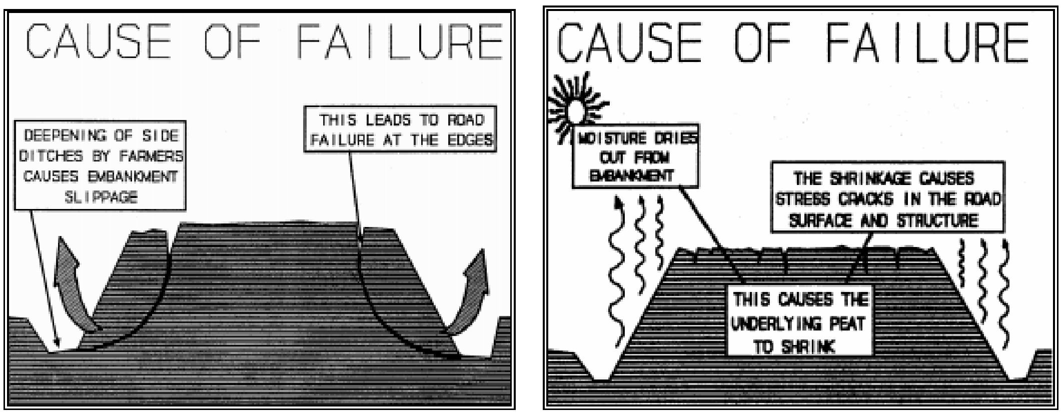

Figure 1 Failure mechanisms of peat/moss roads. **Source:** Willway et al. (2008)

Several solutions are possible to mitigate the presence of inadequate soils in the subgrade. The most effective, but most expensive, method is to completely remove and replace the troublesome soil with more stable material. The soil must be excavated and replaced at a deep enough level that soil shrinkage will not cause significant stresses to develop on the pavement surface. Another option is to strengthen the road with geogrid or a similar material. The reinforcement, usually steel mesh, is pinned to the subbase, allowing it to absorb some of the loading normally transferred to the subbase and thereby decrease the likelihood of road cracking when the subbase shrinks and becomes less able to support loading. If the problematic soil is peat, moss, or a similar material, the least expensive adaption option is recycling of the subbase material. This is accomplished by excavating the surface 18 inches and breaking down the excavated material, harrowing it to the point of increased stability. It can then be re-spread and waterproofed to provide a more stable foundation for the road.

[2] Ibid.

[3] Legislative Budget Board. 2011. "Fiscal Impact of Drought on State Agencies and Public Institutions of Higher Education, Fiscal Year 2011". *2011 Annual Report on Major State Investment Funds*.

[4] Willway et al. 2008. *The effects of climate change on highway pavements and how to minimise them: Technical report*.

[5] Ibid.

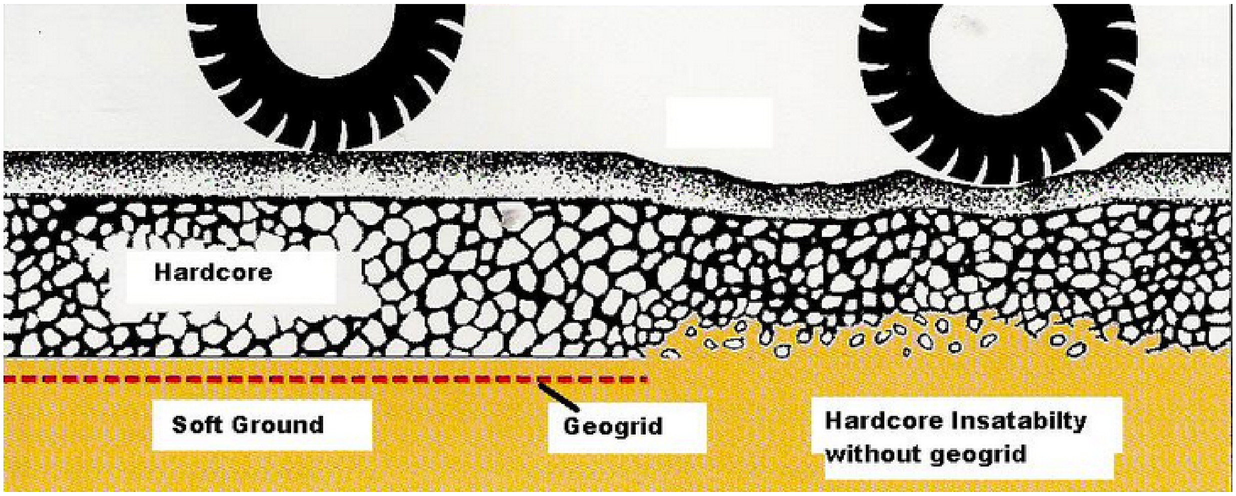

Figure 2 Application of Geogrid for subbase stabilization. **Source:** Surrey Geosynthetics Engineering

Construction & Environmental

Prolonged dry spells desiccate soils, which exacerbates potential for dust and air particulate pollution during construction activities (including road construction). Often, water control is the most feasible option for mitigating dust levels during earthwork. However, during a drought, it may be irresponsible to increase water consumption in order to control fugitive dust. Agencies must determine priorities regarding air quality vs. water use and create policies accordingly. San Joaquin Valley Air Pollution Control District, for example, issued a June 2015 Special Advisory allowing construction operations to proceed without implementing water-dependent dust control measures, unless the fine particulates cause a public nuisance[6].

Freight Response to Drought

California stands as the seventh-biggest economy in the world. As climate change begins to affect the state, some of the sectors driving its economy will experience dramatic shifts. Specifically, more frequent and severe droughts are expected to create significant productivity changes in the agricultural sector in the Sacramento region, which will in turn alter the demand for freight services. Trucks create some of the largest stressors on regional roads, so a change in freight traffic will affect the condition and lifespan of the infrastructure. To prepare for these changes, transportation agencies can study the likely impacts from climate change and create long range plans that take these changes into account.

One method used to predict freight changes is to model climate impacts as "productivity shocks in relevant sectors of the regional economy," then use a computer simulation to connect these shocks with the consequent changes in demand on freight transportation[7]. Using this methodology, transportation

[6] San Joaquin Valley Air Pollution Control District. 2015. "Special Advisory- Emergency Drought Relief Measure: Water-Dependent Dust Control at Construction Sites."
[7] Yevdokimov, Y. & Byelyayev, O. 2005: "Climate Change and Demand for Freight Transportation in Atlantic Canada."

agencies can predict the economic consequences of climate change as accurately as possible, in order to then calculate the altered loading on the regional roadways. This also allows for a reprioritization of infrastructure and transportation spending, if some routes become more or less critical over time due to climate change.

Preparing for Power Failure

Drought is often accompanied by high temperatures, which prompts people to increase electricity use through appliances such as air conditioners. At the same time, less water is available for hydroelectricity production, a significant portion of the region's energy sources. Transmission lines also lose efficiency under extreme heat, further decreasing the amount of energy available on the grid. These factors combine to put the grid at risk of power failure during times of drought, which in turn affects the operation of the transportation system.

Grid Resilience

Climate change affects all aspects of the energy system, from generation to distribution to demand. Rather than exclusively considering adaptation actions for the transportation system, agencies can use this as an opportunity to advocate for a more resilient energy system as a whole. To achieve grid resiliency, the Federal Government outlined 6 priority strategies adaptation in a 2013 Executive Office of the President report:

1. Manage Risk,
2. Consider Cost-Effective Strengthening,
3. Increase System Flexibility and Robustness,
4. Increase Visualization and Situational Awareness,
5. Deploy Advanced Control Capabilities,
6. Availability of Critical Components and Software Systems[8].

The Electric Power Research Institute further categorizes distribution system strengthening (step 2) into three "elements of resilience": prevention, recovery, and survivability. Actions that help *prevent* damage to infrastructure include vegetation management, underground installation, overhead distribution reinforcement, and cyber security. Pole line design can be improved, hydrophobic coating applied where needed, and innovations are possible in dynamic circuit reconfiguration. Actions that enhance system *recovery* include load reduction, restoration management, damage prediction and response, airborne damage assessments, field force data visualizations, and recovery transformers. *Survivability* can be

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[8] President's Council of Economic Advisers & Office of Electricity Delivery and Energy Reliability. 2013. *Economic Benefits of Increasing Electric Grid Resilience to Weather Outages*.

increased through communication with customers, community energy storage, using photovoltaic systems, and providing urgent services like cell phones and traffic lights[9].

Relatively small improvements to grid technologies and operations can make a significant difference in the wake of an extreme event. In 2012, Superstorm Sandy caused billions of dollars in damage and left 8.5 million customers without power. However, the effect of the power outages was mitigated due to recent investments in smart grid technologies, which included smart meters and upgrades to Outage Management Systems. For instance, in the Washington D.C. metropolitan area, advanced meter infrastructure allowed the Potomac Electric Power Company to restore power to 130,000 homes within just two days after the storm[10].

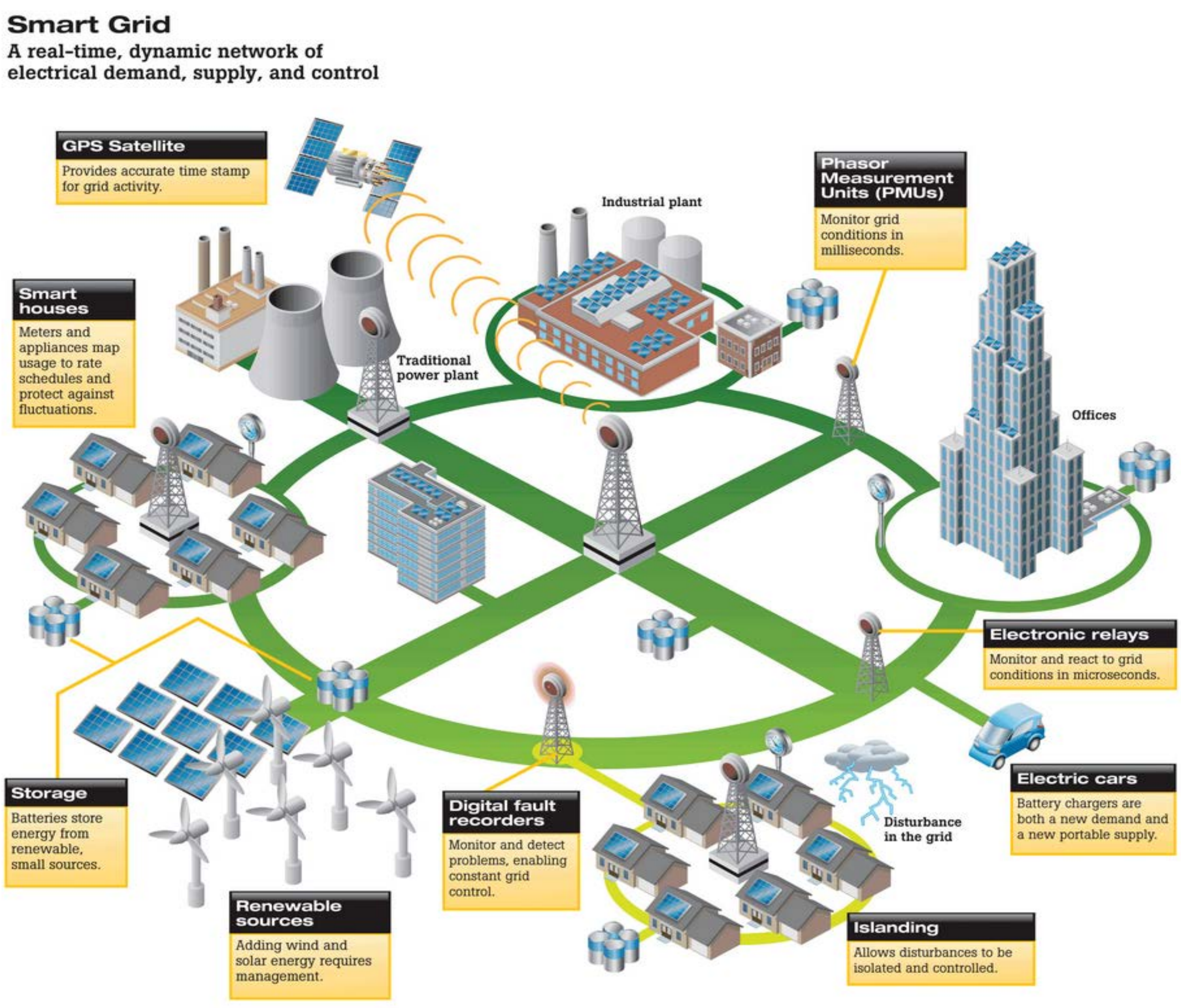

Figure 3 A phasor measure unit (PMU) energy network developed by Fluke Corporation. **Source:** Fluke Corporation

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[9] Electric Power Research Institute (EPRI). 2013. *Enhancing Distribution Resiliency: Opportunities for Applying Innovative Technologies*.
[10] President's Council of Economic Advisers & Office of Electricity Delivery and Energy Reliability. 2013. *Economic Benefits of Increasing Electric Grid Resilience to Weather Outages*.

Reducing Water Use for Fuel Production

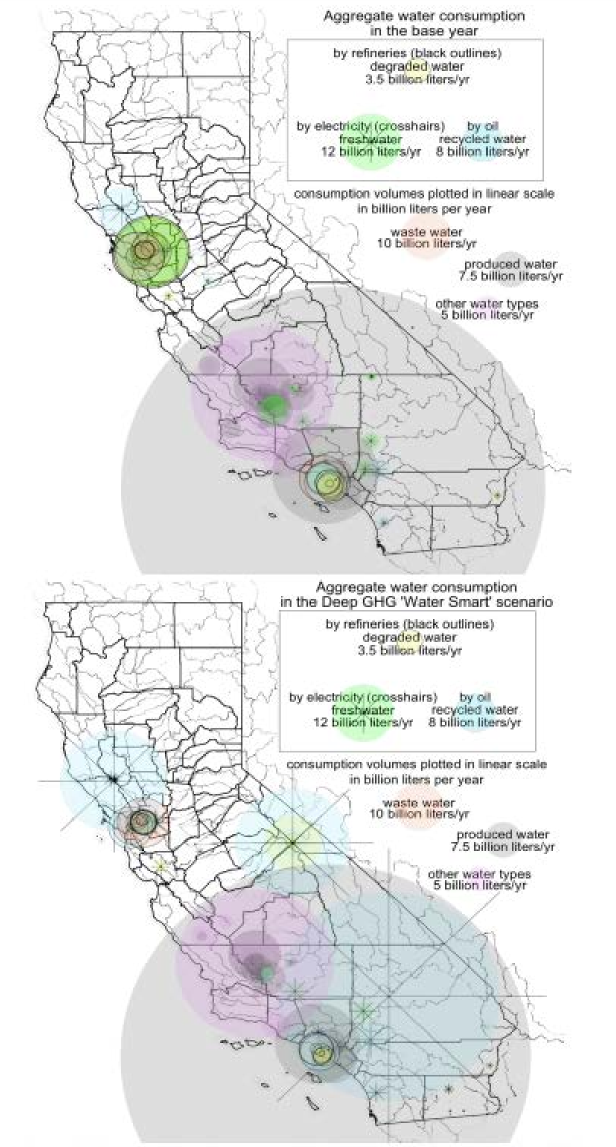

Figure 4 Aggregate water consumption in baseline (top) and Deep GHG Smart (bottom) scenarios for oil production & refining and electricity production. **Source:** Teter et al.(2014)

California is already experiencing its worst drought in recorded history, and climate change impacts will continue to exacerbate this and future droughts. A critical component of climate adaptation is to reduce water consumption as much as possible, and manage the remaining water wisely so as to provide for all critical water needs in the state. As the third largest oil producing state in the U.S., reducing water used in oil production could yield large gains in available fresh water for the state[11]. These reductions in water use may occur through adherence to California's GHG emission reduction goals, and they can be accomplished through improvements in oil production methods, especially regarding water reuse.

Researchers at the UC Davis Institute of Transportation Studies recently calculated the potential water savings from petroleum production over the next 35 years. California's 2050 target is to reduce GHG emissions to 80% of 1990 levels by 2050, which will entail a radical shift away from petroleum-based transportation towards alternative fuels. These different fuels will require different amounts of water per unit energy, impacting the demand on California's water resources. Overall, researchers found that if California meets its 2020 reduction goals, the state can reduce fresh water consumption by 28% in 2030, and meeting its 2050 target can reduce fresh water use by an additional 7%. Adopting policies that would shift to non-fresh water sources where possible would decrease fresh water consumption by a further 25%. In total, this represents a 60% decrease in fresh water use for electricity generation, or 61 billion liters per year[12].

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[11] Tiedeman et al. 2014. *Recent Trends in Water Use and Production for California Conventional and Unconventional Oil Production*. UC Davis Institute of Transportation Studies.

[12] Teter et al. 2014. *Future Transportation Energy Water Use Under California's Climate Goals*. UC Davis Institute of Transportation Studies.

APPENDIX E - ENVIRONMENTAL JUSTICE

Environmental justice ("EJ") seeks to address the equitable distribution of environmental benefits and burdens among different population groups, particularly groups that are underprivileged or disadvantaged. The principles of environmental justice provide important context for framing both climate change and transportation issues. As Naomi Klein observed in a recent article regarding social issues and climate change, "the reality of an economic order built on white supremacy is the whispered subtext of our entire response to the climate crisis, and it badly needs to be dragged into the light"[1]. Making a conscious effort to address environmental justice issues at a local level will help initiate the process of reworking climate change policies into more equitable actions that are holistically beneficial to society.

When analyzing the relative merit of various actions for climate change adaptation, it is important to consider the social equity implications of each option. As part of a California Energy Commission study showcasing how community-based adaptation planning can be applied within a community, the Pacific Institute researchers identified a broad list of adaptation options that addressed equity implications and concerns associated within the City of Oakland. For example:

> **Strategy**: Develop early warning systems for extreme heat events to alert residents when heat conditions pose a health risk
>
> > **Equity Concern**: Must be designed to communicate effectively to all groups, especially the particularly vulnerable; may not address the needs of those who have limited mobility.
> > **Policy Solution**:
> > - Provide warnings in multiple languages,
> > - Provide warnings through multiple culturally or economically appropriate/accessible media streams (e.g. TV, radio, phone, TTY, SMS, people-delivered),
> > - Establish a system of neighborhood outreach workers to disseminate information and check in on especially vulnerable residents,
> > - Conduct reverse 911 phone calls to the elderly and those at risk,
> > - Increase day-time outreach to homeless[2].

[1] Klein, Naomi. 2014: "Why #BlackLivesMatter Should Transform the Climate Debate". *The Nation*.
[2] Garzon et al. 2012. *Community-Based Climate Adaptation Planning: Case Study of Oakland, California*. California Energy Commission's Climate Change Center.

Regulatory Setting

FEDERAL: Executive Order 12898 and U.S. DOT Order 5610.2(a)

In 1994, the Federal Transit Administration and Department of Transportation established EO 12898 (*Federal Actions to Address Environmental Justice in Minority Populations and Low-Income Populations*) to integrate environmental justice into the mission of these agencies. Later, in 2012, The Department of Transportation (DOT) implemented Order 5610.2(a), *Actions to Address Environmental Justice in Minority Populations and Low-Income Populations*, to promote EJ principles in all DOT programs, policies, and activities[3].

A 2012 circular guides agencies that are receiving financial assistance from the Federal Transit Administration towards the implementation of environmental justice. This document lays out the following guiding principles for environmental justice in transportation:

- "To avoid, minimize, or mitigate disproportionately high and adverse human health and environmental effects, including social and economic effects, on minority populations and low-income populations;
- To ensure the full and fair participation by all potentially affected communities in the transportation decision-making process;
- To prevent the denial of, reduction in, or significant delay in the receipt of benefits by minority and low-income populations."[4]

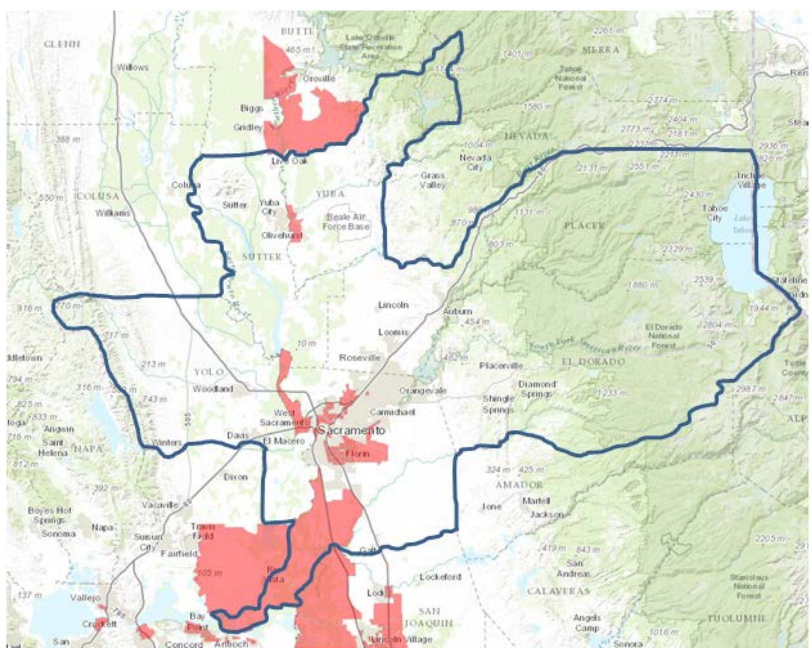

Figure 1 Disadvantaged Communities (DACs) in the SACOG Region.

CALIFORNIA: SB 535 (AB 32)

Assembly Bill 32 (AB 32) sets a comprehensive set of greenhouse gas reduction goals, introducing a

[3] U.S. Department of Transportation (USDOT). 2012. *Department of Transportation Updated Environmental Justice Order 5610.2(a)*.

[4] Federal Transit Administration (FTA). 2012. "Environmental Justice Policy Guidance for Federal Transit Administration Recipients FTA Circular 4703.1."

cap and trade system as the mechanism for greenhouse gas reductions. The cap and trade revenue will be collected into a Greenhouse Gas Reduction Fund (GGRF), which was established by AB 1532, SB 535, and SB 1018. SB 535 mandates that portions of the GGRF must be spent on projects benefitting Disadvantaged Communities (DACs). 25% of the GGRF is to go toward projects *directly benefitting* DACs; 10% to projects *located within* DACs. DACs are identified by CalEPA through methodologies set up in their CalEnviroScreen program. These communities are classified as the top 25% of a total disadvantage score determined from environmental metrics and population characteristics[5].

Current EJ Issues in Transportation Systems

Current practices in transportation tend to cause or exacerbate environmental justice issues. One problem is that investments in highway projects typically dominate transportation budgets, which prioritize suburban and exurban commuters. These prioritized neighborhoods, however, have relatively low percentages of minority and low-income populations. Transportation agencies also largely underutilize citizen engagement. Decisions about the transportation system are consistently made with little to no input from the impacted community members. Even when citizen engagement is used, the affected public often feels that they were brought in only *after* key decisions were made, or there is a lack of *continuous* public involvement. Additionally, agency fragmentation causes difficulties in identifying EJ problems and coordinating efforts to implement solutions. As of now, no step-by-step guidance exists to lead transportation agencies through the process of creating Environmental Justice assessments. Without standardized methodologies, it is difficult to identify best practices or even evaluate the success of various approaches to addressing EJ issues[6].

California agencies have begun to tackle this issue, partly so that they can more fairly distribute the GGRF money to benefit disadvantaged communities, as mandated by SB 375. In the table below, California Air Resources Board (CARB) provides a number of illustrative examples of needs of DACs in their Interim Guidance for Cap and Trade Auction Proceeds. These needs have been identified by community advocates, which in itself is a step towards more environmentally just planning[7].

[5] California Environmental Protection Agency, Air Resources Board (CARB). 2014. *Investments to Benefit Disadvantaged Communities: Senate Bill 535 (De León, Chapter 830, Statutes of 2012)*.
[6] Robinson et al. 2010. *Building on the Strength of Environmental Justice in Transportation: Environmental Justice and Transportation Toolkit*. Federal Transit Administration.
[7] CARB. 2014. *Investments to Benefit Disadvantaged Communities: Senate Bill 535.*

Public Health and Safety
1. Reduce health harms (e.g., asthma) suffered disproportionately by low-income residents/communities due to air pollutants
2. Reduce health harms (e.g., obesity) suffered disproportionately by low-income residents/communities due to the built environment (e.g., by providing active transportation opportunities, parks)
3. Increase community safety
4. Reduce heat-related illnesses and increase thermal comfort (e.g., weatherization and solar energy can provide more efficient and affordable air conditioning; urban forestry can reduce heat-island effect)
Economic
1. Create quality jobs and increase family income (e.g., targeted hiring for living wage jobs that provide access to health insurance and retirement benefits with long-term job retention)
2. Increase job readiness and career opportunities (e.g., workforce development programs, on-the-job training, industry-recognized certifications)
3. Revitalize local economies (e.g., increased use of local businesses/small businesses)
4. Reduce housing costs (e.g., affordable housing)
5. Reduce transportation costs (e.g., free or reduced cost transit passes) and improve access to public transportation (e.g., new services in under-served urban and rural communities)
6. Reduce energy costs (e.g., weatherization, solar, etc.)
7. Improve transit service levels and reliability on systems/routes that have high use by low-income riders
8. Bring jobs and housing closer together (e.g., affordable housing in transit-oriented development, and in healthy, high-opportunity neighborhoods)
Environmental
1. Reduce exposure to local toxic air contaminants (e.g., provide a buffer between bike/walk paths and corridors with high levels of transportation pollution)
2. Prioritize zero-emission vehicle projects for areas with high diesel air pollution

Steps Toward Environmental Justice in Transportation

Once instances of environmental injustice have been identified, careful transportation planning may help mitigate the injustices and prevent future occurrences. According to Caltrans, transportation planning that achieves environmental justice must "invite the full and fair participation of all potentially affected communities; minimize unfair negative impacts caused by transportation projects; and fairly distribute the benefits of transportation projects and policy decisions"[8].

In their *Environmental Justice and Transportation Toolkit*, the Federal Transit Administration developed a number of recommendations for steps that agencies can take towards environmental justice. They

[8] Caltrans. 2010. *Community Primer on Environmental Justice & Transportation Planning*.

identified the most important components of an environmental justice policy as transparency, public outreach, documentation, consistent performance indicators, and communication (Robinson 2010). Specific policy suggestions and actions included:

- Create an EJ task force or advisory committee.
- Ensure representatives of EJ communities are present at decision-making bodies (with voting power).
- Develop measurable performance indicators and analysis metrics.
- Strive toward meaningful public participation, and create equal opportunities for EJ communities.
- With informed awareness, promote compromises and tradeoffs as part of solutions.
- Interconnect technical and public involvement aspects of planning, as well as a mix of transportation, housing, health, land use, and smart growth principles to address EJ issues.[9]

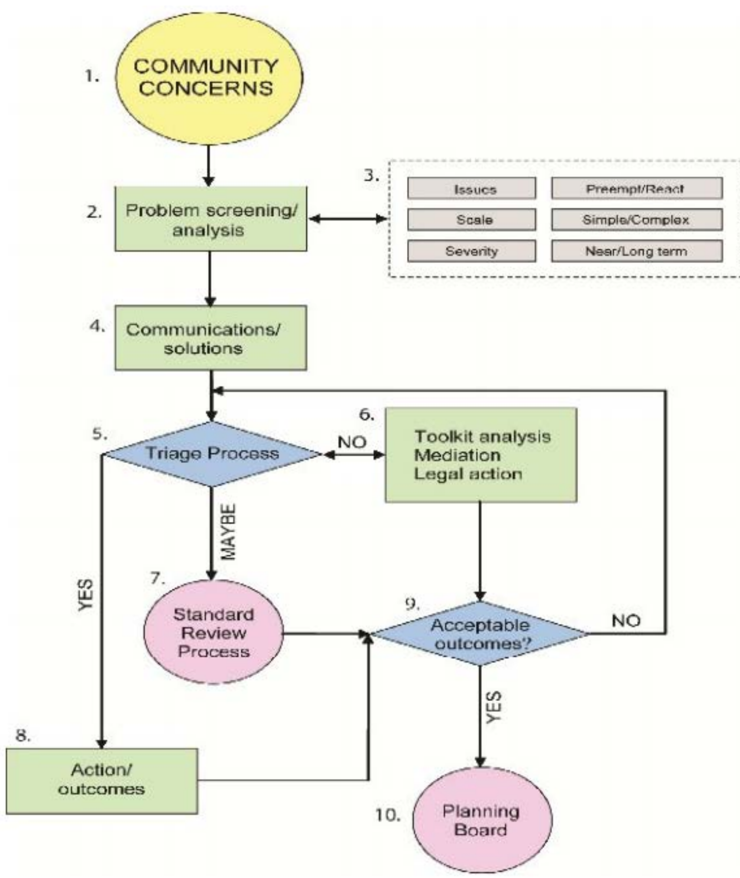

Figure 2 Public Participation Action Model. **Source:** Robinson et al. (2010)

A critical aspect of environmental justice is the empowerment and active participation of the affected community. When soliciting community input, agencies should strive to fully understand the issues vocalized by the public. The FTA recommends a standard process for identifying and addressing these problems: Define, Document, Prioritize, Analyze, Evaluate, Mobilize, and Prosecute. Each of these steps is defined within the *Environmental Justice and Transportation Toolkit*.

The crux of environmental justice lies in the power relationships, both formal and informal, that prioritize certain people's needs over others. These power relationships develop in the context of history, culture, and technology, but they are neither inevitable nor permanent. Rather than accepting "traditional" power dynamics, transportation agencies can intentionally redistribute power to transfer a larger share to historically underrepresented and/or disadvantaged communities.

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[9] Robinson et al. 2010. *Building on the Strength of Environmental Justice in Transportation: Environmental Justice and Transportation Toolkit*. Federal Transit Administration.

SB 375 Transportation Project Funding

California Air Resources Board more explicitly outlines environmental justice criteria through their guide, *Investments to Benefit Disadvantaged Communities*. For a project to qualify as "benefitting" a disadvantaged community (and therefore qualify for that category of GGRF funding), CARB requires that the project either address important needs that are identified by community residents or address key factors that cause the community to be identified as disadvantaged. Outreach efforts to the benefitting community are also required, and the benefits must be quantifiable (metrics need to be tracked that demonstrate progress over time). Fixed-location projects, such as weatherization, renewable energy, and urban forests, are generally easiest to target specifically toward disadvantaged communities[10]. CARB provides tables in Appendix A of the guide, sorted by project type, which outline criteria for a project to be considered "located within or benefitting a disadvantaged community"[11]. Figure 3 demonstrates the overall process for the design and implementation of programs financed by the GGRF.

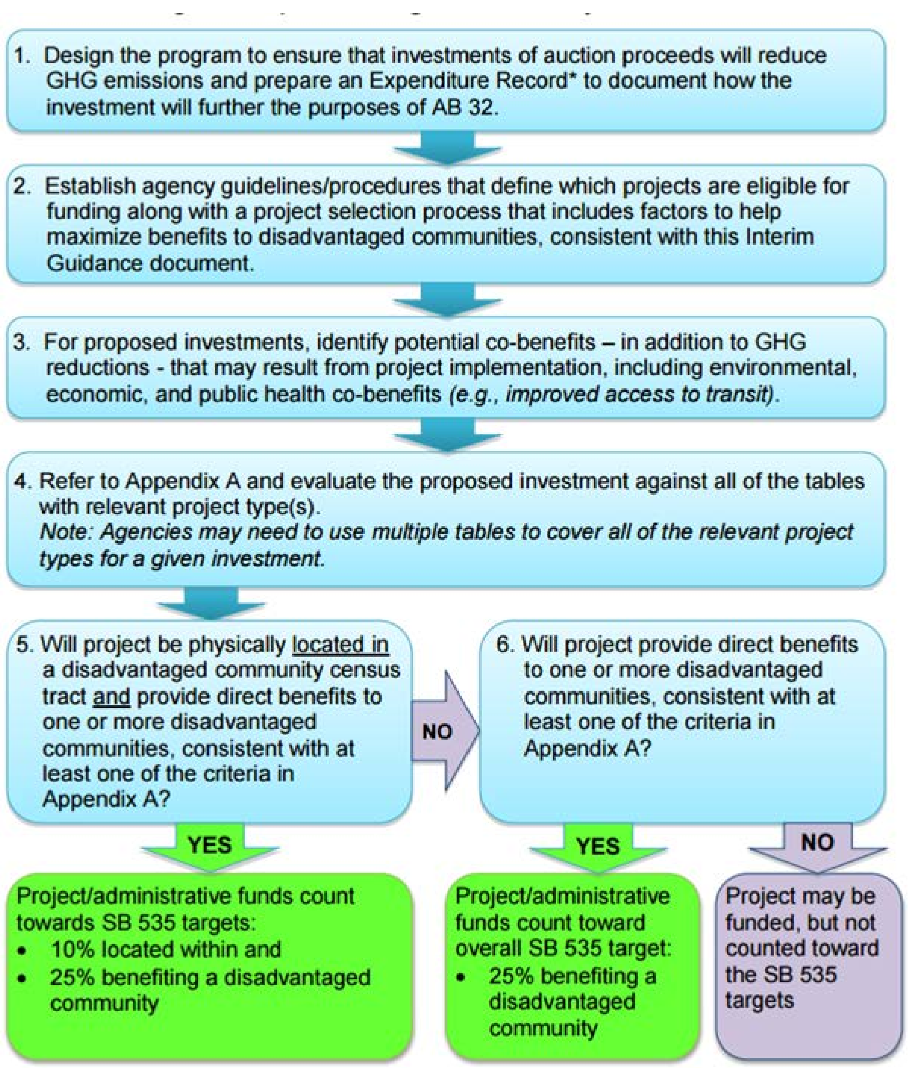

Figure 3 Summary of Process for Administering Agencies to Design and Implement GGRF Programs.

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[10] CARB. 2014. *Investments to Benefit Disadvantaged Communities: Senate Bill 535.*

[11] Ibid.

SB 375/CalEnviroScreen Issues

Although SB 375 attempts to address environmental justice issues in an accurate and equitable ways, some aspects of CARB's approaches and methodologies prove problematic. In part, this is due to the necessarily rigid nature of the analysis to identify discreet "disadvantaged communities" through their CalEnviroScreen program. CalEnviroScreen uses a geographic analysis, but environmental justice at its core is more concerned with comparing groups of people, whether located spatially near one another or not. Similarly, distribution of cap & trade funds is very place-based, but this does not represent a true EJ analysis. The idea of categorizing a census tract as either "advantaged" or "disadvantaged" is itself misleading, since all communities are essentially on a continuum of relative advantages and disadvantages, not in one category or the other. The metrics chosen for analysis and the methods for incorporating these metrics should also be continuously scrutinized and updated, to reflect the best representations possible for assessing the wellbeing of a given community[12].

[12] Duthie, J., Cervenka, K., & Waller, T. 2007. *Environmental Justice Analysis: Challenges for Metropolitan Transportation Planning*.

APPENDIX F - GOVERNANCE

As communities are already experiencing climate and environmental shifts, the need for adaptation response is becoming ever more pressing. Governments are beginning to take on adaptation planning; however faced with limited resources and political constraints, climate action will require the concerted efforts of private, public, non-profit, and research entities to carry out effective change. The preparation process requires vulnerability studies or risk assessments, prioritization of projects and critical infrastructure, allocation of financial and human resources, and information sharing and decision-support tools[1].

Strengthen Regional Cross-Disciplinary Collaboration

Because of the complexity and uniqueness of climate impacts on each geographic region, adaptation planning will require the creativity, compromise, and collaboration across stakeholders from governments, academia, private agencies, and the general public to develop adequate solutions for each respective community[2]. By collaborating with other stakeholders, you can congregate technical knowledge, funding, and staff resources to deliver initial vulnerability assessments and policy language to coordinate comprehensive adaptation planning across sectors.

Southeast Florida

Broward, Miami-Dade, Palm Beach, and Monroe MPOs in Southeast Florida formed the South Florida Regional Climate Change Compact "to coordinate mitigation and adaptation activities across county lines"[3]. These four counties account for about 30% of Florida's population, and are characterized by high density development located around low-lying coastal areas extremely susceptible to flooding caused by rising sea level projections, changing precipitation patterns, and anticipated increases in tropical storm events. Represented by MPOs, DOTs, and transportation and planning councils, this partnership gave birth to a Climate Change Action Plan that established a baseline of GHG emissions for Southeast Florida, and strategies for emission reduction via public transportation investments and advanced technologies in vehicles and biofuels. The Broward MPO administered a South Florida Climate Change Vulnerability and Adaptation Pilot Project and integrated climate policy language into the 2035 Long Range Transportation Plan – "Transform transportation in Broward County to achieve optimum mobility with emphasis on mass transit while promoting economic vitality, protecting the environment, and enhancing quality of life."[4]

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[1] Pew Center on Global Climate Change. 2008. "Adaptation Planning – What U.S States and Localities are Doing."
[2] Ibid.
[3] Parsons Brinckerhoff. 2015. South Florida Climate Change Vulnerability Assessment and Adaptation Pilot Project: Final Report.
[4] http://www.browardmpo.org/services/long-range-transportation-plan/2035-lrtp

New York City

In 2008, Mayor Bloomberg launched the NYC Climate Change Adaptation Task Force/Panel on Climate Change to institutionalize climate change into the planning and policy decision-making processes. The Task Force represents city and state agencies, authorities, and private companies that operate, maintain or control critical infrastructure in the city[5]. Modeled after the IPCC, the Task Force is advised by the scientific NYC Panel on Climate Change (NPCC), which is made up of climate scientists, university researchers, engineers, and risk management experts to provide technical, locale-specific climate data and projections of climate change for New York City, and its impacts on the city's infrastructure. In anticipation of extreme weather events projected to 2050, the Task Force coordinated "A Stronger, More Resilient New York" plan that lays out an elaborate strategy to protect the extensive transportation network; water and sewer systems, electric, gas, and stream production and distribution systems; telecommunication networks; buildings; food supply; and other critical infrastructure[6].

The NPCC is required to meet at least twice each calendar year to review recent scientific data on climate change and its potential impacts, and updated projections are due within one year of the release of IPCC Assessment Reports[7]. They also advise the Mayor's Office of Sustainability and the Mayor's Office of Recovery and Resiliency (ORR) on the development of a communications strategy to disseminate climate change findings to the public, and provide recommendations for the Community Rebuilding and Resiliency Plans for each of the five boroughs. Since its inception, the NPCC has released three technical reports: *Building a Risk Management Response* (2010); *Observations, Climate Change Projections, and Maps* (2013); and *Rebuilding the Knowledge Base for Climate Resiliency* (2015).

Technical and Community Stakeholder Groups

Field experts are critical resources for adaptation planning, as they have the experience and technical knowledge to fill in knowledge and/or data gaps and help stakeholders understand the scientific and engineering aspects of infrastructure and resource vulnerabilities. Community leaders and non-profit organizations can contribute to the local perspective of climate impacts in their neighborhoods, and assist in mobilizing community engagement for climate-related legislation and planning processes. Stakeholder groups can also help local governments leverage funding opportunities and build political clout within the community.

Technical Stakeholder Groups

Agencies form Technical Advisory Groups, Working Groups, Task Force, etc. that consist of technical experts to help officials identify vulnerabilities and assess the adaptive capacity of the infrastructure. In 2007, the Washington State DOT created a Climate Action Team and worked to first develop a vulnerability assessment to identify and rank the most critical infrastructure in all of the state-owned

[5] NYC News and Press Release. 2008. "Mayor Bloomberg Launches Task Force to Adapt Critical Infrastructure to Environmental Effects of Climate Change."
[6] City of New York. 2013. A Stronger, More Resilient New York. PlaNYC.
[7] NYC Panel on Climate Change (NPCC). 2013. Climate Risk Information 2013: Observations, Climate Change Projections, and Maps.

assets. Workshop participants consisted of hydraulic engineers, hydrologists, geologists, GIS specialists, maintenance superintendents, and project development staff to review infrastructure assets that would be vulnerable to climate change. Participants were categorized by geography, expertise, or by experience, and workshops were conducted by region to ensure convenience and active participation from respective staff members (those who could not travel to the workshops attended via Go-To-Meeting). In the span of 6 months, the groups assessed criticality and potential impacts of roadway segments within the state highway network under different climate scenarios. The assets included culverts, bridges, guardrails, maintenance sheds, terminals, and adjacent slopes that could impact the roadway. The facilitators provided GIS data and maps to see "What keeps [participants] up at night?" and how climate changes might worsen or improve those concerns[8].

Community Stakeholder Groups

Community participation is also beneficial to the research process as community members can help refine methodology, data collection, and interpretation of findings for better accuracy and relevance[9]. Oakland Climate Action Coalition (OCAC) is a grassroots cross-sector alliance between community, labor, faith-based, and environmental organizations striving to advance social equity and community priorities within the City of Oakland's climate action planning process. Beginning in 2010, Pacific Institute (PI) researchers partnered with members of OCAC to analyze the impacts and socioeconomic vulnerabilities to climate change, and potential adaptation strategies that can be undertaken within the community. The process involved "research report-back" sessions and community workshops, where PI staff presented their research methods and results to OCAC's Resilience and Adaptation Subcommittee, and facilitated an open discussion with community members on their response to past local weather impacts and how they can improve to better prepare their community for future conditions[10]. This active process helped Pacific Institute establish trusting relationships with OCAC member organizations, and sustain lasting engagement with community members within the climate adaptation planning process. Together, the study identified over 50 adaptation strategies and a series of policy solutions to address social equity concerns associated with each recommendation.

Mainstreaming Climate Adaptation Policies

Effective change happens at the local level, where many city and county jurisdictions have initiated their own comprehensive climate adaptation plans to address the impacts that they are already seeing today. Several states have drafted state-wide adaptation plans, but some city and county jurisdictions are going above and beyond state standards to meet GHG reduction goals and ensuring that their communities will be equipped to handle future weather-related hazards. By streamlining adaptation policies into

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[8] Washington State Department of Transportation (WSDOT). 2011. *Climate Impacts Vulnerability Assessment*.
[9] Minkler, M. and A.C. Baden. 2008. "Introduction to CBPR: New Issues and emphases." *Community-Based Participatory Research for Health: From Process to Outcomes*.
[10] Garzon et al. 2012*. Community-Based Climate Adaptation Planning: Case Study of Oakland, California*. California Energy Commission's Climate Change Center.

existing management and organizational processes, it capitalizes on existing competencies and offers a cost-effective approach without having to invest in new capabilities[11].

On April 29, 2015, California Governor Edmund G. Brown issued an Executive Order that establishes the most ambitious statewide GHG reduction target in North America, and calls for more adaptation activities to address the vulnerability of the state's infrastructure to climate change. This Executive Order will create urgency for regional and local agencies to consider climate vulnerabilities and adaptation in the planning process. The specific elements on climate adaptation includes:

- Incorporate climate change impacts into the state's Five-Year Infrastructure Plan
- Update the state's climate adaptation strategy, Safeguarding California Plan, to identify how climate change will affect California infrastructure and industry and what actions the state can take to reduce the risks imposed by climate change
- Factor climate change into state agencies' planning and investment decisions;
- Implement measures under existing agency and departmental authority to reduce GHG emissions[12]

Policy Coordination

King County, Washington sits at the forefront in the field of climate adaptation planning by building one of the most extensive framework for GHG emissions mitigation and adaptation strategy in the US by aligning ambitious climate goals across county departments. Through an Executive Order on Global Warming Preparedness in March 2006, King County formed an interdepartmental climate change adaptation team to ensure that climate factors were being considered within policy, planning, and investment decisions[13]. In collaboration with University of Washington's Climate Impacts Group, the county produced its first 2007 Climate Plan that addressed priority actions to bring climate change awareness across public and private entities. In October 2006, the King County Council passed a motion that mandated King County departments to submit a Global Warming Mitigation and Preparedness Plan, which helped to pave way for other legislations such as membership in Chicago Climate Exchange, and the creation of a Flood Control District and the Green Building and Sustainable Development Policy[14]. Then the 2008 King County Comprehensive Plan introduced climate change in three new foundation policies that establish a commitment to reduce GHG emission levels by 2010 and 2050, and incorporate climate change considerations in all plans, program, and projects. In 2010, the Council unanimously approved the *King County Strategic Plan 2010-2014* that was established in coordination with thousands of residents and county employees. The Strategic Plan set growth management strategies that address climate change within Transportation, Land Use, Energy, Agriculture, Consumption and Materials Management, and Adaptation[15]. Since its inception, the County's climate mitigation and adaptation

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[11] Federal Transit Administration (FTA). 2011. *Flooded Bus Barns and Buckled Rails: Public Transportation and Climate Change Adaptation*.
[12] CA Exec. Order B-30-15 (Apr. 29, 2015), http://gov.ca.gov/news.php?id=18938.
[13] Pew Center on Global Climate Change. 2008. "Adaptation Planning – What U.S States and Localities are Doing."
[14] http://www.kingcounty.gov/environment/climate/king-county/climate-change-policy.aspx
[15] King County. 2010. *King County Strategic Plan 2010-2014*.

efforts have evolved into their own separate Energy Plans and have been applied in the policy realm across state, regional, and local agencies.

Climate Adaptation Plans and Hazard Mitigation Plans

Every mitigation activity to address our resource vulnerabilities can help lessen the recovery costs and reduce the impacts on human life after each natural disaster. In a 2005 FEMA-funded study, the Multihazard Mitigation Council concluded that "a dollar spent by FEMA on hazard mitigation provides the nation about $4 in future benefits… and FEMA grants to mitigate the effects of floods, hurricanes, tornados, and earthquakes between 1993 and 2003 are expected to save more than 220 lives and prevent almost 4,700 injuries over approximately 50 years"[16].

As a coastal community situated along Monterey Bay, the City of Santa Cruz has endured many of its own disasters such as earthquakes, floods, and droughts, and has been at the forefront of organizing emergency responses to support environmental sustainability and resiliency. In 2007, the City adopted its first Local Hazard Mitigation Plan to formalize the City's efforts to addressing climate change as a threat to its community. After receiving a stamp of approval from FEMA, the City's Climate Action Team collaborated with UC Santa Cruz scientists to develop the City's Vulnerability Study through a $50,000 research grant[17]. Released in January 2011, the assessment identified the following potential climate risks: sea level rise, extreme storm events, flooding, drought, coastal erosion, increased fires risks, ocean acidification, salt water intrusion, increasing temperatures, food and fuel availability, and impacts to ecosystems[18]. The City also worked with other departments in Transportation, Public Works, Planning, Parks and Recreation, and Water to evaluate the resilience of the City's water infrastructure, roads and bridges, and municipal buildings particularly in relation to sea level rise. The Climate Adaptation Plan lists a number of potential action items and acts as an update to the Local Hazard Mitigation Plan and is consistent with the General Plan of 2030. Some examples of the "very high priority" action items are as follows:

- **Seal wastewater pipes** throughout the system that are at or below existing groundwater levels to protect system against rising groundwater,
- Work with Caltrans to **replace and raise Highway 1/9 Bridge** to reduce flooding hazard potential from its low flood clearance and the number and angle of piers in the river,
- **Evaluate and raise levees and/or dredge river** to improve water flow and protect downtown and beach area from San Lorenzo River flooding[19].

[16] Multihazard Mitigation Council (MMC). 2005. *Natural Hazard Mitigation Saves: An Independent Study to Assess the Future Savings from Mitigation Activities*.
[17] Georgetown Climate Center. 2011. "City of Santa Cruz Climate Adaptation Plan."
[18] City of Santa Cruz. 2011. *Climate Adaptation Plan*.
[19] Ibid.

Emergency and Disaster Management Planning

New York City

When a disaster strikes, providing adequate emergency response is critical to preserving infrastructure and restoring transportation services throughout the region. In 2012, Hurricane Sandy put New York City to a true test of disaster preparedness and resiliency, and the ability for public service agencies to coordinate together to restore the city's essential services back into order[20]. In the days before the disaster, the MTA published a press release alerting the public about a possible transit suspension, and outlined the agency's hurricane plan. Some of the measures include:

- Moving buses and trains to higher ground,
- Covering subway entrances and ventilation grates with sandbags and tarps,
- Deploying crews to clear debris from all pumps and drains in subways, tunnels, and bridges,
- Activating and staffing the Incident Command Center to coordinate personnel and manage response,
- Assuring all pump trains, portable pumps and emergency response vehicles are in working condition and ready to be deployed after the storm passes[21].

The crisis also demonstrated how flexible modes of transportation, such as walking and biking, can provide alternative commuting methods that can help the city adapt to the collapse of its transit infrastructure. For example, the number of bicycle commuters tripled to 30,000 on November 1st as commuters from Brooklyn and Queens were stranded at bus stops or struggled to get gas for their vehicles[22]. The extensive network of private commuter vans also remained in operation during the storm that helped fill a key gap in the transportation system. NYCDOT and MTA provided "warming buses" at six affected areas as places for people to get out of the cold, and transported residents to local shelters during the night to avoid hypothermia. The city also collaborated greatly with the New York Police Department (NYPD) to regulate temporary transit operations and controlled traffic flow, such as enforcing a carpooling "HOV3" rule, and maintaining order at gas stations during their peak to prevent fighting. New Jersey Transit also stepped in to provide free park-and-rides, shuttlebuses, and ferries into Manhattan to mitigate the congestion on the open bridges and tunnels[23].

Dane County, Wisconsin

In March 2013, Dane County, Wisconsin created the Climate Change Action Council with the mission "to ensure Dane County government is better prepared for weather extremes brought on by global climate change"[24]. The Council released a Climate Change and Emergency Preparedness report that detailed a variety of climate-related infrastructure and public safety risks within the county, and the anticipated

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[20] Kaufman, S., Qing, C., Levenson, N., Hanson, M. 2012. *Transportation During and After Hurricane Sandy*. NYU Wagner School, Rudin Center for Transportation

[21] Metropolitan Transportation Authority (MTA). 2012. "MTA Prepares for Hurricane Sandy." Press Release.

[22] Kaufman et al. 2012. *Transportation During and After Hurricane Sandy.*

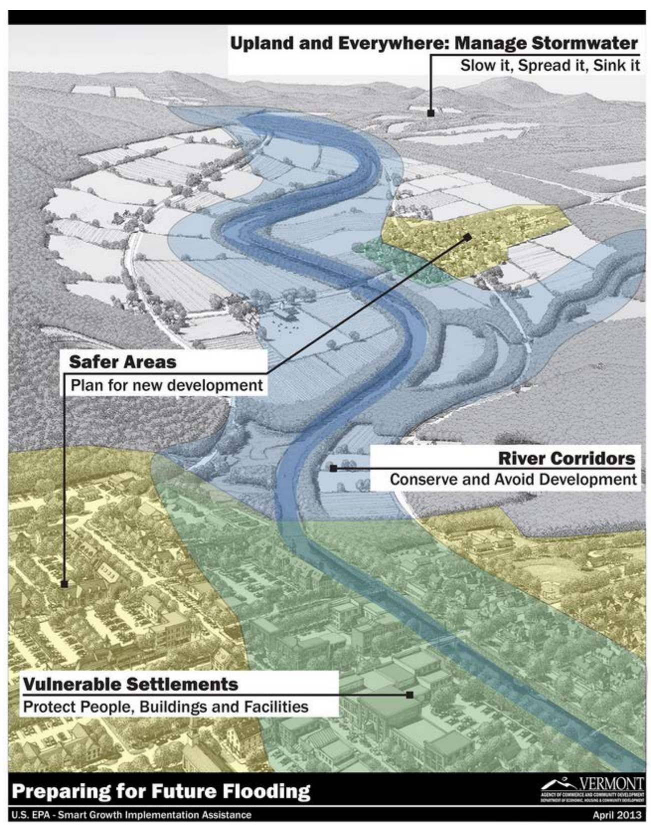
[23] Ibid.

[24] Dane County Climate Change Action Council. 2013. *Dane County Climate Change and Emergency Preparedness*.

emergency management response needed during such events – such as increased calls for 911 calling center, increased dependence on disabled facilities and emergency transportation routes, disruptions in tele-communication channels, and the first responders staffing capacity to handle these needs. The report identified "near-term adaptations" for coping with existing or imminent threats and prepared long-term mitigation strategies for projected risks[25]. In September 2013, the County allocated $1.2 million within its 2014 budget for climate adaptation measures, such as upgrade culvert resilience to handle stormwater, create an emergency sandbag fund for potential floods, and purchase track driven tree remover to clear downfalls from high winds[26] (UW Extension, 2014).

Smart Growth

Smart growth can also offer a valuable framework for communities to integrate environmentally and economically sustainable land use strategies while improving disaster recovery planning for long-term climate impacts. To combat the inefficient use of existing resources in sprawling developments, the smart growth principles aim to promote sustainable development and conservation practices, including: investing in infill developments, foster socioeconomic diversity in neighborhoods, support variety in transportation choices, enhance community vitality, protect and conserve natural resources, encourage public participation, and create a sense of place for residents. Therefore, implementing smart growth strategies can reinforce the co-benefits of reducing GHG emissions in communities while strengthening their adaptive capacity towards climate change.



In the wake of Tropical Storm Irene in 2011, several Vermont state agencies sought assistance from FEMA and EPA through the **Smart Growth Implementation Assistance Program** to identify strategies that can help vulnerable communities prepare for and recover from the devastating damage caused by floods. A team of national experts evaluated state and local policies and public participatory processes to integrate smart growth principles into comprehensive land use plans, Hazard Mitigation Plans, development codes, and municipal regulations in order to enhance flood resilience. The study provided community context, identified future growth areas in safer locations, and recommended policy measures to protect existing vulnerable areas. Some of the policy recommendations include:

[25] Ibid.
[26] University of Wisconsin-Extension. 2013. "$1.2M of climate adaptation funding in 2014 Dane County budget."

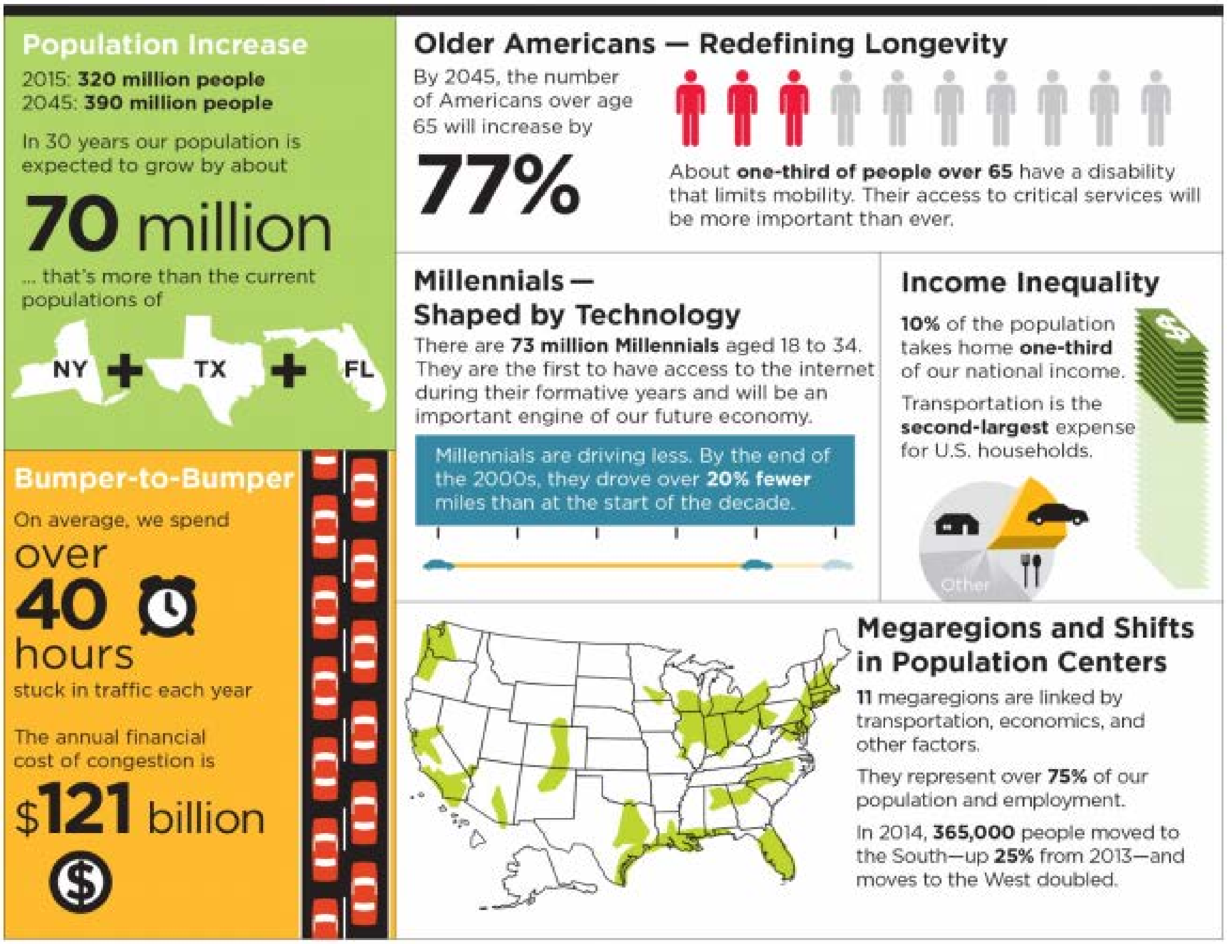
- Work with the community to leverage local property tax revenues and land trust funds to coordinate **buyouts of flood-prone properties**, and use the land as a buffer zone for future floods
- Implement **fluvial erosion hazard zoning** especially in regions with more mountainous terrain, where developments along river corridors can alter river channels and intensify bank erosion, posing serious threats to bridges, culverts, roads, and houses
- Adopt **conservation or cluster subdivision ordinances** that encourage compact developments while requiring developers to protect sensitive natural areas, such as land critical for water retention
- Modify **nonconforming use provisions** to ensure that property owners comply with hazard-resilient measures such as building elevation, flood-proofing HVAC equipment, etc. [27]

Beyond Traffic: Trends and Choices

In February 2015, US DOT released a report called Beyond Traffic 2045 – a 30-year framework for evaluating population growth and changing transportation trends projected in a shifting social and economic landscape within the 21st century. The report highlights:

- By 2050, 11 emerging megaregions could absorb **75%** of the US population, while rural populations continue to decrease,
- Millennial populations moving towards dense urban areas utilizing existing **public transit, biking, and pedestrian** facilities; reduction in trips by personal vehicle in favor of trips by transit and intercity passenger rail,
- Elderly populations over the **age of 65 will increase by 77% by 2045**, meaning that about 1/3 of seniors will have a disability that will inhibit their mobility (so access to critical services will be essential),
- **Growth in internet shopping and e-commerce** will significantly lower household shopping trips, but increase demand for small package home delivery,
- Advanced auto innovation and renewable energy sources will strengthen fuel economy standards; but it will also result in **more than $50 billion in lost gas tax revenues**[28].

[27] Environmental Protection Agency (EPA). 2014. *Planning for Flood Recovery and Long-Term Resilience in Vermont: Smart Growth Approaches for Disaster-Resilient Communities*.
[28] US Department of Transportation. 2015. *Beyond Traffic 2045: Trends and Choices*.



Understanding these new geographic shifts, population characteristics, behavioral trends, and travel patterns will help Metropolitan Planning Organizations and planning agencies to think more creatively about the variety of adaptation options available to increase the flexibility of their transportation system. The availability and reliability of Global Positioning Systems and mobile technologies to provide real-time traffic information has given individuals the power to choose the most efficient routes and modes to their destination. Commute patterns are shifting as "the number of Americans working from home at least one day a week increased by 43% between 1997 and 2010" [29], shifting the way many organizations view the traditional 9-to-5 work schedule at a typical office setting. The new sharing economy has given rise to ridesharing and bikesharing services has decreased demand for personal vehicle ownership, and can offer an opportunity for governments to think about how they can supplement transit services, especially during off-hours. Information technology and supply-chain optimization practices are improving the way manufacturers and shippers plan and distribute their goods, and thereby having a major impact on the way the freight industry operates today.

[29] Ibid.