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Climate Change Vulnerability and Adaptation for Infrastructure and Recreation in the Sierra Nevada

Editors

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Cover Photo: Postfire mosaic along highway north of Wawona entrance inside Yosemite National Park, Ferguson Fire, 2018, by James D. Absher.

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Abstract

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A vulnerability assessment was conducted on the effects of climate change on infrastructure and outdoor recreation in the Sierra Nevada, including adaptation options that minimize negative impacts of climate change and facilitate a transition to a warmer climate. At vulnerable or flood-prone sites, resilience near stream crossings and in floodplains can be enhanced by designing infrastructure to withstand more frequent and severe flood events, and by upsizing or upgrading existing infrastructure to withstand flooding. Some roads and other infrastructure can be decommissioned or moved to mitigate risks. Following wildfires, managers can prioritize slope stabilization projects for infrastructure near unstable slopes and riverbanks, increase monitoring of soil and slope conditions, and restrict public access to sites where unstable soils create safety hazards. Increased recreation is projected for the Sierra Nevada, so adequate staffing and resources will be needed to aid delivery of recreation opportunities and to maintain visitor safety. Limits on visitation through determination of carrying and social capacity may be increasingly necessary, as will communication about alternative recreation areas, alternative activities, and warnings about potential crowding. Expanding partnerships among federal, state, and local agencies will increase the capacity of the U.S. Department of Agriculture Forest Service and other organizations to maintain functional ecosystems, water resources, and recreation and transportation infrastructure.

Keywords: Adaptation, climate change, disturbances, drought, extreme weather, infrastructure, recreation, resilience, roads, Sierra Nevada, wildfire.

Summary

The Sierra Nevada Infrastructure and Recreation Vulnerability Assessment and Adaptation Partnership was developed to identify climate change issues relevant for resource management on national forest units in the Sierra Nevada region of the U.S. Department of Agriculture, Forest Service (USFS) Pacific Southwest Region (Eldorado, Inyo, Lassen, Modoc, Plumas, Sequoia, Sierra, and Stanislaus National Forests and the Lake Tahoe Management Unit).

The 10 national forest units in the Sierra Nevada contain a combined 26,500 mi of roads, 9,300 mi of trails, 684 bridges, 169 dams, over 4,100 buildings and administrative sites, and over 50 campgrounds. Total infrastructure investments for facilities alone have an estimated value of $750 million. The combined effects of increasing use, aging infrastructure design, and changing climatic and hydrologic conditions are increasing the vulnerability of infrastructure and increasing risk for users. Water resource infrastructure, including dams and reservoirs, stores water, reduces flooding, and provides recreational opportunities. Future changes in timing, type (rain versus snow), and amount of precipitation will create challenges when storing and allocating water for irrigation, flood prevention, and energy production.

Outdoor recreation is a huge enterprise in the Sierra Nevada, providing diverse experiences, psychosocial value, and public health benefits to residents of California and beyond. Over 17 million people recreate in Sierra Nevada national forests each year, accounting for $1.6 billion in annual expenditures and $1.3 billion aggregate economic benefits to local businesses and communities. Warm-weather activities (hiking, viewing natural features, camping, etc.) account for the largest proportion of recreation, followed by winter activities (especially downhill skiing) and a broad range of other activities. Nearly all recreation is affected by weather conditions, which affect decisions about if, when, and where to recreate.

The Sierra Nevada is already experiencing the effects of human-caused climate change. Average annual temperature has increased 1.6 °F since 1901 and is projected to increase 6 to 10 °F by the end of the 21st century. Increases in temperature are expected to be higher at higher elevations (+9 °F at 3,000 ft compared to +9.5 °F at 10,000 ft). Precipitation is projected to change by -5 percent to +10 percent and to be more variable, although projections are uncertain.

Higher winter temperatures have resulted in more precipitation falling as rain rather than snow and reduced snowpack in many parts of the Sierra Nevada. Reduced snowpack and earlier snowmelt have led to earlier timing of streamflow, and peak flows are projected to occur 1 to 2 months earlier by the end of the 21st century. As precipitation regimes change from snow dominated to rain dominated, snowpack storage will decline, with the amount of water stored in snowpacks

projected to decrease by 60 percent by the end of the 21st century, with middle elevations experiencing the biggest losses.

Higher temperatures have also been associated with increased wildfire area burned and incidence of large fires. These effects are expected to become more pronounced in coming decades. Higher temperatures (and longer time periods between rain events) will likely increase drought stress in forests, potentially altering the distribution and abundance of dominant plant species over decades to centuries.

Current transportation infrastructure, hydroelectric networks, and recreation resources in the Sierra Nevada are coupled with hydrologic processes and vegetation. Roads and other infrastructure on national forests provide access to recreation opportunities across all seasons. Recreation demand and outdoor recreation economies are increasing with growing populations in California. With projected warming temperatures and more intense precipitation events, higher demand for public access in national forests may coincide with increasing occurrence of floods, landslides, and wildfire. Earlier and larger spring streamflows will potentially lead to prolonged and lower summer low flows for streams that contribute to water supplies, support aquatic systems, and provide recreation opportunities.

Infrastructure

Climate change effects—

Infrastructure can be affected by direct climate change effects, increased climatic variability (e.g., precipitation timing, extreme temperatures, drought severity and duration) and indirect climate change effects such as increased fire and insect outbreaks. Infrastructure networks are interrelated with other resource management programs, and the vulnerability of infrastructure to climate change can influence access to and quality of other natural resources and ecosystem services (e.g., recreation).

Climate change will affect infrastructure over short and long time scales. Extreme events occurring over the course of several hours to several weeks often cause the most significant damage. Roads, bridges, and culverts are susceptible to increased runoff during storm events and failures owing to washouts, plugging, overtopping, stream diversion, and scour. Long-term climatic patterns that affect infrastructure over multiple decades—altered freeze-thaw cycle, timing and length of suitable construction weather, and snowmelt and stream hydrology—can also affect the sustainability of transportation, recreation, and water resource infrastructure.

By the end of the 21st century, streamflows that can lead to flooding (i.e., 50-year events) may increase 30 to 90 percent in the northern Sierra Nevada, and by 50 to 100 percent in the southern Sierra Nevada, particularly during the winter months. Increased magnitude of peak streamflows in winter is expected to damage roads near perennial streams, ranging from minor erosion to complete loss of the road. Associated infrastructure such as bridges, culverts, campgrounds, and facilities near streams and floodplains will be especially vulnerable, potentially affecting public safety and reducing access for recreation and resource management.

Infrastructure can also be indirectly affected by climate-influenced disturbances such as wildfire. Area burned by wildfire has increased in California over the past 30 years, often destroying buildings and associated facilities and infrastructure. When heavy rains fall in areas where fire has removed vegetation, erosion and debris movement can plug culverts, cover roads, and damage downstream structures.

Adaptation options—

At vulnerable or flood-prone sites, resilience near stream crossings and in floodplains can be enhanced by designing future infrastructure to withstand more frequent and severe flood events, and by upsizing or upgrading existing infrastructure to withstand future flooding and erosion. In the most vulnerable locations, roads and other infrastructure can be decommissioned or moved to mitigate risks. Future maintenance and repair operations should occur during periods when weather conditions are optimum and risks to worker safety and site integrity are low.

Altered precipitation regimes will create challenges for dam and water resource managers who allocate water resources to support flood control, energy production, and irrigation. As streamflows become more variable, shifting the timing and amount of water releases from dams can maintain reservoir levels to minimize flood risk in the spring while maximizing water storage for longer periods. To supplement reservoir storage, managers can use off-stream water delivery infrastructure (canals, ditches, holding ponds) to increase water storage or divert excess streamflows.

Responding to changing hydrologic conditions may require investment in monitoring upstream snowpack, soil, and weather. In some locations, alternative monitoring techniques or protocols may be needed. Improving streamflow forecasting and expanding streamflow and snowpack monitoring networks will help managers respond to extreme events by ensuring water allocation for downstream uses. To improve forecasting and response times, managers can expand monitoring efforts to increase their capacity to respond to uncertain and rapidly changing weather, streamflow, and snowpack conditions.

To prevent wildfire damage to infrastructure, vegetation can be managed to reduce fuel loads and increase defensible space around facilities and transportation corridors in the wildland-urban interface. Following wildfires, managers can prioritize slope stabilization projects around infrastructure near unstable slopes and riverbanks, increase monitoring of soil and slope conditions, and restrict public access to sites where unstable soils create safety hazards.

Collaborative adaptation efforts and an "all lands" approach are essential for effective responses to increasing disturbances. Expanding partnerships among federal, state, and local agencies will increase the capacity of the USFS and other organizations to maintain functional ecosystems, water resources, and recreation and transportation infrastructure. Public awareness of the connections among infrastructure, forest ecosystems, and disturbance can be promoted through outreach and education with local communities and stakeholders. This will also allow national forests to obtain feedback from the public, which can in turn help identify and prioritize vulnerable infrastructure and develop climate-smart actions.

Recreation

Climate change effects—

Altered temperature, precipitation, water resources, and seasonality of weather conditions will affect evolving recreation patterns in the Sierra Nevada over the course of the 21st century. Higher temperatures are expected to be a primary driver because most recreational activities are seasonal and vulnerable to changing seasonal conditions and extreme events. As temperatures continue to increase, communities near national forests will incur economic impacts, especially if those communities depend heavily on outdoor recreation.

Summer recreation will benefit from a longer period of suitable weather without snow, especially during the spring and autumn shoulder seasons. Winter recreation (skiing, snowmobiling) will be negatively affected by a warmer climate because of less and more transient snow. Ski areas and other facilities at lower elevations will be especially vulnerable. Hunting may be sensitive to temperature and timing and amount of snow during the designated hunting season. Fishing will be sensitive to streamflows and stream temperatures associated with target species; if summer flows are very low, some streams may be closed to fishing. Water-based recreation (swimming, boating, rafting) will be sensitive to lower water levels during drought years. Gathering forest products for personal and commercial use (e.g., huckleberries, mushrooms) may be somewhat sensitive to the climatic conditions that support the distribution and abundance of items being collected.

Nearly all recreation activities will be negatively affected by projected increases in extreme weather and disturbance events. Wildfire creates near-term (weeks to months) impacts by reducing visitor access to roads, trails, and recreation facilities, and pervasive smoke reduces air quality over large areas within and outside national forests. Severe wildfires kill trees across thousands of acres, altering the aesthetic quality of recreation sites and vistas, and, in some cases, affecting plants and animals that are valued by recreationists. Dead and damaged trees, as well as postfire soil erosion, create significant hazards for recreationists that may last for decades.

Adaptation options—

Adaptation to climate-related events is already evident in the Sierra Nevada. For example, during 2017–18, the USFS issued messaging about air quality impacts from wildfires and smoke, and about closure of roads and recreation areas in response to damage from winter storms. Recreationists may benefit from searching information resources to plan forest visits and may need to develop alternative plans should unexpected events render an area or opportunity unavailable. Substitution of alternative locations and activities is complex and may be less inviting if there is a personal connection to a location or activity. Although recreationists are most likely to adapt to short-term patterns if the primary location is not available, long-term effects on recreation experiences are not well understood.

Increased recreation is projected for the Sierra Nevada because of California's increasing population. Consequently, adequate staffing and resources will be needed to aid delivery of recreation opportunities and maintain visitor safety. as well as protect and restore affected settings. Limits on visitation through determination of carrying and social capacity may be increasingly necessary, as will approaches that incorporate messaging around alternative areas and activities, and warnings about potential crowding. Communication via USFS websites, social media, and smartphone applications will enhance visitor awareness of specific seasons, closures, and limits to types of use. Partnerships and volunteer programs will continue to supplement management for diverse recreation opportunities and settings, supporting information needs and informing adaptive responses.

Specific adaptation strategies include:

- Increase resilience of recreation infrastructure to increasing disturbances.
- Adjust staffing and management during variable shoulder seasons to accommodate changes in seasonal access and recreation locations.
- Adjust visitor management policies and practices to increase management flexibility and facilitate transitions to meet user demands and expectations.
- Increase resilience of recreation sites to changing conditions or increased demand.
- Increase capacity to anticipate and respond to shifting seasonal recreation patterns.

- Increase management flexibility and anticipate fire-related effects at a regional scale.
- Reduce safety risks associated with hazard trees.
- Manage iconic places for resilience using an interdisciplinary approach to provide recreation opportunities.

The Sierra Nevada partnership achieved specific elements of national and regional climate change strategies for federal agencies, providing a scientific foundation for resource management and planning for infrastructure and outdoor recreation in national forests and beyond. First, the scientific basis for current and projected climate change effects on natural resources, infrastructure, and recreation is now well established. Second, a large number of adaptation options have been developed, many of which are a component of current management practice, providing a pathway for slowing the rate of deleterious change in resource conditions. Timely implementation of adaptation will help prevent the deterioration of infrastructure and the huge costs of repairs and replacement. It will also ensure sustainability of facilities, access, and opportunities for recreation. Long-term monitoring will help detect potential climate change effects, as well as evaluate the effectiveness of adaptation options.

Contents

Chapter 1: Introduction

Jessica E. Halofsky[1]

Project Description and Objectives

The Pacific Southwest Region of the U.S. Department of Agriculture, Forest Service (USFS), in collaboration with the USFS Pacific Northwest and Pacific Southwest Research Stations and the Office of Sustainability and Climate, formed a science-management partnership and conducted a climate change vulnerability assessment for infrastructure and recreation in Sierra Nevada national forests. The vulnerability assessment set the stage for developing adaptation options in a series of science-management workshops. The outcomes of the effort, called the Sierra Nevada Infrastructure and Recreation Vulnerability Assessment and Adaptation Partnership, are described in this report. Specific objectives of the effort were to:

- Synthesize the best available science to assess climate change vulnerabilities and develop adaptation options for recreation and infrastructure resources on national forests in the Sierra Nevada.
- Develop a framework and tools for managers to incorporate the best available science, including other complementary assessments, into USFS recreation and engineering program assessments.
- Define priority regional- and forest-level climate change vulnerabilities for integration in the land management planning process.
- Identify priority areas for cross-boundary partnerships and third-party investments to best leverage agency appropriations and to maximize opportunities for shared stewardship.

Climate change is an agencywide priority for the USFS. In 2008, the USFS released a Strategic Framework for Responding to Climate Change (USDA FS 2008). In 2010, the USFS provided specific direction to the National Forest System in the form of the National Roadmap for Responding to Climate Change (USDA FS 2010a) and the Climate Change Performance Scorecard (USDA FS 2010b). These directions were followed by the 2012 Planning Rule (USDA FS 2012), which requires national forests and grasslands to address climate change in the land management plan (forest plan) revision process. Requirements of the Roadmap, Scorecard, and the 2012 Planning Rule are mutually supportive and provide a framework for responding to changing conditions over time.

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National Forest System units in the Sierra Nevada have initiated or will likely initiate the land management plan revision process in the next several years. In preparation for plan revision in the region, and to ensure the use of the best available science in the revision process, the USFS Pacific Southwest Research Station developed a synthesis of relevant science for the Sierra Nevada (Long et al. 2014). The Pacific Southwest Region then used information in the science synthesis to frame a bioregional assessment, which provides context on resource management issues that cross boundaries in the Sierra Nevada region (USDA FS 2014).

The assessment described in this report builds upon the Sierra Nevada science synthesis and bioregional assessment, along with other past climate change assessments conducted in the Sierra Nevada region. For example, EcoAdapt and partners conducted a climate adaptation project for the Sierra Nevada that involved assessing vulnerabilities for key wildlife species, ecosystems, and ecosystem services (Kershner 2014). To support this effort, the Geos Institute developed a report on projected climatic and hydrological changes in the region (Geos Institute 2013).

The assessment described in this report also builds on climate change vulnerability assessments conducted for national forests across the United States, including assessments in the Pacific Northwest (Halofsky et al. 2011, 2017, 2019; Raymond et al. 2014), Northern Rockies (Halofsky et al. 2018a), the Intermountain West (Halofsky et al. 2018b), and Eastern United States (Butler et al. 2015; Swanston et al. 2011, 2016). The processes, products, and techniques used for climate change efforts on national forests are described in a guidebook for developing adaptation options for national forests (Peterson et al. 2011). The Sierra Nevada effort followed the principles and practices in the guidebook.

Approach

Vulnerability assessments typically incorporate three features: exposure, sensitivity, and adaptive capacity (Parry et al. 2007). Exposure is the degree to which the system is exposed to changes in climate. Sensitivity is an inherent quality of the system that indicates the degree to which it could be affected by climate change. Adaptive capacity is the ability of a system to respond and adjust to the exogenous influence of climate. We used scientific literature, model output, and expert knowledge to assess exposure, sensitivity, and adaptive capacity and identify key vulnerabilities for infrastructure and recreation in the Sierra Nevada.

The vulnerability assessment was conducted through a science-management partnership. Science-management partnerships have emerged as effective catalysts for developing vulnerability assessments and land management adaptation at both the strategic and tactical level (Cross et al. 2013, Littell et al. 2012, McCarthy 2012, Peterson et al. 2011, Swanston et al. 2016). Partnerships among scientists in the USFS Research and Development branch, managers in the National Forest System, and other agencies and universities have played a major role in advancing climate change adaptation in the agency (Halofsky et al. 2016). Science-management partnerships typically involve iterative sharing of climate and climate effects information by scientists, and of local climate, ecological, and management information by managers (Peterson et al. 2011). This iterative information exchange aids identification of vulnerabilities to climate change at the local scale and sets the stage for developing adaptation options (Halofsky et al. 2016).

The vulnerability assessment process was initiated with an in-person expert elicitation workshop in July 2018. Attendees included infrastructure and recreation representatives from most of the national forest units, along with science teams, other USFS leaders, and partners. Project objectives and general approaches to the vulnerability assessment were introduced. Science team leads then reviewed the vulnerability assessment outline, potential sources of information, and preliminary results. This was followed by group discussion about potential sources of information for the assessment, and unit-specific drivers, stressors, and issues affecting recreation and infrastructure in the Sierra Nevada.

Following the expert elicitation workshop, science teams for recreation and infrastructure developed the vulnerability assessment, consulting with regional and unit-level land managers as needed. Each assessment team refined key questions that the assessment needed to address, selected values to assess, and determined which climate change effects models best informed the assessment. In some cases, assessment teams conducted spatial analyses or ran and interpreted models, selected criteria for which to evaluate model outputs, and developed maps of model output and resource sensitivities. To the greatest extent possible, teams focused on effects and projections specific to the region and used the finest scale projections that are scientifically valid.

After identifying key vulnerabilities for infrastructure and recreation, scientists, land managers, and stakeholders convened at three 1-day workshops in June of 2019 in the north, central, and southern Sierra Nevada. The workshops focused on presentation and discussion of the vulnerability assessment, and elicitation of adaptation options from resource managers. During these workshops, scientists and resource specialists presented information on climate change effects and current management practices for infrastructure and recreation. Facilitated dialogue was used to identify key sensitivities and adaptation options.

Participants identified strategies (general approaches) and tactics (on-the-ground actions) for adapting resources and management practices to climate change, as well as opportunities for implementing these adaptation actions in projects, management plans, partnerships, and policies. Participants generally focused on adaptation options that can be implemented given our current scientific understanding of climate change effects, but they also identified research and monitoring that would benefit future efforts to assess vulnerability and guide management practices. Facilitators captured information generated during the workshops with worksheets adapted from Swanston et al. (2016). Initial results from the workshops were augmented by continued dialogue with USFS resource specialists.

Study Region Description

This report focuses on 10 National Forest System units in the Sierra Nevada: Eldorado National Forest (NF), Inyo NF, Lake Tahoe Basin Management Unit, Lassen NF, Modoc NF, Plumas NF, Sequoia NF, Sierra NF, Stanislaus NF, and Tahoe NF (fig. 1.1). These national forests provide a variety of ecosystem services, including fresh water, hydropower, diverse plant and animal assemblages, and recreation and economic opportunities. The national forest units in the Sierra Nevada provide about 16 percent of the water supply in California (Brown et al. 2016), providing for both municipal and agricultural uses. The Sierra Nevada national forest units are home to eight wild and scenic rivers, totaling 643 mi, providing natural, cultural, and recreational river-related values (USDA FS 2014). Sierra Nevada rivers generate half of all hydropower in California and 15 percent of all power generated in the state (Dettinger et al. 2018).

Most of the forests and high-elevation landscapes in California are located in the Sierra Nevada, and over 40 percent of the Sierra Nevada region is managed by federal agencies, including the USFS and U.S. Department of the Interior Bureau of Land Management and National Park Service (Minnich and Padgett 2003). The southern half of the region has many specially designated areas, including three national parks, two national monuments, and extensive wilderness areas. Wilderness areas are concentrated along the crest of the Sierra Nevada and on both sides from Lake Tahoe south on the Stanislaus, Sierra, Sequoia, and Inyo NFs (USDA FS 2014). Large inventoried roadless areas border the wilderness.

The 10 national forest units have over 17 million visitors annually. Outdoor recreation is integral to many local communities, and demand for recreation opportunities has increased in recent decades.

The Sierra Nevada region supports large recreation and tourism industries. The 10 national forest units have over 17 million visitors annually. Outdoor recreation is integral to many local communities, and demand for recreation opportunities has increased in recent decades (USDA FS 2014). The population of California is expected to grow 37 percent between 2010 and 2050, and for counties partially or entirely within the Sierra Nevada region, total population is projected to increase by 69 percent by 2050 (California Department of Finance 2012). Higher

Figure 1.1—Ten National Forest System units in the Sierra Nevada.
Lake Tahoe Basin = Lake Tahoe Management Unit.

population will likely increase demand for recreation and increase demand for water resources. Population growth may also lead to increased development in the wildland-urban interface, resulting in challenges in managing wildland fires and protecting infrastructure.

American Indians have been part of Sierra Nevada landscapes for thousands of years (Anderson and Moratto 1996), managing the land by burning, irrigating, pruning, harvesting, sowing, and weeding (USFS 2014). American Indians continue to participate in traditional activities on national forests, including hunting, fishing, trapping, and gathering berries, thus sustaining family and tribal traditions, providing sustenance for families, and continuing a spiritual connection to the land (McAvoy et al. 2005).

Harvesting nontimber forest products is also an important cultural activity for nontribal communities (Richards 1996). Nontimber forest products gathered from national forest in the Sierra Nevada include wild food plants, medicinal plants, floral greens, seeds and cones, posts, poles, firewood, transplants, and Christmas trees (USDA FS 2014).

There is a long history of timber harvest in the Sierra Nevada region. However, timber harvest from national forests has decreased since the 1990s (Charnley and Long 2014). Similarly, grazing on forest lands has decreased in recent years because of market conditions and environmental concerns (USDA FS 2014). Although these activities have recently decreased, past timber harvest and grazing practices, along with fire suppression over several decades, have increased tree densities, shade-tolerant species, and surface fuel loading in forests that were historically characterized by frequent fire (e.g., ponderosa pine [*Pinus ponderosa* Lawson and C. Lawson], Jeffrey pine [*P. Jeffreyi* Balf.], and mixed-conifer forests in the Sierra Nevada) (Collins and Skinner 2014).

These changes in forests have increased their vulnerability to uncharacteristic fire severity and extent (Stephens and Collins 2004, van Wagtendonk 1985, van Wagtendonk and Fites-Kaufman 2006), and fire severity has increased in some forest types in recent decades (Mallek et al. 2013, Miller et al. 2009, Steel et al. 2018). Increased forest density has also increased risk of drought-induced insect outbreaks and tree mortality events, such as the mortality event that occurred in the central and southern Sierra Nevada during the 2012–17 drought (Fettig et al. 2019). With the occurrence of large wildfire and mortality events in the Sierra Nevada, there has been greater focus on increasing the pace and scale of restoration to increase ecological and community resilience to disturbance (Long et al. 2014, USDA FS 2014).

Assessment Overview

This publication contains information on expected climatological and biophysical changes in the Sierra Nevada (chapter 2), projected changes to hydrologic processes and water resources (chapter 3), infrastructure vulnerabilities to climate change (chapter 4), recreation vulnerabilities to climate change (chapter 5), adaptation options that were compiled at the workshops (chapter 6), and conclusions and discussion on potential applications of the vulnerability assessment and adaptation options (chapter 7). Interactions between different resource areas are described throughout, and issues are summarized for the three different Sierra Nevada zones identified by the Pacific Southwest Region (North, Central, and South Zones) where this geographic specificity is relevant.

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Chapter 2: Climate Change Effects in the Sierra Nevada

Jessica E. Halofsky [1]

Climate Overview for the Sierra Nevada

The Sierra Nevada region is characterized by high topographical and climatological diversity (Dettinger et al. 2018), extending 400 mi north to south and 70 mi east to west. Elevations are higher in the southern end of the range, with Mount Whitney (14,505 ft) being the highest peak in the contiguous United States; peaks in the northern part of the range are generally less than 8,800 ft (Minnich and Padgett 2003).

The western portion of the Sierra Nevada region is characterized by a Mediterranean climate, with cool, wet winters and warm, dry summers. The western portion of the Sierra Nevada receives moisture and warm air from prevailing westerly winds off the North Pacific Ocean (Dettinger et al. 2018). As air moves upward over the mountain range, air cools, and moisture condenses into clouds and precipitation. Thus, the western, mountainous portions of the Sierra Nevada receive more precipitation than the eastern portion (fig. 2.1); elevations between 5,000 and 6,000 ft on the west slope are some of the wettest in the region (Dettinger et al. 2018).

The eastern portion of the Sierra Nevada region lies in a rain shadow and thus receives less precipitation (fig. 2.1). The eastern portion of the range is also more heavily influenced by Great Basin climate, with colder winters and more rainfall in the summer (Dettinger et al. 2018). Temperatures are generally cooler and more precipitation falls as snow in the southern portion of the Sierra Nevada than the central and northern portions of the range because of higher elevations (fig. 2.1). However, average annual precipitation decreases gradually moving southward because of the position of the jetstream in northern California and the Pacific Northwest during winter (Minnich and Padgett 2003).

The Sierra Nevada region, and California in general, are characterized by high interannual variation in precipitation. Historically, annual precipitation in the Sierra Nevada has varied between 50 and 200 percent of average, whereas most of the rest of the United States varies between 10 to 20 percent of average (Dettinger et al. 2011). Although the Pacific Ocean has a moderating effect on temperature in the western part of California, other ocean-atmosphere cycles, such as the El Niño Southern Oscillation, contribute to interannual climatic variability in the state and the Sierra Nevada region (Dettinger et al. 2018).

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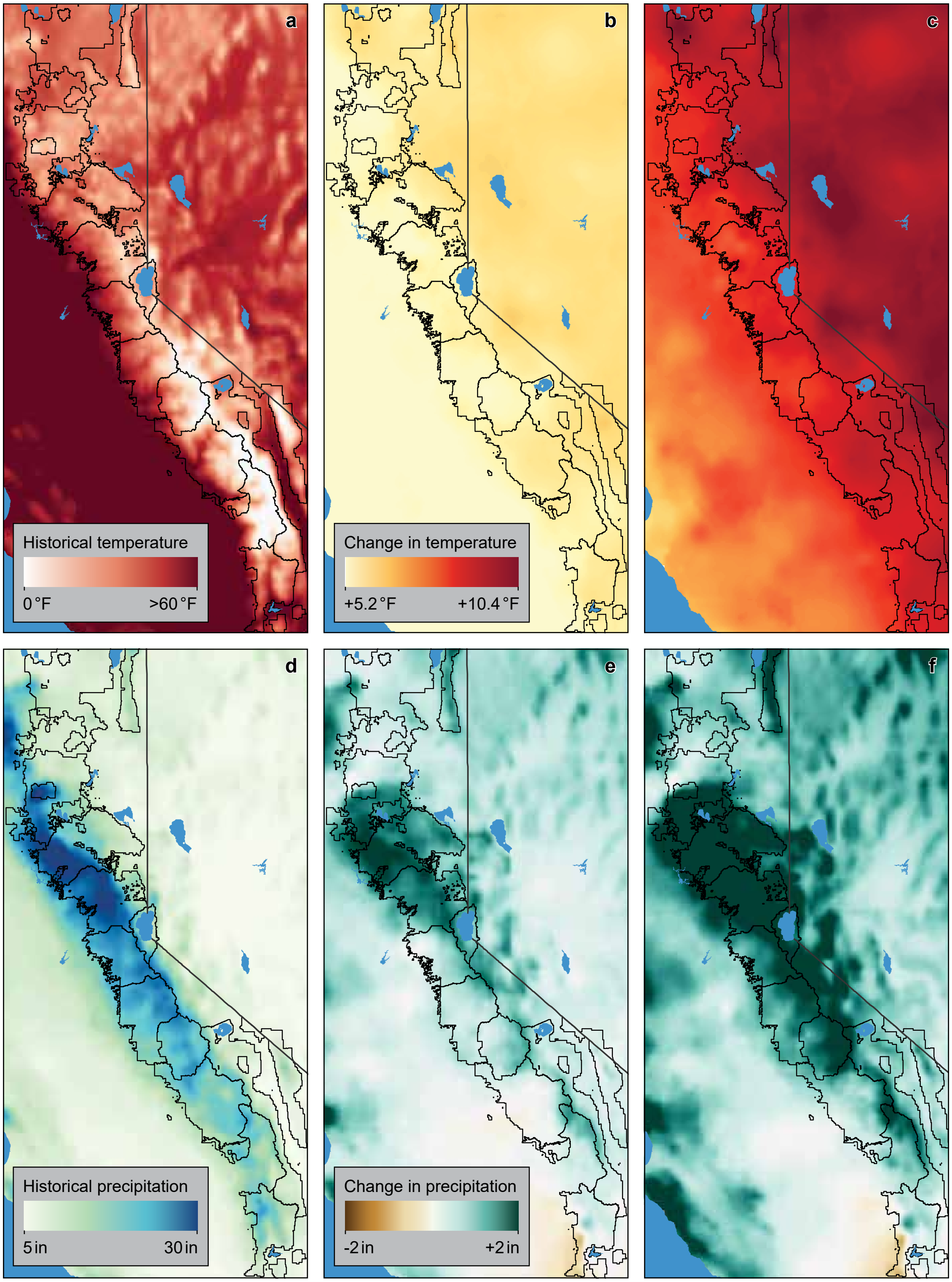

Figure 2.1—Historical (1961–1990) average annual temperature (a) and precipitation (d); and average changes in temperature (b and c) and precipitation (e and f) by 2070–2099, as projected by 10 global climate models under moderate greenhouse gas emissions (Representative Concentration Pathway [RCP] 4.5; b and e) and high greenhouse-gas emissions (RCP 8.5; c and f). Sierra Nevada National Forest boundaries are shown in black. (Data courtesy of M. Dettinger. Adapted from Dettinger et al. 2018. Figure by R. Norheim)

Observed and Projected Climate in the Sierra Nevada

The Sierra Nevada is already experiencing the effects of human-caused climate change. Temperatures have increased in recent decades (Safford et al. 2012, Vose et al. 2017). Between 1901 and 2016, average annual temperatures for the Southwest United States (including California) increased by 1.6 °F (Vose et al. 2017). Temperatures during the decade from 2001 to 2010 were the highest in the 110-year instrumental record for the same region (Hoerling et al. 2013).

Increased winter temperatures have resulted in more precipitation falling as rain rather than snow (Knowles et al. 2006) and reduced snowpack in many parts of the Sierra Nevada; most snow-course sites had declines in April 1 snow-water equivalent (a measure of snowpack) between 1955 and 2016 (Mote et al. 2018). Reduced snowpack and earlier snowmelt have led to earlier timing of streamflow in the Sierra Nevada (Stewart et al. 2005). Increased spring and summer temperatures have also been associated with increased wildfire area burned (Littell et al. 2009, Westerling 2016, Westerling et al. 2006) and incidence of large fires (Dennison et al. 2014). These effects are expected to continue and become more pronounced in coming decades (Dettinger et al. 2018)

A chapter on the Sierra Nevada in the fourth California climate assessment (Dettinger et al. 2018) provides climate projections for the region from the latest global climate model runs. These future climate projections (from a set of 10 global climate models) suggest that temperatures in the Sierra Nevada will, on average, increase by 6 to 10 °F by the end of the 21st century, depending on the concentration of greenhouse gases in the atmosphere (fig. 2.1).[2]

Temperature increases are projected to be lower under RCP 4.5, which assumes that emissions peak by mid-century and stabilize at low levels by about 2080. Projected temperature increases are higher under RCP 8.5, which assumes that emissions continue to rise throughout the 21st century. Under RCP 8.5, projected average annual temperature increases are 9 °F in the northern Sierra Nevada (including the Plumas, Tahoe, and Eldorado National Forests [NFs]), 9.2 °F in the southern Sierra Nevada (including the Stanislaus, Sierra, and Sequoia NFs), and 9.8 °F in the northeast (Modoc and Lassen NFs) and southeast (Inyo NF) portions of the range (figs. 2.1b-c). Under RCP 4.5, projected warming is 3 to 4 °F less (Dettinger et al. 2018). Extreme high temperatures are projected to increase even more than average temperatures (Hayhoe et al. 2018).

[2] The Representative Concentration Pathways (RCPs) used in Intergovernmental Panel on Climate Change reports represent scenarios about future concentrations of greenhouse gases in the atmosphere as a result of human activities.

Projections for precipitation are more uncertain than those for temperature. Future precipitation is expected to change less than temperature, by about -5 percent to +10 percent depending on location in the Sierra Nevada (fig. 2.1e-f). Precipitation may increase somewhat in winter and decrease slightly or stay about the same in other seasons (Dettinger et al. 2018, Hayhoe et al. 2018). However, these changes are likely to be small compared to the wide interannual variability in precipitation in the region (Dettinger et al. 2018).

Although the total amount of precipitation may not change considerably in the future, precipitation extremes are projected to increase. The amount of precipitation from the largest storms, including atmospheric rivers, is expected to increase by 5 to 30 percent compared to a historical period, depending on future greenhouse gas emissions (Dettinger et al. 2018). The number of dry days between storms is also expected to increase (Polade et al. 2017). Higher temperatures (and longer time periods between rain events) will likely increase drought stress in forests because hotter temperatures (and hotter droughts) increase water demand from vegetation far beyond what any small increase in precipitation might provide.

Climatic changes are likely to vary across the Sierra Nevada landscape. Increases in temperature are expected to be higher at higher elevations (+9 °F at 3,000 ft compared to +9.5 °F at 10,000 ft) (Dettinger et al. 2018). Precipitation may increase more in the northern portion of the Sierra Nevada (fig. 2.1f). Topographic influences such as cold air drainage will also result in spatial variability in temperature and precipitation changes (Morelli et al. 2011).

Climate Change Effects on Hydrology

The Sierra Nevada is a critical source of water resources to otherwise water-limited ecosystems and downstream communities. As a result of the Mediterranean climate, approximately 80 percent of total annual precipitation falls during the cool winter months, typically followed by a warm, dry summer (Belmecheri et al. 2015). Precipitation events are driven by orographic uplift, where moisture held in air masses delivered by the mid-latitude jetstream precipitates as air is forced into higher and colder elevations. Because of these orographic effects, higher elevations typically have the highest precipitation and snow accumulation rates. At mid to high elevations, precipitation regimes are largely snow dominated.

Across the Sierra Nevada, annual snowpack accumulation is highly variable and a function of topography, elevation, atmospheric circulation patterns, temperature, incoming precipitation, and vegetation. The snow accumulation season is also shorter than in other mountain ranges in the Western United States, with a majority of precipitation events occurring from December through March. A few large snow events often comprise the majority of the total annual snowpack (Huning and

Margulis 2017). Across the region, the total average amount of annual precipitation stored in mountain snowpacks is approximately two-thirds the volume of water capacity of California's human-made reservoir network (Dettinger et al. 2018). Historically, this water has been slowly released as snowmelt throughout the spring months and into summer.

Although precipitation patterns in the Sierra Nevada exhibit large interannual variability, and will be uncertain in the future, the effects of climate change are already having measurable impacts on hydrological processes and water resources. Low precipitation coupled with above-average temperatures have led to snowpack deficits and severe drought in recent years. Warmer temperatures reduce snow levels by both decreasing the fraction of precipitation falling as snow relative to rain and increasing melt rates, thus reducing snow residence time.

During the 2012–2017 drought, higher temperatures attributed to climate change exacerbated drought conditions and reduced snowpack levels by an additional 25 percent, with declines greater than 40 percent in the most vulnerable elevations (Berg and Hall 2017). The frequency and intensity of these recent droughts are expected to increase through the 21st century, likely resulting in snowpack reductions of 60 to 85 percent from historical levels, depending on future greenhouse gas emissions.

Although patterns and processes of snow accumulation and melt will likely be altered with climate change, much of the Sierra Nevada is characterized by steep environmental gradients and complex terrain. Owing to this heterogeneity, the effects of climate change on snowpack and hydrologic processes may be highly variable across the landscape. However, snowpack at elevations of 5,000 to 8,000 ft are the most vulnerable to warming temperatures, and these mid-elevations comprise over 60 percent of the current snow-dominated extent of the Sierra Nevada.

Climate-related shifts in patterns and timing of snow accumulation and melt will likely have cascading effects on streamflow from catchment to landscape scales. Coupled with declining snowpacks, shifts in streamflow timing have been detected across the Western United States, with rivers in the Sierra Nevada exhibiting some of the highest sensitivity to temperature increases. Over the past half-century in the Sierra Nevada, snowmelt-derived peak streamflows have occurred 10 to 30 days earlier in the spring (Stewart et al. 2005). As precipitation regimes transition from snow dominated to rain dominated, winter and spring streamflows may become flashier, as rain immediately runs off, and rain-on-snow events can trigger rapid snowmelt. Earlier peak streamflows are expected to continue into the 21st century, with advances occurring 80 days earlier than historical averages under a high emission scenario (Schwartz et al. 2017).

Shifts in winter and spring streamflows can also affect summer low flows. Compared to other river systems across the Western United States, streams in the Sierra Nevada show the strongest negative trends in fractional flows during summer months (Stewart et al. 2005). Future declines in summer flows may place increasing pressure on aquatic ecosystems and water resource infrastructure as water becomes increasingly limited during severe drought and periods of peak demand.

The distribution and productivity of forest ecosystems across the Sierra Nevada are largely shaped by water availability. Hydrologic shifts will likely affect vegetation through lower soil moisture and higher evaporative demand. Altered distribution and amount of soil moisture available to plants, along with increasingly dry atmospheric conditions, may lead to increased vulnerability of drought-sensitive plant species and ecosystems. In the Sierra Nevada, peak soil moisture is sensitive to the last day of snow presence, suggesting that future declines in precipitation falling as snow and rapid melt rates may lead to higher soil moisture deficit later in the summer (Harpold and Molotch 2015).

Higher temperatures will also likely lead to drier atmospheric conditions. For example, climatic water deficit (Lutz et al. 2010) and vapor pressure deficit (Ficklin and Novick 2017), both metrics describing the drying capacity of the atmosphere, are projected to increase with warming air temperatures. Increased frequency and extent of drought in the future would reduce soil moisture availability for plants, reducing tree vigor, and, in some cases, causing tree mortality.

Climate Change Effects on Fire and Vegetation

The climatic and topographic diversity of the Sierra Nevada and proximity to other bioregions contribute to its diverse vegetation assemblages (Minnich 2007). Approximately half of California's 7,000 plant species occur in the Sierra Nevada, and 400 occur only in the Sierra Nevada (USDA FS 2014). On the west slope of the Sierra Nevada, vegetation ranges from chaparral and foothill woodlands, to mixed-conifer forests at mid elevations, to subalpine forests at high elevations. Alpine vegetation types are found above treeline. Descending the east side of the range, there are narrow belts of subalpine and pine-dominated forests, with pinyon-juniper woodlands and desert scrub vegetation types at lower elevations (Minnich and Padgett 2003). The Modoc Plateau and the northeast part of the Sierra Nevada region have scattered conifer forests and large areas of singleleaf pinyon pine (*Pinus monophylla* Torr. & Frém.), western juniper (*Juniperus occidentalis* Hook.), and big sagebrush (*Artemisia tridentate* Nutt.). The White Mountains and Inyo Mountains (Inyo NF) are high-elevation desert landscapes with little vegetation cover, but with iconic tree species such as Great Basin bristlecone pine (*P. longaeva* D.K. Bailey) and foxtail pine (*P. balfouriana* Balf.).

Climate change is likely to alter the species composition and structure of vegetation in the Sierra Nevada. Altered disturbance regimes (e.g., drought, insects, wildfire) are likely to be the major catalysts of vegetation change (Safford et al. 2012). The 2012–2017 drought, insect damage, and associated forest mortality in the Sierra Nevada (Fettig et al. 2019) illustrate how extreme climatic events can affect ecosystems in the region.

Wildfire, which is directly affected by climate, is a dominant ecological process in the Sierra Nevada. Modern climate and fire records indicate that over the past century in the Western United States, warm and dry conditions in any given year (primarily in summer, but also in winter and spring) generally have led to larger fires and more area burned (Abatzoglou and Kolden 2013, Dennison et al. 2014, Kitzberger et al. 2017, Littell et al. 2009, McKenzie et al. 2004, Stavros et al. 2014, Westerling 2016, Westerling et al. 2006). Warmer spring and summer conditions led to increased evapotranspiration, lower summer soil and fuel moisture, and longer fire seasons (Westerling 2016, Westerling et al. 2006). Dry fuels and longer fire seasons are associated with higher area burned (Gedalof et al. 2005), although summer precipitation is an important modifier of fire activity (Holden et al. 2018).

A warming climate in future decades will have profound effects on fire frequency and extent in the Sierra Nevada. Simulations by Lenihan et al. (2003, 2008) indicated a 5 to 8 percent increase in annual area burned in California, depending on future climate. Projections by Westerling and Bryant (2008) suggested risk of large fires will increase by 12 to 53 percent by the end of the century across California, depending on climate scenario. For the Sierra Nevada, Liang et al. (2017) projected increases in fire area burned per decade of 393,000 to 457,000 ac. They also projected increases in fire size and decreases in fire rotation. Recent projections by Westerling (2018) indicate that annual average area burned in parts of the Sierra Nevada may double or quadruple by end of century (comparing 2070–2099 to 1961–1990) under RCP 8.5. Although these projections vary (because of differences in model types and assumptions), it is clear that increased fire area burned is likely in a warmer future in the Sierra Nevada. Fire severity may also increase, depending on how climate alters disturbance regimes and fuels (Safford et al. 2012).

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Increases in area burned and moisture deficits are likely to shift vegetation composition to more fire- and drought-tolerant species over decades to centuries. These changes are likely to occur more quickly in areas where disturbance frequency is higher at low to mid elevations. Using the LANDIS-II landscape model, Liang et al. (2017) projected increased recruitment of drought-tolerant species (e.g., oak [*Quercus* spp.], gray pine [*P. sabiniana* Douglas ex Douglas], ponderosa pine, pinyon pine, and Jeffrey pine [*P. jeffreyi* Balf.]) in Sierra Nevada forests in a warming climate, particularly at mid-elevations, because of increased wildfire and moisture limitations; less drought-tolerant species (e.g., white fir [*Abies concolor* (Gordon & Glend.) Lindl. ex Hildebr.], Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco], and Shasta red fir [*A. magnifica* A. Murray]) had much lower recruitment. However, if fire sizes increase substantially in the future, recruitment failures of drought-tolerant species may also occur

In lower elevation mixed-conifer forest, woodland species may increase in abundance. In general, broadleaf trees, such as oaks, may increase in abundance with loss of winter frost and increases in nighttime temperatures (Lenihan et al. 2003, 2008). Increased area burned and drought severity will likely favor shrubs in mid- and low-elevation forests (Airey Lavaux et al. 2016, Minor et al. 2017). Grasslands may also expand in area, particularly in a hotter and drier climate with frequent fire (Lenihan et al. 2003, 2008).

Increased area burned is likely to lead to increased area burned at high severity (Miller and Safford 2012), decreasing the fraction of old-growth forest patches and connectivity of these patches across the landscape (McKenzie et al. 2004). Increasing summer drought stress will decrease growth for many species in mid- to low-elevation forests (Restaino et al. 2016), and increase vulnerability to insects and disease, likely causing tree mortality in some locations (Allen et al. 2015, Fettig et al. 2019). Second-growth forests with high stem density and surface fuel loadings may be particularly vulnerable to drought, fire, and insect outbreaks in the future.

Decreased snowpack and a longer growing season (Kershner 2014; Lenihan et al. 2003, 2008) may reduce habitat for subalpine and alpine vegetation types in some locations in the Sierra Nevada, as conditions become more suitable for lower elevation conifer species. However, warmer temperatures, earlier snowmelt, and longer growing seasons may increase subalpine conifer growth (Graumlich and Brubaker 1986, Peterson and Peterson 2001), and conifer encroachment in meadows will likely increase (Millar et al. 2004). Drought and fire may become more common disturbances (Fites-Kaufman et al. 2007), although north aspects are likely to remain cooler, retain more snow, and provide refugia for high-elevation plant and animal species (Kershner 2014).

Climate Change Effects on Fish and Wildlife

Altered climate, disturbance regimes, and vegetation composition and structure will affect animal species in the Sierra Nevada. Increasing temperatures and changing precipitation will have direct physiological effects on some species. Other species may be affected indirectly through altered phenology (timing of life history) relative to forage plants and invertebrate prey; shifts in geographic ranges and density and ranges of competitor, forage, prey, and symbiotic species (and subsequent changes in biotic interactions); and effects from other stressors such as fire, insects, and disease. Related changes in habitat characteristics and quality will affect animal species viability. These effects will interact with existing stressors, leading to complex responses of wildlife populations to changing climate.

Distribution and abundance of birds, mammals, and amphibians are all expected to shift with changes in climate in the Sierra Nevada (Lawler et al. 2009a, 2009b; Stahlberg et al. 2009). Some species ranges may move to higher elevations as temperature increases (Forister et al. 2010, Moritz et al. 2008, Rowe et al. 2015). However, range shifts will depend on factors such as altered distribution and abundance of plant species, specific habitat conditions, predator-prey relationships, and species physiological tolerances (Inkley et al. 2004). The ability of animal species to disperse or migrate will depend on the availability of migration corridors and suitable habitats, and the concurrent movement of forage, prey, and cover.

Species sensitivity to climate change will vary. Increased variability and more extreme conditions with climate change will likely favor species adapted to frequent disturbance and some invasive species (Friggens et al. 2018). It may be more difficult for endemic and specialist species with narrow habitat requirements or dependencies on specific forage species to find suitable habitat under changing climate. For example, old-growth specialists such as the California spotted owl (*Strix occidentalis occidentalis* Xántus de Vésey) and Pacific fisher (*Pekania pennanti* Erxleben) are likely to be negatively affected by changes in fire regimes and reduced connectivity of late-successional forests (Scheller et al. 2011). In contrast, generalist species with high climatic tolerance, broad habitat and forage requirements, and high dispersal ability may increase in abundance (Pounds et al. 2005).

Aquatic species in the Sierra Nevada will be affected by warmer stream temperatures and changes in the quantity and timing of streamflow. Anadromous salmonid species in California are the southernmost native populations of their species, many of which are already considered threatened or endangered (Katz et al. 2013). Increases in summer water temperatures will likely result in stressful or lethal conditions for coldwater-adapted fish species in many streams in the Sierra Nevada, particularly in the northern and central portion of the range (owing to lower elevations) (Null et al. 2013). Thus, climate change will likely interact with other existing stressors (e.g., degraded habitat, hydropower, nonnative species) to increase risk of salmonid extinction (Katz et al. 2013, Null et al. 2013). Species restricted to limited areas, such as Kern golden trout (*Oncorhynchus mykiss whitei* Evermann), are particularly vulnerable (Katz et al. 2013, Moyle et al. 2011).

Amphibian species will also be affected by warming temperatures and altered hydrology. There are many endemic amphibian species in the Sierra Nevada, many of which have narrow ranges and are sensitive to disturbance and temperature increases (Kershner 2014). For example, mountain yellow-legged frogs (*Rana muscosa* Camp) occur in limited locations, and drying in summer would have detrimental effects (USDA FS 2014). Warmer temperatures are also likely to make frogs more vulnerable to some diseases (Pounds et al. 2006).

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Chapter 3: Climate Change Effects on Hydrologic Processes and Water Resources in the Sierra Nevada

Benjamin S. Soderquist and Charles H. Luce[1]

Introduction

The Sierra Nevada contains 24 major river basins that provide water to downstream ecosystems and human communities. Water resources and ecosystem services are derived from snowpacks accumulated at high elevations, replenishing soil moisture through snowmelt and generating streamflow during the spring and early summer. Streamflows produced from Sierra Nevada snowpack account for about 30 percent of California's total water supply, provide about 60 percent of water consumed by the state's population, and generate nearly half of the state's hydroelectric power (Bales et al. 2011a, Dettinger et al. 2018). Transportation infrastructure, hydroelectric networks, and recreational resources across the Sierra Nevada are tightly coupled with hydrological processes and fluctuations. As climate change leads to warming temperatures and shifting precipitation regimes, understanding the vulnerability of hydrologic functions of the Sierra Nevada will help to anticipate effects on water resources.

Streamflows produced from Sierra Nevada snowpack account for about 30 percent of California's total water supply, provide about 60 percent of water consumed by the state's population, and generate nearly half of the state's hydroelectric power.

Future shifts in hydrologic processes and water resources will span management boundaries. The majority of lands in the Sierra Nevada are federally owned and managed, with about 40 percent of the region (11.5 million ac) falling within 10 national forest units managed by the U.S. Department of Agriculture, Forest Service (USFS) (Britting et al. 2012) (chapter 1) (fig. 1.1). Given that the Sierra Nevada generates so much of the water used in the state, it is not surprising that USFS lands are a primary source of water for many cities, some quite distant from the Sierra. Thus management of these lands affects water supply, timing of when water will be available, and water quality. Given the complexity of climate change and the challenges of making decisions under increasing uncertainty, locally relevant climate information is needed to understand and manage future hydrological shifts that can affect natural resources and ecosystem services provided by national forests.

Scientists frequently describe hydrologic processes and the movement of water in terms of the water cycle and ecosystem water balance. These are concepts that describe the interconnected series of storage pools and transport fluxes that extend from the Earth's subsurface to the upper atmosphere. In this chapter, we use these

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concepts to provide a brief overview of the current hydrologic context for climate change in the Sierra Nevada. We also discuss how altered precipitation, water from snowmelt, subsurface moisture, streamflow, and evapotranspiration are interconnected.

Changes in Precipitation and Snow Water Resources

The Sierra Nevada experiences a Mediterranean climate with about 80 percent of precipitation falling during the winter months (Belmecheri et al. 2015, Dettinger et al. 2018) (chapter 2). Total incoming precipitation exhibits high interannual variability across the region, largely driven by atmospheric river events, in which currents of moisture-laden air are carried inland by jetstreams throughout the winter (Dettinger et al. 2011). Precipitation is orographically enhanced by the mountains as moisture held in air condenses when pushed upward into higher and colder elevations. Orographic effects result in the majority of precipitation falling on the west side of the Sierra Nevada, with precipitation rates sometimes exceeding those of low elevations by as much as 30 times (Dettinger et al. 2004b, Lundquist et al. 2010). On the wetter, west side of the Sierra Nevada, total incoming precipitation is strongly controlled by elevation; middle and higher elevations (greater than 6,500 ft) typically receive the highest annual precipitation (Dettinger et al. 2018). In addition to variation by elevation and terrain, total annual precipitation also varies by latitude, with the northern region of the Sierra Nevada typically receiving more precipitation than the southern region (chapter 2) (fig. 2.1).

Because precipitation regimes of this region are strongly winter dominated, precipitation predominantly falls as snow at higher elevations where temperatures are cooler. The southern Sierra Nevada, which is at a higher elevation than the northern Sierra Nevada, tends to be more snow dominated (Harrison and Bales 2016). Compared to other mountainous regions in the Western United States, the typical Sierra Nevada snow accumulation season is relatively short, and the majority of total annual snowfall is often delivered by a relatively small number of large precipitation events (Huning and Margulis 2017).

Shifts in precipitation type or phase (rain vs. snow) are one of the most direct effects of warming temperatures (Fritze et al. 2011). Over the past 50 years, snowpacks across the Western United States have been declining as a result of warmer winter conditions and shifts in precipitation regimes from snow to rain dominated (Fritze et al. 2011, Mote et al. 2018). Snowpack decline has also resulted from precipitation declines affecting higher and colder mountains in the Northwest (Luce et al. 2013). Unlike mountain ranges in the interior Western United States that typically experience colder climates, winter temperatures across much of the

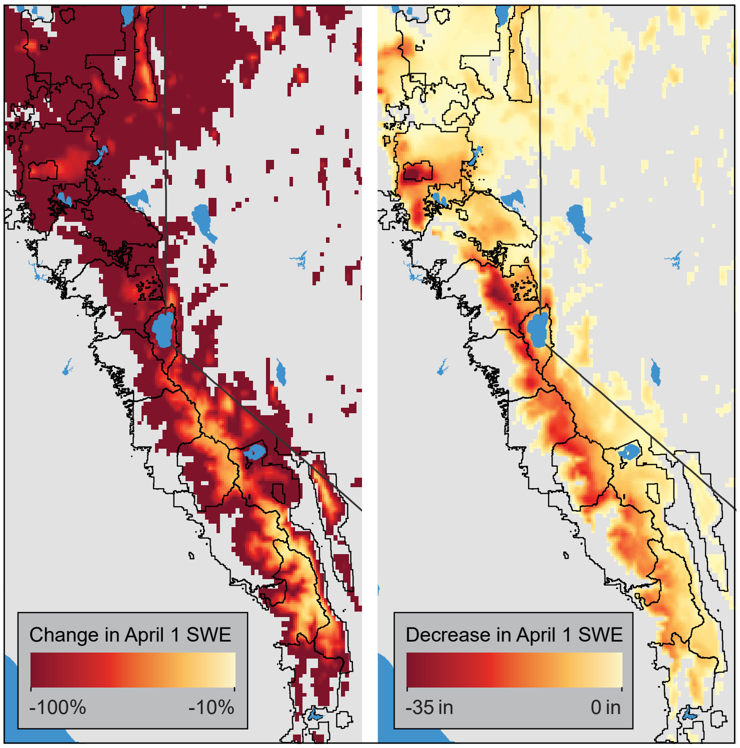

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Figure 3.1—Projected changes in April 1st snow-water equivalent (SWE) across the Sierra Nevada from historical conditions (1975–2005) to the 2080s (2071–2090) based on temperature increases projected from a 20 global climate model ensemble mean under Representative Concentration Pathway 8.5.

Sierra Nevada are relatively mild, and temperatures frequently hover near freezing levels at low and middle elevations. These conditions make a large extent of the Sierra Nevada vulnerable to shifts from snow-dominated to rain-dominated precipitation regimes and reduced snow accumulation (fig. 3.1).

With climate change, projected shifts in precipitation type are largest for mid elevations (6,000 to 9,500 ft), although high-elevation sites (greater than 9,500 ft) will remain above the rain-snow transition zone where precipitation remains largely snow dominated even under warmer conditions (Ficklin et al. 2012, 2013; Sun et al. 2019). Under continued high greenhouse gas emissions, the total snow-dominated area of the Sierra Nevada could be reduced by 19 percent, and the total rain-dominated area could increase 26 percent by the middle of the 21st century (Klos et al. 2014). Shifts in precipitation regimes from snow dominated to rain dominated will likely reduce snowpack storage (Rhoades et al. 2018), alter the timing and magnitude of streamflow (Schwartz et al. 2017), and reduce soil moisture availability in the summer (Ficklin et al. 2012, Klos et al. 2018).

Under continued high greenhouse gas emissions, the total snow-dominated area of the Sierra Nevada could be reduced by 19 percent, and the total rain-dominated area could increase 26 percent by the middle of the 21st century.

With warming temperatures and increasing proportions of winter precipitation falling as rain, historically snow-dominated middle elevations will likely experience the largest reductions in snow-water equivalent (SWE) relative to historical conditions (Dettinger et al. 2018, Lute and Luce 2017, Sun et al. 2019). Peak SWE, typically related to SWE on April 1 of a given year, is projected to decrease by

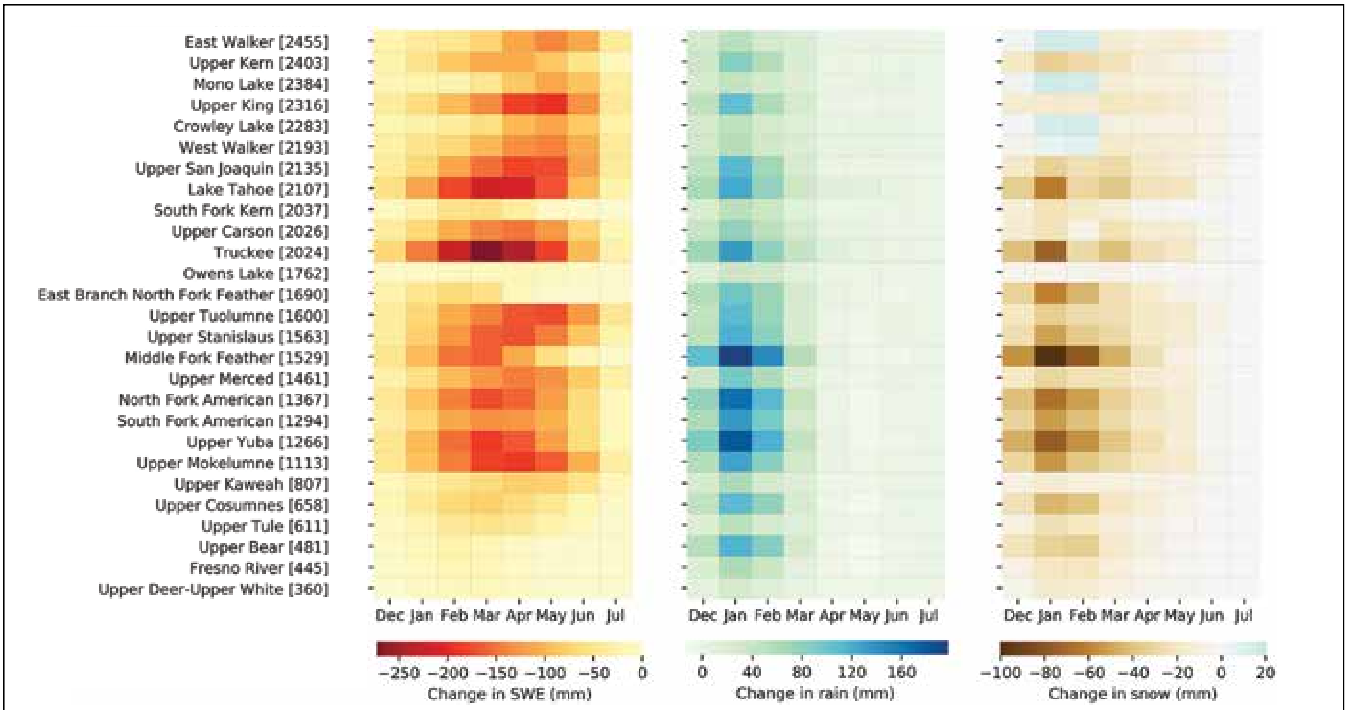

Figure 3.2—Monthly climatological changes (2091–2100 minus 1991–2000) of (left) snow-water equivalent (SWE), (middle) rain, and (right) snow according to the average of the five dynamically downscaled global climate models for Sierra Nevada watersheds. Unit in each panel is inches. Watersheds are ordered from highest to lowest elevation, with the watershed-averaged elevation noted in square brackets (unit: feet). (Figure from Sun et al. 2019)

over 75 percent across many elevations and by as much as 35 inches in portions of the central and northern Sierra Nevada by the end of the 21st century (fig. 3.1). Across these subregions, middle elevations (6,000 to 9,500 ft) currently retain a disproportionate amount of snow-water storage that will likely be reduced by decreased precipitation falling as snow and accelerated melt rates during the late winter and spring (Sun et al. 2019) (fig. 3.2). Overall, snowpacks in the Sierra Nevada are projected to decrease by about 60 percent by the end of the 21st century depending on future greenhouse gas emissions (Dettinger et al. 2018), with some estimates projecting declines as high as 80 percent where snowpacks are most temperature sensitive (Berg and Hall 2017, Ficklin et al. 2013, Rhoades et al. 2018).

Reductions in SWE are also coupled with snow-season length and snow residence time (SRT, how long snow lasts once it has fallen), both measures of the number of days when snow is present on the ground. With warming temperatures, reduced precipitation falling as snow, and accelerated melt rates, snow season is projected to be 39 days less (Rhoades et al. 2018) and SRT 75 days less across much of the Sierra Nevada by the end of the 21st century (fig. 3.3). Future reductions in SRT can be accelerated by feedbacks that further increase snow melt rates (i.e., the snow albedo feedback loop) (Walton et al. 2017). Reduced SRT can have significant

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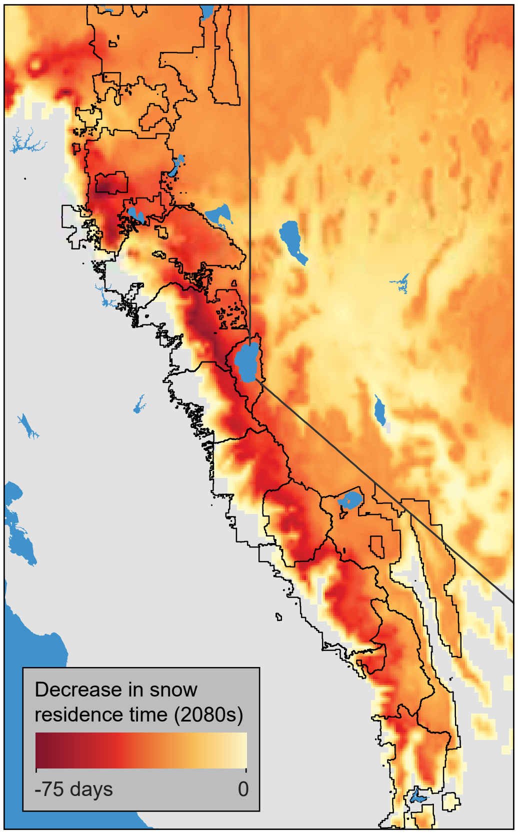

Figure 3.3—Projected changes in snow residence time across the Sierra Nevada from historical conditions (1975–2005) to the 2080s (2071–2090) based on temperature increases predicted from a 20 global climate model ensemble mean under Representative Concentration Pathway 8.5.

ecological effects by shifting the timing of vegetation growth and soil moisture uptake earlier in the spring.

The capacity of Sierra Nevada snowpack to store large amounts of water is important to the function of hydroelectric operations, flood control programs, transportation infrastructure networks, and recreational opportunities (chapter 5). Warming temperatures and highly variable annual precipitation increase the vulnerability of water-limited communities and ecosystems to climate change effects on water resources. The direct impacts of warming temperatures on precipitation type and patterns of snow accumulation will likely affect other hydrologic processes and water resources throughout the year.

Changes in Soil Moisture Inputs and Subsurface Water Storage

Soil moisture and deeper subsurface water storage are critical sources of water to forests and streams in the Sierra Nevada during the extended periods of summer drought that typically occur months after winter snowpacks have disappeared (Bales et al. 2011b, 2018; Holbrook et al. 2014; Klos et al. 2018). Warming temperatures and increasing proportions of winter precipitation falling as rain shift the timing of soil moisture inputs and initiation of drying earlier, affecting dry-season groundwater recharge, soil moisture, and outflow to rivers and streams. (Dettinger et al. 2004a, Ficklin et al. 2013, Luce et al. 2016). In water-limited ecosystems, multiyear subsurface storage could help maintain resilient forests in the proximity of groundwater discharge zones as snow-water storage is reduced and summer drought severity increases (Bales et al. 2018).

Many parts of the Sierra Nevada are particularly vulnerable to larger summer soil moisture deficits driven by earlier snowmelt (Harpold et al. 2015). The combined effects of decreasing snow-water storage, shorter snow residence time, and increased soil drying and plant water use during the spring are projected to reduce summer soil moisture over the course of the 21st century. These shifts will increase the importance of deeper subsurface moisture that can supplement vegetation demand and streamflow later into the dry season. Although critical to hydrologic functions across the landscape, subsurface storage capacities are heterogeneous and difficult to measure directly (Klos et al. 2018).

The effects of changing soil and subsurface moisture availability may also affect recreation and tourism resources. For example, giant sequoia (*Sequoiadendron giganteum* (Lindl.) J. Buchholz) groves in the southern Sierra Nevada provide numerous ecological, aesthetic, and tourism-based benefits. Drought stress experienced by these trees is influenced by topography, snow cover, and subsurface moisture (Stephenson et al. 2018). Future snowpack declines, hotter droughts, and larger summer soil moisture deficits may lead to more severe drought stress and increased sequoia mortality in lower elevation stands (Ray 2016).

Shifts in Streamflow

Streamflow processes in the Sierra Nevada play a critical role in the timing and delivery of water resources to downstream ecosystems and human communities and have been extensively studied in recent decades. In addition to total incoming precipitation, the amount and timing of streamflow are further determined by temperature and precipitation across a watershed, soil and geologic characteristics, and local vegetation that takes up subsurface moisture during the growing season. Because streamflow is coupled with numerous climatic and environmental factors, the effects of climate change on streamflow are less direct than effects on precipitation type and snowpack. However, the effects of increasing temperatures and decreasing snowpacks will likely affect seasonal streamflow in many regions of the Sierra Nevada.

Annual precipitation exhibits high interannual variability in the Sierra Nevada, and spring snowmelt has historically provided a relatively consistent and controlled release of stored precipitation to streams and rivers. Large advances in the timing of snowmelt-derived streamflow are projected to follow earlier snowmelt, with spring flows occurring 30 to 80 days earlier in streams across the Sierra Nevada by the end of the 21st century, depending on greenhouse gas emissions and watershed characteristics (Schwartz et al. 2017, Stewart et al. 2004). This means that storage in the snowpack buffering water supply timing downstream will be reduced, and water managers will be more challenged to supply water through the full growing season.

Shifts from snow-dominated to rain-dominated precipitation regimes can lead to more frequent high streamflow events in the winter and earlier peak flows in the spring (Regonda et al. 2005, Wenger et al. 2010). Future high streamflow events may be further exacerbated by increasingly intense winter rainfall events (Musselman et al. 2018, Pierce et al. 2013, Polade et al. 2017). Over the 21st century, the magnitude and intensity of floods are projected to increase relative to historical conditions, with flood frequencies also increasing under a majority of emission scenarios and remaining stable or slightly decreasing under scenarios that project significant drying trends (Das et al. 2011). Future shifts in flood frequency will likely be driven by the increasing size and frequency of extreme storms, as well as increases in the fraction of total precipitation falling as rain instead of snow (Das et al. 2011). By the end of the century, discharges from 50-year floods may increase 30 to 90 percent in the northern Sierra Nevada and 50 to 100 percent in the southern Sierra Nevada, depending on future temperature increases (Das et al. 2013).

Altered precipitation reduces the skill of statistical runoff forecasting tools used to manage water for flood control and allocation to downstream users, limiting the capacity of water managers to respond to extreme events such as flooding and low flows (Harrison and Bales 2016, Stewart et al. 2015). Under these conditions, water will be managed increasingly as a risk as opposed to a resource to be stored for future use. Higher precipitation intensity and more winter precipitation falling as rain can increase soil saturation, leading to an increased risk of landslides and debris flows (Ren et al. 2014). Increasing frequency of these natural hazards would have serious implications for water quality, human safety, and transportation infrastructure. Risks from extreme wet periods would be exacerbated by increasing occurrence of fire events (Goode et al. 2013).

In this assessment, the Variable Infiltration Capacity (VIC) model was used to simulate streamflow processes for streams across the entire Sierra Nevada. VIC is a physically based and spatially distributed hydrologic model that simulates hydrological processes including snow accumulation and melt, streamflow, and evaporation while accounting for differences in vegetation and elevation (Liang et al. 1994). The climate change projections and modeling approach to simulate stream hydrology follow the methods of Wenger et al. (2010) in which VIC simulations were run for streams at 1/16th degree resolution under historical conditions (1975–2005) and projected into the mid (2040s) and late 21st century (2080s) under the A1B emission scenario.

Our discussion of climate change effects on streamflow focuses on three widely used metrics: (1) change in the number of days when winter flows exceed the 95th percentile (W95, days), (2) change in timing of center of mass flow (CT, days) (Stewart et al. 2005), and (3) change in mean daily summer flows (in both $ft^3 s^{-1}$ and percent), where summer flows for a given year are defined as the period starting from the first day after June 1 when flows fall below mean annual flow rates through September 30. Although these metrics provide only partial quantification of all changes to streamflow, they are ecologically and socially relevant, often tightly coupled with changes in precipitation and snowpack, and provide additional context for the effects of climate change on seasonal water availability.

The frequency of large winter streamflow events will likely increase across much of the Sierra Nevada as winter precipitation becomes increasingly rain dominated (Das et al. 2011, Fritze et al. 2011). Frequent rain-on-snow events at higher elevations where snowpacks were historically stable may lead to rapid snowmelt, which can increase event volumes by as much as 200 percent in the central and southern Sierra Nevada (Musselman et al. 2018). A projected increase in W95 for a stream indicates an increase in the frequency and magnitude of winter flood events under warmer and more rain-dominated precipitation regimes. By the end of the 21st century, VIC-simulated W95 is exceeded as many as 15 days more frequently than historical conditions throughout middle and high elevations in the central Sierra Nevada, with slightly smaller increases projected for streams in the southern Sierra Nevada (fig. 3.4).

Increased W95 frequency occurs in regions where elevations are vulnerable to precipitation switching from snow to rain, and streamflows are less buffered by high groundwater storage capacities. For example, streams in the northern Sierra Nevada experience less variability in winter flows and W95 relative to the central and southern Sierra Nevada, largely because of increased groundwater storage capacities in the north that buffer flashier winter water inputs. This is mainly due to geologic characteristics that result in high infiltration, large groundwater storage capacities, and long water-residence times.

Accurately projecting shifts in streamflow timing is important for water managers. The extensive network of dams and water-delivery infrastructure in the Sierra Nevada stores and allocates water resources to downstream users through managed reservoir discharges throughout the year. Shifts in the timing of peak streamflows can make it difficult to manage reservoir levels for the timing of controlled releases

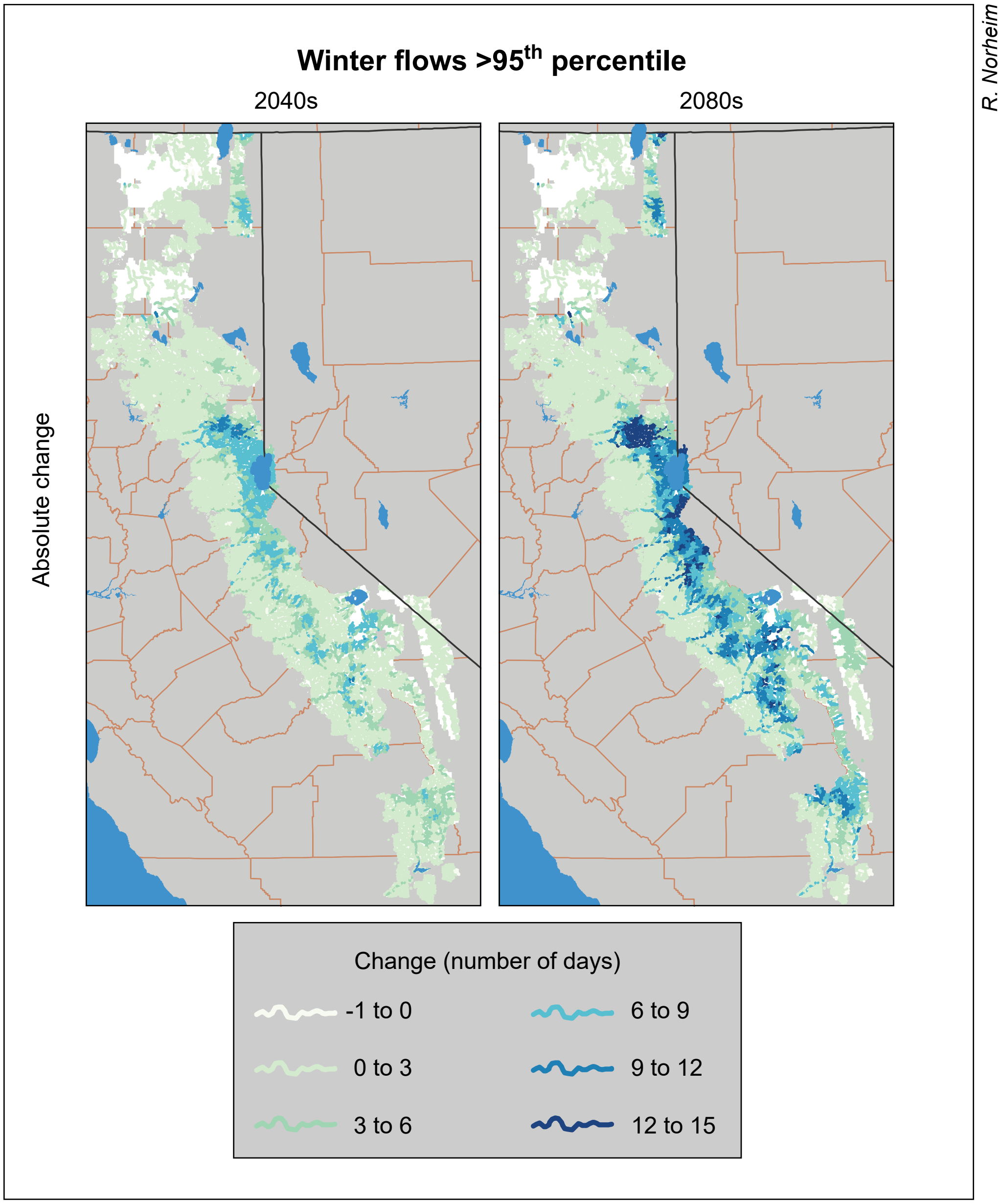

Figure 3.4—Absolute change in the number of days from historical conditions (1975–2005) to the 2080s (2071–2090) when winter flows exceed the historical 95th percentile. An increase in the number of days indicates a higher likelihood of larger and more frequent winter streamflow events and potential flooding. Climate change projections assume temperature increases following the A1B emission scenario.

to create extra storage in reservoirs in advance of large streamflow events, as well as maintain stored water reserves to support power generation and irrigation later in the summer.

Streamflow timing is often described in terms of the timing of CT flow, or the date on which half the total annual streamflow is exceeded (Regonda et al. 2005, Stewart et al. 2005). Because water inputs (snowmelt) are occurring earlier, runoff is occurring earlier. VIC simulations project a shift toward earlier CT across most of the central and southern Sierra Nevada. Advances in CT are largest in the central Sierra Nevada, with spring peak flows occurring nearly 2 months earlier in many streams by the late 21st century (fig. 3.5). Less change in CT occurs farther north because there is less snowpack being affected, and less occurs farther south because high-elevation snowpacks are insensitive to temperature until substantial warming occurs (Lute and Luce 2017). Similar to projections of W95, future shifts in CT are

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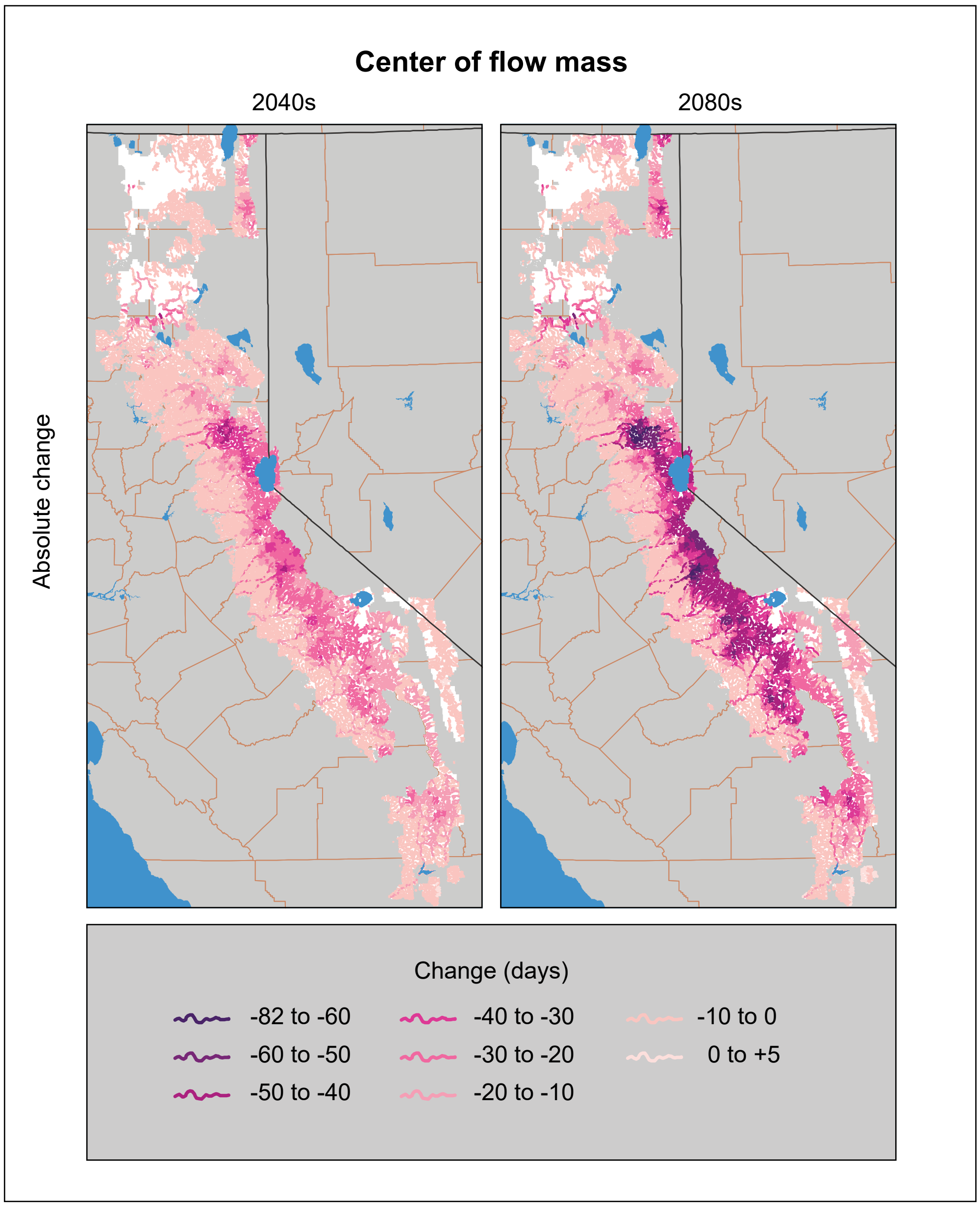

Figure 3.5—Absolute change in the timing of the center flow of mass from historical conditions (1975–2005) to the 2080s (2071–2090). Climate change projections assume temperature increases following the A1B emission scenario.

smaller in the northern Sierra Nevada where streamflow timing remains more consistent as a result of higher groundwater inputs and storage.

Following spring snowmelt and runoff, Sierra Nevada summers are characterized by low precipitation and long periods with warm, dry atmospheric conditions. Summer streamflows are important to the function of aquatic and riparian ecosystems, occurring during periods of greatest demand for energy generation, irrigation, and other forms of downstream water use. Although streamflows are typically at their lowest point during summer and early fall, they can be sensitive to changes in snowpack that occur during the preceding winter and spring. For example, in several Sierra Nevada watersheds, a 10 percent reduction in SWE has historically led to reduced minimum flows of 9 to 22 percent and earlier low flows (Godsey et al. 2013).

VIC simulations indicate that many small streams in the Sierra Nevada are not projected to experience large absolute changes in mean daily summer flows. However, percentage of flow is expected to decrease by as much as 90 percent in the central and southern Sierra Nevada by the end of the 21st century (fig. 3.6). The high percentage of changes occur because flows during this period are generally low, so even a small change in absolute terms can be large in relative terms. In the northern Sierra Nevada, where groundwater inputs buffer streamflows, projected fractional declines in mean daily summer flows are typically smaller. However, recent and continued declines in the frequency of summer precipitation events could potentially prolong the duration and intensity of summer low flows for many streams (Ficklin et al. 2012, Holden et al. 2018).

Streamflow timing, peak flows, and summer flows are influenced by regional climate, snowpack characteristics, local geology and geomorphology, and evaporative demand during spring and summer (Ficklin et al. 2013). Increasing temperatures and changing streamflows will widen the gap between timing of water availability and timing of greatest water demand for ecological, agricultural, hydroelectric, and municipal uses. Shifts in seasonal streamflows can also affect water quality by increasing stream temperatures, decreasing dissolved oxygen concentrations, and increasing sediment loads and transport rates (Ficklin et al. 2013). At local scales, forest and water managers will experience increasing uncertainty in a warmer and more variable climate, with competing demands for water supplies.

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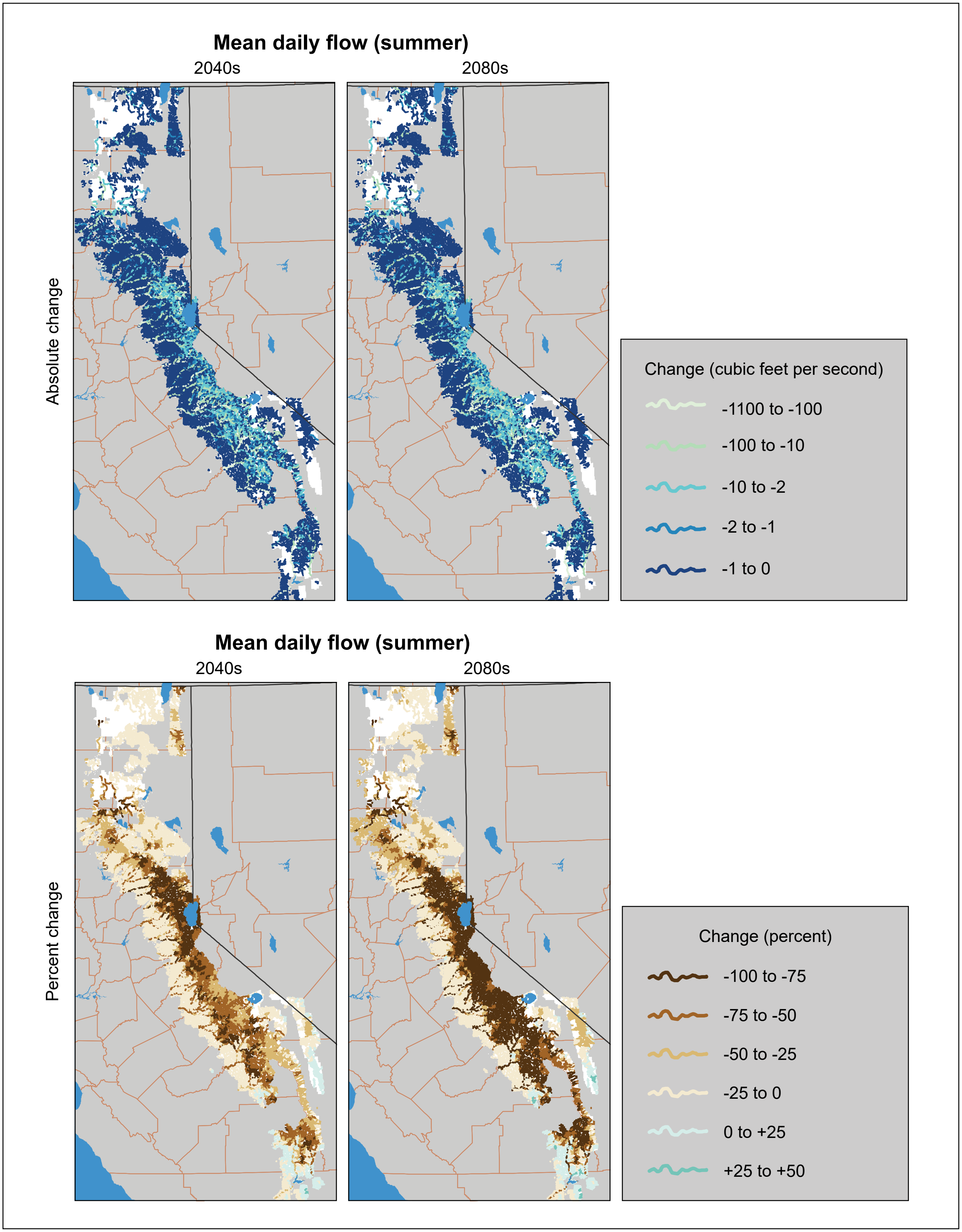

Figure 3.6—Change in the timing and magnitude of mean daily summer flows from historical conditions (1975–2005) to the 2080s (2071–2090). Climate change projections assume temperature increases following the A1B emission scenario.

Changes in Evaporative Demand and Evapotranspiration

The transport of surface and subsurface water back into the atmosphere is a key component of the hydrologic cycle and overall water balance. The transport of water to the atmosphere, or evapotranspiration (ET), is the combined amount of water that is both evaporated from water and soil surfaces and transpired by vegetation. In mountainous regions like the Sierra Nevada, fluxes of water to the atmosphere are largely mediated by climate, with temperature, water availability, and energy availability being the dominant controls on the timing and amount of seasonal ET.

The evaporative demand driving ET is generally characterized by how dry the atmosphere is compared to saturated conditions and is one component of the capacity of the atmosphere to evaporate water. Under warming temperatures, evaporative demand is expected to increase, and given adequate moisture and radiant energy supply, would be expected to increase evaporation. Vapor pressure deficit (VPD), the difference in moisture held in the air under actual conditions compared to saturated conditions, is projected to increase across the Western United States during the 21st century (Ficklin and Novick 2017). Increased VPD indicates increasingly dry atmospheric conditions which can lead to increased ET in areas where there is a sufficient supply soil moisture and continued transpiration by vegetation. Evapotranspiration is also limited to the increase in net radiation (Luce et al. 2016, Milly and Dunne 2017, Roderick et al. 2014).

In the Sierra Nevada, steep elevation and climatic gradients result in both water and energy limitations on ET. At lower elevations, where water availability is often the dominant factor limiting ET, increasing VPD (as a function of warming temperature) may slightly increase soil moisture use, and warming temperature may increase the drought stress experienced by water-limited and middle-elevation forests (Adams et al. 2009, Lutz et al. 2010, Trujillo et al. 2012, van Mantgem and Stephenson 2007). At higher elevations, lower VPD and shorter growing seasons have historically resulted in lower seasonal ET compared to warmer mid-elevations where adequate soil moisture and higher VPD are conducive to higher ET across longer growing seasons. With climate change, the total area where ET has historically been limited by cold temperatures is expected to increase in elevation as temperatures warm. These shifts may subsequently reduce subsurface moisture and streamflow inputs (Goulden and Bales 2014, Trujillo et al. 2012).

Chapter Summary

The Sierra Nevada is already experiencing effects of climate change, and as temperatures rise, shifts in hydrologic processes and water resources will be complex and interconnected across all aspects of the regional water cycle. Subsequent changes in ecosystem services and the availability of water resources will likely have major downstream effects on ecosystems, communities, and economies. The severity of climate change effects will vary both spatially and temporally and be further influenced by interactions with socioeconomic factors such as water rights, population growth, and future decisions regarding water policy.

Large-scale efforts to assess climate change vulnerabilities and adapt current land management practices, infrastructure networks, and human uses of water and forest resources are needed to better prepare for future climate change effects (chapter 6). Much of this responsibility begins with public land managers because a large proportion of Sierra Nevada water resources originates from forested lands managed by the USFS and other agencies. The effects of altered climatic and hydrologic regimes will span management boundaries. Collaborating with adjoining landowners and local communities will be a critical part of adapting to climate change and its effects on water resources. However, limited time and resources can constrain the ability of managers to rapidly respond to uncertain conditions. Integrating management priorities across resource areas (e.g., recreation and infrastructure) will be important for improving the capacity of managers to coordinate management strategies and increase the extent of adaptation actions.

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Chapter 4: Climate Change and Infrastructure in the Sierra Nevada

Gordon R. Keller, Leslie J. Boak, and Michael J. Furniss[1]

Introduction

The Sierra Nevada is a biologically diverse and socially important region of California, providing water, timber, rangeland, recreation, and many other ecosystem services. A significant amount of infrastructure (roads, bridges, structures, etc.) is needed to support these services. In recent years, a period of major drought has led to tree mortality and wildfires. Rainstorms following wildfires have caused debris slides, washouts, and erosion. Billions of dollars of damage to roads, trails, culverts, bridges, dams, campgrounds, buildings, and other infrastructure have been caused by wildfires, extreme rain events, floods, and debris slides.

To address these issues, the U.S. Department of Agriculture Forest Service (USFS) conducted a vulnerability assessment on the effects of climatic variability and change on infrastructure in the 10 national forest units of the Sierra Nevada. The assessment was led by the USFS Pacific Southwest Region in partnership with the USFS Office of Sustainability and Climate, Pacific Southwest Research Station, Pacific Northwest Research Station, and the University of Washington. This assessment is intended to be a resource for the agency and its partners to inform ongoing and future planning and projects. Resources at risk were identified by documenting sensitivities to climate-related factors from the scientific literature and expert knowledge (risk assessment), then options for responding to sensitivities were identified from existing best management practices (BMPs) and information elicited from resource managers (risk management).

The vulnerability assessment has a significant geospatial component, complementing existing products such as the Sierra Nevada Science Synthesis (Long et al. 2014), building on previous vulnerability assessments and adaptation options that focus on resources that do not include the built environment. The assessment will help resource managers and engineers to recognize vulnerabilities to climate change, assess the risk to local infrastructure, and consider adaptation options that would reduce risks. Here we summarize climate

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change vulnerabilities, adaptation options, and specific on-the-ground actions for infrastructure in national forests, including roads, trails, facilities, campgrounds, and dams (box 4.1).

To develop the assessment, we consulted with regional and national forest engineering staff and key partners in the Sierra Nevada to understand resources within their programs that will be affected by climate change. This consultation included information on resource effects that have been observed, additional effects that are anticipated, and ideas for adapting to and minimizing adverse impacts to infrastructure. We reviewed and synthesized the relevant scientific literature, including similar assessment efforts by various agencies (Halofsky et al. 2018). As a result, this assessment is science based, credible, and practical for resource managers and engineers tasked with ensuring the sustainability of infrastructure subjected to stresses exacerbated by climate change (Peterson et al. 2011).

Box 4.1

Factors Related to Vulnerability of Infrastructure to Climate Change (from Furniss et al. 2018)

Transportation system (general)

- Aging and deteriorating infrastructure increases sensitivity to climate impacts, and existing infrastructure is not necessarily designed for future conditions (e.g., culverts are not designed for larger peak flows).
- Roads and trails built on steep topography are more sensitive to landslides and washouts.
- A substantial portion of the transportation system is at high elevation, which increases exposure to weather extremes and increases the costs of repairs and maintenance.
- Roads built across or adjacent to waterways are sensitive to high streamflows, stream migration, and sediment movement.
- Funding constraints and insufficient funds limit the ability of agencies to repair damaged infrastructure or take preemptive actions to create a more robust system.
- Design standards or operational objectives that are unsustainable in a new climate regime may increase the frequency of infrastructure failure in the future.

Roads and trails

- Near streams and rivers
- Cross streams and rivers
- Built on steep, unstable slopes
- Built in steep, wet areas
- Have crossings located in depositional areas
- Have diversion potential (drainage failure will result in stream capture)
- Have the potential for "cascading failure" (a failure will likely cause failures downhill)
- Have unstable fills and sidecast
- Subject to diverted drainage from other roads and facilities

- Built in geologic materials that are unstable, have abundant interflow (shallow drainage), or are difficult to compact
- Have infrequent cross drainage
- Are beyond their design life
- Have designs that are maintenance dependent
- Have little or no regular maintenance
- Have high use without commensurate maintenance
- Are wide and intercept abundant hillslope drainage

Campgrounds and developed recreational facilities

- Near streams and rivers
- Have facilities that attract public use to areas subject to flooding, landsliding, or both
- Accessed by roads or trails that are vulnerable
- In locations where changes in snow affect use
- Have little or no shade to provide respite from extremes of hot weather
- Have high fuel loading and wildfire vulnerability

Buildings

- Accessed by roads or trails that are vulnerable
- Near streams or rivers and subject to flooding
- In areas subject to landslide hazards
- High risk of damage or destruction by wildfire
- Poorly insulated
- Inadequate ventilation
- Substandard plumbing, not protected from the weather
- In locations that are subject to loss or changes due to climatic extremes

Dams

- Inadequate safety provisions
- Inadequate safety inspection frequency
- Inadequate spillways for extreme storms
- Inadequate structural integrity against aging and extreme events
- Subject to cracking or failure caused by earthquakes, extreme flooding, or landslides
- Subject to new hydrologic regimes in areas where snowfall and snowpack are declining.

Ecosystems associated with streams that are subject to impacts from infrastructure

- Have rare species sensitive to changes in sediment or flow
- Have species or communities that are sensitive to sediment
- Infrastructure is located in or near key habitat locations (e.g., fish spawning areas)
- Infrastructure provides or encourages public access to sensitive sites
- Improper maintenance activities (e.g., sidecasting) periodically disturb habitats
- Multiple crossings or road or trail segments in near-stream locations remove shade and may reduce large-wood recruitment
- Riparian habitats along streams that are fragmented by road-stream crossings or other barriers that restrict migration and movement (connectivity) of aquatic organisms. Other factors are stressing communities and habitats

Assessing the vulnerability of infrastructure generally requires several steps: (1) form an interdisciplinary team, (2) identify the relevant assets and infrastructure at risk, (3) evaluate the risk of damage to the infrastructure from climate-related factors and other causes, (4) consider site condition and history, (5) estimate asset sensitivity to climate, (6) identify and rate vulnerability problem spots, and (7) prioritize actions that can minimize the risk. Funding needs can be prioritized to implement adaptation measures suitable for infrastructure resistance and resilience. High-risk sites will generally have high priority. Timely evaluation of risk will help determine where limited funds can be allocated to minimize wildfire and storm impacts.

Many effects of climate variability, climate exposure, and disturbances can damage roads and other infrastructure (chapter 3) (fig. 4.1). Climate-related effects on hydrology will likely be significant in the Sierra Nevada. Small changes in total precipitation are projected for this region but with a general increase. However, storms will be warmer, with more precipitation as rain and less as snow, and snow will melt earlier. Storm patterns are projected to be more erratic, runoff peaks are

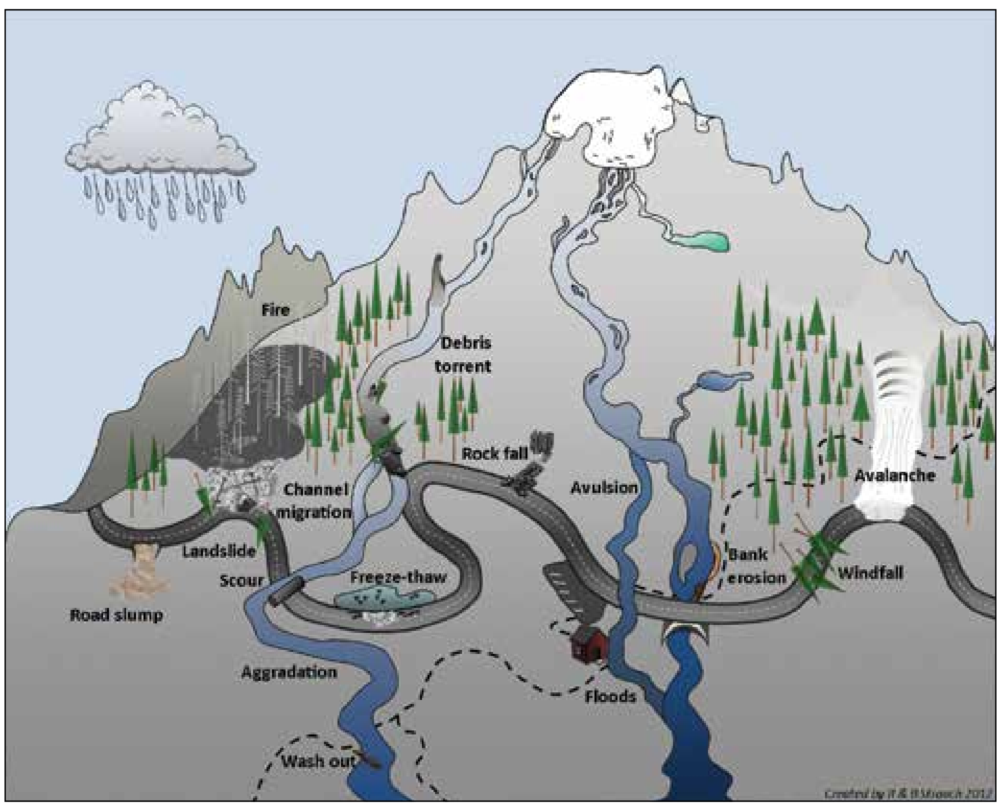

Figure 4.1—Many pathways exist for the effects of climate stressors, climate change, and other disturbances on roads and other infrastructure. Multiple pathways are common. (Figure from Strauch et al. 2014)

expected to occur earlier in the year, and rainfall intensities are expected to be higher. Any of these can modify recreation patterns and timing of construction contracts, increase road use in some areas, increase road damage, promote freeze-thaw problems, and accelerate erosion and gullying. Increased peak flows will increase scour problems and risk for culverts and bridges. Snowpack followed by earlier, warmer rains will likely lead to increased rain-on-snow events, snow avalanches, and stream and river avulsion (formation of a new channel). Sequences of drought and storms, as well as warmer temperatures, will promote more wildfires, followed by increased erosion, landslides, and debris flow events.

For transportation and other infrastructure systems, extreme events of relatively short duration, as opposed to annual or seasonal averages, often cause the most significant damage or are the most disruptive to operations. Heat waves, drought, and flooding affect infrastructure over short time scales (days to months), whereas climate-related changes in the freeze-thaw cycle, construction season length, and snowmelt hydrology affect infrastructure over longer time periods (years to decades) (Furniss et al. 2018).

Geospatial assessment can help evaluate risks to infrastructure and generate maps featuring specified aspects of an area:

- Stream corridors, road-stream crossings, and locations where roads are near streams
- Road systems with alternative routes to provide redundancy to key locations
- Projected increase in stream bankfull width
- Expected decrease in snowpack depth or duration
- Fire intensity in conjunction with steep slopes and soil types susceptible to debris movement

Maps can be generated using existing mapped information or geographic information system (GIS) databases. Different forests have different datasets, depending on which data are available and which data have been entered for forest infrastructure. Where data are not commonly available, useful information may still be available, such as maps of known critical maintenance areas or landslides, stream channels, sites with a history of storm damage, or material sources needed for storm damage repairs. This information can help identify high-risk locations, future problem areas, and resources needed to facilitate repairs after significant impacts occur.

Mitigation measures to minimize climate change can be addressed at the global, national, regional, and local scales. The publication "Climate-Resilient Infrastructure: Adaptive Design and Risk Management" (Committee on Adaptation to a Changing Climate 2018) provides a comprehensive overview of adaptation and risk, and climate issues involving infrastructure. Local and federal governments and agencies such as the USFS are implementing programs to reduce carbon emissions (Reidmiller et al. 2018). Specific actions for reducing emissions include carpooling, using efficient and alternative-energy vehicles, building bike paths, and using efficient LED lighting. Sustainable forest management is important for sequestering carbon and includes good logging practices (e.g., reduced-impact logging), minimizing conversion of forests to other uses, promoting rapid reforestation in timber harvest areas and burned areas, and supporting fuel reduction programs to reduce wildfire intensity. In addition, agencies can use public education to increase awareness of climate change impacts and the need for action.

Climate **adaptation** provides a means by which the negative effects of climate change can be minimized and vulnerability reduced through the implementation of certain practices or tools. This may include policy and planning decisions, as well as design, construction, and maintenance activities to increase infrastructure resilience (Partington et al. 2017). **Mitigation** consists of actions to limit the magnitude of long-term climate change via measures to reduce greenhouse gas emissions (IPCC 2014). In the context of this document, the term "adaptation" will be used most often for measures that engineers can use to improve road resilience and reduce risk of infrastructure damage. However, the term "mitigation" occasionally will be used in a similar context.

Assessment Area

This assessment encompasses infrastructure and facilities found on the 10 national forest units in the Sierra Nevada, as well as a portion of the Cascade Range on the Modoc Plateau, all within the state of California (chapter 1) (fig. 1.1). This includes the Modoc, Lassen, Plumas, Tahoe, Eldorado, Stanislaus, Sierra, Sequoia, and Inyo National Forests (NFs), as well as the Lake Tahoe Basin Management Unit (LTBMU). These units represent 10 of the 18 national forests in the USFS Pacific Southwest Region. These forests represent much of the mountainous eastern boundary of California and are hereafter referred to as the "Sierra Nevada."

Modoc and Lassen NFs are mostly in volcanic terrain on the relatively flat Modoc Plateau at the southern end of the Cascade Range where there are relatively few surface water features owing to the porous nature of the volcanic soil, rock, and cinders (Macdonald 1966). The Plumas and portions of the Lassen and Tahoe NFs are in a transition area between the Sierra Nevada and the Cascade Range with a diverse geologic mix of granitic, metamorphic, and volcanic rock. They have fault-controlled valleys typical of the "basin and range" geomorphic province, characterized by elongated mountains separated by large valleys. To the east is the Great Basin (Durrell 1987). The Inyo NF is mostly on the steep, eastern side of the Sierra Nevada and in the White Mountains, in the rain shadow of the Sierra Nevada. The remaining national forests (most of the Tahoe, Eldorado, Stanislaus, Sierra, Sequoia) and the LTBMU occupy the Sierra Nevada from the foothills to the highest peaks, with elevations ranging from 2,000 to over 14,000 ft, and bounded to the west by the Central Valley. These forests include most of the higher elevations in the Sierra Nevada, particularly on the southern forests, and have the highest snowpack. This terrain is mostly granitic rocks, with some overlying metamorphic rocks at high elevation.

Infrastructure at Risk

The Sierra Nevada national forests contain an immense amount of infrastructure, including 26,500 mi of roads, 9,300 mi of trails, 684 bridges, 169 dams, over 4,100 buildings and administrative sites, and over 50 campgrounds. These represent an investment of about $16.5 billion.

Roads and facilities are subject to a wide variety of climate-induced events including landslides, floods, erosion, freeze-thaw, and fires, all of which can damage or destroy infrastructure (fig. 4.1). Virtually all infrastructure is vulnerable to wildfires, particularly recreation and administrative facilities (fig. 4.2). Roads, bridges, and culverts are susceptible to increased runoff during storm events and failures resulting from washouts, plugging, overtopping, stream diversion,

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Figure 4.2—Forest infrastructure, such as culverts, bridges, and recreation facilities, are often damaged by wildfires.

and scour (fig. 4.3). Storm-induced landslides, debris slides, and rockfalls occur as a result of saturated soils during major storms, particularly if storms include high-intensity rainfall. The combination of fires followed by heavy rains has led to debris flows from deep canyons in steep terrain. Debris flows often damage or destroy most types of infrastructure in their path.

Significant impacts to infrastructure can result from more subtle climate change phenomena, including (1) less snowpack and earlier snowmelt that allow early access to and use of roads, trails, campgrounds, and facilities; (2) more dust on roads during prolonged drought periods; (3) drying of traditional water sources in late summer; and (4) limited funding for maintenance owing to increased allocation of funds to fire management.

Figure 4.3—Examples of forest roads and other infrastructure damaged by flooding and storms.

Vulnerability and Risk Assessment Process

The vulnerability assessment process includes a synthesis of best available science to (1) identify infrastructure at risk; (2) quantify the level of risk relative to value, age, condition, and a combination of climatic exposure and sensitivity to exposure; and (3) summarize appropriate actions needed to minimize the risk. These actions help prioritize where funds are best invested and include adaptation measures needed to increase the resilience of infrastructure.

Various agencies have vulnerability assessment processes, but most follow similar steps (box 4.2). The Federal Highway Administration (FHWA) uses a comprehensive process (USDOT FHWA 2012, 2017a, 2017b): (1) define the objectives and scope, including climate information, actions and products needed, and assets at risk; (2) compile available data on the assets, hydrology, and climate; (3) assess the vulnerability of assets, considering asset history and engineering information; (4) develop and prioritize adaptation options; and (5) incorporate results into decisionmaking (fig. 4.4). Process and results should be periodically monitored and evaluated.

Box 4.2

General Summary of the Key Steps in a Vulnerability Assessment Process

Steps in a generic infrastructure vulnerability assessment process are listed below. Note that the process is typically iterative as the process advances, and outputs depend a great deal on the skills and knowledge of the participants.

- Have a good asset inventory.
- Form an interdisciplinary team.
- Define the assets at risk.
- Examine site data and history.
- Review relevant climate projections and climate-related stressors.
- Summarize relevant hydrologic projections.
- Conduct risk analysis.
- Rank asset vulnerability.
- Prioritize needed work or adaptation measures.

The USFS has a similar process, including (1) define objectives and establish an interdisciplinary team; (2) define the scope of work relative to assets and climate stressors; (3) collect asset information, climate data, and indicators; and (4) identify and prioritize asset vulnerabilities. These steps are followed by guidance and

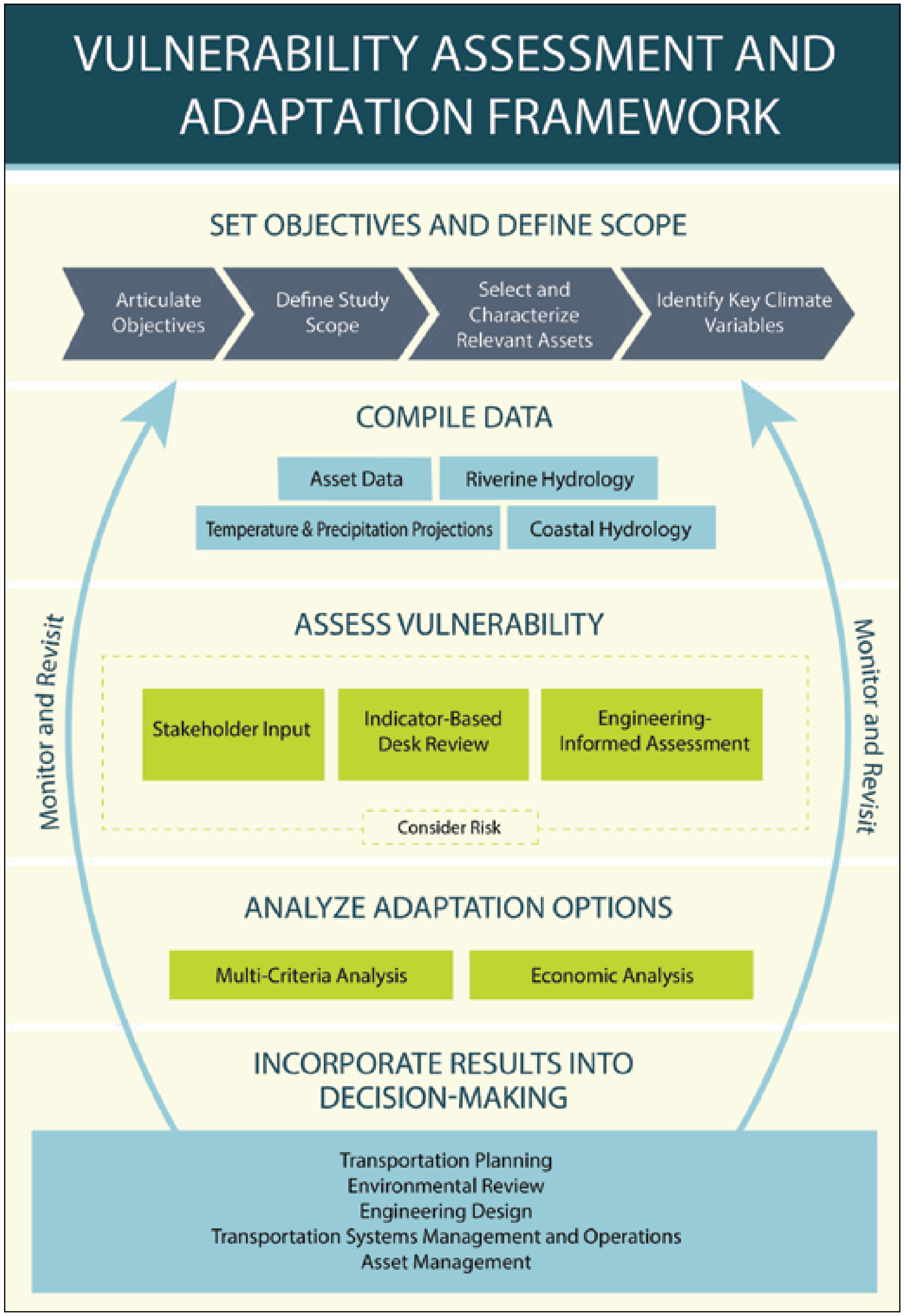

Figure 4.4—A framework for assessing the effects of climate change and extreme weather on infrastructure can be used for both high-level planning and on-the-ground project implementation. This structured approach ensures thoroughness and consistency in designing and maintaining infrastructure in a changing climate. (Figure from USDOT FHWA [2017b])

scoring tools for adaptation strategies of assets at risk (USDA FS 2018). Developing a clear approach minimizes data collection and analyses, streamlines the evaluation process for complex climate change issues and saves money.

The Canadian forest industry follows a similar process, developed by the Public Infrastructure Engineering Vulnerability Committee (Engineering Canada 2016), which has been used in assessing vulnerability of their forest roads (Partington et al. 2018). The California Department of Transportation has developed climate change vulnerability assessments for each of their districts, including District 2 in northeastern California, District 3 covering the Lake Tahoe area, and Districts 6 and 9 that cover the Sierra Nevada region (Caltrans 2018a, 2018b). Their reports address highway vulnerabilities, extreme weather impacts, risk management, and adaptation designs that incorporate climate change into decisionmaking.

Fundamental to all infrastructure vulnerability evaluation processes is the need for good inventories of assets, including roads, bridges, dams, and buildings. Needed expertise is provided by an assessment or interdisciplinary team, consisting of personnel familiar with infrastructure and site history, local terrain sensitivity, climate information, and other relevant information.

Relevant historical observations and future climate projections throughout the Sierra Nevada are needed to help establish exposure of infrastructure to potential climate stressors. Using asset data and history, in conjunction with projected climate and hydrologic data, risk can be assessed for general or specific infrastructure assets. Ranking assets in the context of risk will then help identify asset vulnerabilities and will help prioritize planning, funding, replacement, and maintenance activities.

Assessing and prioritizing are critical because funding and resources are always limited. Potentially problematic areas or sites must be identified and the consequences of damage considered in advance of actual impacts. Table 4.1 presents a risk rating matrix that considers (1) likelihood of an event causing damage or infrastructure failure and (2) consequences of damage or failure, with risk subjectively rated from very high to very low for any given infrastructure asset (Keller and Ketcheson 2015).

For example, a bridge may have a moderate likelihood of failing in a major storm as a result of foundation scour, but the consequences of that failure are high to very high if the bridge is the only access to an area. Alternatively, a road segment may have high likelihood of closure during a major storm because of landslides, but if the road is not a critical route (i.e., there is alternate access) the consequence of road closure is much less severe. Therefore, the overall risk might be assessed as low to moderate. Ideally, infrastructure that is determined to be high or very high risk would be given a high priority and improved, closed, or relocated.

In many cases, assessment should consider the spatial scale, duration of adaptation treatment, and cost effectiveness of the treatment. At a regional scale, climate stressors are likely similar across multiple national forests, with similar potential effects and adaptation measures. Some vulnerable soil types or geologic units may be found on many forests (e.g., decomposed granitic soils found in many areas of the Sierra Nevada are highly erodible). Assessment can also be done at local scales, such as on a specific national forest, ranger district, or watershed, where specific assets are evaluated and specific data about the relevant conditions are likely to be available (Furniss et al. 2018).

Duration of effectiveness should be considered in the assessment, but both short- and long-term treatments have value. Many adaptation treatments are most useful before any significant weather event to prevent damage. Channel cleaning or culvert maintenance are typically short-term treatments, whereas building an overflow channel to prevent stream diversion has long-term value. Some treatments are more cost effective than others. Many vegetative erosion control treatments are particularly cost effective because they are not expensive to implement and are increasingly effective over time. Box 4.3 summarizes common adaptation treatments for roads, considering both short- and long-term value and cost effectiveness. A more complete list of treatments and effectiveness is found in Keller and Ketcheson (2015).

Table 4.1—Example of a risk rating matrix used to evaluate the likelihood and consequences of climate change effects on infrastructure and other resources[a]

	Magnitude of consequences[c]		
Likelihood of damage or loss[b]	**Major**	**Moderate**	**Minor**
		Risk[d]	
Very likely	Very high	Very high	Low
Likely	Very high	High	Low
Possible	High	Intermediate	Low
Unlikely	Intermediate	Low	Very low

[a] The location of conditions within the matrix can differ over time, with a need for ongoing assessment of risk and development of potential responses for reducing the risk of storm damage. (From Keller and Ketcheson [2015])

[b] Chance of occurrence (percent): **very likely** = >90 percent; **likely** = 50 to 90 percent; **possible** = 10 to 50 percent; **unlikely** = <10 percent.

[c] **Major** = loss of life or injury to humans, major road damage, irreversible damage to critical natural or cultural resources. **Moderate =** possible injury to humans, likely long-term but temporary road closure and lost use of major road or road systems, degradation of critical natural or cultural resources resulting in considerable or long-term effects. **Minor** = road damage minor, little effect on natural or cultural resources resulting in minimal, recoverable, or localized effects.

[d] **Very high and high risk** = highest priority for risk reduction treatments; **intermediate risk** = treatments needed; may be incorporated in annual maintenance; **low and very low risk** = treatments may not be necessary.

Box 4.3

Common Adaptation Treatments, Their Effectiveness, and Cost-Effectiveness

Adaptation treatments	Effectiveness		Cost-effectiveness[a]	
	Short term	Long term	Low	High
Road maintenance:				
Conduct grading, cleaning, and shaping maintenance	✓			✓
Road surface drainage:				
Add rolling dips		✓		✓
Add ditch-relief culverts (cross drains)		✓		✓
Add water bars	✓			✓
Implement ditch treatments, armoring, and check structures	✓		✓	
Add leadoff ditches	✓			✓
Implement cross-drain pipes, dips, ditch-outlet protection, and armoring	✓		✓	✓
Stream-crossing structures:				
Maintain culverts	✓			✓
Remove minor channel debris	✓			✓
Provide diversion prevention and armored-overflow protection for culverts		✓		✓
Bridge protection and improvement:				
Maintain channels and clear debris and sediment around footings	✓			✓
Erosion prevention:				
Implement physical erosion control measures	✓		✓	
Vegetate barren areas with deep-rooted, native plants		✓		✓
Prevent gullies by limiting water concentration		✓		✓
Slope stabilization measures:				
Pull back side-cast fill and prevent sliver-fill failure		✓		✓

[a] Cost-effectiveness varies, depending on treatment. Ratings are estimates, based on the authors' experience.

Other Assessments, Guidance, and Resiliency Efforts

The assessment information presented here builds on other climate change assessments and activities that have been conducted for federal lands (Furniss and Howe 2016; Halofsky et al. 2018a, 2018b; Peterson et al. 2014; Vose et al. 2012, 2016, 2018), including those discussed above. Work on transportation analysis and planning, watershed condition surveys and assessments, watershed improvement needs, development of BMPs, the Transportation Resiliency Guidebook, and the Emergency Relief for Federally Owned Roads (ERFO) program all help identify assets at risk and methods to assess the condition and resolve vulnerability of those assets. National forests can efficiently complete localized analyses by building on this existing work (Furniss et al. 2018).

Watershed Condition Assessments

In 2010, every national forest and grassland in the United States completed a Watershed Condition Assessment at the subwatershed scale (hydrologic unit code 6; 10,000 to 40,000 ac). This was conducted using a national Watershed Condition Framework model that rated various factors that influence watershed condition. The model is based on 12 watershed condition indicators, each composed of various attributes (Potyondy and Geier 2011). Each attribute was rated as good, fair, or poor for each subwatershed based on standard quantitative and qualitative criteria. The attribute ratings were then integrated into a combined rating for each ecological process domain and then into an overall watershed condition score. In the watershed condition classification, road density, condition, and proximity to streams contributed significantly to the ratings.

In addition, 11 national forests from throughout the United States, representing each of the nine USFS regions, conducted pilot assessments of potential hydrologic change resulting from ongoing and expected climate warming (Furniss et al. 2013). A pilot assessment approach was developed and implemented. Each national forest identified water resources important in that area, assessed climate change exposure and watershed sensitivity, and evaluated the relative vulnerabilities of watersheds to climate change. The assessments provided management recommendations to anticipate and respond to projected hydrologic changes.

Transportation Analysis Process

Planning for transportation and access in national forests is included in national forest land management plans. The 2001 Road Management Rule (36 CFR 212, 261, 295) requires national forests to use science-based analysis to identify a minimum road system that is ecologically and fiscally sustainable. The goals of transportation analyses are to assess the condition of existing roads, identify options for removing damaged or unnecessary roads, and maintain and improve necessary roads without compromising environmental quality. Transportation analysis has several benefits, including:

- Identifying roads that need improvement or decommissioning
- Establishing a framework to set annual maintenance work and costs
- Improving agency ability to meet BMP requirements of regulatory agencies

Consideration of climate change has not typically been a formal part of the analysis.

The objective of the USFS Transportation Analysis Process (TAP) is to reduce environmental effects and road mileage to levels that can be supported by available financial and human resources. Most infrastructure imposes some costs on the environment, and costs and transportation needs can be balanced to arrive at a sustainable and suitable transportation system. This infrastructure assessment is best integrated with TAP reports and updates as appropriate, including analyses identified in the USFS Travel Planning Handbook (Forest Service Handbook 7709.55). Outputs include:

- Map of the recommended minimum road system
- List of unneeded roads
- List of key issues
- Prioritized list of risks and benefits associated with changing the part of the forest transportation system under analysis
- Prioritized list of opportunities for addressing those risks and benefits
- Prioritized list of actions or projects that would implement the minimum road system
- List of proposed changes to current travel management designations, including proposed additions to or deletions from the forest transportation system

This infrastructure assessment can be used to set priorities for improving roads to increase their resilience and reduce environmental effects. The TAP should be interactive with the Watershed Condition Framework process and vice versa. Every national forest in the Sierra Nevada has completed a travel analysis report that differentiates likely needed roads from those that are likely unneeded and recommended for decommissioning.

Best Management Practices

Implementing, monitoring, and improving practices for the management of water quality and watershed health are central to adapting to climate change. The publication "National Best Management Practices for Water Quality Management on National Forest System Lands, Volume 1: National Core BMP Technical Guide" (USDA FS 2012) provides a set of BMPs for most aspects of forest management, including roads, trails, and recreation (USDA FS 2014). "Volume 2: National Core BMP Monitoring Technical Guide" (USDA FS, in press) provides guidance on monitoring the effectiveness of BMP implementation. These technical guides, which also contain national directives and data management structures, are available for new planning efforts, National Environmental Policy Act (NEPA) analysis, and design, implementation, maintenance, and evaluation of proposed activities, particularly if projects affect water resources. In addition, local BMPs are developed and applied to address site-specific needs and requirements. The publication "Low-Volume Roads Engineering—Best Management Practices Field Guide" (Keller and Sherar 2003) summarizes many of the key BMPs for engineering design and function of roads.

Road and Infrastructure Performance Monitoring

Considerable work has been done to repair storm damage to forest roads and facilities in Sierra Nevada national forests. This was especially true during the declared disasters of 1964, 1983, 1986, 1997, and 2017. National BMPs require national forests to conduct detailed storm damage assessments to determine the location, extent, and cause of damage and to estimate the cost for repairs. In the past, these were primarily a paper exercise at a local level, but in recent years, surveys have been conducted using geospatial tools and mobile technology. Storm damage surveys, when recorded in a GIS, readily reveal how proximity of roads to streams or certain geologic and topographic features affect road failures. These surveys facilitate learning by engineers and resource managers and progressive improvement in practices.

This information can be incorporated into the USFS infrastructure application (INFRA) database for best utilization of the data. The type and basic description of failures need to be accurately recorded so that categorical analysis is possible. To help with consistency, a simple supplemental data sheet (DSR+) was developed and incorporated into national BMPs to resolve these issues and is recommended for general use (fig. 4.5).

Surveying roads during or soon after storms is critical for timely detection of problems such as insufficient drainage, unstable slopes, or vulnerable infrastructure. Observation of problems caused by storm runoff improve understanding of the causes of failure and of designs and prescriptions that reduce both the likelihood and consequences of future failures. Over time, this kind of monitoring illustrates how and where infrastructure can fail, informing the improvement of practices that reduce adverse effects on water quality and watershed function.

DSR+

DSR Supplemental Data Sheet
(Replaces "Description of Damage" Block)

DSR Reference ________________________________

Type and cause of failure

- ☐ **Stream crossing**
  - ☐ Plugged
    - ☐ By wood
    - ☐ By sediment
    - ☐ By wood and sediment
  - ☐ Too much water for culvert
  - ☐ Fill erosion % of fill removed ________
  - ☐ Diversion of stream down road or ditch
    Approx. length of diversion _____ ft.
    Receiving feature
    - ☐ Next crossing
    - ☐ Cross drain
    - ☐ Hillslope
  - ☐ **Cross drain**
    - ☐ Plugged
    - ☐ Diverted
  - ☐ **Landslide from above**
    - ☐ Within 100 feet
    - ☐ 100–1000 feet above
    - ☐ > 1000 feet
  - ☐ **Landslide originating at road**
    - ☐ Cutslope failure
    - ☐ Fill or sidecast failure
    - ☐ Running surface slump
  - ☐ **Stream undercutting**
  - ☐ **Gully**
    - ☐ Excessive road surface runoff
    - ☐ Excessive ditch flow
    - ☐ Cascading cross-drain failure
    - ☐ Gully from above
    - ☐ Other: ____________________________

Estimated Volume

Estimated total volume of earth moved by the erosional event

- ☐ <10 yds
- ☐ 10–100
- ☐ 100-1000
- ☐ 1000–10,000
- ☐ >10,000

Estimated Delivery

Estimated % of material that

______ Is on road
______ Is within 50 feet of a stream*
______Was deposited within 50 of a stream
______ Was deposited in a stream

*Any stream, including draws and ephemeral streams. Does not need to be "live" or flowing at the time of inspection.

Notes

____
____
____
____
____
____
____
____
____
____
____

DSR and notes made by: ____ Date: ___________________________

DSR+ Supplemental Data Sheet, Version 1.0

Figure 4.5—The DSR+ form to be used in damage surveys to supplement the Federal Highway Administration Damage Report Survey (DSR) form to allow categorical analysis of roadway failures.

U.S. Forest Service Transportation Resiliency Guidebook

The USFS, with the help of the U.S. Department of Transportation John A. Volpe National Transportation Systems Center, produced a transportation resiliency guidebook (USDA FS 2018). The guidebook utilizes a conceptual framework for practitioners at a local level to consider climate change and prepare for effects on the transportation system. The guidebook can also be used to help communicate risk associated with climate change to decisionmakers. A high-level analysis, as outlined in the guidebook, allows practitioners to rapidly assess transportation vulnerabilities and prioritize high-risk areas. The guidebook also highlights ways the USFS can make the transportation system more resilient to potential climate change impacts when funding opportunities arise.

Program for Emergency Relief for Federally Owned Roads

The ERFO program was established to assist federal agencies with the repair or reconstruction of tribal and federal lands transportation facilities, and other federally owned roads that are open to public travel, that have suffered serious damage from a natural disaster over a wide area or by a catastrophic failure (USDOT FHWA 2014). The intent of ERFO is to pay the unusually heavy expenses for repair and reconstruction of eligible facilities, with a minimum threshold of eligible repairs of $700,000 for each event. During the past 15 years, ERFO expenditures for Sierra Nevada national forests have exceeded $56.5 million.

ERFO provides assistance to federal agencies whose roads meet the definition of "open to public travel." ERFO is not intended to cover all repair costs, but rather to supplement repair programs of federal land management agencies. Funds for ERFO are provided from the federal Highway Trust Fund and the General Fund through the Emergency Relief Program for federal-aid highways. ERFO funds cannot duplicate assistance under another federal program or compensation from insurance, cost share, or other sources.

ERFO regulations require that damaged roads be repaired to restore traffic. In most circumstances, this limits repairs to a similar type of road in the same location. To incorporate climate-smart practices that improve transportation resiliency, the agency with damaged roads must provide funding for additional work. This additional work is essential in areas where a road is at risk to climate-induced changes in hydrologic regimes, including extreme events (e.g., floods, landslides). This is especially true for roads already in high-risk locations, such as floodplains.

To reduce risk of future failure resulting from climate-induced changes, the Office of Federal Lands Highway can collaborate with other federal agencies to help develop best resiliency practices for incorporation of improved climate adaptation practices and specifications (USDA FS 2018). This will improve climate resilience, ensure durable investments, and promote a sustainable transportation system on federal lands.

Other Considerations

Although experienced engineers and maintenance personnel may be knowledgeable about historical and current system patterns, future climate conditions are uncertain and may be underestimated. Local knowledge from specialists who have historical information about sites and trends can be particularly useful. Box 4.4 presents a number of questions to address during an assessment process for many of the specific design issues discussed below. By considering these questions, many of the infrastructure vulnerabilities and potential problems can be identified.

Similar to natural resource categories (vegetation, wildlife, etc.), infrastructure can be analyzed in a structured, detailed manner based on vulnerability components: exposure, sensitivity, and adaptive capacity (IPCC 2007). Exposure is the potential for infrastructure to be subjected to climate stressors, such as flooding and wildfires. Sensitivity is the degree to which infrastructure would be affected by exposure to climate stressors. Adaptive capacity is the ability of infrastructure to adjust to potential effects from a climate stressor (Furniss et al. 2018), with the goal of resilience. Resilience enhances the capacity of ecosystems and infrastructure to withstand the effects of climate stressors without irreversible change or damage (Peterson et al. 2011). Given the many areas of vulnerability found in infrastructure, USFS management needs to be as flexible as possible to deal with our changing climate and its impacts.

Effects of Climate Change on Infrastructure

Climate change in the Sierra Nevada is expected to cause the temperature to increase by 6 to 10 ^{o}F by the end of the 21st century. Total precipitation is expected to increase slightly in winter, and precipitation extremes and rainfall intensities are expected to increase (Dettinger et al. 2018, Hayhoe et al. 2018). Warmer temperatures will result in a higher proportion of rainfall to snowfall, particularly at 5,000 to 8,000 ft elevation. With less snowfall and warmer temperatures, the snowpack is expected to disappear sooner than historically, opening up the high country earlier (Mote et al. 2018).

Summaries of historical average temperature and precipitation in the Sierra Nevada, as well as projected future values, are found in chapter 2. Extreme events such as “atmospheric rivers” or a “pineapple express,” with large quantities of warm Pacific moisture, are projected to increase precipitation (Warner and Mass 2017).

Box 4.4

Assessment Questions Useful for Determining the Condition and Vulnerability of Infrastructure

Road maintenance:
- Is the road in need of maintenance?
- Are road ruts likely to concentrate water?
- Are culverts damaged, plugged, or in need of cleaning?
- Are rolling dips too worn to direct the water off the road?
- Do ditches need cleaning or armoring to prevent downcutting?

Road-stream encroachment:
- Is the road in a vulnerable location?
- Is the road in a channel migration zone? How much will future streamflows vary?
- Can the road be reasonably moved?
- Which roadway and streambank protective measures are reasonable?

Road surface drainage:
- Is water draining from the road?
- Where is the water concentrated?
- Are the road-surface soils erodible?
- Which surface drainage measures will be most effective?
- Are the ditches stable or in need of armoring?
- Are there a sufficient number of cross drains or dips?
- Where can the water be reasonably discharged?

Culverts and stream crossing structure vulnerability:
- Does the culvert have a potential or history of plugging?
- Is the culvert damaged or known to be poorly installed?
- Does the structure have adequate capacity for anticipated future flood flows?
- Are trash racks or diversion prevention measures needed?
- Would a stream simulation design be the best long-term solution?

Fords and low-water crossing setting and condition:
- Is the road a noncritical route or is there alternative access to the area?
- Is traffic use low and are occasional traffic delays acceptable?
- Is the channel ephemeral or does it have relatively low base flow?
- Does the watershed have large flow fluctuations or have a "flashy" response?
- Does the channel carry a large amount of debris?
- Is the channel entrenched (broad and flat versus deep)?
- Is a low-water crossing the most cost effective or inexpensive structure?

Bridge condition and needs:

- Is the channel near a bridge free of obstructions?
- Is the stream channel aggrading or degrading?
- Is the channel subject to meander and likely to shift laterally?
- Does the bridge have adequate capacity and freeboard?
- Does the bridge have potential scour problems?

Erosion prevention and control:

- Is there concentrated waterflow across the soil?
- Are erosive soil areas exposed and likely to erode?
- Do erosion control measures need to be replaced?
- Does existing vegetation have shallow or deep roots?
- Are gullies starting to form where water leaves the road?

Slope failure potential and stabilization needs:

- Is the slope over-steepened, considering typical stable slope criteria?
- Does the slope have a history of instability, with large or small failures?
- Is the fill slope placed with “sidecast” construction on slopes over 60 percent?
- Are there signs of moisture or seepage on the slope?
- What is the risk of damage from a failure?
- Which stabilization options will be adequate and most cost effective?

Trails:

- Will the timing of trail use change from traditional use periods?
- Is the trail surface hardened to accommodate early-season use?
- How will the trail be maintained after increased use?
- Is the trail clear of hazard trees?
- Does the trail bridge have adequate hydraulic capacity and scour protection?

Facilities infrastructure:

- Will the facility withstand stronger storms and heavier rain?
- Is building insulation adequate to be comfortable with warmer anticipated temperatures?
- Is clearing around facilities adequate to provide defensible space for fire suppression?
- Are fire-resistant materials used in the construction?
- Are campgrounds located in safe locations from floods, debris flows, rockfalls, etc.?
- Are warning systems and evacuation routes identified for disasters?
- Are water systems likely to be depleted during drought periods?

Dams:

- Is there adequate “freeboard” on the dam?
- Are outlets functioning properly?
- Is the spillway clear and does it have adequate capacity?

Although individual storms may be larger, the time between storm events is expected to be longer (Polade et al. 2017). Warmer temperatures combined with more variable weather may also lead to more periods of drought (Dettinger et al. 2018).

Impacts on infrastructure are projected to be more severe than in the past, both from floods and drought-related forest fires. Modoc Plateau forests (at relatively low elevation) will likely be only slightly affected by altered precipitation and modestly affected by higher temperatures. Peak flood flows might be less but are uncertain. The southern Sierra Nevada forests with higher average elevations are expected to see moderate temperature increases and relatively little increase in precipitation, leading to more fire vulnerability. The northern Sierra Nevada is expected to see the biggest increase in precipitation (Dettinger et al. 2018). In addition, microbursts (similar to small localized tornados) have periodically been observed in the northern Sierra Nevada, a result of extreme weather conditions that are expected to increase in frequency and intensity.

Examples of the climatic variability impacts facing the Sierra Nevada were observed in northern California in 2017 and 2018. In 2017, record flooding created a crisis at the Oroville Dam where the primary spillway was extensively damaged (repair costs exceeded $1.1 billion), and possible use of the untested emergency spillway triggered the evacuation of almost a quarter million people in the Central Valley (Wikipedia 2017). In 2018, in the same watershed and only 15 mi away, the town of Paradise was destroyed by a wildfire, resulting in the most damaging wildfire in California history. Eighty-five residents died, 19,000 structures were destroyed, and insurance repair estimates were $7.5 to 10 billion (USA Today 2018).

Hydrology-Infrastructure Interactions

Projected climate change effects on snowpack, rainfall, and streamflow will have adverse impacts on forest infrastructure. Altered snowpack and periodic increased streamflow may increase some recreation opportunities and decrease others (chapter 5). Snow residence time is expected to decrease, especially on the west side of the Sierra Nevada at low to mid elevations, opening up this zone to forest users on a date earlier than in the past (see the Variable Infiltration Capacity [VIC] maps in chapter 3, as well as explanation of the development of the VIC maps).

Streamflows that can lead to flooding (i.e., 50-year events) may increase by 30 to 90 percent in the northern Sierra Nevada, and by 50 to 100 percent in the southern Sierra Nevada (Das et al. 2013), particularly during the winter months. More mid-elevation rain rather than snow, combined with warmer temperatures, will likely lead to these higher winter and early spring flows. Figure 4.6 shows flooding and three record streamflows on the Feather River (Plumas National Forest) in 1986, 1997, and 2017. Major flows will stress the capacity of many old bridges and culverts in the region, as well as cause more streambank erosion and scour. In addition, projected increases in rainfall intensity will exacerbate surface drainage, upland erosion, and gully formation, as well as increase the likelihood of landslides, rockfalls, and debris flows.

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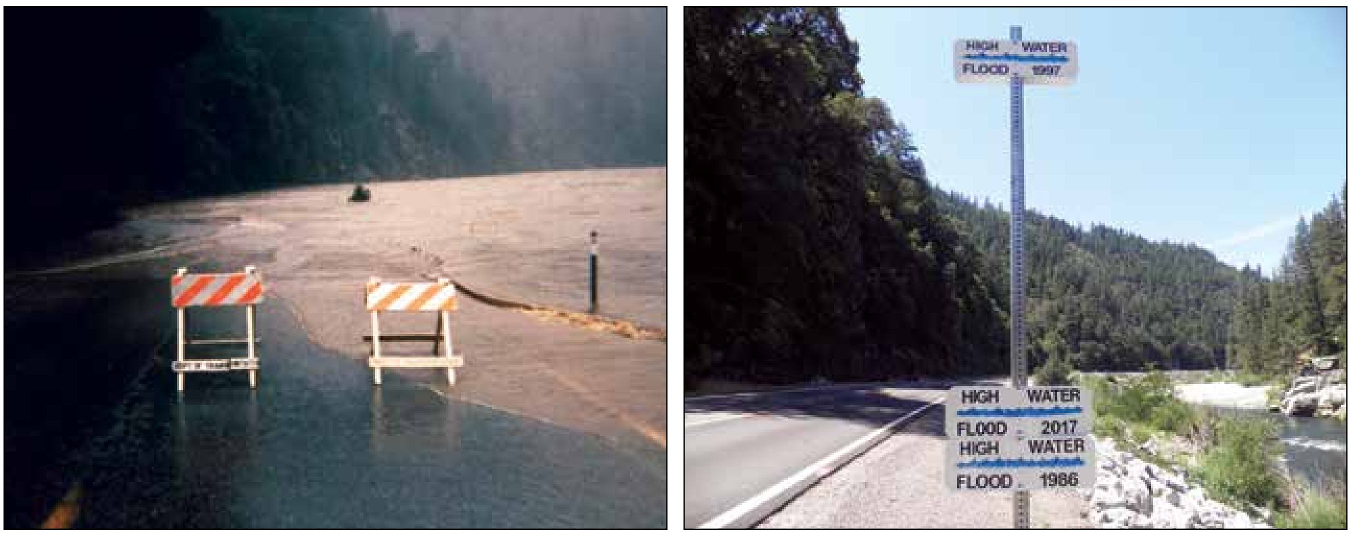

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Figure 4.6—Flooding in the Feather River Canyon along State Highway 70, and the three high-water levels that have occurred there in the past 33 years. Large floods occur infrequently but are inevitable, and wise design and maintenance anticipates extreme events and builds in resistance to adverse effects.

Forests on the Modoc Plateau may see a general decrease in peak flood flows. The eastern Sierra Nevada and White Mountains lie in the rain shadow of the Sierra Nevada and have less precipitation, colder winters, and more summer rainfall (Dettinger et al. 2018). Peak streamflows and summer low flows are less likely to see significant changes compared to the rest of the Sierra Nevada.

Early snowmelt and spring runoff, especially combined with rain-on-snow events, could exceed the capacity of old dams or their ability to discharge incoming flows. Early peak flows and prolonged low, late-summer flows will likely adversely affect recreation (chapter 5), agriculture, and other demands for summer water. Lower summer flows will be most pronounced in smaller, headwater streams. Mean daily summer flows will likely decrease, particularly in the southern Sierra Nevada, and peak spring flows may occur 30 to 80 days earlier in streams by the end of the century compared to historical spring flows (Schwartz et al. 2017). Figure 4.7 shows how hydrologic flow can be affected by changes in the mean and variance of climate and weather (Field et al. 2012). Climate change is expected to increase the frequency and magnitude of peak flows and flooding in winter, and shift peak flows earlier in the season throughout most of the Sierra Nevada.

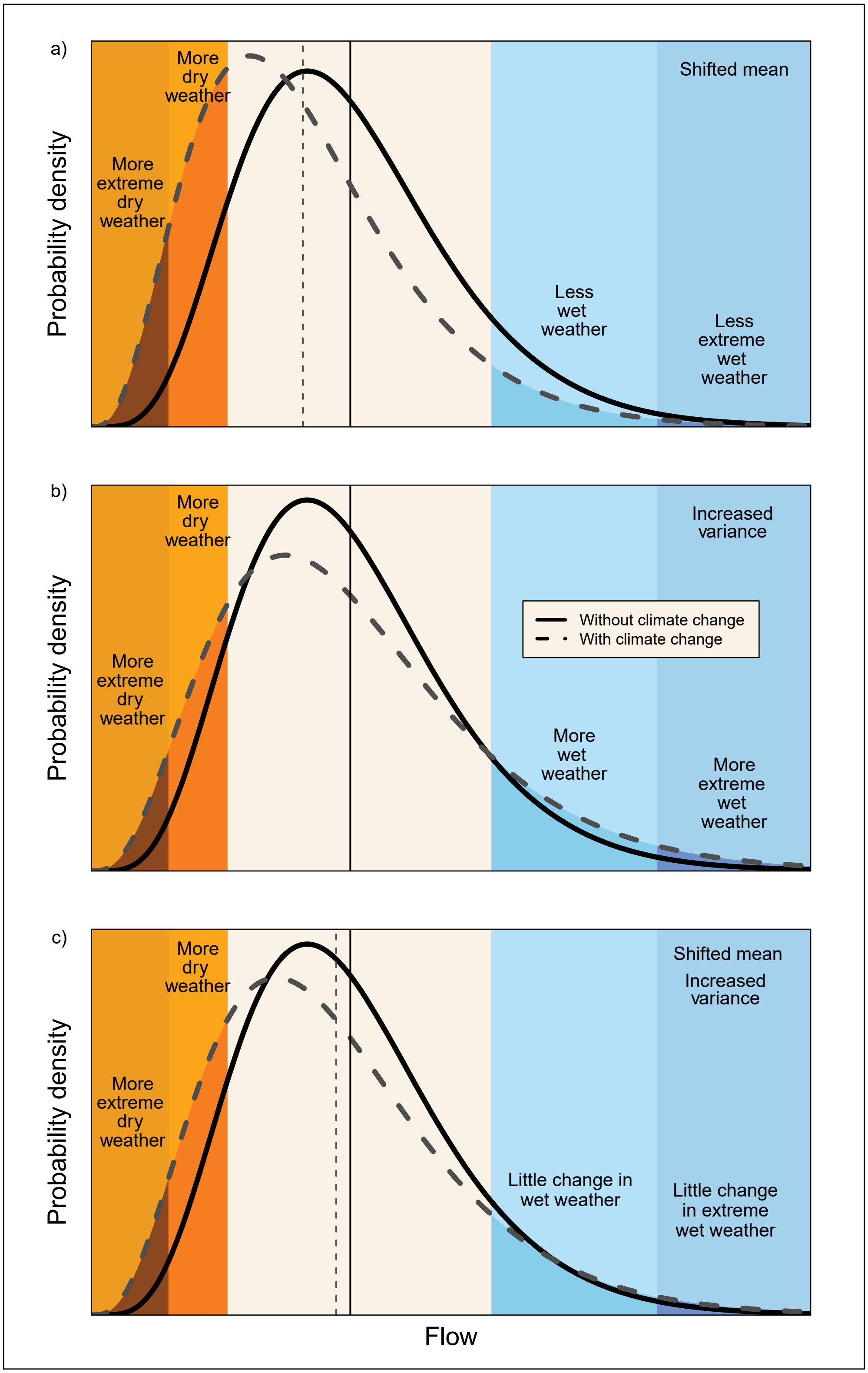

Figure 4.7—Conceptual diagram of how hydrologic flow can be affected by both a change in the mean and change in the variance of climate and weather. Climate change is expected to increase the frequency and magnitude of peak flows and flooding in winter, and to shift peak flows earlier in the season. (From Field et al. [2012])

Warmer temperatures, higher evapotranspiration, and less available subsurface moisture might reduce groundwater supplies, adversely affect water systems, and make fewer water sources available for construction projects or fighting wildfires, particularly in late summer or fall. In addition, longer, drier summers may increase dust problems on forest roads and facilities.

Short- and Long-Term Effects

The Sierra Nevada may already be experiencing the effects of climate change, given recent warmer, milder winters, altered seasonality, and variable weather patterns. The magnitude of climate change effects will vary spatially across the Sierra Nevada, with some variability between the northern, relatively low Modoc Plateau, and the southern higher mountains of the central Sierra Nevada and White Mountains. The following effects on infrastructure have been observed:

- Higher winter peak flows are taxing the designs of culverts and old bridges.
- More intense rains are causing erosion and mobilizing sediments, locally damaging road cross-drain culverts and channels.
- Heavy rains from atmospheric rivers saturate slopes and trigger landslides.
- Large, severe fires are damaging facilities and shifting funds and resources away from planned infrastructure, recreation, and resource projects.
- Flood-damaged roads, combined with limited funding to repair them, reduce agency capability to respond to wildfires and other large disturbances.
- Lower summer streamflows affect recreation, water supplies, and dam operations.

These are all issues that land managers are facing today and will likely continue to face in the near future (Furniss et al. 2018).

Potential benefits of milder winters and less snowpack include lower costs for snow removal, a longer construction season for high-elevation projects, earlier access to mountain recreation areas on roads and trails, and more early-spring rafting opportunities (chapter 5). The disadvantages of climate change outweigh the advantages, but more flexibility will be needed in many aspects of forest management in order to adapt to uncertain climatic patterns.

Geologic Hazards and Infrastructure

Climate change increases the likelihood of impacts caused by geologic hazards. These include flooding, landslides, rockfall, debris flows, avalanches, surface erosion, and avulsion. Roads, culverts, and bridges are the infrastructure most commonly affected by geologic hazards, especially floods and landslides (fig. 4.8).

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Figure 4.8—A bridge abutment undermined (scoured) during a flood (left) and a road closed by a landslide (right).

Threats to human life and safety also exist for some geologic hazards. Risk assessment and associated adaptation options are discussed below.

Debris flows typically occur in areas with steep slopes, particularly when subjected to an intense rainstorm following a wildfire. This combination of events occurs periodically and will likely increase in a warmer climate. Debris flows typically begin in headwater areas as accelerated erosion and rills that move large amounts of sediments into drainage channels. Once enough sediment is moved into the channel and begins moving downslope, collecting additional rock and sediment, a debris flow is formed. At least 28 debris flows have occurred in the southern Sierra Nevada in the past 25 years (DeGraff 1994, DeGraff et al. 2011). Others have occurred in the northern Sierra Nevada.

Debris flows are difficult to prevent and often cause significant amounts of damage to buildings, campgrounds, roads, and any infrastructure in their path, particularly after a fire has removed most vegetation on a slope. The preferred approach to addressing this hazard is to identify areas of potential slide hazard and move the facility or evacuate the site during storms. As a preventive action, forest thinning and ecological restoration can also reduce the severity of forest fires in dry forests. The U.S. Geological Survey has often assisted the USFS in landslide hazard mapping and identifying areas of high debris flow risk after forest fires (Tillery and Matherne 2013) (figs. 4.9 and 4.10).

Debris slides are relatively common after heavy rains and typically occur on steep slopes (greater than 60 percent) where soil depth is moderate, as in a colluvial swale. This circumstance is aggravated if a fire has removed the vegetation and left the soil water repellent (Luce et al. 2012), leading to increased runoff and mobilization of soil. Reestablishing vegetative ground cover, preferably with deep roots, quickly after a fire is one of the best ways to prevent debris slides and subsequent debris flows. Several

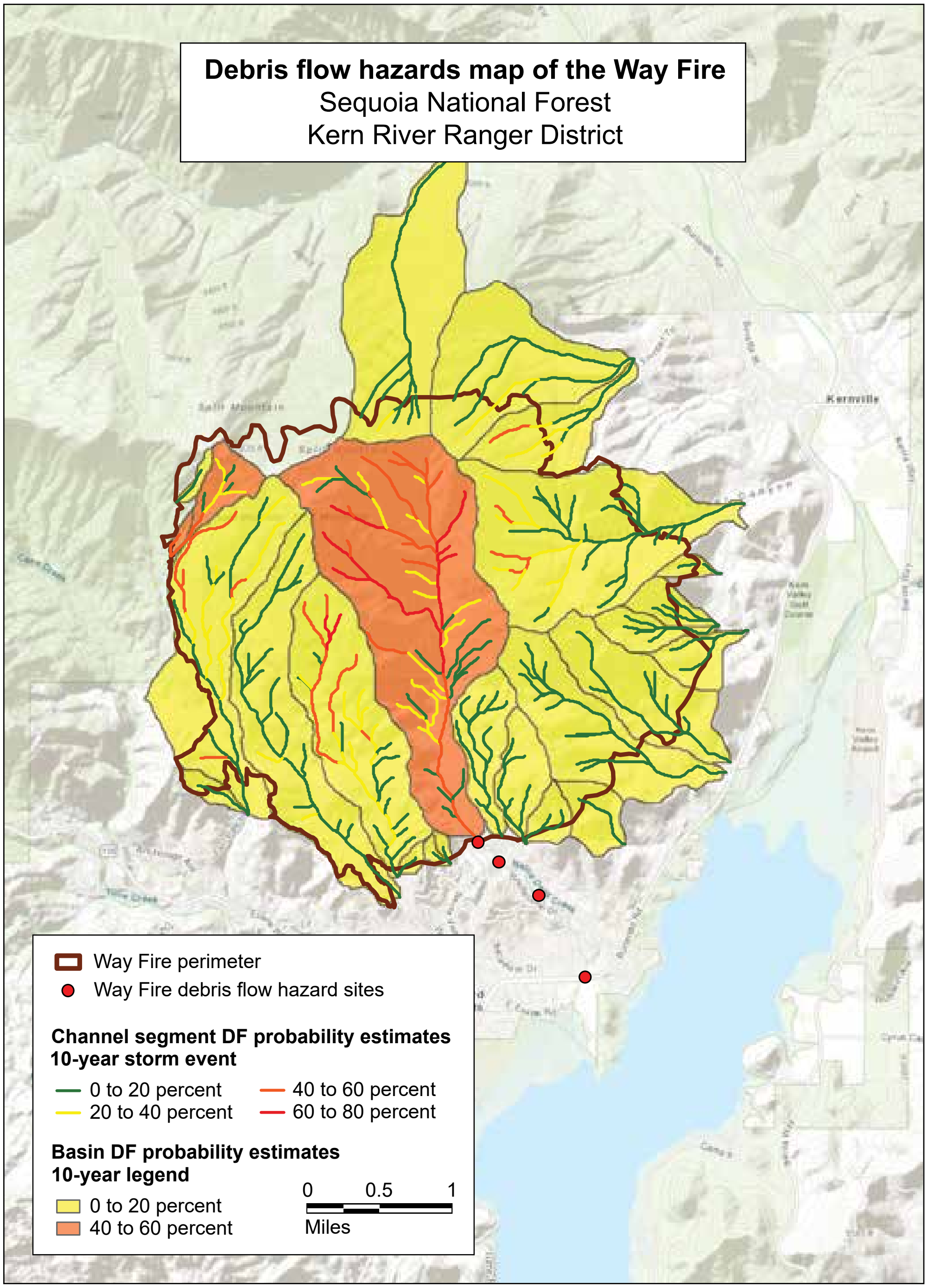
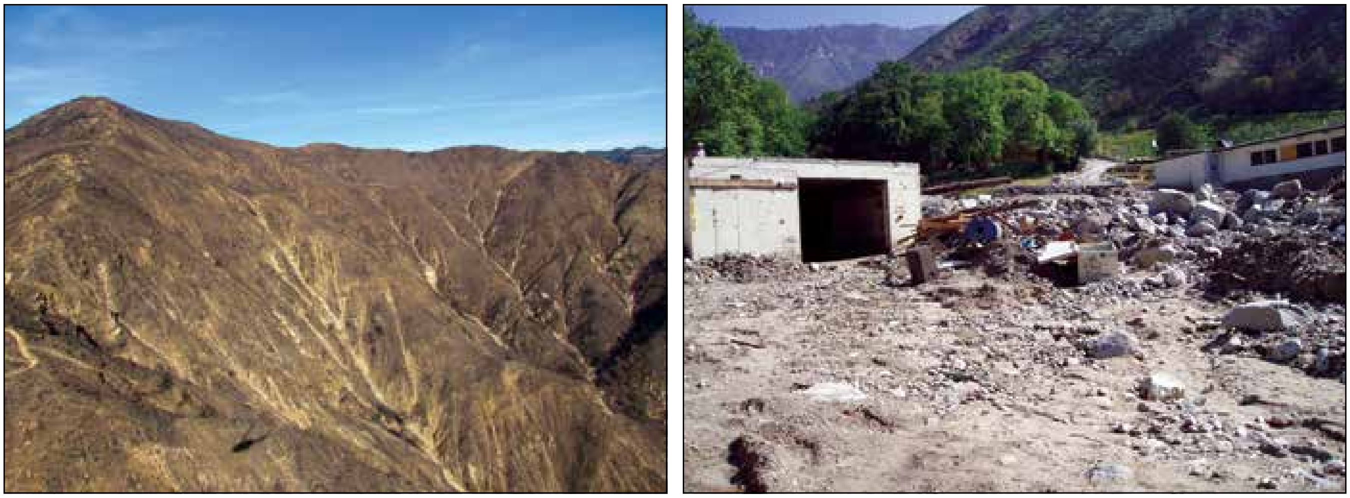


Figure 4.9—Example of a U.S. Geological Survey and U.S. Forest Service debris flow (DF) hazard map with channel and basin slide probabilities for the Way Fire, Sequoia National Forest, 2014.

other slope stabilization measures can be used in critical areas, including constructing debris catchment structures and diverting water away from the slide area.

Rockfall is also a common problem in many areas along roads where rock is fractured and can be dislodged during heavy rain or during freeze-thaw cycles.

Allen King



Gordon Keller

Figure 4.10—A burned upper watershed where rills and debris flows are beginning to form (left), and damage to a forest facility hit by a debris flow downslope of a fire area (right).

Although rockfall on roads is most problematic, rockfall can also damage buildings and hydroelectric facilities. In areas where rockfall is known to be a problem, mitigation measures such as scaling loose rock, adding rock bolts, or adding rockfall prevention netting are often implemented.

Snow avalanches are another hazard that is likely to worsen in a warmer climate, especially when heavy snows are followed by warming conditions. These conditions increase the likelihood of snow avalanches that represent a hazard to winter recreation, ski facilities, and other infrastructure.

Adapting Transportation Infrastructure to the Effects of Climate Change

Roads, trails, bridges, and other infrastructure in the Sierra Nevada were developed over more than a century to provide access for mineral prospectors, loggers, hunters, and recreationists. Transportation infrastructure provides access that is largely determined by where these activities historically occurred in relation to land management objectives. National forests, national parks, and other federal lands are intended to protect water supply, timber and range resources, and wildlife and to provide multiple uses and enjoyment to the public. Access to public lands promotes use, stewardship, and appreciation of their value as a resource contributing to the quality of life (Louter 2006). Today, reliable and strategic access is critical for people to recreate, extract resources, monitor and manage resources, and respond to emergencies (Strauch et al. 2014).

The location of roads and trails can increase vulnerability of the transportation infrastructure to climate change. Many roads and trails were built on steep slopes because of the rugged topography of the region, and cut slopes and side-cast material have created landslide hazards. Past timber harvesting and its associated road network in national forests have contributed to the sensitivity of existing infrastructure by increasing storm runoff and peak flows that affect road-crossing structures (Croke and Hairsine 2006, Schmidt et al. 2001, Swanston 1971).

The 10 national forest units in the Sierra Nevada region contain 26,560 mi of roads (table 4.2) and 9,296 mi of trails (table 4.3). Of the existing roads, 4,282 mi are suitable for passenger vehicles (typically gravel or paved surface), 19,612 mi are suitable for high-clearance vehicles such as pickup trucks, and the remaining 2,667 mi are currently in storage (roads not currently being used) and closed to vehicles. Road density is typically higher at low elevations and adjacent to mountain passes near major highways.

Roads and trails cross many streams and rivers, and most road-stream crossings are culverts or bridges that were installed decades ago. Many roads and trails were constructed in valley bottoms near streams to take advantage of gentle grades, but proximity to streams increases sensitivity to flooding, degrading aquatic resources, altering channel migration, increasing bank erosion, shifting the location of alluvial

Table 4.2—Road miles and estimated deferred maintenance and repair costs for passenger car system in Sierra Nevada national forests

National forest/unit	Basic custodial care (stored for future use)[a]	High-clearance vehicle system[b]	Passenger car system[c]	Total forest road system	Passenger car system cost[d]
	Miles				*Dollars*
Eldorado	664	1,476	537	2,678	24,806,871
Inyo	0.2	1,873	125	1,999	5,766,422
Lassen	305	2,479	633	3,418	29,199,259
Modoc	175	3,654	535	4,365	24,678,185
Plumas	203	3,009	564	3,778	26,049,451
Sequoia	173	950	471	1,595	21,754,385
Sierra	236	2,000	386	2,624	17,845,837
Stanislaus	360	2,211	395	2,967	18,231,895
Tahoe	513	1,822	549	2,885	25,335,913
LTBMU[e]	34	133	82	251	3,822,757
Total	2,667	19,612	4,282	26,560	197,490,975

[a] Roads placed in storage (more than 1 year) between intermittent uses. Basic custodial maintenance is performed. Road is closed to vehicles.

[b] Open for use by high-clearance vehicles.

[c] Open for and maintained for travel by a prudent driver in a standard passenger car.

[d] Deferred maintenance cost for passenger-car roads is $46,124 per mile, based on national data generated from a 2017 random sample of the passenger-car system in the U.S. Forest Service. Although this cost may not be directly valid for a particular region, it is adequate for estimation purposes. Costs for high-clearance vehicle roads and basic custodial care cannot be estimated with confidence and are not included.

[e] LTBMU = Lake Tahoe Basic Management Unit.

fans and debris cones, and increasing the risk of road damage. Most road-stream crossings use culverts rather than bridges, and culverts are generally more sensitive than bridges to increased flood peaks and associated debris (Furniss et al. 2018).

Roads and associated facilities are usually the most significant investments in forest infrastructure that are affected by climate variability and change. A wide variety of vulnerability adaptation measures exist that can be cost effective and reasonably implemented or incorporated to reduce the likelihood of storm damage and minimize adverse environmental impacts. Box 4.5 lists a few key references that specifically discuss adaptation measures useful to reduce the vulnerability of roads to storms. Inadequate road drainage facilities and practices are typically the highest priority for adaptation treatments, including road surface drainage measures and drainage crossing structure and channel problems that can lead to structural failures and watershed damage. Relatively inexpensive measures for improving the drainage of road surfaces are particularly cost-effective and can prevent significant road damage, hillslope erosion, and sediment delivery to streams.

Transportation infrastructure adaptation treatments, discussed in the following sections, are grouped as shown below. Each of these topics is significant in road and trail design and management, and each can be profoundly affected by climate change-induced droughts, fires, and floods:

- Road maintenance
- Road management and closure
- Road-stream encroachment

Table 4.3—Trail distance and trail bridges in Sierra Nevada national forests

National forest/unit	Trail distance	Trail bridges in INFRA database
	Miles	*Number*
Eldorado	854	64
Inyo	1,509	55
Lassen	453	11
Modoc	127	0
Plumas	845	26
Sequoia	1,051	18
Sierra	1,243	18
Stanislaus	1,373	12
Tahoe	1,461	43
Lake Tahoe Basin Management Unit	380	14
Total	9,296	261

Note: The numbers may be slightly inaccurate because of data reporting errors and the fact that several trail bridges have been destroyed recently in fires (Garrett Villanueva, personal communication, Regional Trail Program Manager, U.S. Forest Service, Pacific Southwest Region, 35 College Drive, South Lake Tahoe, CA 96150).

Box 4.5

Key References for Road and Infrastructure Adaptation

- Natural disaster reduction for roads (PIARC 1999). A World Roads Association publication outlining disaster prevention measures for infrastructure. http://www.piarc.org
- Burned Area Emergency Response (BAER) treatments catalog (Napper 2006). This U.S. Department of Agriculture Forest Service publication describes a number of drainage, channel, and erosion control treatments useful to minimize damage from storms after a wildfire. Treatments also apply to risk reduction of storm damage. https://www.fs.fed.us/eng/pubs/pdf/BAERCAT/lo_res/06251801L.pdf
- Highways in the river environment–floodplains, extreme events, risk, and resilience (FHWA-HEC 17) (Kilgore et al. 2016). This U.S. Department of Transportation Federal Highway Administration (FHWA) publication offers technical guidance and methods for assessing the vulnerability of transportation facilities to extreme events and climate change in riverine environments. https://www.fhwa.dot.gov/engineering/hydraulics/pubs/hif16018.pdf
- Storm damage risk reduction guide for low-volume roads (Keller and Ketcheson 2015). A Forest Service publication discussing a range of options for nonrecurring treatments on existing or future low-volume roads that reduce the potential for resource impacts and damage resulting from storm events. http://www.fs.fed.us/t-d/pubs/pdfpubs/pdf12771814/pdf12771814dpi100.pdf
- Synthesis of approaches for addressing resilience in project development (FHWA-HEP-17-082, 2017). An FHWA publication that discusses many adaptation strategies and measures for roads and highways, both in a coastal and upland environment. https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/teacr/synthesis/index.cfm

- Road surface drainage improvements
- Culvert and stream-crossing structure protection and improvements
- Fords and low-water crossings
- Bridge protection and improvements
- Erosion prevention and erosion control
- Slope stabilization measures
- Miscellaneous roads issues (contracting effects, asphalts roadway freeze-thaw effects, decommissioning and closure, fire detours)
- Trails issues

Each of these categories has preventive measures that are relatively simple to implement and are cost effective, as noted in box 4.3. Other less common measures may involve structure replacement, road relocation, major rehabilitation, and structural improvements. These expensive actions need justification during the assessment process based on analysis of risk, potential damage, need, and cost effectiveness. Many adaptation treatments are site specific, so field analysis and good judgment are needed for prescribing and designing on-the-ground treatments. An analysis team with knowledge of an entire national forest road system must weigh the benefits of high-cost treatments at a few sites versus treatment of a larger number of lower cost treatments. Leaving more sites untreated in order to treat a few sites with high-cost solutions may leave more resources at risk than treating more sites and cutting back on the higher cost treatments. However, an incremental approach to implementing adaptation measures is advisable, given funding limitations, and may help reduce the risk of overspending (USDOT FHWA 2017a, 2017b).

Road Maintenance

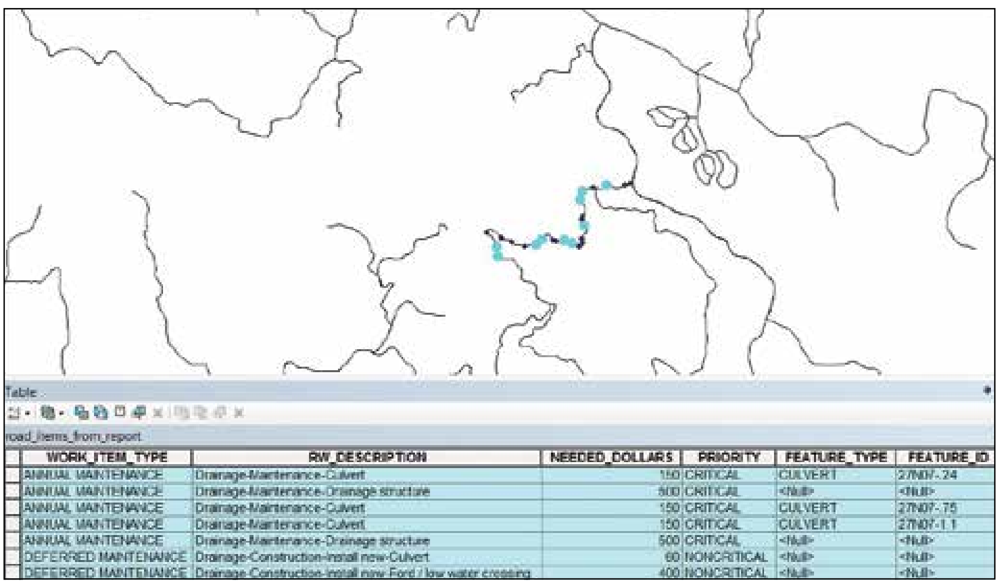
Routine maintenance is important for roads to function properly any time of year, and particularly when large storms occur. This protects the investment and adjacent resources. Figure 4.11 shows roads badly in need of road maintenance and roads that are vulnerable to additional damage from a storm. When a large storm occurs, inspection and maintenance become critical, particularly for properly functioning road surface drainage and stream crossing structures. This applies to roads of all maintenance levels.

Knowledgeable local individuals often have useful historical information on problem sites. Figure 4.12 is an example of data from the INFRA database from Plumas National Forest where critical road maintenance areas and features have been identified. These include areas with soils subject to erosion, undersized culverts, and known problem areas. Documenting issues and developing a list of maintenance priorities allows a road manager to maximize the effectiveness of a

Vincent Barandino

Pete Hochrein

Figure 4.11—Ruts and erosion in the road surface because of lack of surface drainage and maintenance. Roads in this condition are particularly susceptible to storm damage.



WORK_ITEM_TYPE	RW_DESCRIPTION	NEEDED_DOLLARS	PRIORITY	FEATURE_TYPE	FEATURE_ID
ANNUAL MAINTENANCE	Drainage-Maintenance-Culvert	150	CRITICAL	CULVERT	27N07-.24
ANNUAL MAINTENANCE	Drainage-Maintenance-Drainage structure	500	CRITICAL	<Null>	<Null>
ANNUAL MAINTENANCE	Drainage-Maintenance-Culvert	150	CRITICAL	CULVERT	27N07-.75
ANNUAL MAINTENANCE	Drainage-Maintenance-Culvert	150	CRITICAL	CULVERT	27N07-1.1
ANNUAL MAINTENANCE	Drainage-Maintenance-Drainage structure	500	CRITICAL	<Null>	<Null>
DEFERRED MAINTENANCE	Drainage-Construction-Install new-Culvert	60	NONCRITICAL	<Null>	<Null>
DEFERRED MAINTENANCE	Drainage-Construction-Install new-Ford / low water crossing	400	NONCRITICAL	<Null>	<Null>

Figure 4.12—Example of INFRA database maintenance data, identifying critical and noncritical maintenance needs, west side, Plumas National Forest.

maintenance budget. On occasion, maintenance of road surfaces and ditches can lead to increased sediment production following treatment (Luce and Black 2001). Therefore, road maintenance should occur only when really needed, such as to:

- Remove logs and debris from around the inlet area of culverts.
- Remove debris from the inlet area of ditch-relief, cross-drain culverts.
- Remove debris from trash racks upstream of culverts.
- Clean ditches to avoid blockage and ponding of water that can saturate the road subgrade and fill material.

- Replace missing riprap armor around the inlet and outlet of culverts.
- Reshape surface drainage features (e.g., rolling dips, water bars, etc.).
- Remove unwanted berms that have formed along the outside edge of the road.
- Grade and shape the roadway surface to maintain a distinct inslope, outslope, or crown shape to move water rapidly off the road surface, keep the roadbed dry, and prevent concentration of water.
- Remove ruts in the road surface that trap and concentrate water.
- Patch potholes and seal cracks in asphalt surfaces to prevent water intrusion and accelerated road damage.
- Compact the graded roadway surface to keep a hard driving surface and prevent loss of fine material.

Ditch cleaning exposes erodible soils and reinitiates existing cutslope erosion processes, generating chronic sources of road sediment. As a result, "light touch" ditch cleaning is generally advised. The result of less ditch cleaning over time can be vegetation encroachment and lower hydraulic efficiency. Brushing activities cuts the stems in the ditch but can leave stubs that trap debris. This further reduces ditch efficiency and can cause plugged ditches. A balance is needed between maintaining hydraulic efficiency and keeping a rough or armored surface or vegetative cover to reduce ditch erosion.

Ditches that are of greatest concern are those that are hydrologically connected to the stream system. To maintain hydraulic efficiency of the ditches but allow for stabilization of the adjacent cutslopes, ditches need to be oversized so that adequate capacity is maintained in the absence of regular cleaning. Any ditch enlargement needs to be done such that cutslopes are not undercut, creating a new source of erosion and instability. Some sites may not be appropriate for oversized ditches and will require another technique, such as outsloping or insloping without a ditch and rolling the grade to manage water.

Additional road maintenance or improvement items that are useful for long-term prevention of damage include the following:

- Armor ditches in areas of particularly erodible soils or steep grades.
- Add more frequent ditch-relief cross drains, water bars or rolling dips.
- Convert an inslope section of road to an outslope drainage configuration.
- Install diversion-prevention dips at or downslope of stream crossing culverts that have the potential to divert the stream down the road or ditch.
- Add riprap armor or soil bioengineering protection around the inlet of undersized culverts or bridges.

- Plant deep-rooted vegetation on over-steep cut and fill slopes or slopes with a history of movement.
- Install a "deep patch" slope stabilization repair on chronically settling fills.

Due to cost, most roads will not receive the maintenance needed to prevent chronic impacts and storm damage. Stored roads receive minimal maintenance. Unneeded roads can be decommissioned, with no ongoing need for maintenance. For most roads that cannot be closed and will likely receive inadequate maintenance, adaptation measures with good drainage will be critical. To stretch maintenance funds, it is beneficial when roads are as self-maintaining as possible.

Road Management and Closure

National forest staff are examining tradeoffs between providing access and maintaining and operating a sustainable transportation system that is safe, affordable, and responsive to public needs, and that causes minimal environmental impact. Management actions being implemented to meet these objectives include developing more comprehensive access and travel management plans, reducing road maintenance levels, storm-proofing roads, upgrading drainage structures and stream crossings, reconstructing and upgrading roads, converting paved roads back to gravel roads, placing roads in storage, closing roads with decommissioning or obliteration, and converting some roads to trails. In fire-prone areas, it may be necessary to maintain redundant and alternative road systems and evacuation routes.

Temporary closure of roads and road-use restrictions have always been problematic. With shifting seasons and less snowpack, the public will likely want to access national forest lands when roads, trails, and off-highway vehicle facilities are still saturated and not suitable for use. Waiting until soils are dry enough and strong enough to support traffic is a challenge. The USFS, in cooperation with the FHWA, has been studying ways to monitor in-place soil moisture with instruments and remote sensing. Promising technologies are being developed (FHWA CTIP 2018). In extreme cases, road closure may be the best option.

Roads can be closed through storage, decommissioning, or obliteration. Each removes the road from use and makes it less vulnerable to storms. The Sierra Nevada region currently has 2,667 mi of roads in storage. Road storage refers to measures to keep traffic off the road, but the basic road template is preserved. Closure can be for many years, but the road is planned to be reopened eventually for land management activities. Closure devices such as gates, fences, earth berms, trees, brush piles, and boulders are used to prevent use of a road. These options provide flexibility to temporarily reduce costs and impacts, while also considering social and economic factors. These roads can be reopened with minimal effort during emergencies such as firefighting.

Permanent road closure occurs when a road is no longer needed to meet forest resource management objectives. Treatment options may include reestablishing drainage patterns, stabilizing slopes, restoring vegetation, blocking road entrances, installing water bars, removing culverts, removing unstable fills, pulling back road shoulders, scattering slash on roadbeds, or completely eliminating roadbeds (36 CFR 212.5; Road System Management; 23 USC 101) (Luce et al. 2001). These measures can greatly reduce negative road impacts caused during storm events.

Road decommissioning and road obliteration are two types of road closure treatments (fig. 4.13). Decommissioning involves permanent measures, such as allowing natural reestablishment of vegetation and, if necessary, initiating restoration of ecological processes interrupted or adversely affected by the unneeded road. Decommissioning includes blocking the entrance, removing culverts and reestablishing natural drainage patterns via outsloping or very frequent water bars, pulling back road shoulders, and scarifying and seeding the road surface. Road obliteration involves removal of the road template and reclamation or restoration of the land to resource production. This is typically the most rigorous, costly, and permanent option for road decommissioning. Road closure issues are discussed in Forest Service Manual 7700, "Traffic Management," Chapter 7730–Road Operation and Maintenance (2008).

Figure 4.13—Road closure options include decommissioning (left) and complete roadway obliteration (right). Stormproofing with measures such as outsloping, frequent water bars or dips, and other treatments helps to ensure that maintenance is not needed to prevent damage.

Road-Stream Encroachment

Historically, roads were located where construction required the least amount of excavation, so most of the initial roads were located on river terraces adjacent to a river or on channel floodplains. These areas, referred to as channel migration zones (CMZs) (Rapp and Abbe 2003), are where rivers shift in response to storm flows, sediment, and obstructions to shape and reshape their floodplain. Areas where there are significant changes in stream gradient, or alluvial fan areas, are particularly problematic, because the stream channel may fill with sediment over time and shift its channel. Also, road work such as raised embankments or levees often block a stream's access to its historical floodplain or an overflow channel, thus concentrating more flow in the channel, potentially causing erosion and scour problems, or creating these impacts downstream.

The normal shifting of rivers frequently undermines or removes road sections, causing high repair costs and travel disruptions. At times, the road may capture the entire river, resulting in complete relocation of the channel to the road alignment. A road located in or near the CMZ is an encroachment on the river and its natural function. Figure 4.14 shows road damage and a total road washout caused by constriction of the natural stream channel or construction across a historical floodplain.

A common management response to road damage is to move the road or restrain the river with rock armor placed on the road fill to protect the road from erosion. The roadbed elevation may be raised above expected flood levels and the

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Figure 4.14—Roads located on the edge of a channel migration zone (left) and across a floodplain (right).

fill armored to maintain the alignment. The river reacts to this displacement by shifting the erosion downstream or by removing an obstruction such as an under-sized bridge or culvert crossing.

Roads located along streams, in floodplains, and in or adjacent to CMZs are high-risk sites that are best avoided. High-risk roads can be closed or relocated away from the channel or upslope on a hillside, outside a potential CMZ. Although relocation may be costly and administratively and physically difficult, relocating roads away from streams, floodplains, and CMZs will eliminate future costly channel encroachment repairs and loss of road function for extended periods. In addition, channel functions will be better managed if road features do not interfere with natural stream processes. Figure 4.15 is an example of forest infrastructure data showing locations where existing main roads are within 164 ft of a stream.

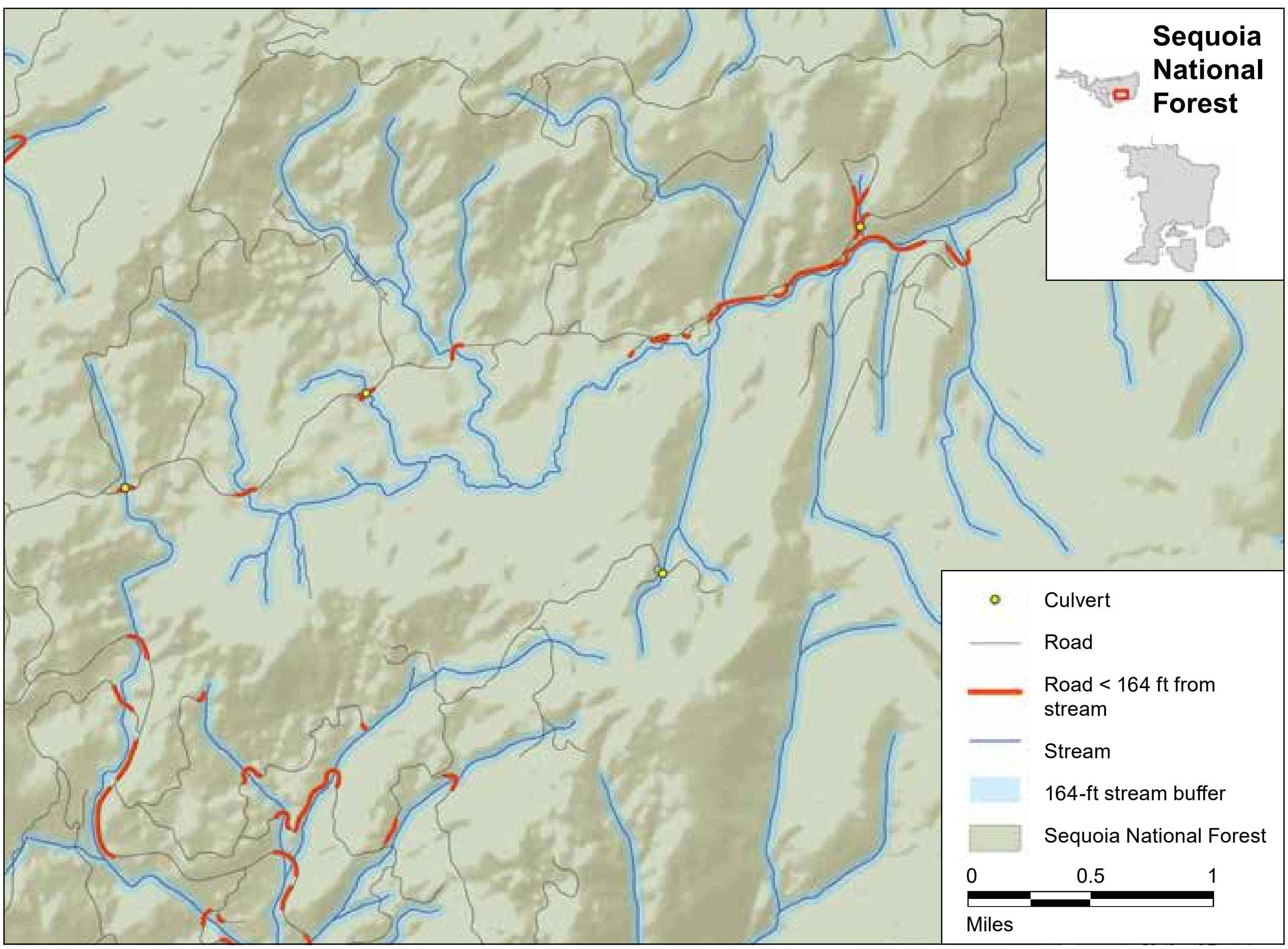


Figure 4.15—Map created using INFRA database showing locations where existing main roads are within 164 ft (50 m) of a stream and may be vulnerable to increased streamflows, road-stream crossing failure, stream diversion, and channel migration.

Sierra Nevada VIC model maps (see chapter 3) show areas of increased future bankfull flow near existing roads. Stream crossings may need to be armored, but areas where the road is parallel to or along the stream may be vulnerable during large storms that cause flooding or lateral channel migration.

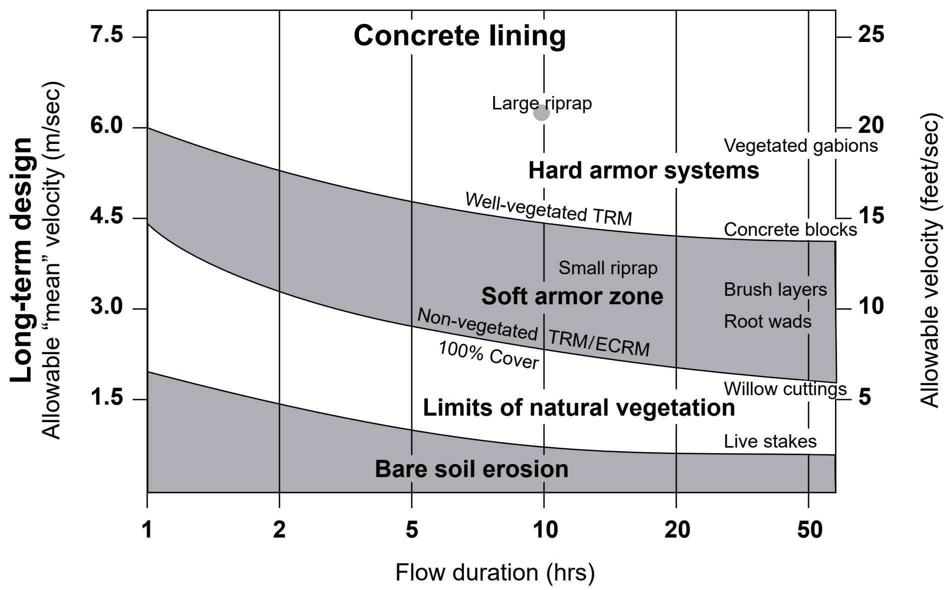
If road relocation is not an option, a detailed review of stream processes at the site and geomorphic processes in the watershed can be used to determine the hydraulic forces and channel dynamics that need to be included in treatment selection and design. Common problem areas are on the outside bend where considerable stream energy is expended and in areas of potential channel meander and avulsion. Aggradation of the streambed or channel widening owing to loss of riparian vegetation can contribute to channel migration. A relatively smooth but resistant treatment (including concrete or riprap) will only pass the stream energy to the next downstream unprotected bank, likely exacerbating the problem.

Local streambank and channel stabilization measures—

If streamflow velocities exceed the threshold velocities of the materials for movement (shear stresses), erosion and scour will result. These problems often occur where a structure has confined or redirected the flow of the channel, where flows have increased in the channel, or where natural protection such as vegetation has been removed from the channel or around a structure. Therefore, measures are needed to reduce the flow velocities, redirect the flow, dissipate the energy of the flow, provide scour resistance below the likely depth of scour, or armor the areas with materials that can resist the flow's forces.

A variety of streambank stabilization treatments are available to minimize the susceptibility of structures or streambanks to disturbance-caused erosion processes. They may be engineered grade-stabilization structures or vegetation-oriented remedies, ranging from conventional plantings to a combination of biological and engineering elements, such as soil bioengineering (McCullah and Gray 2005). Measures include the use of rock riprap, gabions, concrete slabs, cable concrete, turf-reinforcing mats, vegetation, and various biotechnical treatments. River engineering is an evolving field, and measures should not be undertaken without consulting qualified engineers and geomorphologists. Additional local and systemic problems can be created through improper design and implementation of river engineering techniques.

Figure 4.16 provides general guidelines for selecting channel and bank stabilization measures as a function of mean channel velocity and the duration of flow (i.e., how long the area is subject to inundation). Note that a transition zone is often needed between a hard-armor zone and the native streambed material. Ideally this work is tied into a stable channel feature such as bedrock or large boulders. “Environmentally sensitive channel and bank protection measures” (McCullah and Gray 2005) presents an excellent summary of the many river training, channel modification, and bank stabilization/armoring options available.



Notes:
1. Hard armor—includes concrete, riprap, gabions, concrete blocks, etc.
2. Soft armor—included turf reinforcement mats (TRM), erosion control revegetation mats (ECRM), vegetated geocells, and many biotechnical treatments
3. Available data shows considerable variability in limit velocities.

Figure 4.16—Allowable velocities and flow duration for various erosion and bank protection measures. (Figure adapted from Fischenich [2001], with information from Theisen [1992] and McCullah and Gray [2005])

Use of rock riprap—
Rock riprap is one of the most commonly used and misused erosion and scour protection measures. It confers resistance to high stream velocities when properly installed, is widely available, relatively low cost, durable, and adaptable to many sites. Vegetation can grow through riprap with use of live stakes driven through the riprap, and riprap can tolerate some movement owing to the self-healing behavior of loose rock. It can move to some degree, deform, conform to scour areas, and still provide erosion or scour protection. It can effectively armor an entire channel cross-section (above water and under water), armor streambanks to the expected high-water level, and armor a plunge pool or stilling basin. Riprap can be placed at the outlet of pipes, along the downstream edge of a structure, in a scour hole, or around and along channel protrusions, such as bridge piers.

The two most common reasons for riprap failure are improper sizing and poor installation. The most rigorous sizing criteria are based on shear stresses or tractive forces exerted by flowing water and sediment moving along the rock surface. The

FHWA publication “Design of Riprap Revetments, HEC-11” (Brown and Clyde 1989), provides a comprehensive design process for riprap sizing, using permissible tractive forces and velocity, along with design examples. “Bridge Scour and Stream Instability Countermeasures, HEC-23” (Lagasse et al. 2009) also discusses riprap design.

Design and installation details important to the success of riprap include (fig. 4.17):

- Use well-graded riprap to provide a dense armoring layer. The riprap layer should be at least as thick as the maximum rock size, preferably 1.5 times the maximum.
- Use hard, durable, and angular rock.
- Place riprap on a filter layer of either gravel or geotextile. The filter allows water to drain from the soil while preventing soil particle movement behind or beneath the riprap. In critical applications, a multiple filter layer may be desirable. A sand cushion over geotextile can prevent damage to the geotextile.
- Key in riprap around the layer’s perimeter, particularly along the toe of an armored slope and at the upstream and downstream ends of the rock layer, such that scour will not undermine the whole structure, nor make an end run behind the structure. Extend the protection through a curve or beyond the area where fast or turbulent flow is expected. Excavate the toe key to the depth of expected scour, or to at least several feet deep.
- Place riprap with an excavator or by hand to help achieve interlocking of the individual pieces. Dumped riprap will result in an uneven layer thickness and an unstable structure overall.
- Add extra volume of rock or an extra length of gabions at the toe of the protected area to help prevent scour and undermining of the structure.

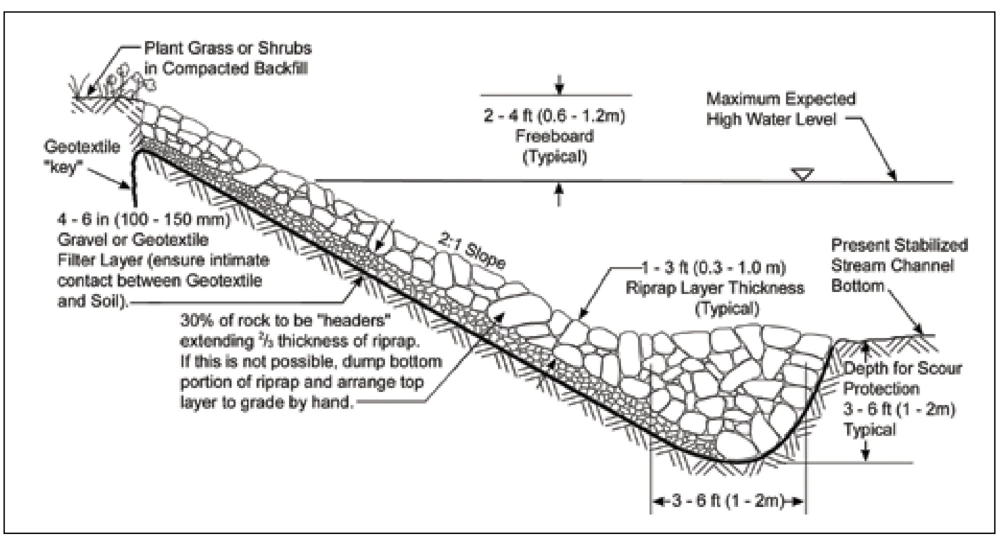


Figure 4.17—Typical riprap installation details for streambank protection. (Figure from Keller et al. [2011])

Other solutions for streambank instability—

Solutions for streambank instability often involve a combination of physical and soil bioengineering techniques. Streambank stabilization measures are often needed at road-stream crossings where a road fill may encroach on the stream, a culvert fill is placed across the stream, or where a flow constriction accelerates streamflow velocity, leading to local scour. The basic categories of protection measures for structures and streambanks are those that (1) armor the soil and increase local resistance to erosion and (2) reduce the force of water against the structure or streambank through flow redirection or energy dissipation.

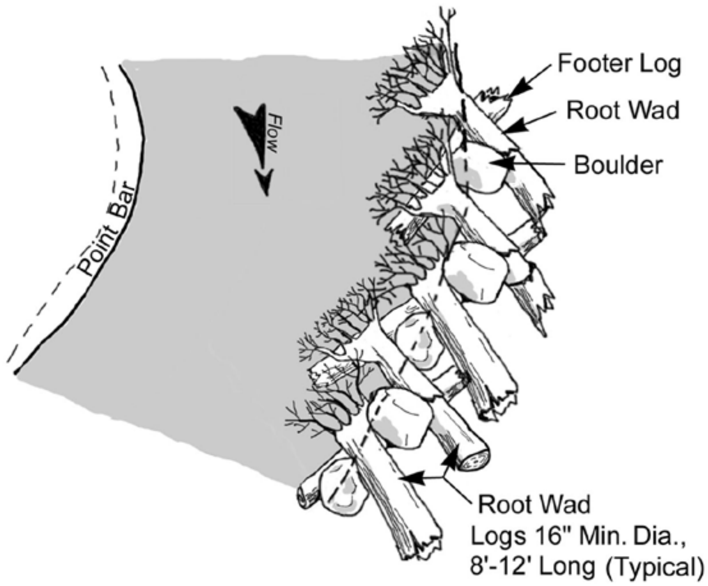
Examples of ways to increase local resistance to erosion include:

- Conventional natural vegetation
- Soil bioengineering measures such as live stakes, joint planting, brush mattresses, and live fascines
- Conventional engineering measures such as rock riprap, gabions, concrete structural biotechnical measures, erosion control blankets, turf reinforcement mats, root wads, boulder revetments, and articulated concrete blocks

The force of water can be reduced by river training structures such as spur dikes, groins, vanes, J-hooks, jetties, barbs, weirs, drop structures, in-channel logs (large woody debris) and boulders, increasing channel sinuosity, and vegetated floodways. A combination of methods is often used. Treatments such as use of wood and vegetation are typically most desirable, both to emulate natural energy dissipation features, and to help create the best fish habitat. Figure 4.18 shows a style of streambank stabilization using logs, rootwads, and boulders, where channel flow velocities are moderate. Log, rootwad, and boulder revetments have the advantage of creating channel roughness along with streambank protection, and they also create fish habitat. The Natural Resources Conservation Service Engineering Field Handbook, Chapter 16, “Streambank and Shoreline Protection” (USDA NRCS 1996) emphasizes use of vegetation, soil bioengineering, and biotechnical methods, as well as traditional structural streambank stabilization methods. Another useful reference for streambank stabilization is the Washington State Department of Fish and Wildlife publication “Integrated Streambank Protection Guidelines” (Cramer and Bates 2003).

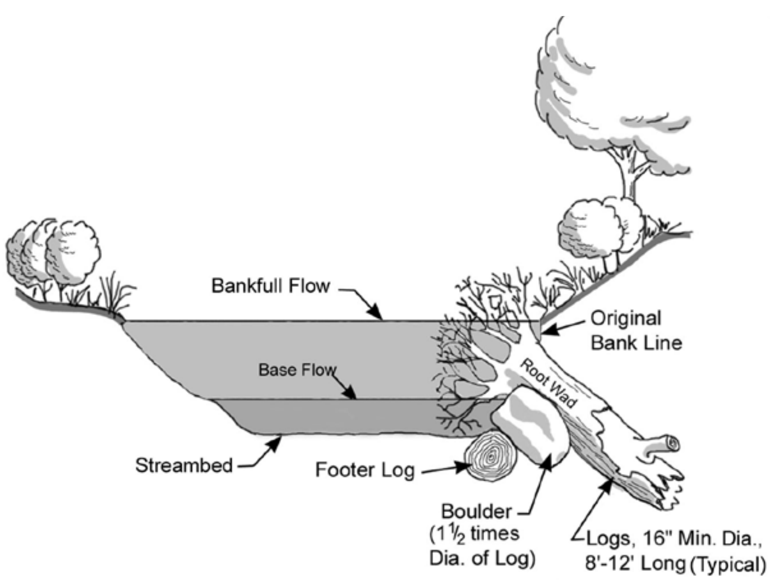
Soil bioengineering solutions for streambank instability—

Soil bioengineering is a technology that uses sound engineering practices in conjunction with integrated ecological principles to take advantage of the benefits of vegetation systems, arranged in specific ways, for long-term root support to prevent or repair damage caused by stream scour. Soil bioengineering systems create resistance to sliding or shear displacement in streambanks as they develop



Log, rootwad, and boulder streambank revetment plan view

Note: rock and log size will vary depending on site conditions



Log, rootwad, and boulder streambank revetment profile view

Figure 4.18—Typical log, root wad, and boulder streambank stabilization measures. (Figure adapted from Rosgen [1996], Eubanks and Meadows, and USDA NRCS [1996])

roots or fibrous inclusions. Environmental benefits derived from woody vegetation include diverse and productive riparian habitats, shade, organic additions to the stream, cover for fish, temperature reduction, and improvements in aesthetic value and water quality. Vegetation usually becomes increasingly effective over time and seldom needs maintenance. Useful information on streambank stabilization is found in “A Soil Bioengineering Guide For Streambank And Lakeshore Stabilization” (Eubanks and Meadows 2002).

Under certain conditions, soil bioengineering installations work well in conjunction with physical structures to provide more permanent protection and function, enhance aesthetics, and create a more environmentally acceptable product. This combination is commonly called biotechnical stabilization. Soil bioengineering systems normally use plant parts in the form of live cut branches or rooted plants or both. For protective measures for streambanks, live stakes, live fascines, joint planting through rock (vegetated riprap), vegetated geogrids and gabions, live cribwalls, branch packing, and live brush mattresses are all used in various configurations as appropriate for a specific location. Figure 4.19 shows joint planting systems with live stakes tamped through riprap.

Robbin Sotir

Gordon Keller

Figure 4.19—Biotechnical streambank stabilization using rock riprap and live willow stakes.

Other channel redirection and bank protection measures—
Many treatments have been developed to help protect structures and are used as river training structures to confine, direct, or focus the flow of water, as well as to provide some armoring and energy dissipation. Flow redirection techniques include the use of spurs, dikes, jetties, vanes, J-hooks, groins, barbs, floating log weirs, engineered logjams and large woody debris, boulder drop structures, and porous weirs. They are most commonly constructed with rock or boulders, and frequently used in conjunction with vegetation. These are useful when flow needs to be deflected or directed

away from the streambank, a structure, or the road. Rock-cross veins, boulder-drop structures, and stone weirs are used to focus the flow of water, prevent channel erosion and head cutting, as well as provide pool habitat. Floating log weirs protect the streambanks and rise and fall with the streamflow. Examples of rock vanes and rock drop structures are shown in figure 4.20. As discussed previously, moving the road or structure may be the best long-term solution and considered a BMP.

Useful publications that address many considerations in river dynamics, channel morphology, assessment of stream condition, and effects of structures on the channel (and vice versa) are "Applied River Morphology" (Rosgen 1996) and "Environmentally Sensitive Channel And Bank Protection Measures" (McCullah and Gray 2005).

Road Surface Drainage

With traffic and time, ruts will form in most roads, necessitating periodic maintenance. In the absence of maintenance, the best road drainage measures to prevent ruts are rolling grades, rolling dips, or water bars, or an inslope or outslope road. The following measures are used to construct and improve roads to prevent the concentration of water, move water rapidly off the road, facilitate control of water, and prevent storm damage:

- Close or relocate/reconstruct road segments with excessively steep road grades. The steeper the road grade, the more difficult it is to achieve road surface drainage. With steep grades, even roads with moderate cross slopes keep water on the road surface for a long distance. Road grades less than 10 percent are easiest for control of surface flow. Grades less than 6 percent are helpful on roads receiving infrequent maintenance.

John McCullah

John McCullah

Figure 4.20—Flow redirection measures used to protect streambanks and structures showing spur dikes (left), and rock drop structures or weirs (right).

- Maintain positive surface drainage with an outslope, inslope, or crown roadway section (fig. 4.21). A cross-slope of 4 to 6 percent is typical. Six percent may be ideal for drainage and require the least maintenance. Two percent may be adequate for a hardened surface and on flatter grades, such as a paved road.
- Roll grades or undulate the road profile frequently to provide locations to disperse water off the road.
- Use frequently spaced leadoff ditches to prevent the accumulation of excessive water in roadway ditches.
- Use roadway cross-drain structures such as rolling dips (or pipe cross-drain culverts, open top culvert flumes, or deflectors) to both move water across and off the road surface, and to move water from the inside ditch across and off the road surface. Space the cross-drain structures frequently enough to remove all surface water without excessive water accumulation. Because these features are intended to cut off and discharge accumulated ditch water, they must be cut to the bottom of the ditch, which may be relatively deep, and dam the ditch on the downgrade side.
- Protect cross-drain outlets with rock (riprap), brush, or logging slash to dissipate energy and prevent erosion, or locate the outlet of cross drains in stable, nonerodible soils, rock, or well-vegetated areas. Use downspouts to move water down a fill slope to a stable outlet area. A stable outlet location is critical. The ideal spacing from published tables needs to be adjusted to meet field conditions. Closer cross-drain spacing may eliminate the need for outlet armoring and minimize water concentration.
- Construct water bars on infrequently used roads or closed roads to control surface runoff and remove water from the road before it accumulates into an amount sufficient to cause erosion. Water bars are road surface features that do not intercept the ditch and may redirect road surface flow into in-board ditches on strongly insloped templates.
- Repair entrenched roads that are difficult to drain. The road may effectively become a canal. Ideally raise the road grade above the level of the adjacent terrain with fill material to be able to drain the road surface.
- Use catch-water ditches (intercept ditches) across the natural ground above a cutslope in areas with high intensity rainfall and overland flow. These ditches are useful to capture overland sheet flow before it pours over the cutslope and erodes or destabilizes the cut. However, be aware that catch-water ditches that are not properly maintained can become counterproductive pools of water above slopes, increasing the probability of slope failure or gully erosion.

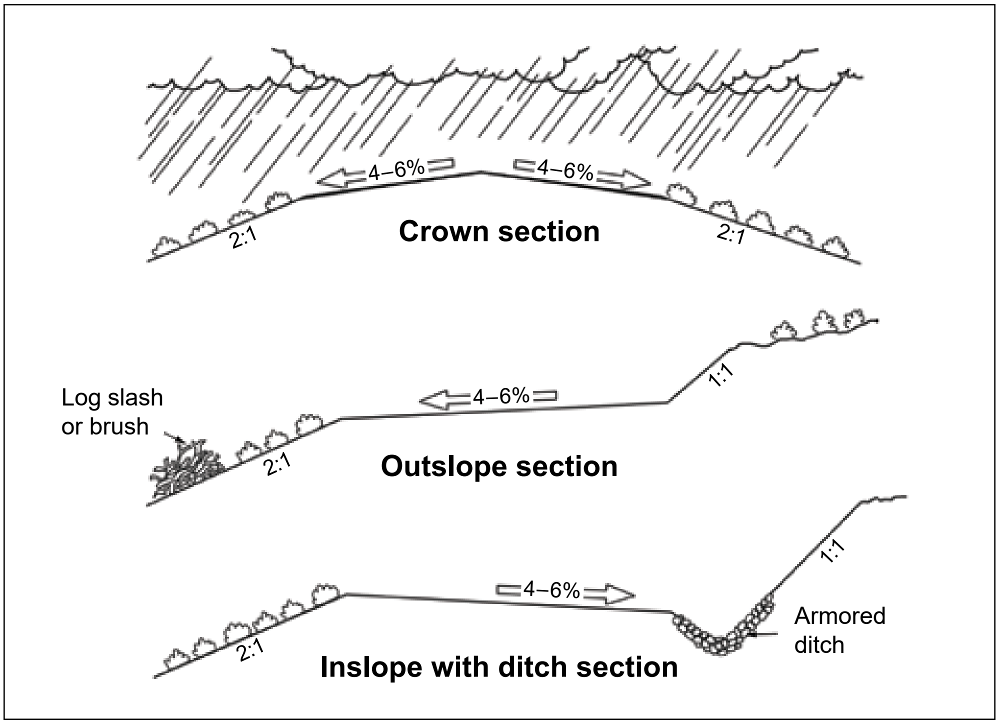


Figure 4.21—Basic road surface drainage options based on the shape of the road surface in cross-section: crown, outslope, and inslope sections. (Figure from Keller and Sherar [2003])

Note that many of the measures listed above may not be necessary if the flow can be adequately dispersed or the concentration or amount of water reduced. If ditch erosion occurs or armor is needed at the outlet of a pipe, ditch, or dip, it is a sign of too much concentrated flow. Adding more cross drainage or leadoff ditches may reduce the flow in the problem area.

Spatial and terrain analysis tools developed to assess road risks, such as the Water and Erosion Predictive model (Flanagan and Nearing 1995), Geographic Road Analysis and Inventory Package (GRAIP) (Black et al. 2012; Cissel et al. 2012a, 2012b), and NetMap (Benda et al. 2007), are often used to identify hydrologic effects and guide management on projects needing drainage and erosion control. For example, an analysis on the Umatilla National Forest determined that 12 percent of the road system contributes 90 percent of the sediment, which helps prioritize treatment plans focused on the most critical sites (Nelson et al. 2010). Similar findings have been observed with GRAIP modeling on other national forests (Furniss et al. 2018). Adequate drainage, as well as road surface armoring, could prevent much of that sediment loss.

For all water drainage applications on road surfaces, it is important to know the soil and hillslope conditions where water is discharged from the road onto the slope. Most mass slope failures below roads, as well as many gullies, result from excessive concentration of surface water running off the roads and saturation of marginally stable or unstable hillslopes. More detail on these drainage adaptation measures is found in “Storm Damage Risk Reduction Guide For Low-Volume Roads” (Keller and Ketcheson 2015). Information on road surface drainage, road damage prevention, and water quality protection is available in the “The water/road interaction technology (WRIT) series” (USDA FS 2000).

Using rolling dips (broad-based dips)—
Rolling dips (or broad-based dips) are designed to divert and remove water off the road surface and the roadway ditch while safely allowing for the passage of low-speed traffic (figs. 4.22 and 4.23). Rolling dips are a cross between a water bar and a grade break. They have a reverse grade to direct water off the road rather than down the road. Like water bars, they rely on a mound or high point at the downhill side to reverse or change direction of the flow of water.

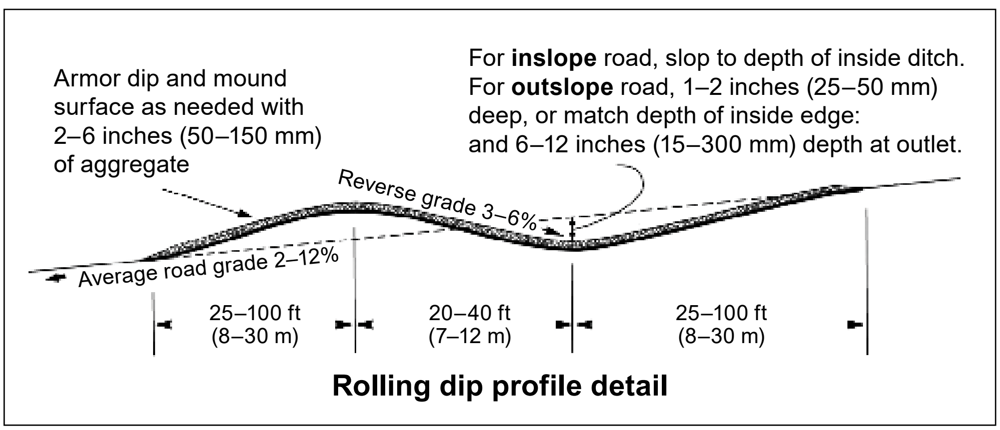


Figure 4.22—The form of a rolling dip, with a mound and reverse grade to prevent water from going past the dip. (Figure from Keller and Ketcheson [2015])

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Figure 4.23—Installation of typical rolling dip cross drains on roads. Rolling dips are commonly used on forest roads to remove water off the road surface. They can also be used as a dip to prevent stream diversion down the road and direct flow back into the natural drainage.

Rolling dips usually cost less, require less maintenance, and are less likely to plug and fail during a storm than culvert cross-drain pipes. The outlet area is often armored with rock to prevent erosion or the formation of a gully. Rolling dips are appropriate on low-volume, low- to moderate-speed roads (15 to 30 mi hr^{-1}). Rolling dips are typically not constructed on road grades over 8 to 10 percent, particularly for truck traffic.

Rolling dips should be constructed nearly perpendicular to the road, or ideally at a slight skew (of 25 degrees maximum), to minimize damage to truck frames driving through them and effectively change the direction of waterflow. The bottom of the dip should have a 2 to 5 percent outslope to ensure positive drainage. The entire structure should be long enough, typically 75 to 200 ft, to comfortably pass vehicles and equipment. Armoring material may be needed in the bottom of the dip where it intercepts the road subgrade to prevent rutting in soft soils, and at the dip outlet. The mound and dip should be armored with gravel or rock, particularly in soft soils, to maintain the shape of the rolling dip during traffic use. Operators need to understand the form and function of a dip, so the dip is not damaged during grader maintenance.

Converting inslope roads to outslope—
Conversion of roads from an inslope template, typically with an inside ditch, to an outslope road has long-term advantages, particularly to improve the road resilience to storms (and if a road will receive minimal maintenance). However, this can be an expensive treatment, involving a considerable amount of labor and earthwork. Outsloping is an ideal treatment for decommissioning roads so that they are self-maintaining.

On an outslope road, the roadway template is narrow (not requiring a ditch). As a result, there is a small cut and fill, slumping in the cut slope is less of a problem, initial construction is inexpensive, and minimal maintenance is required. The dispersed flow avoids concentrating water that is quickly moved off the road—road runoff does the least damage when it flows directly off the road and downslope, not down a roadway ditch. Without a ditch, additional width and cutslope excavation are not needed. Because ruts and berms concentrate water on any road surface, an outslope road functions best when built in conjunction with rolling dips. Thus, an outslope road can be the most desirable roadway template to use if it suits the local conditions. On most roads, some combination of inslope and outslope exists to accommodate the terrain, drainage needs, and traffic safety. To function properly, maintenance on an outslope road must not build up any berm along the outside edge of the road.

Outsloping is not appropriate where significant amounts of intercepted water from the cutslope occurs, or where a slippery, icy, or highly erodible road surfaces and fillslopes are a concern. Clay-rich soils, some silts, volcanic ash soils, and polished limestone rock all can be slippery when wet. Intercepted water in the cutbank may cause erosion or instability downslope. Drivers can feel unsafe, particularly on outsloped curves and in steep terrain. In steep terrain and on steep grades where the road surface may be slippery or have snow and ice, it is safer to use an inslope road template. In some cases, an inside ditch may be used along with an outslope road template where there are seeps or springs in the cutbank.

Figure 4.24 shows the form and relative dimensions of an inslope versus an outslope road. Conversion of an inslope road to outslope requires removing some of the fill and road shoulder material, and typically filling the ditch. New material may need to be imported to fill and raise the roadbed at the inside ditchline. Although an outslope road and rolling dips are among the most effective road surface drainage measures, other measures such as open-top culverts, small canals, and rubber deflectors have been used. However, these other measures have limited effectiveness and require maintenance, so are not commonly recommended.

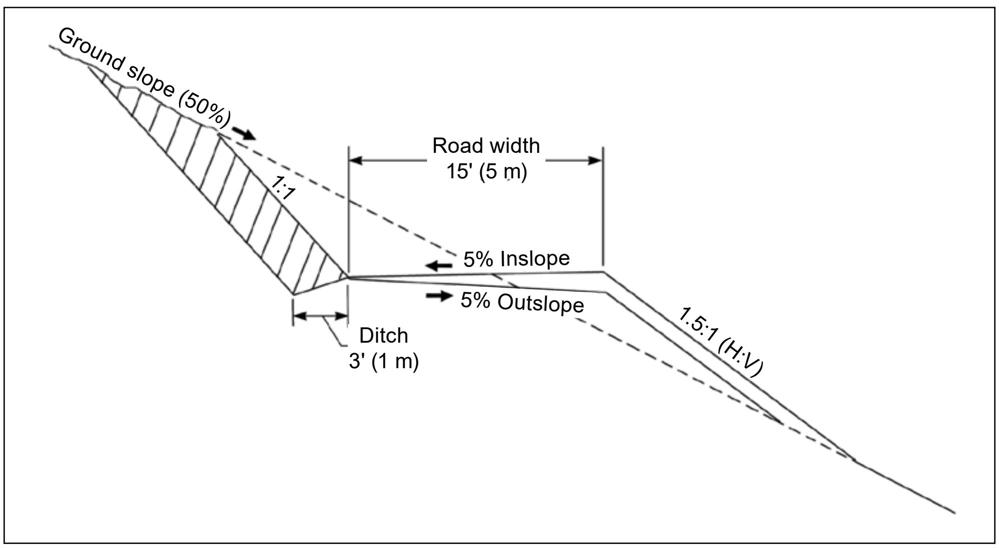

Figure 4.24—Road template of an inslope versus outslope road. The outslope requires less earthwork, less overall road width and loss of productive land, and best prevents water concentration. Backup cross-drains are usually needed in case the outslope road develops ruts. (Figure from Keller and Ketcheson [2015])

Cross-drain culverts (ditch-relief culverts)—

Culvert cross drains (relief culverts) are conduits buried beneath the road surface to discharge ditch runoff from the toe of the cut to the outside edge of the road. They are crucial on most inslope and crown roads to prevent excess concentration of water in the ditch. They are the most common type of ditch relief for road drainage and are most appropriate for high-standard roads where a smooth road surface profile is desired. They are also common on low-standard roads anywhere a ditch is constructed. However, cross-drain pipes are an expense, and the relatively small culvert pipes used for cross drains are susceptible to plugging during storms. During major storms, numerous small cross-drain culverts can plug and fail when intense rain mobilizes large amounts of sediment and debris.

Relief culverts are typically constructed with circular or arch pipes, or rectangular concrete or wooden boxes. An 18-inch-minimum diameter round culvert is most often used for ditch relief to help prevent failure from debris blockage. Smaller pipes plug easily. Some state forest practice rules require 18 inches as minimum size. Additional cross-drain pipes reduce the spacing between pipes and reduce the volume of runoff. Pipe size and spacing can be calculated by using the Rational formula with small-road watershed and local rainfall intensity-duration data. However, pipe size and spacing are more commonly based on local experience or on a recommended spacing from engineering tables and figures as discussed below. Plastic HDPE pipes are sometimes used because of their light weight and ease of construction. However, they can burn and be destroyed in a forest fire, so use on forest roads should be limited.

Culvert cross-drain pipe installation details are seen in figure 4.25. Culvert cross-drain pipes should be installed with an angle of 15 to 30 degrees skew to the centerline of the road, using a minimum outslope of at least 2 to 3 percent. Both are important to move water efficiently into the pipe and to prevent plugging. In addition, the outslope should be at least 2 percent steeper than the ditch grade it is draining to reduce deposition at the inlet and prevent debris from plugging the culvert. A berm or ditch-block structure is usually needed in the ditch immediately beyond the cross drain to ensure that water turns and enters into the pipe. This ditch block should completely fill and span the ditch. An excavated inlet basin is also commonly used. The pipe should exit at ground level to prevent a waterfall and erosion. On very steep ground, the pipe outlet area may need specific reinforcement such as live stakes and riprap. If significant outlet erosion occurs, additional cross drains may be the best solution to reduce the quantity of water.

The recommended range of spacing of cross-drain culverts, or rolling dips, varies (fig. 4.26). Spacing for maximum distance between rolling dips in cross-drain construction on forest roads is site specific and should be adapted for projected climate conditions and existing soil and slope conditions. Local experience and judgment should be used in selecting appropriate spacing values, based on field performance, topographic location, location of natural drainages,

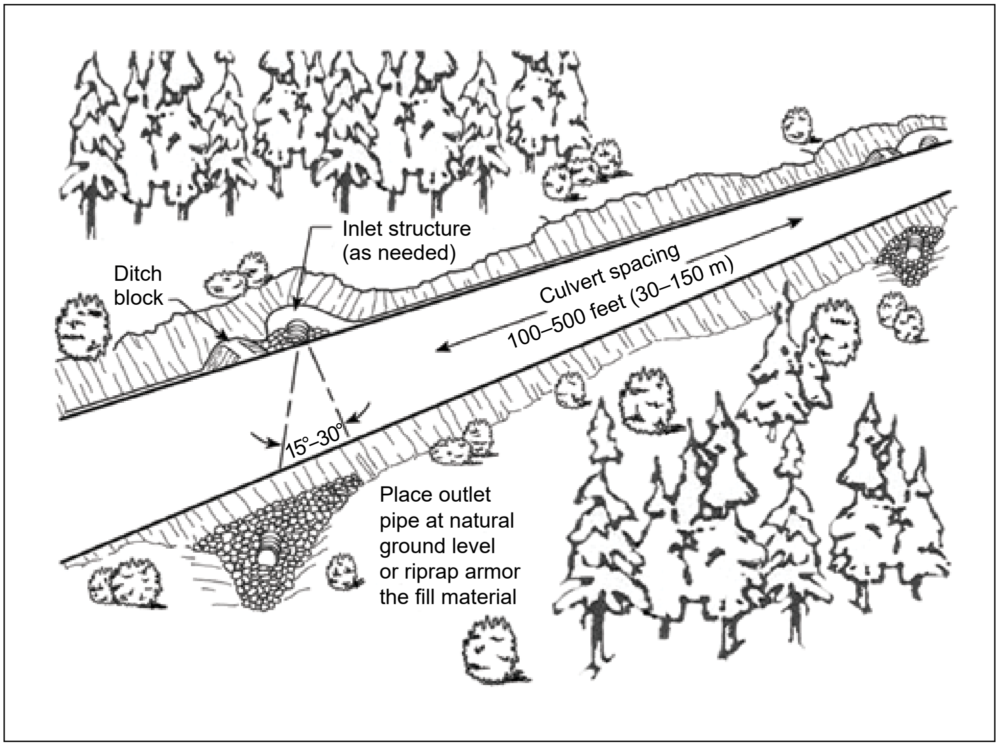

Figure 4.25—A typical culvert cross-drain installation. (Figure from Keller et al. [2011])

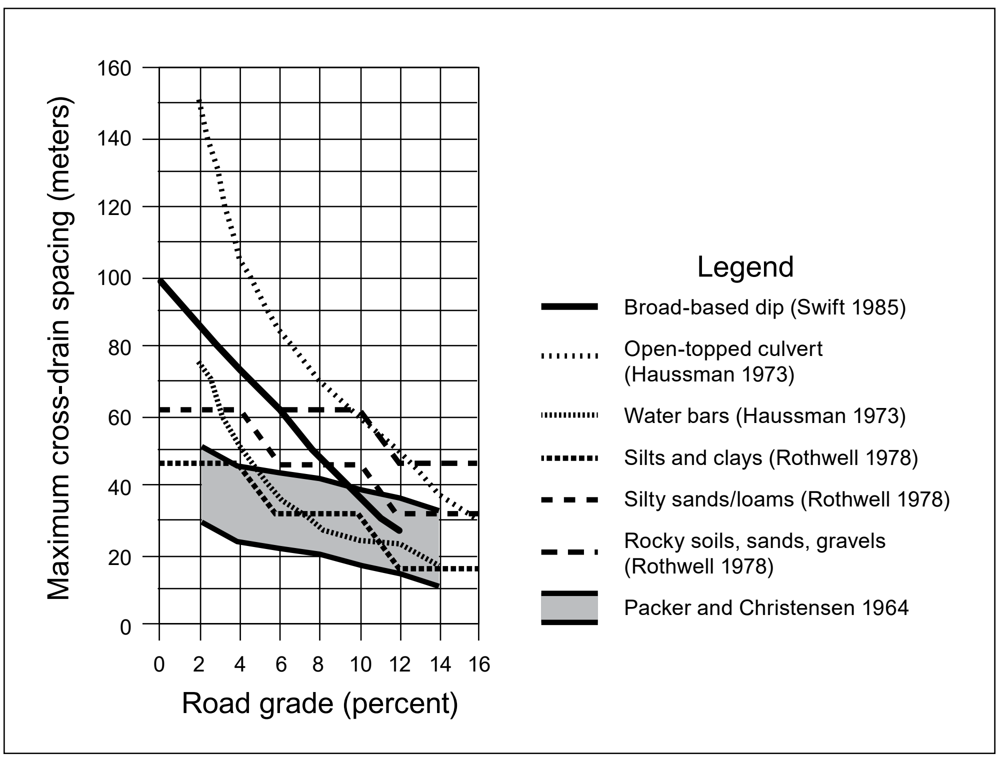

Figure 4.26—Range of recommended cross-drain spacing, as a function of road grade. Note: Conversion 1 m = 3.28 ft. (Figure from Copstead et al. [1998])

soil type, road surfacing material, rainfall, traffic, approach grade, and other local conditions. In sensitive areas (e.g., near riparian zones), spacing might be much closer than in adjacent upland areas.

Ditches and ditch treatments—

Ditches collect, move, and discharge water from the roadway. They should be large enough to carry the anticipated accumulation of water, and possibly be somewhat oversized to function during major storm events, especially when ditches have not been cleaned or maintained for a long time. They can also be a source of erosion if too much water is in the ditch or its velocity is too high. Water is removed from the ditch with ditch-relief cross drains, rolling dips, and leadoff ditches. If water cannot be adequately dispersed or removed from the ditch, then the ditch can be armored, commonly with rock or vegetation, or the velocity can be reduced with small check-dam structures. Check dams are problematic and need attention to installation detail. If a ditch is armored or lined, it may need to be initially "oversized" to accommodate the armor and still have the needed flow capacity. With armoring or check dams, the ditch can be difficult to maintain.

Leadoff ditches or turnout ditches are another way to discharge water and prevent accumulation of excess water in the roadway ditches (fig. 4.27). They

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Figure 4.27—A leadoff ditch discharging into the forest before reaching a live stream at the bottom of the grade (near the parked vehicles).

are an inexpensive alternative to culvert cross drains and should be used at every opportunity where the terrain is suitable. They usually do not use pipes that might plug in a storm. They are used in flat terrain where there is no cutbank at approaching drainage crossings, and at fill areas across a swale or ravine. In flat terrain, a leadoff ditch may need to be quite long to reach the forest and works best with an elevated roadway. They are also used at switchbacks where the road quickly changes direction across the slope to divide the waterflow. As with rolling dips or culvert cross drains, they should be discharged in nonerosive areas or protected outlets to prevent erosion. Alternatively, if terrain or circumstances do not allow for the use of a leadoff ditch, it may be possible to discharge the ditch water into a sediment catchment basin. To disconnect the road drainage from the stream, discharge the water into the forest or a vegetated area before the ditch reaches a stream channel, as seen in figure 4.27.

Water that runs in the ditch can erode and move large quantities of soil and debris. If a ditch is clearly necessary, frequent ditch-relief cross drainage is ideal to prevent water accumulation and reduce or prevent ditch erosion. However, this is not always possible where the ditch is deep or the road template is strongly insloped. Alternatively, when cross drains are not possible to construct, an eroding ditch can be armored with graded rock to decrease the velocity of water, prevent

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Figure 4.28—A rock-armored ditch to prevent downcutting and erosion of the ditch.

erosion and downcutting, and allow for the deposition of sediment (fig. 4.28). For slow velocities, a ditch armored with grass may have adequate lining. Small rock riprap is typically used, and for most ditches, a graded 3- to 6-inch rock size is ideal. A geotextile is sometimes placed under the rock as a filter to separate the rock from the soil and keep soil from washing out.

Ditch or pipe outlet armoring—

The accelerated velocity of water leaving a roadway ditch or culvert pipe can cause severe erosion or gullying if discharged directly onto erodible soils. Aligning and discharging culverts and cross-drain dip-drainage structures at the natural ground level away from a live stream and into a stable, nonerodible soil area will help reduce erosion. When necessary, the pipe, dip, or drain-outlet area can be stabilized, and the energy of the water dissipated, by discharging the water onto a few cubic yards of graded rock riprap (fig. 4.29). Outlet erosion is a sign that closer cross-drain spacing is needed.

Other energy dissipation measures include stilling basins or settling ponds, reinforced splash aprons, gabion baskets, or dense vegetation, slash and limbs, logs, boulders, or bedrock. When using slash, press the material into good contact with the ground, or mixed with varying sizes of debris to provide a ground-surface protection layer.

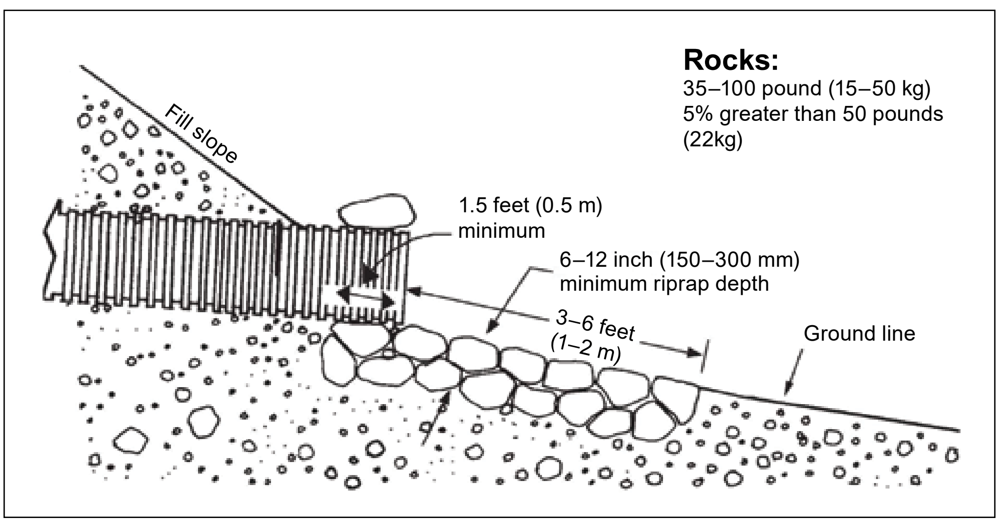

Figure 4.29—Detail of culvert-pipe outlet protection using small rock for riprap. (Figure from Keller and Sherar [2003])

Drop inlets and culvert cross-drain inlet protection—
Culvert inlet control structures, or drop inlets, are occasionally placed in the inside ditch line at the location of a culvert cross drain. Drop inlets are commonly constructed with concrete or masonry boxes or from round metal or concrete pipe. They need to be consistent with the size of the ditch and pass the accumulated flow in the ditch. They are an alternative to a typical excavated culvert inlet basin (catch basin) and are typically used where the ditch carries large amounts of sediment or is eroding and downcutting. Figure 4.30 shows some drop-inlet types. Inlet structures are useful to change the direction of water flowing in the ditch into a cross-drain pipe, particularly on steep grades, and are particularly useful to stabilize the ditch elevation at the level of the inlet window before entering the culvert, thus preventing downcutting erosion in the ditch. Concrete and masonry box structures often have a bottom set below the cross-drain pipe elevation, so that this area or reservoir serves as a trap for sediment (sand trap).

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Figure 4.30—A variety of culvert cross-drain drop-inlet structures are used on forest roads.

Entrenchment problems—
Many roads become entrenched after years of road maintenance or erosion, effectively leaving the road in a condition like a canal. Water can only run down the road and not escape, or in a flat location, the water just sits on the road like a "bathtub," saturating the subgrade. In some circumstances and if not too entrenched, leadoff ditches may be possible to divert the water. The best adaptation measure for long-term protection of the road is to raise the road to a level above adjacent terrain. Material can be imported or can be found excavating ditches along the road, or both (fig. 4.31). Once the roadbed or trail surface is above the adjacent terrain, it can be drained to move water from the surface.

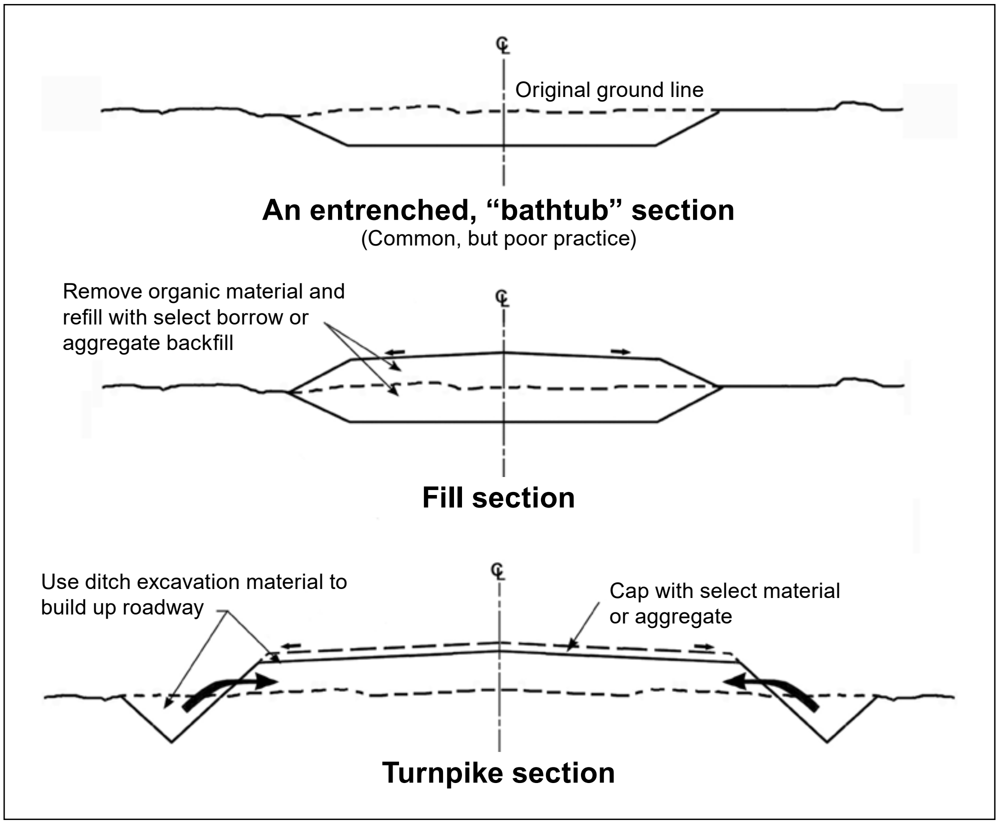

Figure 4.31—Road options in wet, flat terrain to elevate and drain the roadway surface. (Figure from Keller et al. [2011])

Culvert and Stream Crossing Structure Protection and Improvements

Roads constructed several decades ago often have culverts and bridges that are at the end of their design life, making them more susceptible to damage by extreme hydrologic events. Many stream crossings with culverts were designed to accommodate 25-year peak flows. Current standards typically require sizing for 100-year flows. Until recently, culvert sizing was generally expected to last only 25 years, representing a high probability of failure. For example, the probability of exceedance is 56 percent over a 20-year design life, and 87 percent over 50 years (Furniss et al. 2018, Gucinski et al. 2001). Now, because of age, undersizing of structures, and increased flows owing to climate change, culverts represent a vulnerable infrastructure feature, one that can cause road closures, high cost, and significant watershed impacts. Figure 4.32 shows typical forest INFRA data identifying the location of 36-inch or larger culverts on a forest road system in Sequoia National Forest. Pipes this size and larger are expensive and cause the greatest damage if they fail. Failure of the numerous small culverts found on forest roads also leads to cumulative watershed damage.

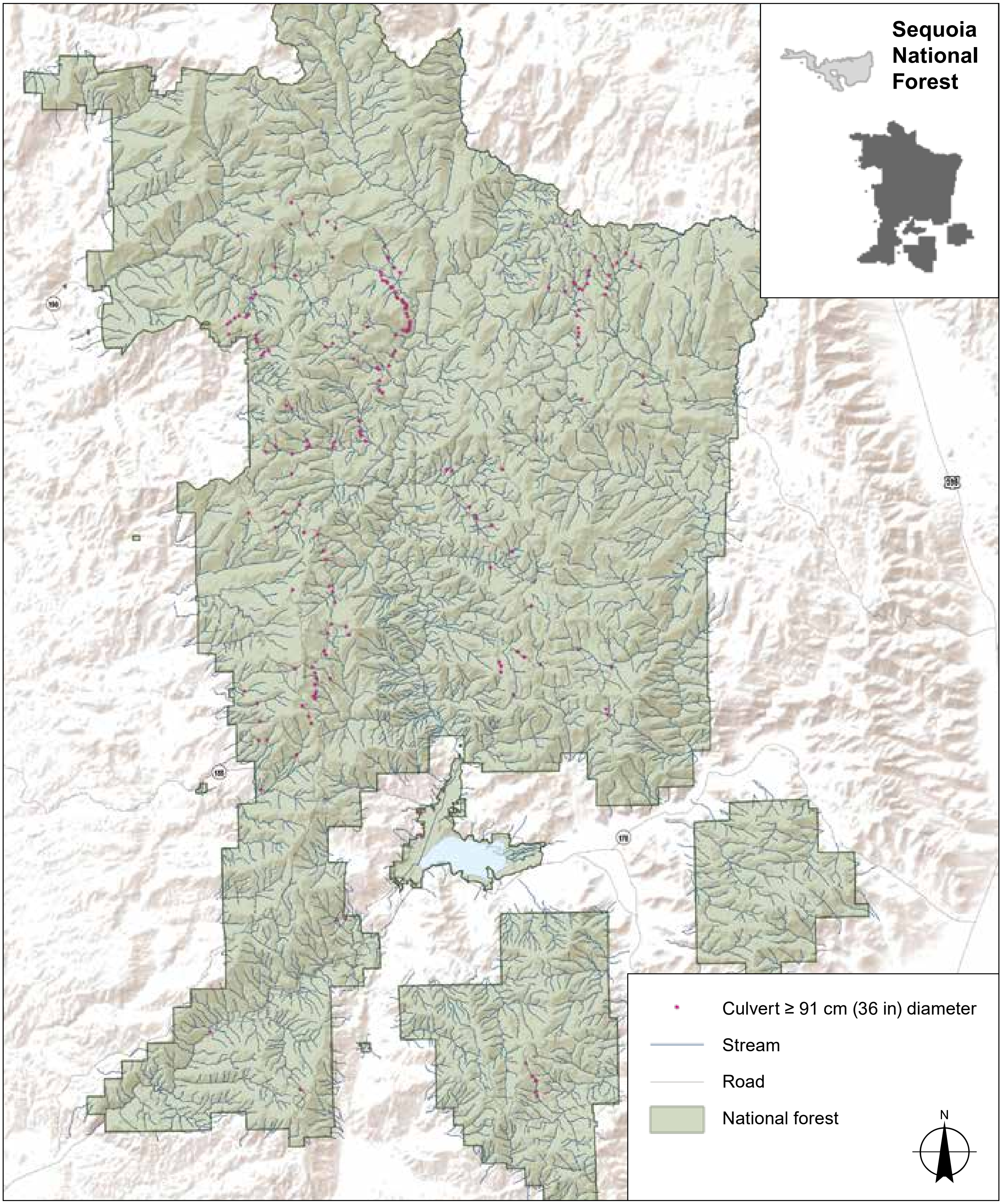

Figure 4.32—Example of forest INFRA data showing 36-inch or larger culverts on the road system, Sequoia National Forest.

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Figure 4.33—Problematic culverts owing to piping under the structure (left) or deterioration from a worn bottom (right). These culverts are at high risk of failure, particularly during major storms.

Culverts may need to be replaced, reinstalled, or realigned because of poor alignment, poor performance (e.g., piping under the old culvert), plugging, or deterioration. Furniss et al. (1998) and Cafferata et al. (2017) provide insight into culvert failures during storms and provide information to reduce the likelihood of culvert failures. Examples of a problematic undermined culvert (culvert piping) and an old, deteriorating culvert, both with high risk of failure during storms, are shown in figure 4.33.

Historically, many relatively small culvert pipes have been installed because of lack of analysis, low cost, or availability of small pipes. However, small pipes tend to plug with sediment and debris, particularly in semiarid regions (e.g., Sierra Nevada foothills) where channels are typically dry but subject to periodic flash floods or debris torrents. Small pipes can also be a problem in steep, rocky mountainous terrain. Channels that transport large amounts of coarse sediments frequently plug culvert pipes. In these areas, either relatively large box culverts or small bridges are preferred. Alternatively, simple unvented fords that pass a large amount of debris over the top of the structure may be most appropriate. Culvert reinstallation and alignment considerations include the following:

- Minimize channel modifications.
- Avoid constriction of the bankfull flow channel width.
- Use a stream simulation design with a pipe width exceeding bankfull width.
- Maintain the natural channel grade and alignment.
- Use high-quality, well-compacted bedding and backfill material.
- Use inlet, outlet, and streambank protection measures.
- Prevent stream diversion.

- Add trash racks in channels that carry large amounts of debris.
- Provide for aquatic organism migration upstream and downstream where needed.

Culverts should be aligned as close as possible to the specific reach of the channel where it is being placed. Locating culverts on channel bends should be avoided, but if necessary, the culvert needs to fit into the bend as much as possible, keeping in mind plugging and scour possibilities at the inlet and bank scour at the outlet. The pipe should be set at the elevation of the natural stream-channel bottom. Consider the average channel thalweg elevation through that reach of the stream. A culvert set too low can fill with sediment, lose capacity, and possibly cause headward (upstream) channel erosion. A culvert set too high can create a waterfall at the outlet, causing downstream channel scour and a possible fish passage barrier. Culverts installed as described here may also constitute a fish barrier simply by increasing the water velocity through the pipe. Culverts specifically designed for aquatic organism passage may include oversizing the pipe and burying the bottom in stream substrate to simulate natural channel characteristics.

Where aquatic organism passage and migration are needed or suspected, stream crossings should be evaluated, designed, constructed, and maintained based on USFS guidance for assessment and design (Clarkin et al. 2005, Stream Simulation Working Group 2008). Stream simulation installations both promote aquatic organism and fish passage, as well as provide a design that is well adapted for higher streamflows, as discussed below.

"Incorporating climate change into the design of water crossing structures" (Wilhere et al. 2016) offers a methodology for sizing culverts based on climate models and projected streamflows in the Pacific Northwest. Recommended culvert designs are then based on expected increases in bankfull width, considering cost, risk, and uncertainty in the analysis.

Culvert and channel maintenance—

Culvert maintenance and periodic cleaning of the pipe and channel near the inlet to the pipe are critical to proper function. Lack of maintenance contributes to many culvert failures. Ideally, pipes will receive maintenance before any major storm, although that can be guaranteed only by performing maintenance routinely and after the last major storm (fig. 4.34). Common culvert maintenance includes the following:

- Keep the inlet clear of wood, sediment buildup, rocks and vegetation.
- Ensure that headwalls are in good condition.
- Reline worn culvert barrels or replace the pipe.

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Figure 4.34—Culverts needing maintenance and with a high risk of plugging and failure because of logs across the inlet (left) and damage to the inlet (right).

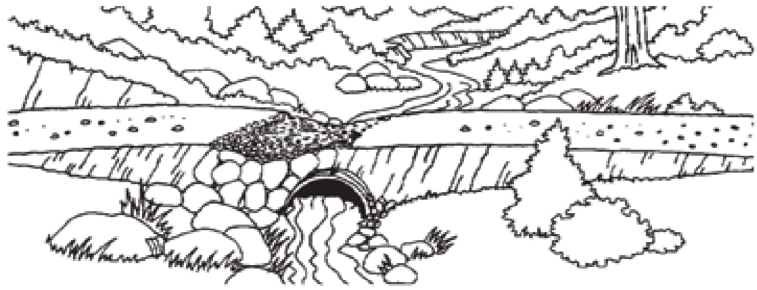
- Replace damaged or missing splash aprons or riprap.
- Bend back damaged metal blocking the entrance.

Culvert diversion prevention and overflow protection—

Stream diversion at culverts is a significant problem in many upland watersheds and can cause damage when water is diverted down the road. Diversion prevention is a cost-effective adaptation treatment for culverts at risk of overtopping and washing down the road. The physical consequences of exceeding the capacity of a stream crossing structure usually depend on the degree of exceedance, crossing fill volume, fill characteristics, soil characteristics, and the flow path of the overflowing stream discharge. When the structure capacity is exceeded, or if the culvert pipe plugs with debris, the stream backs up behind the fill. If the low point of the crossing is the ditch line, the water will divert down the road rather than flow directly over the road fill and back into the natural channel. At some point, the water will leave the road and erode fill and the hillside all the way to a channel (fig. 4.35).

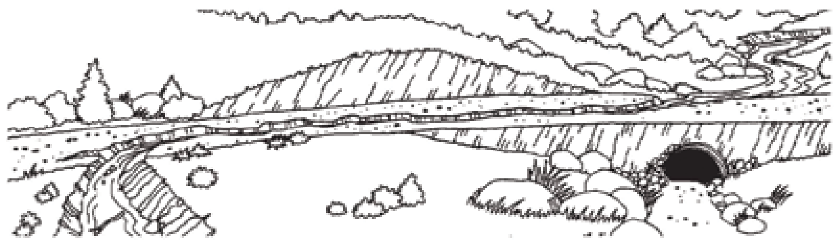
If the low point is over the pipe, or an armored dip is constructed in the roadway near the structure, water will flow across the road and return quickly to the channel (fig. 4.35a). Armoring of the dip or low point prevents erosion, downcutting, and additional damage to the road and fill. Also, in fire areas where considerable sediment and debris are mobilized and risk of culvert plugging is high, the entire fill embankment has been armored with geosynthetics, turf reinforcing mats, shotcrete, or gabion mattresses. A comprehensive discussion of roadway embankment overflow protection is found in “Minimizing Roadway Embankment Damage From Flooding: A Synthesis of Highway Practice” (Briaud and Maddah 2016).

Good installation

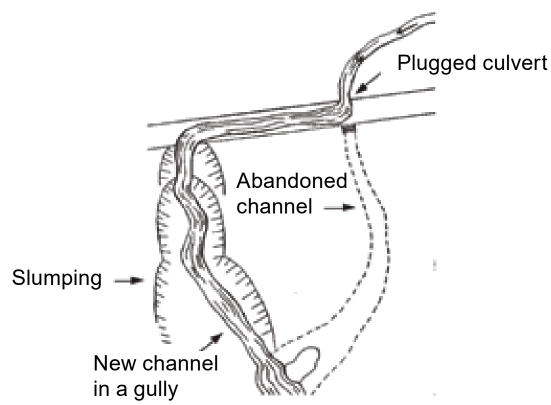


a. Armored dip over a low fill to prevent stream diversion

Poor installation



b. Sketch of a stream diverted down the road, forming a new channel



c. Consequence of stream diversion out of its natural channel

Mark Russell

Mark Russell

Figure 4.35—Existing undersized culvert fitted with an armored overflow dip to pass water without stream diversion or washing out the fill (a). Lower figures (b and c) show a stream diversion where a plugged culvert crossing sends water down the road rather than staying in its natural channel, causing considerable offsite damage. The bottom photos show a gabion mattress and turf reinforcing mats used to protect an embankment against overflow damage. (Figure adapted from Furniss et al. [1997])

Gordon Keller

Gordon Keller

Robin Stoddard

Robin Stoddard

Figure 4.36—Stream diversion caused by plugged, large culvert pipes (left) and subsequent cascading failure and road damage down the road (right).

Figure 4.36 shows stream diversions and subsequent damage to roads, where the roads were washed out for several hundred feet. Diversion potential exists on roads that have a continuous climbing grade across the stream crossing or where the road slopes downward away from a stream crossing in at least one direction.

In most cases, diversion will create much more damage than streamflows that breach the fill but remain in the channel. Research in Redwood Creek, California showed a 10-times increase in sediment delivery owing to gullying and debris slides triggered by stream diversion compared to a washout of the stream-crossing.[2] Stream diversion can be caused where a channel has severe aggradation, particularly on a fan deposit, where the channel periodically aggrades and shifts to a new location.

Stream diversion can also occasionally be caused by accumulations of snow and ice in a channel or on the road that directs overflow out of the channel.[3] Snow removal operations need to consider this potential effect and configure removed snow such that stream diversion will not occur (Furniss et al. 1997).

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[2] **Weaver, W. 2019.** Personal communication. Geomorphologist, Pacific Watershed Associates, Inc., PO Box 4433, Arcata, CA 95518.

[3] **Swanson, F. 2018.** Personal communication. Research geologist, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Forestry Sciences Laboratory, 3200 SW Jefferson Way, Corvallis, OR 97331.

On high-standard roads with risk of stream diversion but where travel speeds make a diversion dip or rolling dip undesirable, a designed failure point can be built into the road. This soft spot in the road that will wash out if flow goes over it is located where a dip would otherwise be located. This relatively soft failure point in the road subgrade can be constructed with fine gravel or sand rather than compacted soil).[4]

With the dip or a designed failure point, water can be diverted back into the natural drainage before flowing down the road, causing road and additional resource damage (see fig. 4.23). The cost of an overflow dip or designed failure point is small compared to the cost of replacing the entire fill, repairing major damage to the road, or the resource cost of the large, persistent gullies that diversions usually cause. Furniss et al. (1997) discussed the physical effects of diversion potential and provides design considerations for remediation of existing crossings with diversion potential.

Use of trash racks—

In forest environments, a common mode of failure is culvert plugging with organic debris, sediment, and rock, as opposed to failure resulting from lack of flow capacity. Storm damage studies in the Pacific Northwest determined that over 80 percent of culvert failures were caused by plugging from woody debris, sediment slugs, or debris torrents (Furniss et al. 1998). Trash racks can be very effective in preventing pipe plugging in channels with significant amounts of organic debris (fig. 4.37). Trash racks should be placed upstream of a pipe, or in some cases, placed immediately at the inlet of the culvert. Large debris racks are also occasionally placed in channels upstream of bridges. If a trash rack is placed upstream of a pipe or bridge, access to the location is needed for periodic cleaning.

Trash racks should be limited to stream crossings where culverts are undersized or prone to plugging, and require routine maintenance. Better solutions are typically the installation of a larger pipe, use of an overflow pipe or dip in case of plugging, or modifying the site to use a low-water crossing.

Consideration for the use of a trash rack at a crossing should include careful evaluation of the site and the conditions under which debris accumulation will occur. Trash racks can potentially cause more bank scour as water tries to flow around the structure, causing channel diversion. Trash racks can also create barriers to fish passage. Trash racks can become a liability if not maintained and need cleaning prior to storm events.

Many materials for and configurations of trash racks have been used (figs. 4.37 and 4.38). Most plugging wood size is near to or greater than the diameter of the

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[4] **Gubernick, B. 2019.** Personal communication. Watershed restoration geologist, U.S. Department of Agriculture, Forest Service, Eastern Region, Technical Services Team, 8901 Grand Avenue Place, Duluth, MN 55808.

Gordon Keller

Vincent Barandino

Figure 4.37—Use of trash racks to prevent plugging of a culvert from upstream sediment and debris.

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Figure 4.38—Two types of trash racks upstream of culverts, shown before storms (left photos, looking downstream) and full of debris after major storms (right photos, looking upstream). Note that trash racks must be cleaned and maintained.

culvert. Debris-rack bar spacing should be less than the diameter of culverts and close enough to catch large rocks and debris moving in the channel. A spacing of two-thirds the minimum culvert dimension is common. However, spacing that is too close will promote plugging of the trash rack and unnecessary cleaning and maintenance. Thus, spacing largely depends on the size distribution of material moving in the channel. Again, culvert size should be matched to channel width to minimize plugging and maintenance problems.

A slanted trash rack over the culvert inlet is more self-maintaining, since organic debris will slide up the rack, keeping the entrance to the culvert free. However, the inlet capacity of the culvert is diminished owing to the change in entrance hydraulics. The altered inlet hydraulics should be considered in sizing the pipe. Figure 4.38 shows trash racks before and after a storm event, indicating the need for maintenance and cleaning of the structure after a storm. Flared inlet sections on pipes or wingwalls serve to turn debris and funnel it through the pipe. A trash rack may be the least desirable way to prevent long-term pipe plugging, but it is a simple and inexpensive option that increases the resilience of existing pipes.

In areas where wildfires have recently burned, fine sediment, ash and debris are typically mobilized. A riser pipe with trash rack is used to prevent total plugging of small pipes where there is a lot of debris or sediment in the drainage (fig. 4.39).

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Figure 4.39—Two different designs of trash racks added to culverts in areas where wildfires occurred.

Stream simulation—

Newer or replaced infrastructure will generally have higher resilience to future conditions if climate change is considered in the design. New culverts and bridges are often wider than the original structures to meet agency regulations and current design standards. In the past 15 years, many culverts have been replaced to improve aquatic organism passage and stream function, using open-bottomed arch structures that are less constricted during high flows and accommodate fish passage at a range of flows. Natural channel-design techniques that mimic natural stream-channel condition upstream and downstream of the crossing are being used at these crossings.

In addition, culverts on non-fish bearing streams but in critical locations are being upgraded as funding and opportunities allow to make them more storm resilient. Thus, many structures built or replaced today need to ensure both aquatic organism passage and a 100-year storm event. The concept of stream simulation promotes these objectives and offers a desirable way to adapt culvert crossings to climate change. Both bridges and large multiplate steel culverts, often called "buried bridges," are ideal for stream simulation, because they can typically exceed the bankfull channel width, maintaining or creating a natural stream-channel bottom through the structure.

The stream simulation approach for designing road-stream crossing structures is a pragmatic and sustainable solution to maintain passage for aquatic organisms at all life stages, while meeting vehicle transportation and climate resilience objectives. The stream simulation design process integrates fluvial geomorphology concepts with engineering principles to create a natural and dynamic channel through the road-stream crossing structure. The premise of stream simulation is that the creation of channel dimensions and characteristics similar to those in the adjacent natural channel will enable fish and other aquatic organisms to experience no greater difficulty moving through the structure than if there were no crossing. Stream simulation channels are designed to adjust laterally and vertically to a wide range of floods and sediment or wood inputs without compromising the movement needs of fish and other aquatic organisms or the hydraulic capacity of the structure. Figure 4.40 shows a traditional hydraulic design culvert compared to a design that can achieve stream simulation.

Properly designed stream simulation projects for aquatic organism passage typically function well during major storms (fig. 4.41), particularly where the structure width is equal to or greater than the channel bankfull width. Several stream simulation culvert projects were evaluated on the Green Mountain National Forest, Vermont, in September 2011, following Hurricane Irene, with flows exceeding the 100-year design flood. Each structure survived with minimal problems, and performed flawlessly, maintaining aquatic organism passage at each site. Only some movement of the bed material was observed (Gillespie et al. 2014, Gubernick 2011). Many other conventional culverts and bridges in the region were damaged or destroyed. For a comprehensive discussion on stream simulation and aquatic organism passage, see Stream Simulation Working Group (2008).

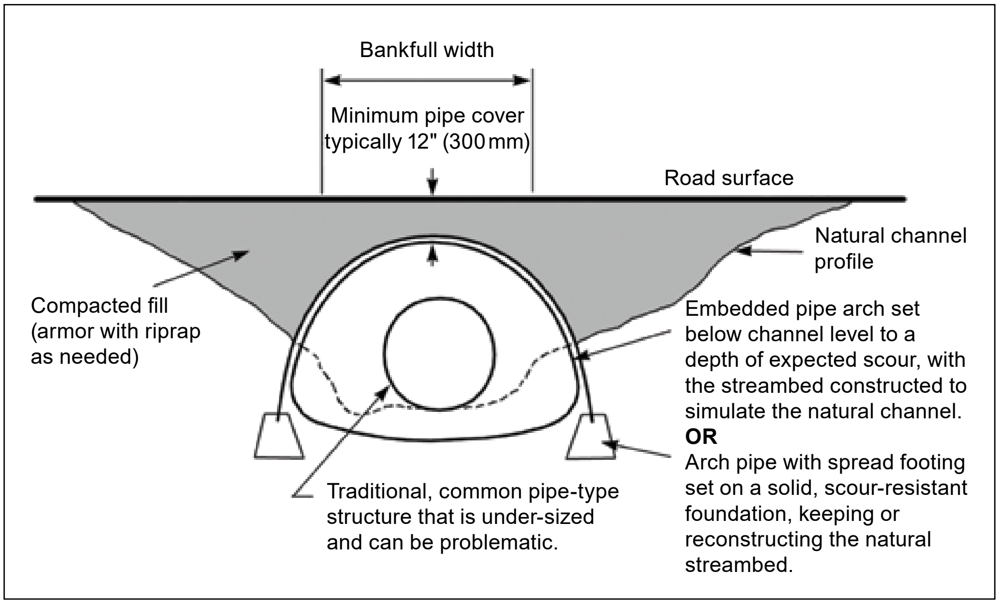

Figure 4.40—An improved or stream-simulation culvert installation compared to traditional culvert installations. (Figure from Keller and Ketcheson [2015])

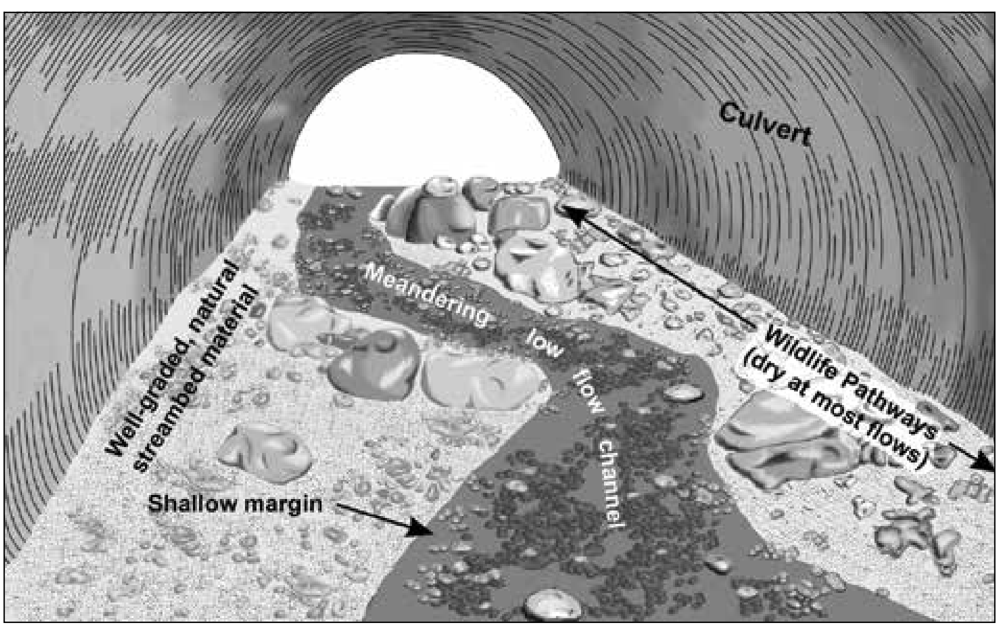

Figure 4.41—A stream simulation design through a culvert and a stream-simulation culvert installation. (Figure from Keller and Ketcheson [2015])

Fords and Low-Water Crossings

Fords and low-water crossings offer an alternative to culverts and bridges for stream-crossing repairs or replacement on low-volume roads where road use, streamflow conditions, and topographic setting are appropriate. Their construction or repair requires specific site considerations and geomorphic, soil, hydrologic, hydraulic, and biotic analyses. Conversion or selection of a ford is particularly useful if a culvert pipe has a history of plugging from channel debris. Fords, particularly vented fords, can be an effective adaptation strategy for road-stream crossings that have failed. They can be constructed to pass large flows and large amounts of debris, and provide suitable aquatic organism passage. As seen in figure 4.42, a large waterway open area is provided, the natural substrate material is maintained through the structure for aquatic organism passage, and it is designed to be overtopped, even if the vents plug with debris.

Gordon Keller

Figure 4.42—A large vented ford that is resilient and has a predominantly natural stream channel bottom, ideal for aquatic organism passage. High flows can pass readily over the structure, but aquatic organisms are unchallenged by the natural channel bottom.

Low-water crossings may have a simple rock reinforced (armored) driving surface, or an improved, hardened surface such as gabions or a concrete slab may be used. Vented fords combine the use of culvert pipes, box culverts, or open bottoms to pass low flows and a reinforced driving surface over the culverts to support traffic and keep traffic out of the water most of the time (fig. 4.43). The reinforced driving surface over the vents resists erosion during overtopping at high-water flows. The entire wetted perimeter of the structure should have a "U" shape and be protected to a level above the anticipated design high-water elevation.

The main advantages for using low-water crossings or fords are outlined below. Many of these considerations reflect the uncertainty and potential impacts of climate change, thus making fords a desirable adaptation solution.

- Fords are relatively low-cost hydraulic structures, particularly when compared to bridges. Initial cost can be moderately high, but they require minimal maintenance and repairs if properly designed.
- Fords are generally more "forgiving" than large culvert structures. When flow data are unreliable, a ford can be easily designed to protect the wetted flow area and allow for uncertainty in peak flow.
- Fords can be used with minimal delays most of the time without the cost of larger structures, such as bridges, which need to span the peak-flow limits.
- Fords can easily accommodate low normal flows and occasional high peak flows.
- Fords are not susceptible to plugging failures, because the design involves most of the flow over the top of the structure. Thus, they are good designs in drainages subject to debris torrents or in drainages that carry large amounts of debris.

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Figure 4.43—Examples of a simple rock-armored ford in an ephemeral channel (left) and a vented ford on a perennial stream channel (right).

In streams carrying large amounts of debris, the driving surface over the vent may be removable, such as a cattle guard, permitting debris to be cleared after a large flow event. Figure 4.44 shows a large pipe that had plugged several times in large storm events. The pipe was eventually replaced with a concrete vented low-water crossing designed with a metal cattle guard top that can be removed for cleaning. For additional technical information, see "Low-Water Crossings: Geomorphic, Biological and Engineering Design Considerations" (Clarkin el al. 2006).

Figure 4.44—A 10-ft diameter culvert that plugged several times with debris (top photos) and was replaced with a vented low-water crossing (bottom photo).

Bridges

There are 684 USFS-owned bridges in the Sierra Nevada region that are regularly inspected per FHWA criteria. Of these, 145 are structurally deficient and need work, but are still in service (table 4.4). Some structures coded as bridges in the INFRA database are actually "buried bridges," or major culverts with a span of over 20 ft. Some structurally deficient bridges may be adequate and are coded incorrectly. Many older bridges are constructed of timber, and the remaining bridges are constructed of concrete and steel. Many timber bridges, which were constructed during the 1960s, are relatively short, resulting in scour near bridge abutments. Most timber bridges are nearing the end of their intended lifespan, whereas most concrete and steel bridges have a longer lifespan, were designed adequately for flows, and are still in good condition. New USFS bridges and bridge replacements are designed in accordance with the agency's aquatic organism passage stream simulation guide (Stream Simulation Working Group 2008), making bridges more resilient to climate change (Furniss et al. 2018).

Bridges are a major investment, requiring protection to prevent failures. Good bridge design and bridge-scour protection measures should be built into the initial design. However, changes over time can affect the hydrology of the watershed,

Table 4.4—Bridges and bridge condition in Sierra Nevada national forests

National forest/unit	Adequate bridges	Structurally deficient bridges	Total bridges
Eldorado	26	10	36
Inyo	25	1	26
Lassen	13	68	81
Modoc	14	0	14
Plumas	82	54	136
Sequoia	62	0	62
Sierra	162	7	169
Stanislaus	117	4	121
Tahoe	31	0	31
Lake Tahoe Basin Management Unit	7	1	8
Total	539	145	684

Note: Numbers include bridges plus major culverts (over 20-ft span). The large number of structurally deficient bridges on some forests is likely due to coding differences in the INFRA database.

thus increasing stormflows, putting older bridges at risk. Watershed characteristics may change because of new land uses, logging, or forest fires. Climate change will contribute to more intense storms, longer duration storms, or runoff from rain-on-snow events. Thus, old bridges may have marginal hydraulic capacity for storm runoff. Some bridge protection may be needed over time and added in the form of erosion and scour protection to prevent undermining of foundation piers or abutments. Bridges are costly, so scour prevention measures are a high priority. These include the following:

- Foundation repairs and grouting
- Clearing the channel of trees and debris
- Riprap placement around piers or abutments
- Channel lining with riprap or gabions
- Redirecting flows with barbs or rock jetties

Bridge work is facilitated by an interdisciplinary team including hydrologists, geomorphologists, earth scientists, engineers, and fish biologists.

For structures with inadequate flow capacity, the superstructure can be raised to increase freeboard. In some cases, an overflow dip can be built into approach fills, particularly fills that block a historical floodplain, to provide a controlled failure point that can be repaired rather than losing the bridge structure. Channel maintenance, as discussed earlier, can also increase the bridge flow capacity and reduce the chance of plugging or blockage during a storm.

Many changes can occur at a bridge site and in the watershed upstream of the bridge over time. Climate change and variability in hydrologic dynamics can affect peak flows and the amount of sediment transported through the stream system. More snowmelt runoff may be expected at times in some watersheds because of climate variability and extreme events. Thus, bridges should be carefully evaluated for increased storm damage risks that were not anticipated at the time of construction. Understanding the processes at work in the watershed upstream and downstream of a bridge site is critical for determining the most cost-effective treatment.

Channel maintenance and debris and sediment clearing—
Channel debris and vegetation may cause scour problems or plugging for bridges. Common countermeasures for an existing bridge with debris problems include:

- Monitor debris buildup for prompt removal.
- Clear upstream debris and vegetation.
- Install debris catchers or deflectors (maintenance required).
- Remove sediment or areas of aggradation that decrease channel capacity.

Channel clearing and maintenance help maintain bridge flow capacity. Any "symptoms" are likely the result of natural stream and riparian processes, or altered processes resulting from the presence of the structure itself, an encroaching roadway, or land use upstream. Most treatments are only temporary and will require occasional new clearing of debris and vegetation. The best long-term solution should consider the replacement of the bridge with a longer, higher structure, or relocation of the structure to a less susceptible site.

Undesirable vegetation and debris should be removed from the channel near the structure, particularly for the bankfull width of the channel. This work is often controversial, because channel disturbance should be minimized, yet the structure flow capacity should be maximized, and risk of blocking a bridge should be minimized. A balance is needed to remove counterproductive vegetation yet leave vegetation needed for channel stability and ecological benefits. Clearing and removal of channel material can be damaging and difficult. Therefore, decisions regarding channel clearing are facilitated by an interdisciplinary process.

Figure 4.45 shows a channel with vegetation encroachment, some of which should be removed to prevent potential blockage of the channel during a flood. Vegetation established in a stream-channel bottom is not normal unless there has been a change in the runoff pattern or volume. Understanding the watershed condition and what has caused the change can provide insight on ramifications of the change for streamflow at the structure site.

Aggradation in the channel can reduce the cross-sectional area of a bridge and thus reduce flow capacity (fig. 4.46). This tends to occur on a river bend where a point bar develops on the inside of the bend. Some channel deposits need to be periodically removed to maintain bridge flow capacity. This material is typically sandy gravel, so it may be useful as fill or surfacing material in another area. Some gravel and boulders are needed in the channel to provide bed material for fish spawning.

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Figure 4.45—Stream channel under a bridge that needs clearing and tree removal if flows are being blocked or diverted, or there is risk of plugging the bridge.

Gordon Keller

Bob Gubernick

Figure 4.46—Bridges with significant channel aggradation. In the left photo, the left bank has formed a point bar on the inside of a river bend that needs removal to maintain bridge flow capacity. The point bar will rebuild with time, creating a continual maintenance problem at this bridge site. Bends are often poor locations for bridge sites because of persistent sediment deposition and channel changes.

Increasing freeboard—

Lack of capacity and freeboard can lead to bridge failure by catching floating debris that can push the superstructure off its abutments (fig. 4.47). Stream channels in areas of aggradation, on alluvial fans, and carrying significant amounts of large woody debris all have the potential of plugging a bridge. In these areas, bridges should be evaluated for their freeboard and consideration given for raising the structure if possible. Freeboard should typically be a minimum of several feet, depending on conditions in the upper watershed. Alternatively, some channel clearing may be warranted (after consideration of potential adverse environmental impacts).

Gordon Keller

Figure 4.47—A failed bridge because of a lack of freeboard and accumulation of debris behind the bridge deck.

Solutions to lack of freeboard are not simple. Either the structure can be replaced with a longer span to increase the waterway open area of the structure, or the superstructure (girders and deck) can be raised. The success of these measures depends on the shape of the topography around the bridge. Raising the bridge deck in flat terrain may accomplish nothing if the flood waters just spread out across a floodplain, but a longer structure could be more useful. Figure 4.48 shows a Bailey Bridge superstructure with marginal freeboard and debris stuck in the superstructure after a flood. The problem was solved by adding height to the abutments and piers, thus raising the deck and placing a new concrete superstructure across the span.

Figure 4.48—A bridge with marginal freeboard (left) whose abutments and piers were raised (right) to add freeboard and flow capacity.

Bridge scour and protection—

Bridge foundation scour is one of the most common causes of bridge damage or failure during storm events. Common forms of scour at bridge sites are contraction scour, general channel scour, and local scour around piers and abutments (fig. 4.49). Determining the depth of scour and amount of potential bedload movement need to be evaluated at bridge sites, particularly if the site has historical scour problems or appears undersized. In coarse, rocky channels with boulders, scour depth may be less than 2 ft; in gravel channels with cobbles, scour may be several feet deep; and in fine sandy river channels, scour of over 50 ft has been observed.

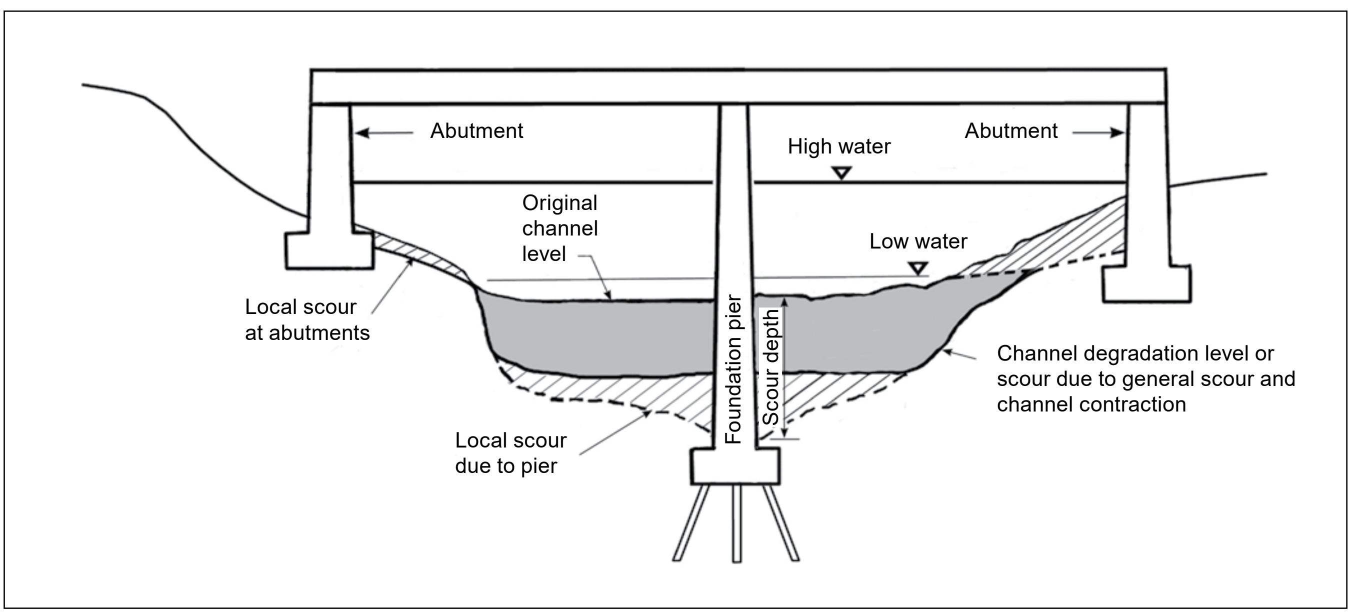

Figure 4.49—Scour types and common scour problem areas around a bridge. (Adapted and reproduced with the written authority of the Transportation Association of Canada, from Neill [1973])

Determining scour depth requires evaluation of the channel and bed material characteristics. Programs developed by the U.S. Army Corps of Engineers have methods for determining scour depth. Bridges that are classified as "scour critical" in the National Bridge Inventory System are potentially vulnerable, high-risk structures that should be given priority for adaptation measures. Common mitigation measures used for protecting bridges against scour include:

- Locate a structure where the local materials are not scour susceptible (e.g., coarse rock, bedrock).
- Widen a structure to avoid constricting the flow channel, thus avoiding flow acceleration.
- Armor the entire channel with scour-resistant materials (grouted gabions, riprap, concrete, etc.).
- Protect the channel, streambanks, and abutments against local scour, using vegetation, root wads and logs, riprap, sack concrete, articulated concrete blocks, vegetated turf reinforcing mats, gabions, etc. (fig. 4.50).
- Redirect stream channel flow with barbs, spur dikes, weirs, cross vanes, etc.
- Install deep foundations, placed below the anticipated scour level, such as relatively deep spread footings, or drilled or driven piles.
- Add shallow scour-cutoff walls, gabion or concrete splash aprons, plunge pools, or a riprap layer along the downstream edge of an in-channel structure.
- Install deep cutoff walls or deep sheet piles below the depth of scour, or to scour-resistant material (e.g., bedrock).

Figure 4.50—Bridges with scour protection provided by rock riprap (left) and gabions (right) around the abutments. Protection is needed for bridges that are located on bends in the stream.

Additional information on scour can be found in Kattell and Eriksson (1998), Lagasse et al. (2009), USDOT FHWA (2009), and Richardson and Davis (2001).

Stream channels are dynamic and tend to meander or shift laterally, longitudinally, and vertically over time, particularly in low-gradient environments. They can change flow direction during flood events and may reoccupy some historical floodplain deposits. Figure 4.51 shows a bridge site where stream meander or change in flow direction eroded a bridge abutment and approach fill. The repair involved extending the concrete wingwall and providing upstream bank protection with riprap. The best solution would have been a longer bridge span, but spans long enough to accommodate stream meander are often impractical. Evaluating the location of bridge abutments for long-term channel stability and possible stream channel adjustments aids bridge resilience.

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Figure 4.51—Abutment scour caused by channel meander (left). The repair (right) extended bank protection upstream from the bridge. Note that the bridge constricts the original stream channel.

Erosion Prevention and Control

Erosion prevention on roads, the entire road prism, and on disturbed areas is fundamental for the conservation of topsoil and protection of water quality. Road and trail surfaces, roadway cut and fill slopes, and disturbed developed areas all contribute to accelerated erosion. More intense storms and increased runoff promote more soil movement, erosion, and sedimentation to local water courses, so prevention of erosion is an important adaptation strategy. The two main causes of erosion are concentration of flowing water and lack of ground cover over the soil.

Erosion control measures need to be implemented immediately following construction and every time an area is disturbed. They particularly need to be implemented before the first winter period following construction or ground disturbance, and before a major storm event. In areas of construction, ground cover is difficult to achieve, so sediment is typically trapped around the site. The area of disturbance can also be limited and areas can be progressively rehabilitated.

Waterflow concentration should be prevented, or eroding channels should be armored or stabilized to reduce erosion. Trapping sediment before it enters natural drainage channels is critical, but priority should be given to treatments at the erosion source. Bare ground can be covered with matting or mulch to reduce initial erosion and promote vegetation growth.

Surface erosion from road surfaces, shoulders, cuts, and fills is significant (Gucinski et al. 2001). Movement of sediment can occur during and after road construction, after road maintenance, during logging or mining activities, if a road is closed but not stabilized, or from poor land management practices near the road. Roughly half of the erosion from a logging operation comes from the associated roads and skid trails. Mass erosion rates from roads are typically one to several orders of magnitude higher than from other land uses (Gucinski et al. 2001). Much of that erosion occurs during storm events and during the first year after construction.

Erosion control requires prevention of short-term erosion from bare or exposed soil, and control of long-term erosion through the establishment of vegetation. In steep or severe conditions, a retaining wall, ground armoring with rock, or a gully plug can be effective. Good erosion control treatments typically promote germination and growth of plants, encouraging natural recruitment from the surrounding native plant community. Conserving native topsoil and respreading it over an area help promote native plant growth.

An erosion control plan describes local conditions, possible problems, possible solutions, and costs for control, and they can include an evaluation of the most effective physical, vegetative, and biotechnical treatments. Short- and long-term measures can be planned, as well as an evaluation of needs such as fertilizers, irrigation, and protection measures. “Erosion Control Treatment Selection Guide” (Rivas 2006) and “Erosion and Sediment Control Practices for Forest Roads and Stream Crossings” (Gillies 2007) describe erosion control principles, erosion control treatments, and treatment selection by engineers and other specialists.

Where erosion occurs along roads—

Most disturbed road areas, including the road surface, road fills, some road cuts, shoulders, and drainage ditches, are exposed to erosion at some time. Other associated areas such as landings, skid roads, construction staging and storage areas, and borrow pits and quarries can erode and produce sediment. Common types of road erosion include sheet and rill erosion on the cutbank (and fillslopes), ditch and road surface erosion, and gully erosion when water becomes concentrated (fig. 4.52). Physical, vegetative, soil bioengineering or biotechnical methods can be used to reduce erosion. Effective erosion control requires assessment of the situation, attention to detail, inspection and quality control during installation, and post-project maintenance.

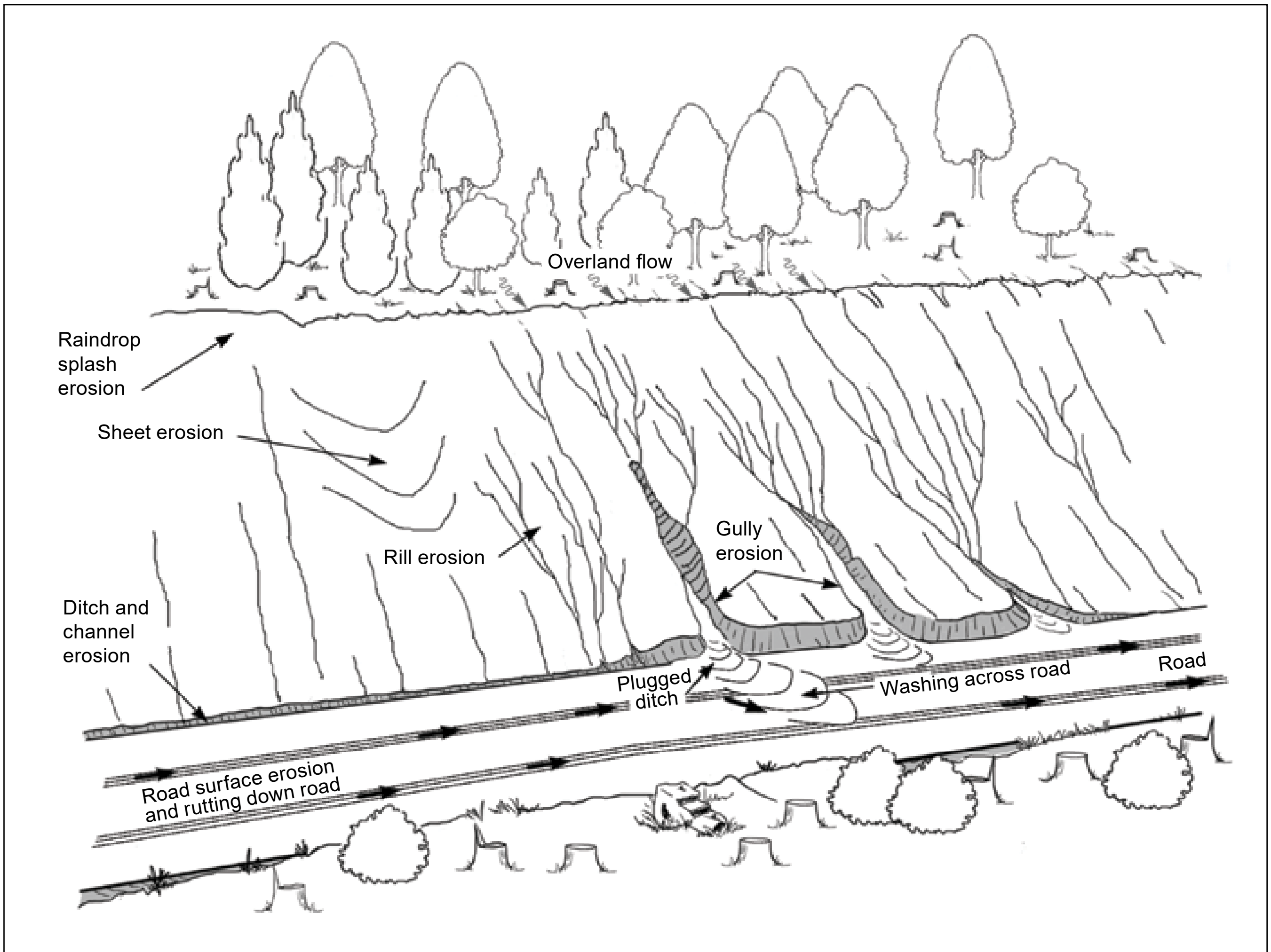

Figure 4.52—Common types and sources of erosion along a road. (Figure from Keller et al. [2011])

Physical methods for erosion control—

Drainage control and ground cover are the key elements for erosion. Water concentration must be prevented by dispersing the flow, or water must be controlled. Concentrated, fast-flowing water has a large amount of energy and therefore a great ability to scour, erode, and form gullies. Many physical erosion control measures are used to help disperse or control the flow of water (e.g., armored ditches, berms, check dams, turf reinforcing mats). Other measures that disperse and control surface drainage (e.g., rolling dips, road shaping, use of ditch relief culverts and leadoffs) were discussed previously.

Physical methods include the wide range of materials used to provide protective ground cover such as mats and netting, straw, wattles, silt fences, turf-reinforcing mats, slash and mulches, bonded fiber matrix, rock, and concrete (fig. 4.53), often used in conjunction with drainage and vegetation. Other methods include:

- Berms to control and direct waterflow, or berm removal to disperse runoff.
- Walls, barriers, and sinks or sediment basins to trap sediment.
- Mulch and soft ground cover with straw, wood chips, slash, leaves, bark, shredded paper, mats, bonded-fiber matrices, etc. to temporarily protect the ground surface against erosion.
- Hard armor/ground cover with rocks, riprap; articulated concrete blocks, geocells, gabions, etc. for permanent ground cover.
- Rock on the roadway surface, particularly on steep road grades, erodible soils, areas of concentrated waterflow, and hydrologically connected roads at approaches to stream crossings.
- Rolled erosion control products (erosion control and revegetation blankets) and mats to provide ground cover and promote vegetation. Mats and blankets need to have good contact with the soil and be pinned down in accordance with the manufacturers' recommendations.
- Turf reinforcement mats to armor high flow channels.
- Silt or sediment fences to trap sediment, particularly around work sites.

Gordon Keller

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Figure 4.53—Common physical erosion control measures, including straw and netting (left), wood chips, and straw wattles (right), provide ground cover and surface stabilization until vegetation can grow.

- Stabilizers and tackifiers to modify the soil surface to make it more resistant to erosion.
- Hydromulching and hydroseeding.
- Modified soil surfaces (terracing, roughening, etc.) to control runoff and aid revegetation.
- Water bars, rolling dips and other cross-drain structures to disperse and divert water from the road surface and ditches.
- Check dams and rock armor used in ditches to reduce velocity and prevent downcutting and erosion.

Vegetative methods—

Vegetation is the most desirable type of long-term ground cover in forest and range settings and provides the following benefits:

- Reduces raindrop impact via top growth and leaf litter
- Reduces runoff velocity via increased roughness from growing plants and leaf litter
- Provides structural integrity (reinforcement) of the soil via the root system
- Filters chemical pollutants and sediments from runoff
- Increases water infiltration into the soil
- Increases percolation through the soil, the lateral movement of water in the soil
- Increases evapotranspiration, the vertical movement of water to the air through plant tissues

Vegetative methods use grasses, brush, and trees for ground cover, root strength, and soil protection with inexpensive and aesthetic natural vegetation (fig. 4.54). Live vegetative hedgerows on contours help trap sediment on a slope. Good soil preparation is key to the long-term success of vegetative treatments. The quality and fertility of the soil directly affect its productivity and ability to grow vegetation. Compacted soils can be loosened with scarification or subsoiling, and the addition of organic material. Sterile soils may need amendments to promote growth. Other chemicals or minerals in soil may retard growth and need mitigation. Physical methods such as netting can be used to protect seeds and promote germination.

Vegetation selected for use needs good growth properties, hardiness, dense ground cover, and deep roots for slope stabilization, with local native species being preferable. Nonnative annual grasses may be needed to protect disturbed areas against surface erosion for the first few years. The erosion control plan and consultation with local botanists and native plant guides are important prior to prescribing vegetative treatments. “Roadside Revegetation: an Integrated Approach to Establishing Native Plants” (Steinferld et al. 2007) describes benefits and issues associated with establishing native vegetation.

Gordon Keller *Gordon Keller*

Figure 4.54—Common types of vegetative erosion control measures, including grasses on a closed road (left), deep-rooted shrubs and trees, and grass on a cutslope (right).

Use of deep-rooted, native vegetation—

The type and source of vegetation should be carefully chosen to best accomplish the specific objective. Information such as location, aspect, climate and microclimate, soil type, fertility, time of planting, and subsequent land use are critical factors in making the final design determination. Local botanists, soil scientists, and native plant specialists can provide input for vegetative treatments. The advantage of vegetation with deep root systems is that it is resistant to drought, and deep roots provide slope stabilization. Many grasses provide dense ground cover but have shallow roots that do little to deter shallow mass failures on steep slopes when they become saturated (fig. 4.55).

Gordon Keller *Donald Gray*

Figure 4.55—A failure at the depth of shallow-rooted grasses (left), and a deep root system from pine trees that provides stability to the slopes (right).

Soil bioengineering and biotechnical erosion control methods—
Soil bioengineering and biotechnical treatments and their costs vary, depending on site conditions and values at risk, and most are labor intensive. As noted previously, soil bioengineering uses integrated ecological principles to assess, design, construct, and maintain living vegetative systems to repair damage caused by erosion and slope failures (Sotir 2001). Biotechnical treatments combine the use of vegetation with physical structures, such as vegetated gabions or vegetated reinforced soil slopes (Gray and Leiser 1982). Biotechnical stabilization is a specialized field, and consultation with experts and other guides is recommended. Common soil bioengineering and biotechnical treatments include the following:

- Live stakes (willow and others) embedded in the face of the slope
- Fascines/bundles/wattles-bundles of branches that are laid in a trench along contour lines that sprout and grow
- Brush laid onto terraces in the slope, covered with moist soil and compacted
- Vegetated reinforced soil slopes (i.e., geosynthetic reinforced soil slopes with brush placed on each lift with the reinforcement) (fig. 4.56)
- Vegetated gabions and walls: retaining structures interplanted with live vegetation cuttings
- Live cribwalls: wooden cribwalls with material that will sprout are constructed with vegetation layers

John McCullah

Figure 4.56—Biotechnical slope stabilization and erosion control usinga vegetated reinforced soil slope.

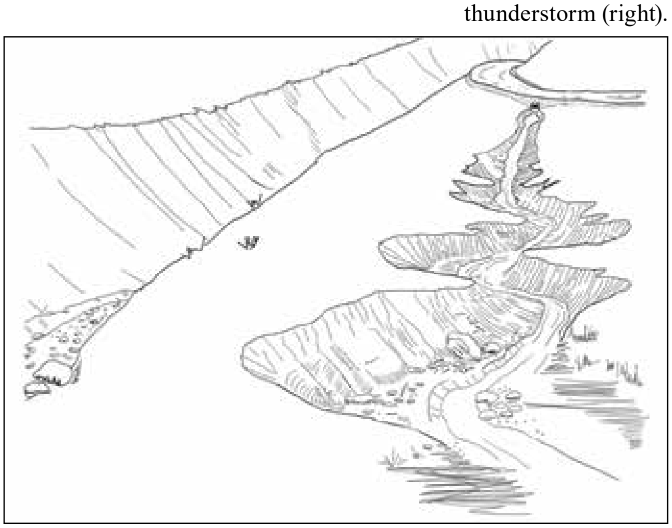
USDA NRCS (1992) and Lewis (2000) described bioengineering techniques, providing field personnel with basic soil bioengineering concepts and examples of techniques especially effective in stabilizing and revegetating upland roadsides.

Gullies and gully prevention—

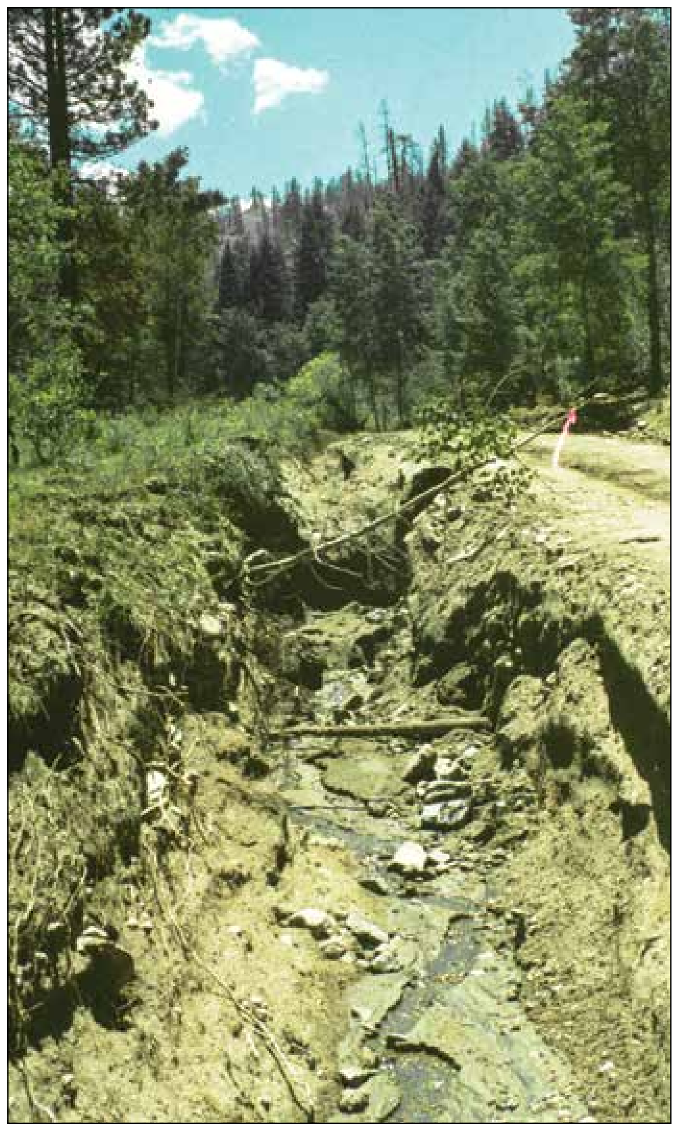
Gullies are a specific form of severe erosion typically caused by concentrated waterflow on erodible soils. Gullies can have major impacts on an area by taking land out of production and by lowering the groundwater table, as well as being a major source of sediment. They can be caused by concentrated water flowing off roads or can affect roads by creating another drainage crossing (fig. 4.57). Gullies often form and enlarge with each high-intensity rainfall event. If a gully can be prevented by diverting or dividing a concentrated flow of water, a great deal of damage can typically be prevented.

Figure 4.57—Gully formation below a road where excessive water was discharged from a ditch-relief cross-drain culvert (below) and in a ditch line below a wildfire area after a thunderstorm (right).

Heather Ross



Gordon Keller



Gullies can often be prevented by investigating and removing the water source causing the gully. Gully formation at the outlet of cross-drain structures or road drainage points is a common problem. Gully formation, or gully initiation along a road, is a function of the contributing area, or road length, type, and the ground slope over which the water runs (or hillslope gradient). These relate to the volume of water accumulated and the energy that causes erosion. Resistance to gully formation is a function of soil and vegetation characteristics where the water exits onto the slope, so drain exit location is important. Thus, the spacing of road drainage features is particularly important to prevent the formation of gullies.

On many steep slopes, there is potential for gully initiation after around 200 ft if the pipe exits on an unprotected hillslope. An outlet discharging on forest litter will take a longer distance to initiate a gully, and with an energy dissipator below the outlet, the initiation distance may be 1,000 to 2,000 ft. Gully initiation is likely on shorter segments of road that have an inslope versus an outslope because of the more concentrated flow at the outlets. Controlling the road length draining to the culvert effectively controls the contributing area and the amount and velocity of water, thus preventing gully initiation.

Figure 4.58 depicts gully initiation as a function of contributing road length and hillslope for soil with three levels of erodibility. The low soil erodibility data were collected in volcanic soils in central Oregon, the medium erodibility data from granitic soils in the Idaho batholith (similar to Sierra Nevada granitic soils), and the high erodibility data from young basalt and glacial deposits on the Olympic Peninsula, Washington.

Gully stabilization—

Stabilization of gullies begins with removing or reducing the source of water flowing to and through the gully. Gully stabilization structures are not usually desirable on natural stream channels and should be used in natural drainages only to correct severe problems, and then only after careful study. For gullying of ditches or gully formation below the road, the best solution is prevention by adding more frequent drainage features to reduce the concentrated water volume.

A gully can typically be stabilized with vegetation or refilled with dikes, or small dams, built at intervals along the gully. Stabilization of the base of the gully is often necessary to allow sideslopes to be stable enough to become revegetated. Reshaping and stabilization of the over-steepened gully sides may also be needed, as well as some treatment on the headcut area. Gully stabilization can require a lot of work and expense, and efforts frequently fail.

Typical gully stabilization check-dam structures are constructed of rock, gabions, logs, wood stakes with wire or brush, rock and brush, bamboo, and

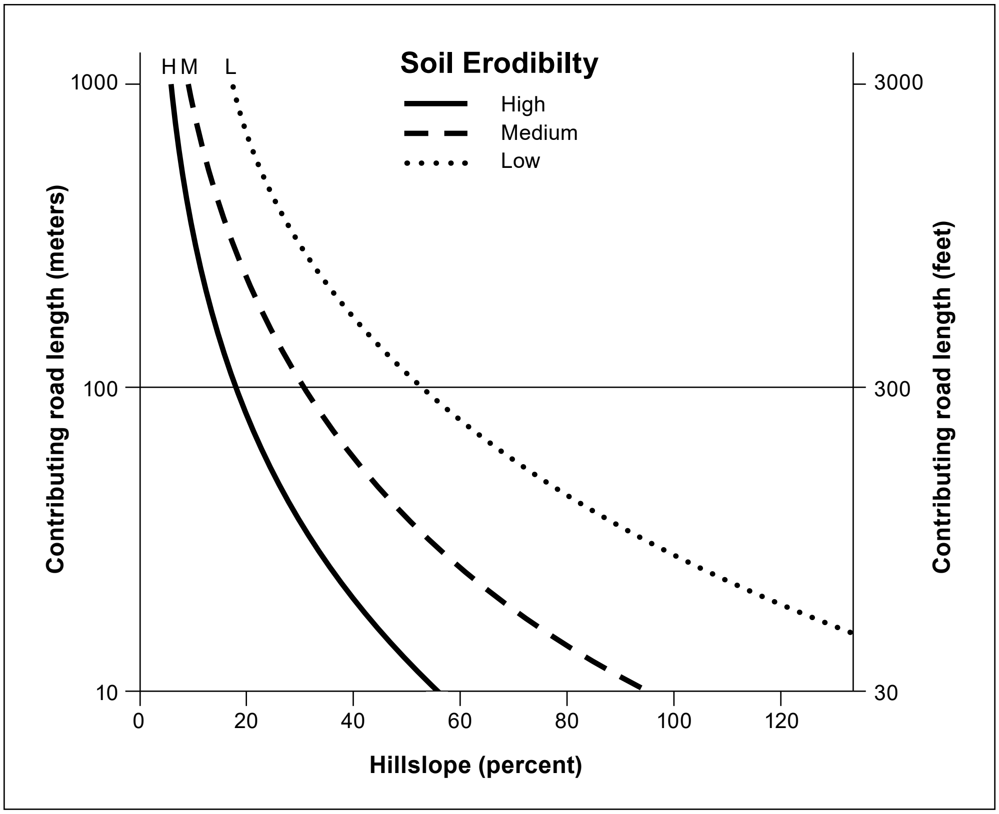


Figure 4.58—Gully initiation data from the contributing road length as a function of hillslope for various soil erodibility categories. (Adapted from Cissel et al. 2012a.)

Gordon Keller

Gordon Keller

Figure 4.59—Gully stabilization structures made of logs (left) and of loose rock (right).

vegetative barriers. Loose rock structures are somewhat forgiving and can deform and still function (fig. 4.59). The rock should be well graded, but it will still be porous, detaining water temporarily and then attenuating the runoff water. Gabions are commonly used but can be problematic and need extra care in installation.

They are subject to settlement, piping through the rock, and flow diversion around or under the structure. A geosynthetic filter material should be placed behind and under the structure to minimize piping. A headcut structure is also typically needed to stabilize the upslope or top-most portion of the gully and prevent additional headward movement. Design details for successful gully stabilization structures include (fig. 4.60):

- Design a weir, or a notched or U-shaped spillway for the peak-flow capacity to keep the waterflow concentrated in the middle of the channel.
- Key the structure into the adjacent banks tightly and far enough to prevent erosion around the ends of the structures.

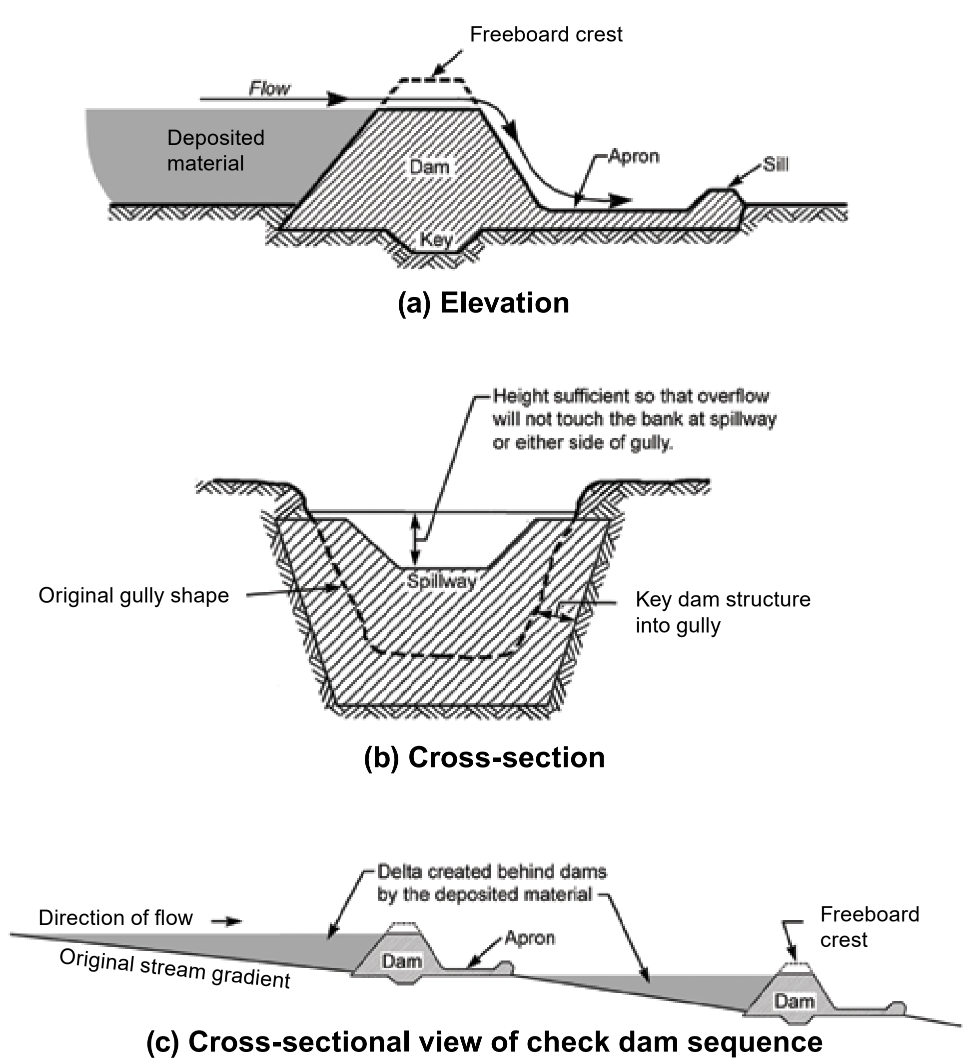


Figure 4.60—Check-dam design used to control or stabilize a gully. Note the details for keying the structure into the gully, having a U-shaped weir, and protecting the toe area against scour with other downslope structures. (Figure from Keller and Ketcheson [2015])

- Bury the structures deep enough in the channel to prevent flow under the structure.
- Spill the water over the structure onto a splash apron or protective layer of rock, or into a pool of water to prevent scour and undermining of the structure.
- Space the structures close enough so that flow over the structure spills into backwater caused by the next structure downstream.
- If rock check dams are used, use well-graded rock so that the structure is relatively impermeable. Using vegetation with the rock will add integrity to the structure.

Slope Stabilization Measures

Landslides and slope instability are significant problems in some areas of the Sierra Nevada, particularly with projections for increased total rainfall and rainfall intensity. Slide stabilization measures can be key climate adaptation tools. Techniques such as vegetation establishment and drainage management are simple and inexpensive, whereas retaining structures are effective but quite expensive. Loose, high-risk fill material can be removed to reduce storm damage. Other stabilization techniques include road relocation, drainage measures, use of vegetation, flattening slopes, removing slide material, slope terracing, buttresses, retaining walls, reinforced fills, biotechnical structures, soil nails, and deep-patch reinforcement. Slope stabilization techniques that are cost effective and sustainable are described in Fay et al. (2012), Prellwitz and Steward (1994), Keller et al. (2011), and Turner and Schuster (1996).

Achieving stable cut and fill slopes—

Cut and fill slopes are routinely constructed in new construction or road reconstruction and repair projects. Oversteep cut and fill slopes are a hazard during storm events and risk failure. Failed slopes typically need to be repaired or removed. They usually do not involve analysis, but rather are constructed at slope angles thought to be stable, based on local experience and general guidelines focused on producing stable slopes in most soils most of the time. If a specific problematic, unstable, or wet area is encountered, the road is realigned near the area or various stabilization treatments are used. Table 4.5 presents stable slope ratios for cuts and fills in a variety of soil and rock types; existing slopes steeper than these values have a risk of failure during storms.

Cut slopes and fill slopes—

For most cut slopes, typical slope angles are based on the general soil or rock type and field observations. For most rocky, silty to sandy soils in the Western United

Table 4.5—Common stable slope ratios for different soil/rock conditions

Soil/rock condition	Slope ratio (horizontal:vertical)
Cuts:	0.25:1 to 0.5:1
Most rock	0.25:1 to .05:1
Very well-cemented soils	0.75:1 to 1:1
Most in-place soils	1:1 to 1.5:1
Very fractured rock	1.5:1
Heavy clay soils, volcanic ash	2:1 to 3:1
Soft clay-rich zones or wet seepage areas	2:1 to 3:1
Fills:	
Fills of most soils	1.5:1 to 2:1
Fills of hard, angular rock	1.33:1
Low cuts and fills (less than 7 to 10 ft)	2:1 or flatter (for revegetation)

Note: All slope references are shown as horizontal:vertical (H:V). However, current Federal Highway Administration FP03 specifications use the designation vertical:horizontal.

States, cut slopes of 1:1 or 0.75:1 (horizontal:vertical) are used. In rock cuts and rocky or cemented soils, near vertical cutslopes can be used, and a 0.25:1 slope is commonly used. In clay-rich, fine-grain soils or zones of saturation, flatter slopes such as 2:1 or 3:1 may be required for stability. Stable cut slope angles are specific to local soil, weather, and groundwater conditions, so local experience is critical.

For fill slopes, a slope of 1.5:1 to 2:1 is recommended for the majority of soils. Rock fills can be stable on slopes as steep as 1.33:1 or even 1:1 with angular rock and careful placement. To achieve good vegetative stabilization on a constructed fill slope, the slope should be 2:1 or flatter, especially for low fills. On slopes steeper than 30 to 40 percent, the base of the fill should be placed on a terraced surface to key the fill into the slope and prevent a failure along the plane of contact between the fill and natural ground. The foundation is critical to the stability of the fill. On slopes over 50 to 65 percent, a full-bench road should be constructed and no fill constructed.

In gentle terrain with slopes less than 50 percent, a balanced cut and fill design is used where material excavated from the cut slope is placed into the adjacent roadway fill embankment (fig. 4.61). On slopes of 50 to 65 percent, the suitability and stability of balancing the cut and fill material should be carefully evaluated, depending on local soil conditions. On steeper slopes, a steep full-bench cut slope is typically used with no fill slope.

Thin sliver fills are a common problem on old roads where construction was done by sidecasting the fill material on steep slopes. The material may by only

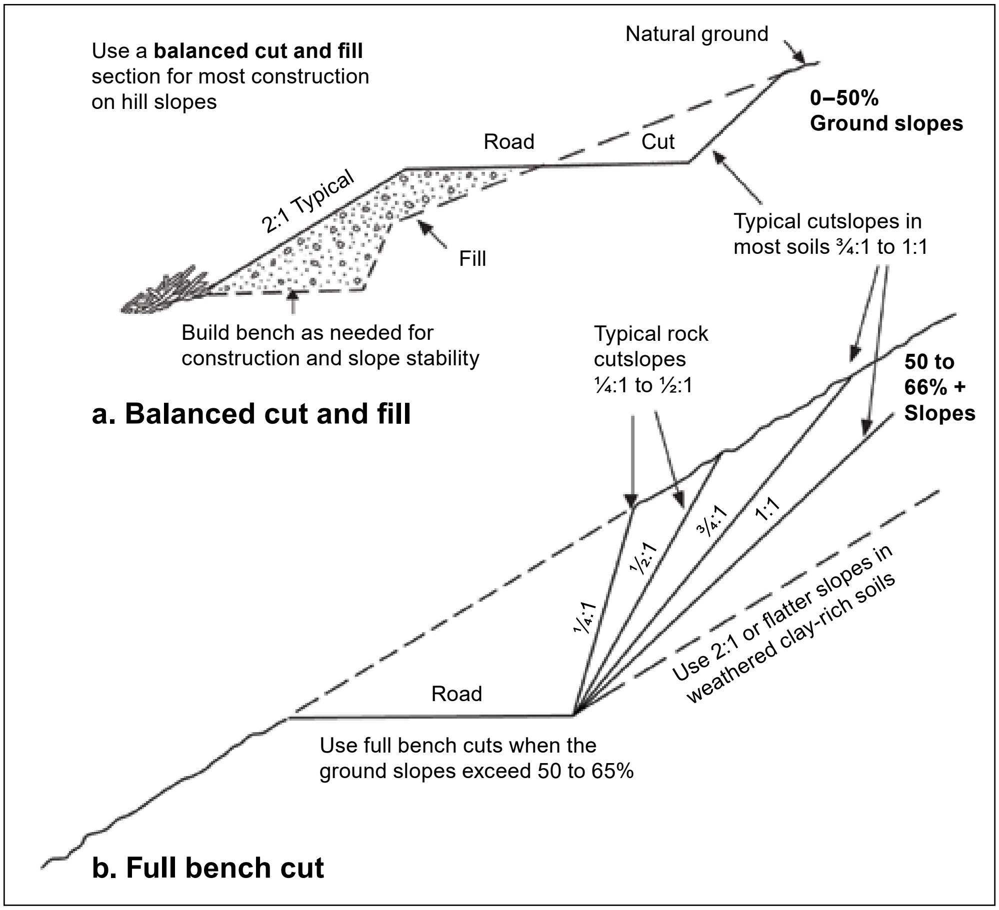


Figure 4.61—A balanced cut and fill, and commonly used stable cutslope angles. (Figure from Keller et al. [2011])

2 to 4 ft wide at the road surface elevation. These slopes commonly have failures or problems with settlement, particularly during major storms. These sites can be repaired by pulling back the fill material with an excavator. The resulting road will be narrower but have a stable platform. The road can also be widened by excavating and shifting into the hillside.

Increasing stability with structures—

Retention structures are used in many applications with roads. Their primary use is to resolve a space constraint on steep ground, where a wall is needed to support the roadway in a tight location and avoid a large cut or fill. They are also used to rebuild the roadway where fills fail to avoid cutting into a hillside in a slide area, support a roadway across a narrow saddle, buttress a marginally stable slope, and provide vertical, low-profile abutments for bridges.

Retaining walls are relatively expensive structures and are not routinely used for vulnerability reduction. They should not be used without considering road relocation, cutting into the hillside to place the road prism on a full bench, or using a reinforced or rock fill. However, when needed, walls and buttresses offer a positive solution to support the roadway (fig. 4.62). Their use can avoid creating additional slope stability problems, avoid long fill slopes that may be erodible or unstable, and keep the toe of fills out of drainages. Mohney (1994) describes the use, selection, and design of a variety of retaining walls.

Gordon Keller

Gordon Keller

Figure 4.62—Commonly used slope stabilization structures include a rock buttress (left) and a gabion retaining wall (right).

Walls constructed into cut slopes need to be designed to allow ditch cleaning without undermining the wall or damaging its facing. Walls need to be designed and constructed in the context of an existing or potential failure plane of any slide and the depth of failure. The size and height of the wall are determined based on slope stability analysis to ensure that the structure will have enough mass to resist the driving forces of the slide or slope. A wall needs to be deep (tall) enough to have its base placed on firm, in-place material (ideally bedrock) below the depth of slide movement or a slide plane. Walls should be built with a subsurface drain behind the structure. In some cases, a lightweight structure constructed with sawdust, shredded tires, or geofoam, can be designed to minimize the driving forces if the wall is placed on a slide or has a marginal foundation material.

Gravity structures are typically made of reinforced concrete, cellular bins, gabions, masonry, dry rock walls, or large rocks. The size of the structure depends on the height of the wall needed to fit the site and provide the desired roadway width and elevation. Other design factors include loading conditions on the wall, and allowable foundation conditions. Gravity structures are commonly built up to 25 ft high. Above this height, gravity structures become difficult and expensive to build. For simple gravity structures, the base width is typically 0.6 to 0.7 times the height to achieve a stable design for simple loading conditions. With traffic loading, the base:height ratio is 0.6 to 0.8. For a hillslope immediately above the wall, the base:height ratio is 0.7 to 1.0. A wider base may be needed for unusual conditions such as a soft foundation, high lateral loads, or seismic loads. Structures should be set onto firm, in-place materials.

Earth-reinforced systems, reinforced soils, geosynthetic confined soils, or mechanically stabilized earth (MSE) walls offer an economical and effective alternative to traditional gravity-type structures for most wall heights and applications. For walls over roughly 15 ft high, MSE walls offer significant cost advantages over gravity structures. In the case of rural or forest low-volume roads, where access may be difficult and when the budget is limited, the use of prefabricated or lightweight materials, combined with local or onsite soils, as used in MSE technology, is generally recommended.

MSE walls use a variety of facing materials, including tires, wood beams, straw bales, modular concrete blocks, gabions, concrete panels, geotextile or turf reinforcing mats, and other facings. Soil reinforcement is typically achieved using geotextile and geogrid reinforcing layers, although welded wire, chain link fencing, metal bars, and metal strips have been used. Welded wire and geotextile walls are among the simplest to design and use (fig. 4.63). Soil-reinforced gabion designs have also been developed in which typical gabion baskets form the face and gabion wire mats are used to reinforce the backfill. Reinforcing spacing is typically 3 ft (the height of a basket). The length of reinforcement is a function of the wall height and loading conditions, similar to other MSE designs. MSE wall design and construction are described in Berg et al. (2009).

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Figure 4.63—A welded wire, mechanically stabilized earth wall (left) and a geotextile wall (right) are both used because of their relatively low cost and ease of construction.

Drainage improvements—
Wet areas, clay-rich or deeply weathered soil pockets, and shear or fault zones require relatively flat cut slopes to reduce the risk of failure. Seeps, springs, or wet areas, almost always require special consideration and drainage. In any excavation, the water table should be below the exposed surface (where practical) to prevent instability. If an excavation opens a wet area, or a fill is placed on a wet area, extra measures must be taken to drain the slope, flatten the slope more than normal, or buttress the toe of the slope. A stable, wet slope angle may be roughly half the angle of the same stable, dry slope.

Drainage measures, including cut-off trenches or underdrains, toe drains, drainage blankets or filter blankets, and horizontal drains are used to both remove the water and lower pore-water pressures within the slope. Any reduction in the water table or pore pressures in the slope will improve slope stability. Underdrains are commonly placed along roads in wet cut slope and seepage areas.

Biotechnical slope stabilization and use of deep-rooted vegetation—
Biotechnical slope stabilization, combining structures with vegetation, can be very cost effective to stabilize slopes and produce a natural-looking structure, particularly for shallow failures. Vegetation use is strongly encouraged because it is typically inexpensive, though labor intensive, and improves slope stability. Deep-rooted shrub and tree species are preferred over shallow-rooted grasses for most applications. Biotechnical measures have low initial cost, are visually pleasing, have minimal maintenance, and promote root strength. Vegetative stabilization should not be used by itself for stabilizing large and deep-seated slides.

Deep patch shoulder strengthening—
Uncompacted fills on steep slopes often progressively settle, are a maintenance problem, and are at risk of failure. Grading does not stop the settlement but starts a long-term commitment to continual roadway repair. Deep patch reduces or stops the continual settlement and decreases road maintenance costs. Deep patches have slowed or stopped slope surface movement on sections of roads crossing areas of large-scale slope movement.

The deep patch design is a shallow road-fill slope repair where the upper 3 to 6 ft of the subsiding section of roadway is excavated, the fill material is replaced with compacted select backfill, and several layers of geogrid or geotextile are installed (fig. 4.64). Wilson-Musser and Denning (2005) contains additional information about this technique.

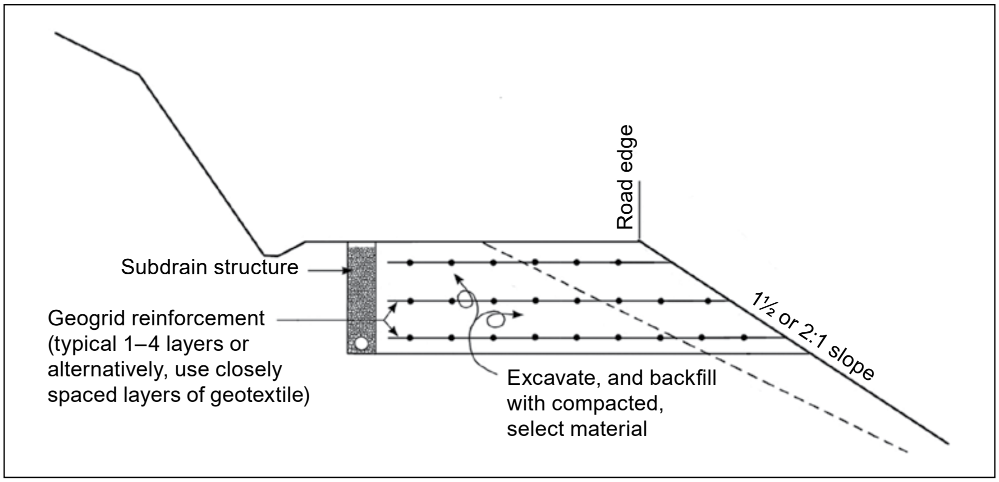

Figure 4.64—Cross section and installation of a typical deep-patch road-embankment repair. (Figure from Keller et al. [2011])

Sidecast fill pullback for slope stabilization—

Sidecast fill material, or loose material placed on top of native soil on a slope, can absorb water and fail on the plane at the base of the sidecast material. These old, thin, poorly compacted fills are common failure areas, particularly on steep slopes. Newer roads do not use as much sidecast construction, and excess material is ideally end-hauled to another flatter area or to a disposal site. However, there are still fill slopes that exhibit instability and warrant treatment because of an excessively steep slope, rotting logs in the fill, local groundwater conditions, and climate stressors (fig. 4.65).


Bill Shelmerdine

Figure 4.65—Road-fill failure in a sliver fill that was partially supported by old logs. The failure triggered a downslope debris slide.

On steep natural slopes (steeper than 50 to 60 percent), a road fill failure can trigger a debris slide downslope of the road fill. These debris slides can then travel for great distances, increasing the volume of material involved in the slide and damaging the hillslope itself, particularly if infrastructure is at the bottom of the slope. Most fill failures that cause such an event are identifiable and preventable. Small scarps and curved cracks in the road surface, particularly in the outside half of the road, are indicators of fill settlement or incipient failure.

In addition to deep patch repairs, sidecast fill pullback or removal of high-risk fill material is a positive method to reduce the risk of failure. However, just pulling back sidecast fill (and end hauling it to a stable disposal site) has the drawback of narrowing the roadway. In some cases, a roadway ditch can be eliminated to gain road width. Additional cutting into the hillside or changing the road grade or alignment may be required. If the road standard is changing from maintenance level 3 to 2 or from level 2 to 1, narrowing the road may not be a problem. Detection and mitigation measures are discussed in Collins (2008).

Debris flow/debris torrent mitigation—

Debris flows are common in forests on steep terrain following wildfire and an intense rainstorm. More wildfire-flood-debris flow events can be anticipated as a result of climate change. Debris flows are a mass movement involving rapid flow of debris of various kinds, including mud, rocks, and logs down a channel. They begin as rills, and erosion moves large amounts of sediment into local channels. They are a high-density mudflow, containing abundant coarse-grained materials and typically result from heavy rain. They have the ability to mobilize a lot of material in a semiliquid, concrete-like slurry, moving down channels with high energy. They can be destructive to any infrastructure in their path, as well as dangerous to people. Figure 4.66 shows the source area of debris flows on a steep, fire-scarred slope, and damage to roads and a culvert from a debris flow; note the quantity of large boulders being moved in each debris flow.

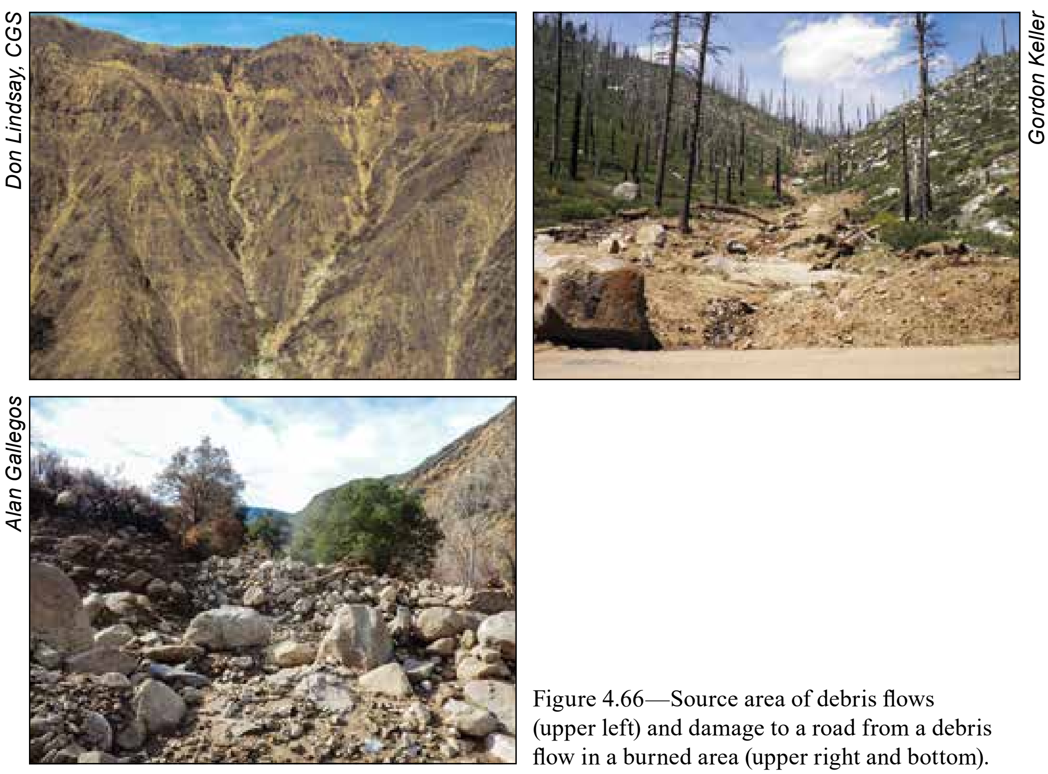

Figure 4.66—Source area of debris flows (upper left) and damage to a road from a debris flow in a burned area (upper right and bottom).

The best adaptation treatment is usually to move or close any infrastructure in a location determined to be at high risk of damage from a debris flow. A variety of management and physical mitigation measures can be used, including:

- Move recreation vehicle trailers and close vulnerable facilities and campgrounds when heavy rains are forecast.

- Promptly replant upper watershed areas with grasses and deep-rooted shrubs so they will hopefully mature prior to heavy rainfall.
- Disperse drainage on headwater roads with outsloping or frequent cross-drains to minimize the concentration of water in drainages that can lead to debris flows.
- Build debris retention structures. This can include gabion walls, “porous” open check dams and slotted concrete dams, debris flow netting, and ring nets to trap sediment or large, coarse boulders and logs.
- Build debris-flow deflection structures to change the direction of debris flows away from infrastructure.

Because most facilities and infrastructure cannot be moved easily, trapping sediment and debris is a common solution, but the challenge is to construct a debris retention basin or structures large enough to hold the volume of anticipated material. Multiple gabion structures are often used to construct a series of retention areas in a debris flow-prone drainage. Care must be taken to avoid building structures that simply force the flow around the structure. Debris-flow deflection structures have been constructed at critical locations upslope of infrastructure such as a bridge or buildings to deflect the slide material away from the infrastructure (fig. 4.67). Debris flow mechanics and mitigation measures are well documented in Chen (1997) and Piton (2016).

Debris slides are common in forest terrain after heavy rains but are typically more localized, occurring on slopes over 60 percent, particularly in pockets of

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Figure 4.67—Debris slide retention structures (a gabion wall and ring net, upper photos), a debris retention basin (lower left), and a debris flow-deflection structure (lower right) installed to mitigate damage from a debris flow or slide upslope of a road or buildings.

colluvial soil or shallow soils over a distinct bedrock contact. Slope stabilization measures can be used, as discussed above. Debris torrents are flows with a high liquid content and move with high velocity. They can be very destructive but are not common in the Sierra Nevada.

Rockfall prevention—

Rockfall refers to quantities of rock falling freely from a cliff face. A rockfall is a fragment of rock (a block) detached by sliding, toppling, or falling, that moves along a vertical or subvertical cliff, proceeds downslope by bouncing and flying along ballistic trajectories or by rolling on talus or debris slopes (Varnes 1978). Rockfalls occur on steep slopes in fractured rock deposits during storms or periods of freeze-thaw, and are a significant safety hazard for people. To counteract instability, an engineer can choose from a wide range of protection solutions adopted to suit a particular situation (fig. 4.68).

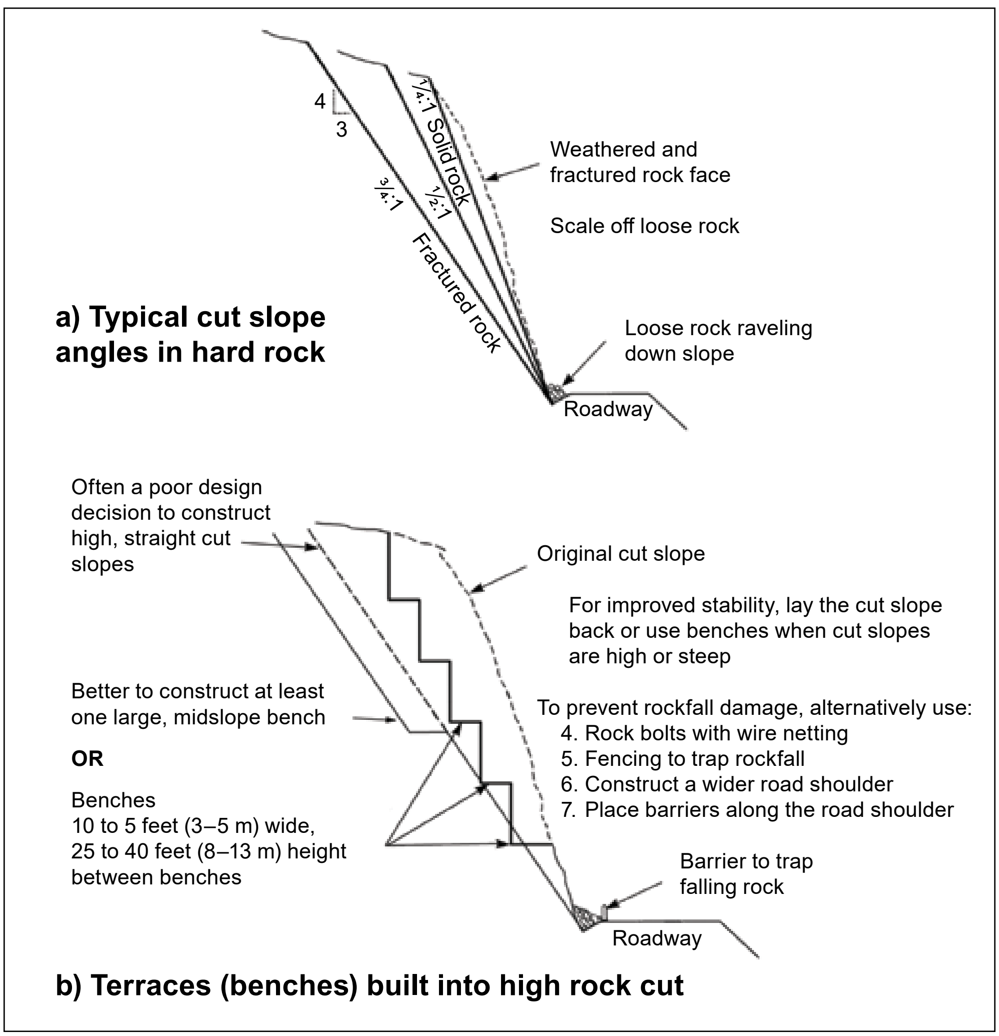

Figure 4.68—Rockfall prevention and protection measures. (Figure from Keller et al. [2011])

Rockfall netting (rolls of fabric with lacing, metal fencing) is provided as a blanket to cover the surface of slopes to protect infrastructure built on the foot of the slopes, or to trap rock against the slope before it rolls or bounces onto a road. Rock bolts may be used to pin down specific rock blocks. Rock anchors usually involve a specific design and are used on forest roads only in problematic areas. Gabions constructed as a retaining wall are an alternative to keep stones which may fall from a cutslope or cliff from endangering traffic on a road.

Other solutions are catch fences and rockfall protection embankments or berms. Solutions may require a combination of scaling, rock bolting, buttressing, constructing terraces, and wire mesh or netting system. Scaling is used to remove loose rock, terraces catch rockfall, and road shoulder barriers prevent the rock from reaching the roadway. Other mitigations include the installation of traffic signs along the road to warn of falling rock in mountainous areas where the road has a history of rockfall problems. Removal of loose rock, unstable soil, trees and other debris from the slope is the best adaptive measure to prevent rockfall during storms. Rockfall analysis and mitigation are described in detail in Muhunthan et al. (2005) and Turner and Schuster and Highland (2003).

Miscellaneous Road Issues

A variety of road adaptation measures can be considered when evaluating impacts of climate stressors such as atypically cold periods, shifting seasons, early thawing, intense storms, periods of drought, and wildfires. Potential problems include timing and implementation of contracts, impacts on asphalt roads, fire-related road issues and detours, removal of hazard trees after fires, freeze-thaw problems, and lack of water and dust from roads during periods of drought.

Contracting—

Warmer temperatures are making areas in national forests open up earlier in the spring than in the past. As a result, recreationists, contractors, and loggers will likely request that roads be opened earlier than has been done historically. Erratic weather makes it difficult to implement road maintenance contracts. Campgrounds need to be opened earlier. Storm damage and fire rehabilitation require additional contracting beyond typical work. Agencies will need an increased level of flexibility and have adequate experienced staff and contracting officers to respond to changing seasons and unanticipated events. On the other hand, improved access owing to hotter, drier conditions may be beneficial for preparation and implementation of contracts.

Freeze-thaw and fire effects on asphalt—

Variable climatic conditions are making road pavement management more difficult. In alpine terrain where roadway subgrades are frozen, early or unseasonal thawing combined with traffic can lead to pavement damage. Management under freeze-thaw conditions is a common problem in the northeastern United States and can be a problem at higher elevations in the Sierra Nevada on roads unaccustomed to early traffic. Many freeze-thaw and springtime road management solutions have been documented to minimize road damage, and modified pavement designs or road management are commonly used (Kestler 2003, Kestler et al. 2011). Soil moisture measuring devices can be used to support management decisions to open or close roads.

Intense heat from wildfires has also been observed to damage pavement. For example, Sierra National Forest reported premature cracking and oxidation of roads within a fire area.[5] Heat from a fire can make asphalt stiffer and more brittle, resulting in thermal cracking from hot and cold cycles, and premature failure. In addition, most paved roads in the Sierra Nevada have reached their design life and are in marginal to poor condition. Additional traffic from increased recreation, fire suppression, and rehabilitation activities will further damage paved roads. Some paved roads have already been converted to gravel roads to improve traffic safety.

Fire suppression routes and detours—

During and after forest fires, some forest roads receive atypically heavy traffic from fire suppression activities, as well as during rehabilitation efforts. Closed roads may be opened up for fire access and be subject to access with lowboys, engines, and crew busses. These roads are in most cases not stabilized to support heavy traffic, so considerable rutting or dust is produced. Alternate detour routes are often specified to accommodate normal traffic as well as fire suppression equipment. These activities create additional work after fires to repair roads or close them again.

Hazard trees—

Higher temperatures likely will increase forest drought stress (Polade et al. 2017), leading to increased tree mortality. When dead trees along a road have the potential to fall, they are considered hazard trees and should be felled and removed. Hazard trees present a safety risk both to forest visitors and employees. Additional funding and resources are needed to remove these trees, immediately or at least soon after the fire. Hazard tree removal was accomplished along State Highway 70 on Plumas

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[5] **Berry, J. 2020.** Personal communication. Geotechnical project engineer, U.S. Department of Agriculture, Forest Service, Pacific Southwest Region, 1323 Club Drive, Vallejo, CA 94592.

National Forest soon after the Camp Fire in 2018 (fig. 4.69). On smaller forest roads, hazard tree removal is most often done by maintenance crews on an as-needed basis, and roads and facilities are often closed for some period.

Gordon Keller

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Figure 4.69—Hazard-tree removal along Highway 70 in Plumas National Forest following the Camp Fire in 2018 (left). Other roads may remain closed as a result of hazard trees caused by drought and insect outbreaks (right).

Droughts and dust—

Prolonged droughts or a short rainy season followed by a long, hot summer—typical of California weather—commonly lead to dusty conditions on unsurfaced forest roads. Either more dust is tolerated on most forest roads, or additional dust suppression materials are needed on log-haul roads or heavily used recreation roads. Fugitive dust (very small particles) reduces vegetative growth in the adjacent forest, removes needed fine particles in the road surface, increases erosion problems, and is a traffic safety concern because of reduced visibility.

Increased road operation and maintenance costs should be anticipated for dust suppression during drought. Many dust palliatives are available, depending on soil type and local conditions (Bolander and Yamada 1999). Water is the most commonly used dust suppressant, but during a drought, water sources may be limited and distant. Blading should be performed when natural soil moisture is optimum, or water trucks can be used to maintain soil moisture. Calcium chloride is the next most commonly used dust palliative in Sierra Nevada forests.

Trail Issues

Many of the adaptation options for roads discussed above also apply to making trails more resilient to climate change. Land managers can follow a similar assessment process for trail systems as for roads. The Sierra Nevada region has an extensive trail system with 9,300 mi of trails in a variety of ecosystems, managed and maintained in collaboration with various partners and trail user groups (table 4.3). With the expected changing climatic and hydrologic regimes, trails will need to be increasingly resilient to higher peak flows and flood frequency, so design changes may need to accommodate projected peak flows rather than historical peak flows (Strauch et al. 2014).

With declining agency budgets, increasing the resilience of trail systems will require creative approaches. Partnerships are helping national forests throughout the Sierra Nevada region to maintain parts of its trail system (Furniss et al. 2018) (chapter 5). Trails like the Pacific Crest Trail, and many trails in the high country and wilderness areas, benefit from the external partnerships.

Adaptation treatments include moving some trail segments away from creeks or meadows, improving trail bridges, hardening the trail surface of some wet areas, adjusting trail maintenance timing and season of use, limiting trail access, and developing more flexible agreements with partners to deal with earlier trail use and longer season of use (chapter 5).

Trail bridges—

There are about 261 trail bridges in Sierra Nevada national forests (table 4.3). Trail bridges, similar to road bridges, will require more robust designs to deal with increased stream flows in the future. In addition, trail bridges are more susceptible to forest fire damage, because they are typically constructed with wood. Trees are often close to trails and bridges, which are more likely to be damaged by falling trees during a fire, as well as by burned hazard trees in the future (fig. 4.70). Hazard trees are also a danger to hikers. Trail bridge location and design are discussed in Groenier and Gubernick (2009).

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Jonathan Berry

Figure 4.70—A typical wood trail bridge (left) and a trail bridge damaged by a wildfire (right).

Adapting Facilities Infrastructure to the Effects of Climate Change

Sierra Nevada national forests have 4,100 fire, administrative, and other facilities (table 4.6). The facilities serve many purposes, ranging from administrative offices in urban areas to backcountry cabins. Total current replacement value for these facilities is $743 million.

Since 2004, every national forest in the Sierra Nevada has had a facility master plan (FMP). Some forests have done updates, but most FMPs need updating. Following a standard template, an FMP documents four main management options: (1) retain, (2) decommission, (3) convert to alternate use, or (4) acquire. Each existing building has a management option listed. Owned and leased buildings are included, and proposed future acquisitions are discussed. The FMPs are considered to be valid for 10 years, at which time they need to be updated. Climate change assessment and adaptation could be considered in future revisions of FMPs.

The USFS has a capital improvement program, which is a national-level funding mechanism that funds top-ranked projects. This is typically the only funding source for new facilities. Most maintenance and decommission projects are managed by national forests or the regional office. To date, emphasis has been on developing energy-efficient facilities for which national funding is available for selected projects striving for "net zero" emissions (Meyer et al. 2013). Energy savings performance contracts have been implemented that seek to reduce energy requirements. These utilize third-party financers and contractors to develop large-scale (greater than $1 million) energy-efficiency measures.

Table 4.6—U.S. Forest Service fire, administrative, and other buildings in Sierra Nevada national forests

National forest/unit	Buildings	Total deferred maintenance	Current replacement value
	Number	- - - - - - - - - *Dollars*	- - - - - - - - -
Eldorado	473	41,265,903	95,050,389
Inyo	485	3,892,305	73,723,832
Lassen	298	6,729,014	70,754,840
Modoc	240	3,722,401	40,291,219
Plumas	385	18,605,314	65,005,451
Sequoia	488	11,448,707	98,308,197
Sierra	614	62,010,896	95,255,509
Stanislaus	384	5,450,490	57,054,758
Tahoe	449	15,550,224	54,229,305
Lake Tahoe Basin Management Unit	284	18,813,600	93,564,002
Total	4,100	187,488,854	743,237,502

Source: U.S. Forest Service INFRA database (report II BLD FMP V–FY18 DM/CRV).

Increased use of wood in building projects links USFS facilities with healthy forests. Wood products in building systems have a lower carbon footprint than functionally equivalent products (steel, concrete), and require less energy if used in wall systems (Ritter et al. 2011). However, because wood is flammable, additional fire protection measures may be desirable in facilities.

Adaptation measures and building design modifications to accommodate a warmer climate include better insulation in structures, modified roof design with respect to snow load and the weight of rain on snow, and modified footing depth with respect to the frost protection line (Olsen 2015). Although the USFS uses current building standards for structures, a warmer climate and more frequent forest fires may warrant altered designs.

An ongoing concern with some units is the existence of many old facilities, such as fire guard stations, that are in poor condition but for which funds are too limited to improve or renovate. With an expected increase in fire frequency, the fire management organization may want to retain some of these structures to facilitate suppression. In the meantime, facilities maintenance personnel and funds are often too limited to prevent deterioration of the facilities.[6]

Developed Recreation Sites

Developed recreation sites are common assets that are often vulnerable to climate-related stresses. Damaged recreation sites reduce access for visitors, expose forest visitors to hydrologic and geologic hazards, and may cause considerable economic loss to businesses in the local area (chapter 5). Camping is one of the most popular warm-weather activities in the Sierra Nevada. Many campgrounds are located near streams and some are located in floodplains. Campgrounds located near streams are particularly vulnerable because of risk of flood damage. Similar issues may affect boating sites along streams, and some lakeshore sites may become less accessible if water levels decrease during droughts. Dump sites can also be affected by water-related disturbance. Figure 4.71 shows a trailhead with a parking area and facilities damaged by flooding and debris.

Adaptation measures to minimize climate vulnerabilities include moving developed recreation sites back from the margin of rivers or placing only expendable or flood-proof improvements in the area of potential flooding (chapter 4). Facilities need to be managed such that they can be evacuated quickly in the event of forecast flooding or other disasters. Redundant access roads may be desirable

[6] Andrea Seiler (2018), facilities engineer, U.S. Department of Agriculture, Forest Service, Plumas National Forest, 159 Lawrence Street, Quincy, CA 95971.

Penny Luehring

Penny Luehring

Figure 4.71—A trailhead, parking lot, and facilities damaged by debris and flooding.

in some locations, or wide-access roads can be used as evacuation routes. Some campgrounds may be able to stay open longer during the year, whereas others may need to be closed or operate at a reduced capacity.

Wildfire Resilience

Recreation infrastructure and facilities in forest areas will be vulnerable to wildfire damage (chapter 5). Administrative buildings, interpretive sites, and visitor centers are high-value facilities that are often constructed of wood and would be costly to repair or replace. Hotels, lodges, and cabins located in or near federal lands are often wood structures surrounded by high levels of natural fuels, and access for fire suppression can be difficult. Downhill ski areas, and cross-county ski areas and Sno-Parks to a lesser extent, typically have dense clusters of recreational infrastructure and lodging, with the potential for high economic losses.

Thinning, prescribed burns, and clearing the forests around the structures can make them more resilient to wildfire and create “defensible space” for fire suppression. Partnerships can help to increase implementation of fuel treatments. Using nonflammable materials and metal roofing can make structures more fire resistant and tolerant of heavy snow loads (fig. 4.72).

Fires in any area result in the mobilization of a large quantity of sediment ash and debris once the rains begin. Drainage systems around buildings, as well as for roads and trails, need to be large enough to handle projected increases in rainfall intensity and increases in sediment and debris. Traditionally used 18- and 24-inch culvert pipes can be upgraded to 36-inch pipes, and more anticlogging trash racks and screens may be needed to prevent drains from plugging.

Gordon Keller

Figure 4.72—Recreation buildings that have a metal roof plus sufficient defensible space around them will be more resilient to wildfires.

Water Systems

Water supply systems are critical infrastructure for facilities, administrative sites, campgrounds, ski areas, and occasionally trailheads. Pipelines can be damaged by fires and floods, as well as some historical water conveyances such as flumes and ditches. Periods of drought will lower the groundwater table in some areas, possibly drying up or reducing the yield of springs. Intense rainstorms often overwhelm water diversion structures and temporarily contaminate the water supply. Water quality in lakes (including municipal water supplies) and streams can also be damaged by wildfires.

Water supply sources and systems can be adapted to climate stressors by burying pipelines currently on the ground surface and by "fireproofing" pump houses and related facilities. Wells or springs with a history of marginal water yield may need to be evaluated, wells deepened, water storage increased, or alternative sources of water located. Some historical flumes have been damaged by fires and may need to be reconstructed. Removal of vegetation near the flume will reduce its vulnerability to fires.

Adapting Dam Infrastructure to the Effects of Climate Change

Sierra Nevada national forests contain 185 dams (table 4.7). Forty-two are owned by the USFS. The remaining dams are owned by others (authorized dams operated under special use permit, within an easement, congressionally withheld, or under Federal Energy Regulatory Commission license). In addition, many forests have a number of small impoundments, stock ponds, and irrigation dams that are not in the INFRA database and are typically not a hazard or problem. However, failure of these structures can cause some resource damage. Inventoried dams are categorized based on their hazard level. If a high-hazard dam fails, it is highly probable that human lives will be lost. A significant-hazard dam has a low probability of loss of life but high probability of environmental and economic loss.

Table 4.7—U.S. Forest Service dams and Federal Energy Regulatory Commission (FERC) dams in Sierra Nevada national forests

National forest/ unit[a]	Dams (in INFRA database)	FERC projects currently underway	FERC relicensing projects between 2020 and 2030	FERC relicensing projects between 2031 and 2045
		Number		
Eldorado	5	0	3	1
Inyo	4	3	4	1
Lassen	11	1	2	4
Modoc	119	0	0	0
Plumas	14	1	3	3
Sequoia	2	1	4	2
Sierra	2	1	4	3
Stanislaus	6	1	6	3
Tahoe	6	3	2	0
Lake Tahoe Basin Management Unit	16	0	0	0
Total	185	11	28	17

[a] Modoc National Forest and Lake Tahoe Basin Management Unit do not currently have any FERC projects.

Spillway capacity requirements are a function of hazard level. High-hazard dams are required to pass the “probable maximum flood (PMF).” Significant-hazard dams must pass a half-PMF flood. Low-hazard dams must pass a 100-year flood. The size of the flood a dam must pass can be lowered through an incremental damage assessment which analyzes risk downstream. Most USFS-owned dams were not built to a rigorous standard and may not be designed to accommodate increased flood flows. A changing climate will increase the magnitude of floods at various recurrence intervals, including the PMF. Increased PMF could exceed 30 percent based on climate model simulations that show significant potential for higher atmospheric mean and maximum water vapor concentrations, leading to higher maximum precipitation values across the United States (Dettinger 2011, Kunkel et al. 2013). A dam built in the context of climate change risks will need specifications for design and management that accommodate expected future conditions.

Increasing temperature and periods of drought in the future are expected to reduce water supplies for agriculture, industrial uses, human consumption, and fisheries, particularly during late-summer months when water is most needed. In regions where long-term projections indicate lower annual precipitation values, dams are usually a buffer to water shortages. As a result, there may be increased emphasis on maintaining current dams, adding storage to existing dams, and new applications for additional dams on public lands, particularly upstream from areas where private uses of water exceed or nearly exceed streamflows during critical water-need seasons. Additional dams and hydroelectric generation can also contribute to meeting renewable energy goals.

Instream flows for the health of fish populations will likely become an intense focus in areas affected by long-term drought. High-elevation dams, well beyond the limits of fish migration, could be key to the long-term health of fish habitat downstream. For example, many dams constructed in the Emigrant Wilderness Area were specifically built for fisheries. There could be a similar strategic re-utilization for other high-elevation dams in the future.[7]

Rain-on-snow events, which can intensify peak flows, may become more common at mid and higher elevations, and less common at lower elevations (chapter 3). Flow hydrographs in mid-elevation zones will change from snowmelt dominated to rainfall dominated, thereby increasing peak flows early in the season. Dams that are in the rain-snow transition snow zone will be increasingly subject to flows that were not characteristic during the time of their design and construction. It will be critical to assess storage capacity, spillway capacity, and operable gates. Evaluating dams for safety hazards, and periodic inspections, which are part of routine work by national forests and coordinated at the regional level, may become even more important in the future. Dam inspections should be planned after major storm events.

Gates, valves, and overflow or water release apparatuses need to be inspected and repaired to ensure that increased inflows during major storms can be released. Freeboard on dams needs to be evaluated to ensure that the dam will not be

[7] **Romero, S. 2019.** Personal communication. Regional geotechnical and dams engineer, U.S. Department of Agriculture, Forest Service, Pacific Southwest Region, 1323 Club Drive, Vallejo, CA 94592.

overtopped (fig. 4.73). Because reservoir pool elevations may fluctuate considerably during periods of drought or heavy rainfall, managers need to be flexible and make adjustments for recreational use of facilities around lakes as the shoreline changes. Some boat ramps may need to be lengthened or docks built with an adjustable elevation platform to guarantee annual use of facilities (chapter 5).

Gordon Keller

Figure 4.73—An earthen dam with minimal freeboard and risk of overtopping because of a blocked spillway.

Any spillway and associated apparatus should be functional and free of debris and vegetation. If increased inflows are anticipated, the spillway capacity should be determined. If the spillway is too small for the anticipated flows, then it should be increased in size to allow the passage of the routed hydrograph resulting from the flood recurrence level, be it the PMF, half PMF, or 100 year. Many strategies can ensure the safe passage of the inflow-routed hydrograph. For example, if the dam freeboard is marginal, the spillway can be deepened to lower the maximum pool level of the dam. Figure 4.74 shows dams where spillways in earth and rock are deepened to prevent failure of the old dams from overtopping or because of inoperable gate valves and structures. The disadvantage of lowering the pool water level is that water storage is lost, which can be a problem during drought years when water is needed.

Fires around dams have created many problems, including damage to access roads, transmission lines, penstocks, structures, and other improvements. Fires on

Herman Wendell

Gordon Keller

Figure 4.74—To prevent failure of old dams from overtopping or because of inoperable gate valves and structures, spillways of earth and rock are built or deepened.

dams have also presented problems directly for small dam embankments. Some dam embankments are covered with vegetation, and when a fire burns across the dam, the vegetation is burned, and if roots burn, deep holes or voids can be created in the embankment (fig. 4.75). If the roots do not burn immediately, they will decay in several years, leaving possible voids in the dam embankment that can leak and cause dam failure. Prevention measures include lowering the pool elevation of the water to take pressure off the dam face, or compacting the dam face to fill voids. Keeping trees with deep roots off the embankment is the best solution.

Jonathan Berry

Jonathan Berry

Figure 4.75—An earthen embankment of a dam where wildfire has burned the vegetation and tree roots, leaving deep voids in the embankment. Fire increases the risk of piping and dam failure.

Federal Energy Regulatory Commission Relicensing

Sixteen of the 18 national forests in California have Federal Energy Regulatory Commission (FERC) authorized hydropower projects, for a total of about 119 hydropower projects. In the Pacific Southwest Region, there are about 26 small hydropower projects that fall under FERC-exempt category, administered under special-use authorizations. Currently, 10 licensed dams are undergoing various stages of the FERC relicensing process on six Sierra Nevada national forests. Over

Table 4.8—Summary of infrastructure types, vulnerabilities, and adaptation actions

Infrastructure asset or issue	Vulnerability	Adaptation action
Road:		
Maintenance	Lack of financial and human resources Demand for work after floods and fires Shifting timing of work	Inspect roads after storms Keep current on maintenance items Repair roads in problematic locations Increase flexibility in hiring personnel
Management	Lack of financial and human resources Lack of contracting flexibility	Maintain adequate staff Maintain trained staff Decommission unneeded roads
Location	Road-stream encroachment Flooding and washouts Landslide-prone areas	Move vulnerable sections of roads out of channel migration zone Armor weak streambanks Redirect streamflow away from streambank Stabilize unstable slopes
Surface drainage	Washouts Erosion/sedimentation Water quality degradation Gully formation	Remove water from road surface Outslope roads Use frequent rolling dips, cross drains, and leadoffs Armor pipe and dip outlets Armor eroding ditches
Culverts	Culvert failures Washout from poor installation Lack of capacity Plugging with debris, logs, and sediment	Keep channel clear Repair damaged culvert sections Add stream-diversion protection dips Add trash racks to trap debris Use stream simulation designs
Low-water crossings	Washouts Additional traffic delays	Install only on noncritical routes Use vented fords to pass most flow
Bridges	Bridge failure Foundation scour Loss of freeboard or capacity Timber bridges burned by wildfire	Keep channel clear of debris and vegetation Armor foundations and areas of scour potential Redirect channel flow away from abutments Remove vegetation near bridges Remove aggradation deposits Increase freeboard

the next 10 years, approximately 28 additional projects are expected to start the relicensing process, which will involve most Sierra Nevada national forests (table 4.8). An additional 17 more dams will enter the relicensing process during the following 15 years.

Many of the dams being relicensed are large and operated by municipalities and non-municipalities such as South Feather Water and Power Agency, Pacific Gas and Electric, and Southern California Edison. Many are high-hazard dams because of

Table 4.8—Summary of infrastructure types, vulnerabilities, and adaptation actions (continued)

Infrastructure asset or issue	Vulnerability	Adaptation action
Erosion control	Erosion	Maintain adequate drainage
	Sediment and soil loss	Maintain adequate ground cover
	Gully formation	Plant grasses and deep-rooted vegetation
		Prepare soil to grow vegetation
		Add gully-control structures
Slopes	Slope failures	Construct stable cut and fill slopes
	Rockfall	Add drainage and deep-rooted vegetation
	Debris flows	Add slope stabilization measures as needed
	Accelerated erosion	Pull back unstable sliver-fill slopes
		Add debris basins and check dams
		Use deep patch on settling fill slopes
		Remove loose rock and add rockfall protection
Trails	Trail closures and restricted use	Promote trail partnerships
	Trail damage	Relocate vulnerable trail locations
	Trail-bridge damage	Modify trail bridge designs
		Strengthen trail maintenance capabilities
Facilities	Damage from fires, floods, and wind	Move vulnerable buildings and facilities
	Aging structures	Have storm- and fire-evacuation plans in place
	Depleted water systems	Use fire-resistant materials (e.g., metal roofs)
		Do thinning for defensible space around structures
		Drill or deepen water wells
Dams	Lack of capacity during floods	Clear or lower marginal spillways
	Overtopping or piping failures	Remove vegetation on embankments
	Inoperable gate and control structures	Repair inoperable control structures
	Lack of available water during droughts	Plan for future major storms and droughts
Other	Lack of timely contracting	Hire more contracting officers
	Pavement freeze-thaw damage	Use springtime road-use restrictions
	Fire support road damage	Designate fire-detour routes
	Hazard tree danger	Have crews available to remove hazard trees
	Dust on dry unsealed roads	Provide funding for dust palliatives

their size, storage capacity, and vulnerable populations downstream. FERC licenses extend for 20 to 50 years, a time period in which many climate-induced events may occur. With increasing human population, hazard levels downstream of some dams will likely increase. Instream flows for the health of fish populations will become more of a focus, especially if prolonged droughts occur.

With increased human populations come increased water demands. Some reservoirs will have a longer recreation season with a warming climate (chapter 5). Large storm events are part of the global water cycle and supply water to the Western United States. Although most of these storms are weak systems, the storms can release large volumes of rain and snow along with strong winds, causing flooding events, especially if the storms stall after making landfall. These types of storms stress dam infrastructure and require water releases that could affect the function of downstream bridges and recreation facilities.

Hydroelectric power generation is the least expensive energy alternative currently available, filling gaps for power generation during peak demand periods and when energy from renewables drops off significantly (e.g., in the evenings). A changing climate could significantly alter hydroelectric power generation capacity, which depends on water stored in reservoirs. Less water means fewer turbines will be online at any given time or will be operated at less than optimal levels to meet peak demands. Increased storage may be a partial solution. However, economic viability of the hydroelectric facilities will be an issue for many utilities, given the age and increased maintenance requirements of many facilities.

Chapter Summary

The 10 national forest units in the Sierra Nevada provide a significant amount of water for the state, major recreation opportunities, and a wide range of other resources. The major road systems, including thousands of bridges, culverts and fords; a major trail system; numerous dams; and thousands of buildings are all part of the infrastructure needed for sustainable management of the forests. These facilities represent a major investment in infrastructure that will be increasingly vulnerable to current and future stressors associated with climate change. Key climate stressors include warmer temperatures, larger storms, more intense precipitation, reduced snowpack, altered timing of peak streamflows, periods of drought, and large wildfires.

This assessment has described the many types of infrastructure (roads, bridges, dams, buildings, campgrounds, etc.) found in Sierra Nevada forests and their vulnerabilities. Specific measures are discussed that can be taken to adapt to projected climate change effects, thus minimizing damage from storms and fires (box 4.6).

Box 4.6

Summary of Road-Related Adaptation and Vulnerability Reduction Considerations

The following can be considered when trying to reduce the potential impacts of climate change and storms on facilities (Keller and Ketcheson 2015).

- **Recognize and plan for local climate change.** Climate change is happening and is expected to worsen over time, so we can expect more variable weather, more intense storms, more droughts and associated wildfires, all which affect infrastructure and transportation.
- **Identify areas of historical or potential vulnerability.** Some high-risk sites are well known. Chronically undersized culverts typically have a history of failure. Geologically unstable materials or slopes, roads on steep slopes with sidecast fills, roads that cross steep channels subject to debris flows, wet slopes, areas subject to flooding, and areas of high soil erosion near streams all have high vulnerability to storms.
- **Avoid problematic and high-risk areas.** Consider road closure or relocation to avoid problematic areas and poor road locations. This includes steep slopes (greater than 60 percent), deep-seated rotational landslides, areas prone to shallow rapid landslides and debris torrents, avalanche chutes, rock-fall areas, wet areas, saturated soils, and highly erodible soils.
- **Use appropriate minimum design standards.** Road width should be minimized, while still considering traffic safety and user needs. Adaptation treatments may be used to adjust the standard of new roads as appropriate and result in less earthwork, lower cuts and fills, and less concentration of runoff, all of which reduce risk of damage or failure during storms.
- **Employ "self-maintaining" concepts into the selection and implementation of treatments.** Road systems are extensive, but resources for road maintenance are often limited. Implementing those treatments that reduce the amount of road miles that need frequent and costly maintenance will allow resources to be applied more optimally. Examples include outsloping wherever feasible, additional cross drains, and redundant or larger drainage structures.
- **Incorporate relevant, cost-effective technology.** Apply appropriate technology to improve identification of priorities and for planning, design, and reconstruction. This includes the use of GIS and global positioning system technology; geosynthetics for filters, separation, and reinforcement; mechanically stabilized earth retaining structures; riprap sizing criteria for bank stabilization; and soil bioengineered and biotechnical slope stabilization and erosion control measures, etc.
- **Perform scheduled maintenance.** Scheduled maintenance should be performed at a regularly planned frequency to be prepared for storms. Ensure that culverts have their maximum capacity and ability to pass debris and aquatic organisms, ditches drain well, and channels are free of debris and brush that can plug structures. Keep the roadway surface shaped to disperse water rapidly and avoid areas of water concentration. Because channel clearing can be controversial, using an interdisciplinary decision process is advised, limiting clearing to pieces that pose an immediate risk to a structure.

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- **Use simple, positive, frequent roadway surface drainage measures, and use restrictions.** Good roadway surface drainage should be provided to disperse water off the road frequently and minimize water concentration. Where soils cannot support traffic when wet (e.g., volcanic ash), restrict use during wet seasons to prevent rutting and gullying. Outslope roads whenever practical and use rolling dip cross drains for surface drainage rather than a system of ditches and culverts that require wider roads and more maintenance. Cross drains, insloping and outsloping, and rolling road grades need to be in good working order.
- **Properly size, install, and maintain culverts.** Improperly installed, undersized, and plugged pipes are common reasons for culvert failure during storms. Improper alignment or grade relative to channels and ditch lines, excessive woody debris in the channel, excessive channel constriction, excessive allowable headwater elevations, excessively wide inlet areas, and inadequate capacity all contribute to pipe plugging and subsequent failure. Concrete or masonry headwalls greatly improve the resistance of culvert to failure during overtopping. Maintain inlet configurations and remove debris that may plug the pipe to ensure proper function during storms.
- **Use simple fords or vented low-water crossings.** Simple fords or vented low-water crossings (vented fords) should be used as often as appropriate for small or low-flow stream crossings on low-volume roads, instead of culvert pipes that are more susceptible to plugging and failure. Protect the entire (100-year) wetted perimeter of the structure and the downstream edge of the structure against scour, and provide for aquatic organism passage as needed.
- **Stabilize cut and fill slopes.** Unstable fill slopes should be removed or treated as needed to improve stability. Cut and fill slopes should be well covered (stabilized) with vegetation to minimize surface instability problems, as well as to minimize surface erosion. Uncompacted sliver fills and settling or cracking fills are a high priority for stabilization or removal. Fill slopes may also be undercut and oversteepened by a stream or channel. Failing, oversteep slopes from road construction where material enters a stream can cause downstream problems to the watershed and promote plugging of structures.
- **Use deep-rooted vegetation to "anchor" soils.** Promote slope stability by using deep-rooted vegetation for soil bioengineering and biotechnical treatments. Combine plants having deep and strong roots with a mixture of shallow-rooted grasses for good ground cover and erosion control on slopes, preferably using native species.
- **Design high-risk bridges and culverts with armored overflows.** High-risk bridges and culverts can be designed with armored overflow areas near the structure in case of overtopping, or with a controlled "failure" point that is easy to repair and minimizes environmental damage. Alternatively, oversizing the structure and allowing for extra freeboard on bridges will maximize capacity and minimize risk of plugging. Do not constrict the natural channel. Consider culverts with a span at least that of the bankfull channel width and bridges that span the floodplain.

- **Eliminate diversion potential.** All stream crossings, especially culvert crossings, should be designed and constructed (or upgraded) to have no-diversion potential. Stream crossings in steep channels that are subject to debris flows should be designed, constructed, or upgraded to withstand debris flows without being washed out or resulting in subsequent streamflow diversion. Structure damage from a plugged culvert may be minimal, but road damage from a stream diverted down the road can be extensive.
- **Use scour prevention measures for structures on questionable foundation materials.** Bridges, retaining structures, and structural foundations should be placed into bedrock or on firm, in-place material with good bearing capacity to minimize foundation failures. Apply foundation-strengthening and scour-prevention measures when foundation conditions are known to be marginal or a bridge is susceptible to scour.
- **Be aware of channel morphology and stream channel changes near a bridge, culvert, ford, or road along a creek.** Significant changes in stream gradient, from a steeper reach to a flatter area, can cause channel aggradation and subsequent plugging of structures or a stream diverting out of its channel. This is particularly problematic on alluvial fans where natural avulsion and channel migration can damage roads and structures. Tight bends in a channel promote concentration of flow to the outside edge, often leading to scour, and woody debris tends to accumulate at bends. Road work or "improvements" might also cut off a stream's natural access to its floodplain.

There is an extensive and expensive inventory of infrastructure in this region, yet funds are very limited such that even routine maintenance is typically beyond the capacity of current personnel and funding. The additional challenges posed by climatic variability and change will make it more difficult to ensure long-term functionality of infrastructure, so assessing vulnerabilities, ranking resources at risk, and prioritizing adaptation actions are critical (table 4.8). Implementing "climate change thinking" and "stormproofing" in day-to-day resource management and agency operations, something that is already underway throughout the USFS, will improve the likelihood of sustaining critical infrastructure for future generations.

Considerable infrastructure data are available in current geospatial and INFRA databases. Also, many climate and hydrologic projections are available to help identify areas of increased temperatures, changes in timing and amount of streamflow, and changes in snowpack (see chapter 3 and Dettinger et al. [2018]). This information can be combined on forests to show areas of greatest vulnerability such as where roads are located near streams with likely increased flows or where culverts will be subject to increased flows (fig. 4.76). Maps can be produced showing road systems in conjunction with areas of anticipated changes in snowpack (fig. 4.77).

Figure 4.76—A combined map showing the road system, road areas near a stream, culverts, and projected streamflow changes (in ft^3 sec^{-1} [cfs]) on the Eldorado National Forest in northern California. Note that many culverts are not exactly on the stream crossing location because of global positioning system mapping resolution.

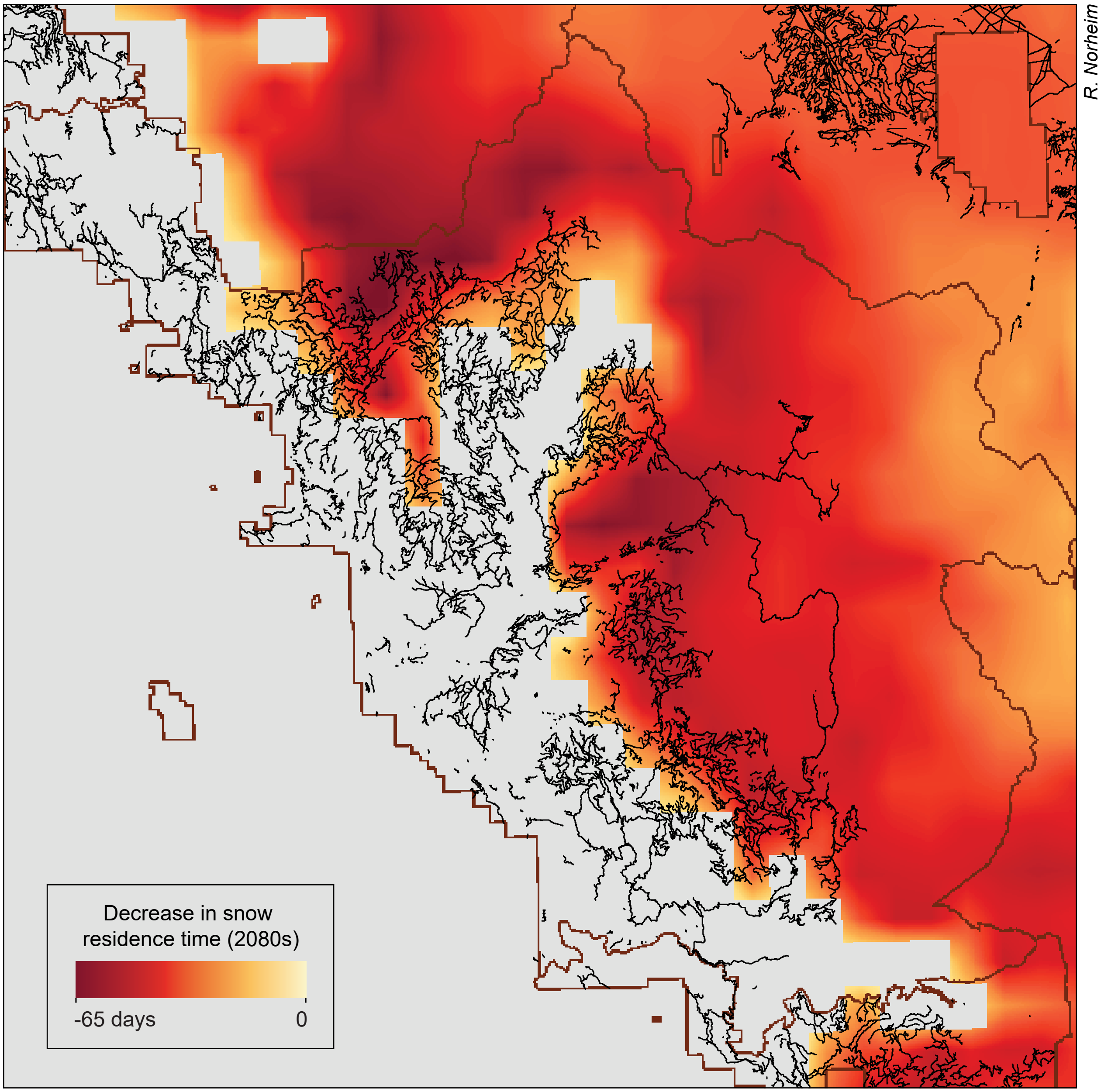

Figure 4.77—Map showing the forest road system (black lines) and decrease in projected snow residence time in the central Sierra Nevada.

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Chapter 5: Effects of Climate Change on Outdoor Recreation in the Sierra Nevada

Patricia L. Winter, José J. Sánchez, and David D. Olson[1]

Introduction

This chapter considers social vulnerability to climate change by assessing the effects of climate change on outdoor recreation in the Sierra Nevada bioregion (Fischer et al. 2013) (fig. 5.1), and providing the information needed to manage for risk and to minimize loss (Aplet et al. 2010). By considering current and projected effects, we hope to better equip land managers and stakeholders with information that can aid management and planning for socioecological resilience.

The report expands the emphasis on recreation provided in a recent science synthesis for the Sierra Nevada (Long et al. 2014). Although the final aim is to assist the development of adaptation strategies and tactics, with emphasis on reducing vulnerability, exposure, and uncertainty (e.g., Aplet et al. 2010), the complexity and uncertainty involved require an adaptive management approach to effectively address climate change effects (Arvai et al. 2006, Clark 2002, Joyce et al. 2009). More recent examinations of recreation-related impacts, including this chapter with its greater level of detail and focus, are essential to informing adaptation that improves resilience around outdoor recreation management and use.

Nationwide, outdoor recreation provides substantial economic benefits. In 2016, the Outdoor Recreation Jobs and Economic Impact Act required an assessment of the outdoor recreation economy and its effects on the overall economy of the United States. According to the Bureau of Economic Analysis (USDC BEA 2018), outdoor recreation accounted for 2.2 percent of the nation's gross domestic product in 2016, and between 2015 and 2016, the outdoor recreation economy grew faster (a 1.7 percent increase) than the overall economy in the same period (1.6 percent overall increase). Conventional outdoor recreation accounted for 32.7 percent of the gross output for recreation, and boating and fishing alone, as the largest core activity in 2016, produced $36.9 billion of that output.

California's economic contribution from outdoor recreation is likewise significant. Among the top 30 employment sectors in California, the contribution is even greater in northern California and the Sierra Nevada where total outdoor recreation-related employment ratios to total population are triple the statewide average (BBC Research & Consulting 2010). California State Parks reported 2,269,082 visits in the

Among the top 30 employment sectors in California, the contribution is even greater in northern California and the Sierra Nevada where total outdoor recreation-related employment ratios to total population are triple the statewide average.

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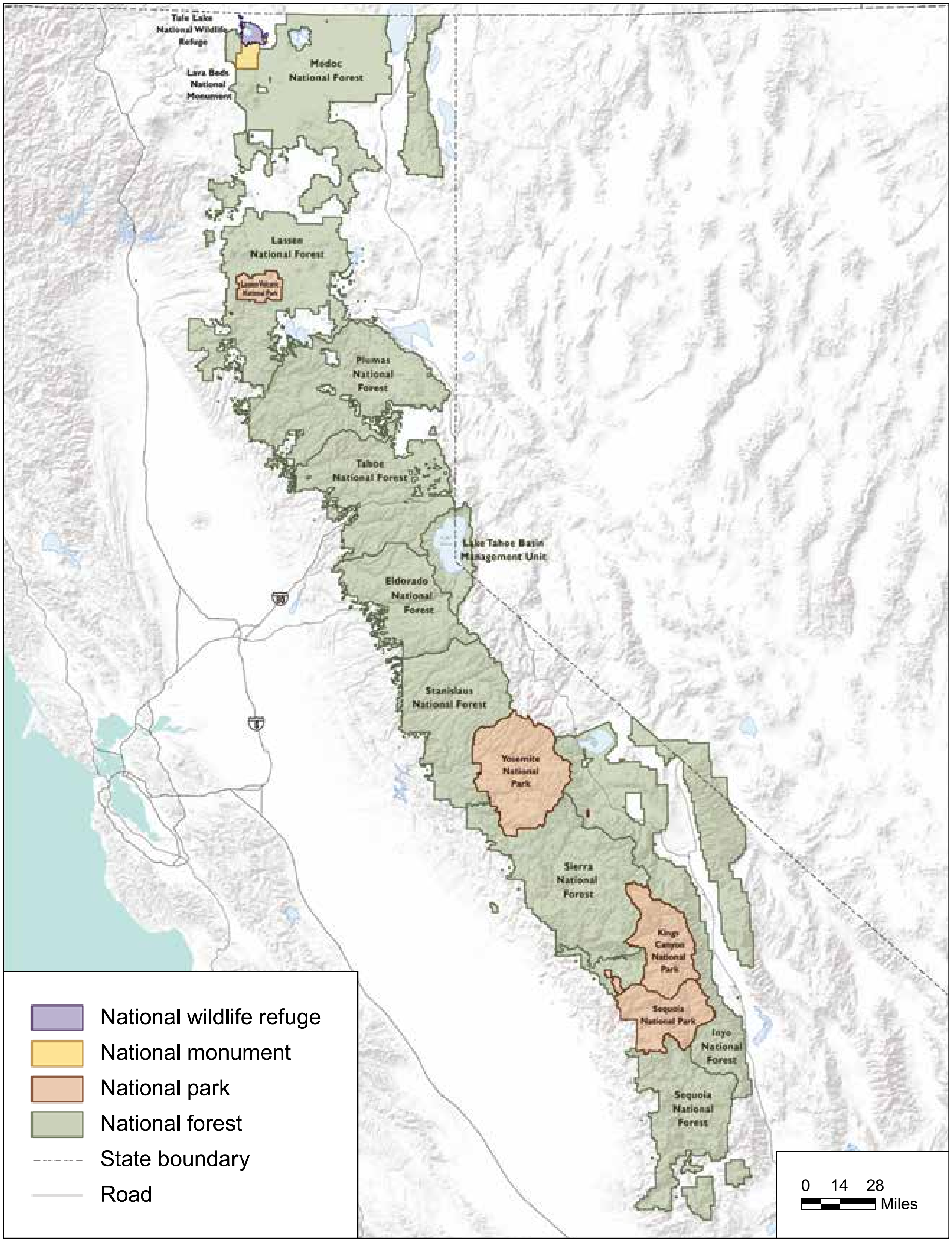

Figure 5.1—The Sierra Nevada assessment area.

2015–2016 reporting period for the Sierra District alone, bringing in revenue of $5,180,272 (California State Parks 2016). Outdoor recreation on federal lands accounted for about 23 million visitation days on average annually (table 5.1). This translates into a further contribution to the state economy. Statewide direct expenditures for outdoor recreation on federal lands are highest in the Sierra region, accounting for about one-third of the contribution from federal lands. In 2008, the economic benefit to the state from outdoor recreation in the Sierra Nevada alone was $333 million (BBC Research & Consulting 2010).

Economic benefits from outdoor recreation and tourism are important to the communities adjacent to, and surrounded by, national forests in the Sierra Nevada. Many rural economies in the region depend on recreation and tourism (Chan and Wichman 2018, Hatchett and Eisen 2018), and related projects can be conducted in

Table 5.1—Total annual visitation to federally managed parks, forests, monuments, and refuges by geographic zone

Zone	Unit	Total annual visits	Confidence interval
			Percent
North	Modoc National Forest (NF)	146,203[a]	38.4 ±
	Tule Lake National Wildlife Refuge	60,000[b]	
	Lava Beds National Monument (NM)	135,286[c]	
	Lassen NF	269,108[d]	23.5 ±
	Lassen Volcanic National Park (NP)	507,256[c]	
	Plumas NF	357,253[d]	22.3 ±
Central	Tahoe NF	1,660,202[a]	17.8 ±
	Lake Tahoe Basin Management Unit	7,721,000[a]	23.2 ±
	Eldorado NF	1,202,000[e]	8.9 ±
	Stanislaus NF	1,085,000[e]	12.0 ±
	Yosemite NP	4,336,890[c]	
South	Inyo NF	2,309,000[a]	8.5 ±
	Sierra NF	610,878[e]	15.0 ±
	Devils Postpile NM	109,571[c]	
	Kings Canyon NP	692,932[c]	
	Sequoia NP	1,291,256[c]	
	Sequoia NF	777,000[a]	24.2 ±

[a] 2016 reporting estimate, NVUM NRM website.
[b] Sexton et al. (2012).
[c] SSRSR reports online, National Park Service, 2017 data accessed in 2018.
[d] 2015 reporting estimate, National Visitor Use Monitoring Natural Resource Management (NVUM NRM) website.
[e] 2017 reporting estimate, NVUM NRM website.

ways that further enhance opportunities for forest community residents (Charnley 2014). These economic contributions influence community well-being (Charnley 2014, Winter et al. 2014a). Furthermore, communities whose economies depend on natural resources and are adjacent to national forests are likely to experience the effects of climate change earlier than other communities in the state (Wear et al. 2012).

Considering benefits beyond direct and indirect economic values, outdoor recreation provides myriad individual, community, and societal benefits (Winter et al. 2014b). These include the opportunity to connect with forests, nature, wildlife, and other humans, which has been shown to produce several desirable outcomes including more environmentally sustainable behaviors (Winter et al. 2019, Zelenski et al. 2015), and, in some cases, support for conservation (Zaradic et al. 2009). Time in nature contributes to overall well-being and has been used as an intervention to encourage flourishing (Capaldi et al. 2015).

Accounts from hikers along the John Muir Trail cited multiple factors that contributed to their experience, including being with others, solitude, and overall spiritual benefits (Hitchner et al. 2019). Similar accounts were reported in a review of multiple wilderness studies (Winter 2013). A survey of whitewater rafters along the Kern River revealed visitor motivations included enjoying nature, escape, being with others who share a similar appreciation for nature, and learning new things (van Riper et al. 2018).

Public health also benefits from exposure to nature and outdoor recreation (Barton et al. 2009, Winter et al. 2014b). This is an important consideration when assessing the value of natural areas, representing an essential element of analyses of recreation vulnerability to climate change (Winter et al. 2019). Recreation opportunities in the Sierra Nevada assessment area help to counteract the health risks associated with a sedentary lifestyle (Kondo et al. 2015), as evidenced by an estimated $76.6 billion in reduced costs for medical care at the national level (Pratt et al. 2000). Although these value estimates vary based on the assumptions and populations involved, another analysis showed that if the number of physically active children (ages 8 to 11; three times a week for 25 minutes of high-calorie-burning activity) increased from the current 31.9 percent to 50 percent, $8.1 billion in direct medical costs would be saved over their lifetimes (Lee et al. 2017). Evidence suggests that parks and green spaces can help remedy some income-associated inequalities in health outcomes (Mitchell and Popham 2008, South et al. 2018).

National forest recreation represents significant public health benefits, owing to the level of recreation use and range of activities (Kline et al. 2011). An assessment of contributions to physical activity, calculated through Metabolic Expenditures (an approach to estimate energy expended during a visit based on primary reported activities; Ainsworth et al. 2000, Cohen et al. 2007, Winter et al. 2019), revealed a significant contribution toward physical health. Overall patterns of estimated health benefits from physical activity disproportionally benefitted visitors of higher socioeconomic status. However, benefits favored lower income community members adjacent to forest lands (within a 60-mi road radius of the forest). This finding mirrors comparable work in urban settings pointing to the importance of urban parks within a walkable radius of communities, especially for those who are socioeconomically disadvantaged (Jennings et al. 2016).

Recreation opportunities offered on public lands in the Sierra Nevada are as diverse as the ecosystems of this mountain range. We describe that diversity and its influences on recreation in order to facilitate climate-informed planning and management.[2] Adopting this approach broadens the range of choices available to managers toward sustainable resource management (Vose et al. 2012).

Relationships Between Climate Change and Outdoor Recreation

Demand for outdoor recreation opportunities as well as the supply and quality of opportunities in the assessment area are sensitive to climate change effects. Effects may be direct or indirect and may vary in duration and magnitude. Climate change effects are already evident in the Sierra Nevada (chapter 2), and further change is anticipated. In this section, we review current and anticipated effects on outdoor recreation. Recent observed changes and additional projected changes affect recreationist decisions and the derived benefits in many ways. Climate change also affects the contributions of recreation to physical and mental health (Evans 2019).

Direct effects may be experienced through altered ambient temperature, both minimum and maximum. As described in chapter 2, changes in temperature have already occurred in the region. An overall increase in the minimum and maximum air temperatures in the Sierra Nevada has occurred over the past 20 years, and annual average temperatures have increased (see chapter 2). The rate of temperature increase varies by elevation (Jardine and Long 2014), so effects vary by recreation destination, season, and type of activity. Projected effects of higher temperatures on outdoor recreation are expected to be moderate to high in the assessment area. (Reynier et al. 2015).

[2] In this chapter's focus on recreation, we will not include the full array of ecosystem services represented in the assessment area, including the importance of the non-use values in the bioregion (Cordell et al. 2003, Williams and Watson 2007). An overview of ecosystem services and the assessment area can be found in Patterson (2014).

Recreationists are more likely to seek respite from heat in natural areas as average temperatures rise (Morris and Walls 2009), increasing overall participation, especially in warm seasons, and extending the warm-weather recreation season. However, thermal comfort will likely influence the types of locations visited and activities pursued on warm days (Chen and Ng 2012, Potchter et al. 2018), and unusually hot days may lead to a notable decline in visitation (Richardson and Loomis 2004, Rosselló-Nadal 2014). Anticipated increases in the number of annual high-heat days (chapter 2) or elevated temperature extremes across the region may have effects beyond that of an increase in average temperature. Moderate changes may result in extended recreation seasons; for example, reduced length of cold-weather seasonal closures may increase the number of days recreationists seek opportunities in forest areas (Rosselló-Nadal 2014). Increased recreation associated with temperature increase may have adverse impacts on sustainable recreation management (Ellison et al. 2018).

Increasing air temperatures will also increase surface water temperatures (Hunsaker et al. 2014). The change in water temperatures is of considerable concern in the assessment area, owing to its network of lakes, rivers, and streams. In addition to serving as habitat for endemic species of fish, many streams support prized fishing opportunities that may be adversely affected by continuing effects of a warmer climate (Hunsaker et al. 2014, Reynier et al. 2015).

Altered precipitation may affect some aspects of recreation in the assessment area (Reynier et al. 2015). There will be more rain than snow with increasing temperature, with the most significant changes occurring in the northern Sierra Nevada at lower elevations (Jardine and Long 2014) (chapter 3). Snow-dependent recreation across Sierra Nevada national forests will be especially sensitive to this shift (Reynier et al. 2015), reducing the length of the winter recreation season and participation in snow-dependent activities (Wobus et al. 2017). Although projected changes in the Sierra Nevada in cross-country skiing, snowmobiling, and downhill skiing are smaller than projected for other Resources Planning Act assessment regions (USDA FS 2016), the benefits to recreationists and economies from snow-based activities in the Sierra Nevada require consideration.

Although overall precipitation may not shift substantially across the assessment area, extended drought (fig. 5.2) and extreme weather through atmospheric-river events (chapter 2) will have immediate and extended impacts on recreation use. Reduced waterflow caused by extended drought, or reduced water levels in lakes and reservoirs, may negatively affect recreation opportunities and access (Hand and Lawson 2018a). Drought tends to affect summer recreation differently, where water-dependent activities may decrease, while dryland activities may increase

(Prestemon et al. 2016). Altered temperature, snowmelt timing, and precipitation have impacts on whitewater boating, although the impacts vary across the Sierra Nevada, depending on whether the river is managed through hydropower projects (Ligare et al. 2012).

Figure 5.2—Oaks killed by extended drought (photo taken in Madera County, California).

Conversely, an abundance of water through atmospheric-river events may lead to large increases in waterflow, extended high water levels that require shifts in management approaches, and longer term impacts in which water-based recreation and adjacent habitat are altered or damaged from extreme events (Huang et al. 2018). For example, extreme events have been shown to contribute to elevated pollutant loads in rivers, which may compound ecosystem impacts and human health concerns about use for some areas (Clow et al. 2011, 2013). Human behaviors also shift after extreme events, especially when recreationists actively seek to modify an area to restore preferred-use opportunities (e.g., Milburn and Winter[3]).

[3] Milburn, L-A.S.; Winter, P.L. 2015. Final report: Cattle Canyon participant observations. California State Polytechnic, Pomona. Unpublished report. On file with: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, 4955 Canyon Crest Drive, Riverside, CA 92507.

Observations conducted on the Angeles National Forest revealed that recreationists used preexisting deeper pools created naturally or by other recreationists, thus "dam building" was infrequently seen. An uptick of new dam building occurred immediately after a large rain event, where artificially built structures and natural pools had been washed away or eroded (see footnote 3).

Other ecological shifts exacerbated by climate change may result in adverse effects on ecosystems, wildlife, fish, and the health of recreationists. For example, algal blooms are associated with many factors, including effects from climate change. Although risks from inhalation appear to vary, direct exposure from water contact can be toxic to both people and animals (Backer et al. 2009, Derlet et al. 2009).

Additional indirect effects may be associated with changes in ecological features and ecosystem inputs, including vegetation, wildlife, and water. For example, demands for access and use may increase if high rainfall leads to a shift in flowering species (box 5.1, fig. 5.3). Postfire recovery may include an array of blooms not seen elsewhere (fig. 5.4). Higher than average snowfall or an extended snow season may lead to increased recreational use of an area, which must be managed effectively to preclude severely diminished visitor experiences owing to perceived crowding, or inability to access desired opportunities. Perceptions of degraded quality of an area or resource may result in altered visitor behaviors, including decisions to not visit an area (Ferguson et al. 2018, Morris and Walls 2009).

Additional indirect effects may influence the recreational setting and its features through wildland fire. In Sierra Nevada forests, fire may result in an area closure and preclude access, discourage access because of smoke, diminish viewsheds, and reduce economic benefits from recreation through limited access or diminished resource quality (Wigtil et al. 2016) (figs. 5.5 and 5.6, box 5.2). Annual area burned has increased in recent decades in the Sierra Nevada, with temperature and drought influencing this increase (Gonzalez 2012). Use of prescribed fire to reduce fuels and avoid large, high-intensity fires and their effects on ecosystems and public health necessitates some tolerance for emissions and other fire-related, short-term impacts (Schweizer and Cisneros 2014). Survey results for visitors to Yosemite Valley suggest that a majority of visitors were aware of the park's prescribed fire program and "were likely to tolerate short periods of occasional smoke or reduced visibility caused by prescribed burns" (Blotkamp et al. 2010).

Wildfires near urban areas represent much larger health-related concerns (Sierra Nevada Conservancy 2017), including the impacts of degraded air quality on local communities, recreationists, and tourists in the Sierra Nevada (see Burley et al. 2016, Bytnerowicz et al. 2013, Cisneros et al. 2010, Preisler et al. 2010). Some

Box 5.1

Unusual Rainfall Created Super Bloom, Leading to "Poppy Apocalypse"

An unusually robust rainy season in 2019 affected one southern California town to the extent it was challenged to rapidly shift its management of a natural resource area. In March 2019, Lake Elsinore experienced what was labelled a "poppy apocalypse" when, in a single day, over 100,000 visitors converged on the town of 60,000 residents to view the California poppy (*Eschscholzia californica* Cham.) "super bloom" in Walker Canyon. Visitation far exceeded the projected numbers for the location, resulting in overflowing parking areas, insufficient bathroom facilities, vehicles stopped on adjacent roads causing safety concerns and traffic jams, and trampling of flowers as visitors left the paths and trails to see and photograph the flowers.

Steve Manos, the mayor of Lake Elsinore, declared a short-term emergency, employing additional personnel to manage visitation, placing limits on parking in the immediate area, and requiring shuttle access for a fee. Appeals were issued on news and social media sites to communicate a message about responsible visitation. By mid-April, the flowers began to drop their petals, requiring a mile or more hike into the canyon to see the remaining blooms. Manos was quoted as saying "The super bloom has been unlike any event we have experienced before."

Summarized from the following sources: www.cbsnews.com/news/california-poppy-super-bloom-crowds-overwhelm-lake-elsinore; www.desertsun.com/story/news/environment/2019/03/21/want-see-poppy-super-bloom-lake-elsinore-youll-have-pay/3234318002 (May 2019).

James D. Absher

Figure 5.3—Closeup of California poppies in bloom (photo taken in Madera County, California).

James D. Absher

Figure 5.4—Flowers in bloom after wildfire (photo taken in Madera County, California).

James D. Absher

Figure 5.5—Postfire landscape in Nelder Grove, Sierra National Forest.

Figure 5.6—Postfire mosaic along highway north of Wawona entrance inside Yosemite National Park, Ferguson Fire, 2018.

of these impacts may continue to increase in severity under climate change owing to increased temperatures, a longer period of elevated temperatures, and altered precipitation (Winter et al. 2019). In recent years, air quality impacts from wildfires have become significant health events and are now, in fact, the greatest source of air pollution exposure faced by the American public. In addition, as wildfires increase in duration, communities often face multiple weeks of exposure. In 2018, fine particulate levels exceeded the 24-hour standard in the Western United States over 3,700 times. (https://www.fs.fed.us/blogs/pardon-our-smoke; accessed 5/10/2019).

Longer term effects may be compounded where ability to restore an area is limited by available resources or capacity. One limit is available funding sources for recreation sites and amenities. Emergency restoration funds under Forest Service Manual 2523.01 allow the agency to conduct emergency stabilization through Burned Area Emergency Response (BAER), which provides for the use of Wildland Fire Management funds for emergency rehabilitation of burned-over National Forest System lands and water. Recreation per se is not included under BAER funding because the loss of recreation-related facilities and amenities is not

Box 5.2

Wildfires Result in Smoke and Health Advisories, Leading to Closure of Recreation Areas

In 2018, the Lions Fire, Ferguson Fire, and other wildfires had significant impacts on communities and outdoor activities in portions of the Sierra Nevada. On July 24, the National Park Service closed Yosemite Valley, Wawona, and the Mariposa Grove of giant sequoias, owing to diminished air quality and visibility from the Ferguson Fire on nearby Sierra National Forest.

Health effects from the diminished air quality were of concern. For example, on July 30, a stage 2 health advisory was issued for Mono County, recommending that people refrain from strenuous outdoor activities, including in the popular Mammoth Lakes area. Smoke from the Lions Fire was visible near Reds Meadow Road (Minaret Vista and Devils Postpile National Monument), Mammoth Mountain, and the town of Mammoth Lakes. Numerous fires throughout the state affected air quality in the eastern Sierra Nevada.

On July 29–30, an air quality alert was also issued for San Joaquin, Mariposa, Stanislaus, Merced, Madera, Fresno, Kings, Tulare, Tuolumne, and Kern Counties. The forecasted impact was based on elevated particulate matter in the size range of 2.5 microns ($PM_{2.5}$). Yosemite Village recorded unhealthy air quality on July 29, with very unhealthy air quality in the afternoon.

Trails and recreation areas in national forests were closed as a result of unhealthy air quality from multiple fires. For example, an emergency closure was issued for the Fern Lake and Beck Lake Trails on Inyo National Forest. An emergency trail closure and a Forest Order were issued to close a large portion of Sierra National Forest (west of the North Fork of the San Joaquin River, north of the Middle Fork of the San Joaquin River and South of Iron Creek).

Yosemite Valley and the Mariposa Grove were reopened in mid-August, although selected areas remained closed. The Fern Lake and Beck Lake Trails on the Inyo National Forest were reopened on August 30, while trails on the Sierra National Forest remained closed.

Summarized from the following sources: www.sierrawave.net/community-meeting-in-mammoth-for-lions-fire; www.fs.usda.gov/detail/inyo/news-events/?cid=FSEPRD590115; www.sierrarecmagazine.com/the-inyo-national-forest-to-re-open-fern-beck-trails; www.travelyosemite.com/alerts/2018/ferguson-fire.

generally considered an emergency, and recreation managers cannot access funds used by national forests to respond to fire events (Chavez and McCollum 2004).

Lack of funds and capacity to restore damaged areas can extend the effects of wildland fire events and postfire damage for many years (box 5.3). Where extensive damage occurs to recreation infrastructure, the ability to recover or restore an area for visitor use may represent extended losses to the recreating public by way of reduced benefits and limited substitution opportunities. Surrounding communities may be affected by loss of recreation and tourism revenue (Winter et al. 2014a).

Box 5.3

Gabrielino Trail Restored After Almost a Decade

The 2009 Station Fire, and subsequent damage caused by postfire rain, erosion, and fallen trees left large portions of the Gabrielino Trail, a 26-mi trail on Angeles National Forest, closed to public use for almost a decade. In 2016, a plan was developed to restore the trail. The Gabrielino was the country's first National Recreational Trail designated under the National Trails System Act in 1968. In September 2018, U.S. Department of Agriculture, Forest Service (USFS) employees joined volunteer groups, community members, and sponsors in celebrating completion of the extensive restoration effort. The reopening occurred on the 50th anniversary of the trail designation, the culmination of a successful partnership involving grants to hire contractors for technical aspects of trail restoration, U.S. Forest Service funding and personnel, and over 1,900 contributed volunteer hours.

Sources: Cardine (2018), MWBA (2018).

Indirect effects of climate change on recreation will be affected by social change (USDA FS 2016). Interest in overall participation, and types of activities engaged in, are influenced by interests in technology, increasing urbanization, economic conditions, changing age-related demographics, and cultural shifts embedded in ethnicity, race, and community. Furthermore, increasing population may result in increased conflicts over residential developments abutting natural resource areas, as well as increased demand and popularity of some spaces. This increased demand and popularity, though desirable in the sense of greater participation and engagement in recreation and experiences in the outdoors, may necessitate limits or controls on access. The overall experience may be diminished owing to a sense of crowding associated with even modest increases in the total number of participants and days of participation (USDA FS 2016).

These larger trends are considered to have a moderate impact on forest systems (Reynier et al. 2015) but a low potential for increasing sensitivity under climate change. Interaction of these trends with other impacts may be of greater concern. The intersection of recreation settings and opportunities sought by communities of color and the areas projected to be altered by climate change will determine the degree to which vulnerable populations may be affected. For example, if locations popular among Latino visitors require more extensive closures either short term (to mitigate risk) or longer term (for recovery from damage), an environmental justice perspective suggests a need to identify substitute areas for use, and enhanced efforts to expedite restoration (ideally including an assessment of how the area might be improved to serve diverse visitors). Latino recreationists have been found to prefer recreation settings with more developed amenities, likely in support of extended families in the recreating group (Roberts et al. 2009). Loss of these enhanced built amenities, which require resources and time to restore, are of concern when the loss affects underserved groups.

Communities dependent on the outdoor recreation and tourism economy may see some increases in use from extended recreation seasons but may also see increased impacts to the community's way of life and ecosystem services (Lal et al. 2011). Furthermore, recreationists on many forests tend to stay within the local area. Impacts in the form of access and the range of opportunities available within a close travel distance may increase or decrease. The ability of economically disadvantaged community members to travel farther to alternate destinations may be constrained when local areas are adversely affected by climate change.

Recreation Participation and Economic Value

An update to the 2010 Resources Planning Act (USDA FS 2016) assessed current and projected recreation use in the Pacific Coast Region (U.S. Forest Service [USFS] Pacific Northwest and Pacific Southwest Regions, which include the Sierra Nevada assessment area) by groups of activities (table 5.2). "Region" in this analysis is based on point of origin of the visitors, rather than on their destination (a distinction worth keeping in mind throughout this section). It is not specific to recreation use in the assessment area. Askew and Bowker (2018) identified the Pacific Coast region as having the greatest stability in recreation activity participation and consumption overall, with smaller climate-associated effects than other regions assessed, or with wider ranges of variation that are unclear.

Increases of 50 percent or more were outlined for some categories of activities (table 5.2). Developed site use, including visiting developed and interpretive sites, is expected to increase in the Pacific Coast region. Developed sites as used here include developed camping and picnic sites; interpretive sites include nature centers and historical sites (Askew and Bowker 2018). Nature observation, including birding and nature viewing, is projected to increase more than 50 percent. Backcountry activities in wilderness and primitive camping are projected to increase as well. Motorized water activities show the highest projected increases in motorized use. Increases at or above 50 percent with and without climate change also include fishing, developed skiing, and floating.

Some activity types show small to marginal effects associated with climate change, including visiting developed sites, nature observation, backcountry activities, motorized activities (off-roading and motorized water use), fishing, and nonmotorized water activities. Activities affected by climate change in the 5-percent-or-more range include developed and undeveloped skiing and motorized snow activities (decreased by climate change). Whitewater recreation activities are affected in various ways, depending on elevation and the type of run (Ligare et al. 2012).

Table 5.2—Modeled projections of the effects of climate change on recreation in the Sierra Nevada assessment area[a] for 2060[b]

Recreation activity	Number of participants in 2008	Projected change without climate change[c]	Projected change with climate change	Net effects of climate change[d]
	Millions	- - - - - - - - - - - - *Percent*	- - - - - - - - - - - -	
Developed site usage:				
Visiting developed sites	31	68	67	-1
Visiting interpretative sites	26	72	71	-1
Observing nature:				
Birding	13	69	71	2
Nature viewing	31	66	65	-1
Backcountry activities:				
Challenge activities	5	54	57	3
Horseback riding on trails	3	78	75	-3
Day hiking	17	67	63	-4
Primitive area use	18	53	55	2
Motorized activities:				
Motorized off-roading	9	47	49	2
Motorized water activities	10	80	78	-2
Motorized snow activities	1	52	44	-8
Consumptive activities:				
Hunting	3	9	19	10
Fishing	10	52	54	2
Nonmotorized winter activities:				
Developed skiing	5	91	96	5
Undeveloped skiing	1	22	32	10
Nonmotorized water activities:				
Swimming	25	75	74	-1
Floating	6	55	53	-2

[a] Data are from the "RPA Pacific Coast Region" (USDA FS 2016), which includes the Sierra Nevada assessment area.
[b] Model output is based on an average of results under the A2, A1B, and B2 emission scenarios.
[c] Percentage changes for total number of participants are compared to 2008.
[d] Net effects of climate change equal "with climate change" minus "without climate change."

Areas for which an increase in climate change effects are projected can be a focus in sustainable recreation plans. A helpful tool for assessing delivery of sustainable recreation activities, and a requirement of the 2012 USFS Planning Rule, is the Recreational Opportunity Spectrum. Although not covered in detail here, the Recreational Opportunity Spectrum provides for a variety of outdoor experience under six management class categories including primitive, semiprimitive nonmotorized, semiprimitive motorized, roaded natural, rural, and modern developed. Physical, social, and managerial characteristics are included (Hand et al. 2018).

More broadly, the USFS framework for sustainable recreation (USDA FS 2010) outlines the importance of restoring and adapting recreation settings; implementing "green" operations; enhancing communities; investing in special places; forging strategic partnerships; promoting citizen stewardship; knowing visitors, community stakeholders, and other recreation providers; providing the right information; building a solid financial foundation; and developing the workforce. An emphasis on knowing the visitors along with their values and preferences relies on monitoring systems and data, including the National Visitor Use Monitoring (NVUM) Survey.

The USFS NVUM program is the nationwide, systematic assessment of recreation visitation, conducted in 5-year rotations for each national forest. A total of 27 activities (and one other category) are examined. Overall use for each forest/unit, as reported in table 5.1, paired with national park and national monument data, speak to the importance of recreation use in the assessment area.

The NVUM surveys (round 4), reported between 2015 and 2017, covered the 10 national forests/units in the assessment area, and indicated that the majority of visitation (74.9 percent) involved warm-weather and winter activities (table 5.3, fig. 5.7) (note that more than one main activity could be reported by respondents; percentage of the total represents weighted estimates for visits involving single or multiple main activities). The categories of activities under "other" are probably less susceptible to climate change than the other categories listed, although variations may occur.

The activities reported in table 5.3 and categories in fig. 5.7 indicate that warm-weather activities account for 41.9 percent of recreation visits, with hiking/walking and viewing natural features being most popular. Hiking and walking accounted for over 2.5 million visits per year, and viewing natural features another 2.4 million visits. Additional warm-weather activities contributing to this activity category included other nonmotorized use, bicycling, developed camping, picnicking, backpacking, horseback riding, and primitive camping.

Snow-based winter activities were the second most frequently reported category of main activities, with downhill skiing accounting for 31 percent of overall

Table 5.3—Twenty-eight main activities for national forests in the assessment area (2015–2017)

Main activity	Frequency	Percentage of total
Warm-weather activities:		
Hiking/walking	2,583,474	15.0
Viewing natural features	2,445,312	14.2
Other non-motorized	643,251	3.7
Bicycling	559,879	3.2
Developed camping	484,178	2.8
Picnicking	232,997	1.4
Backpacking	187,954	1.1
Horseback riding	60,678	0.4
Primitive camping	31,099	0.2
Total	7,228,822	41.9
Winter activities:		
Downhill skiing	5,348,025	31.0
Cross-country skiing	309,583	1.8
Snowmobiling	31,267	0.2
Total	5,688,875	33.0
Wildlife activities:		
Fishing	629,632	3.6
Hunting	182,427	1.1
Viewing wildlife	184,925	1.1
Total	996,984	5.8
Gathering forest products:		
Gathering forest products	99,784	0.6
Water-based activities, not including fishing:		
Motorized water activities	175,772	1.0
Nonmotorized water	155,601	0.9
Total	331,373	1.9
Other activities:		
Relaxing	1,512,490	8.8
Driving for pleasure	448,112	2.6
Some other activity	438,796	2.5
Off-highway vehicle use	113,150	0.7
Nature center activities	111,442	0.6
Motorized trail activity	85,205	0.5
Nature study	68,362	0.4
Resort use	46,312	0.3
Visiting historic sites	57,516	0.3
Other motorized activity	28,404	0.2
Total	2,909,789	16.9
Total for all activities	17,255,625	100

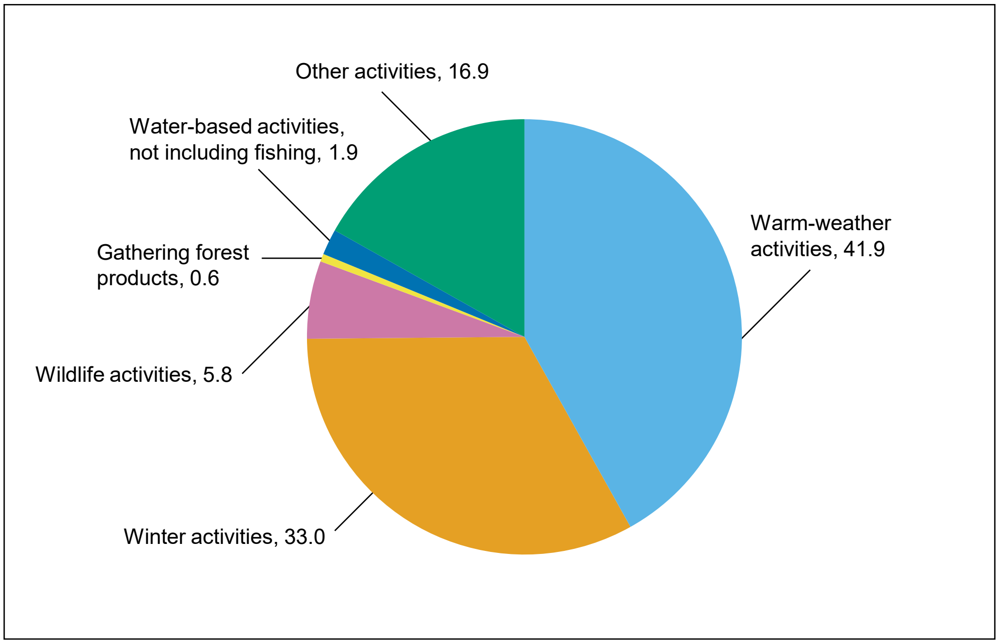

Figure 5.7—Percentage of total national forest visits by category of primary activity.

Table 5.4—Total annual expenditures within 50 mi of the survey site by nonlocal and local visitors to the assessment area, by spending category

Spending category	Nonlocal spending ($2017)[a b] Total annual expenditures	Nonlocal spending ($2017)[a b] Spending for each category	Local spending Total annual expenditures	Local spending Spending for each category
	Thousands of dollars[c]	*Percent*	*Thousands of dollars*[c]	*Percent*
Lodging	406,069	26.9	4,190	3.1
Camping fees	26,737	1.8	5,353	4.0
Restaurant	308,794	20.5	19,151	14.2
Groceries	176,481	11.7	25,733	19.1
Gas and oil	197,544	13.1	41,396	30.7
Local transportation	8,049	0.5	489	0.4
Entry fees	122,299	8.1	16,879	12.5
Recreation and entertainment	156,573	10.4	10,151	7.5
Sporting goods	49,307	3.3	9,016	6.7
Souvenirs and other expenses	57,314	3.8	2,381	1.8
Total	1,509,167	100	134,741	100

Note: Spending totals were calculated using the procedures outlined in White (2017) and parameters and spending averages used by the U.S. Forest Service office of Ecosystem Management Coordination.
[a] Nonlocal refers to trips that required traveling more than 50 mi to the survey site.
[b] Data source is the fourth round of the National Visitor Use Monitoring (NVUM) surveys.
[c] NVUM data, 2015–2017.

annual visitation at over 5.3 million visits. Cross-country skiing and snowmobiling represented 1.8 and 0.2 percent of total visitation.

Wildlife-related activities, including fishing (3.6 percent), hunting (1.1 percent), and viewing wildlife (1.1 percent), accounted for 5.8 percent of overall visitation, representing just under 1 million visits. Water-based activities including motorized and nonmotorized, other than fishing, accounted for 1.9 percent of visits, and gathering forest products was less than 1 percent of visitation.

Total annual expenditures within 50 mi of the survey site (viewed as local community area adjacent to the survey forest/unit location) was considerably higher among those travelling from outside a 50-mi radius, than for locally originating visitation (table 5.4). Lodging expenditures accounted for 26.9 percent of expenditures among nonlocal visitation, followed by restaurants at 20.5 percent. Gas and oil was the primary spending category for local visitation.

The **economic value** of recreation is the benefits that recreationists received from engaging in a recreation activity. This differs from the **economic impact** of recreation, which measures how spending by recreationists affects economies in a geographical area. Rosenberger et al. (2017) estimated recreation economic values using the benefit transfer method based on the updated Recreation Use Visitor Database (Loomis 2005, Rosenberger and Loomis 2001) and annual visitation estimates from the NVUM survey. The same procedure was used to estimate the annual economic benefits to individuals recreating in the national forests in the Sierra Nevada. Equation (1) uses the NVUM dataset on the total annual recreation visits per national forest and the percentage of primary activity to obtain the estimated number of visits per activity.

$$\textit{Visits per activity} = \textit{Annual NF recreation visits} \times \textit{Percentage of main activity} \quad (1)$$

The conversion coefficient derived by Rosenberger et al. (2017) is multiplied with visits per activity to translate visits into primary activity days. The conversion coefficients are the average number of days a recreation activity lasts for a national forest visit. For example, backpacking has a 2.8 conversion coefficient, meaning a national forest visit for backpacking lasts on average 2.8 days.

$$\textit{Primary activity days} = \textit{Conversion coefficient} \times \textit{Visits per activity} \quad (2)$$

Next, primary activity days are multiplied by the average economic value for each recreation activity that was updated by Rosenberger et al. (2017) to estimate the aggregate recreation benefit value:

$$\textit{Aggregate recreation benefit value} = \textit{Average economic value} \times \textit{Primary activity days} \quad (3)$$

For example, using the NVUM dataset for the Lake Tahoe Basin Management Unit (LTBMU), we multiplied the percentage of main activity with the annual number of national forest visits (over 7.7 million in 2015) to obtain the number of visits per activity. To estimate the primary activity days, we multiplied the conversion coefficient with the number of visits (Equation 2). Finally, we multiplied this value with the average economic value (Equation 3). The same procedure was undertaken for all other national forests in the assessment area. Annual aggregate economic values ranged from $11.1 million (Modoc National Forest) to $604.2 million (LTBMU).

The annual economic benefit for each zone was estimated by aggregating the economic value of each national forest within a zone (table 5.5). The North Zone had the lowest aggregate economic benefit at $60.3 million, followed by the South Zone at $293.1 million, and the highest was the Central Zone with an annual value of $923 million. Downhill skiing had the highest annual economic benefit for both Central and South Zones, whereas fishing was the highest for the North Zone.

It is important to understand whether there are differences in visitation patterns or activities that are sensitive to climate change effects. Overall projected visitation under climate change was explored by Smith et al. (2016). Visitors who felt their personal identity was tied to an area, who believed the area provided unique opportunities not available elsewhere, and who had family ties to the area were less likely to foresee changes in how they would recreate under climate change than those whose identities were not similarly tied to an area (Smith et al. 2016). In addition, expenditures offer a way to understand social vulnerability, where economic benefits to local communities may shift under climate change (Fischer et al. 2013).

In the following sections, we consider the Northern, Central, and Southern Sierra Zones of the assessment area individually to further explore recreation activities supported in the region, economic contributions, niche recreation opportunities and special places, and current or expected climate change effects specific to these opportunities and places. NVUM reports provide insight into how recreation visitors might respond to climate change effects, wildfires, and other factors that make a national forest inaccessible. Visitors were asked to select one of several substitute choices, if for some reason they were unable to visit the national forest where they were contacted. On most forests, the majority of visitors indicate that their substitution behavior choice is activity driven (going elsewhere for the same activity). This overall response pattern is independent of questions surrounding place attachment, place dependence, and recreation specialization, which all intersect with likely substitution behaviors (Kainzinger et al. 2018, Orr and Schneider 2018).

We consider these patterns of reported likely substitution, as well as the average distance respondents were willing to travel to arrive at a different location. This is

Table 5.5—Estimate of annual aggregate economic benefits for the assessment area, all zones combined

Activity participation[a]	All zones economic benefit
	2016 dollars
Warm-weather activities:	
Hiking/walking	206,908,496
Viewing natural features	152,145,214
Bicycling	44,363,206
Developed camping	36,427,954
Other nonmotorized	41,918,724
Backpacking	12,394,747
Picnicking	10,791,680
Horseback riding	4,070,833
Primitive camping	1,793,947
Total	510,814,801
Winter activities:	
Downhill skiing	422,518,140
Cross-country skiing	14,717,980
Snowmobiling	1,461,653
Total	438,697,773
Wildlife activities:	
Fishing	48,133,575
Hunting	17,544,811
Viewing wildlife	10,610,993
Total	76,289,379
Gathering forest products:	
Gathering forest products	6,301,155
Water-based activities, not including fishing:	
Nonmotorized water	20,417,077
Motorized water activities	11,822,182
Total	32,239,259
Other activities:	
Relaxing	123,915,062
Some other activity	24,910,419
Driving for pleasure	27,005,615
Resort use	7,961,398
Off-highway vehicle use	5,410,316
Motorized trail activity	4,511,528
No activity reported	2,780,544
Visiting historic sites	2,971,991
Other motorized activity	1,191,581
Nature center activities	6,987,297
Nature study	4,409,061
Total	212,054,812
Total for all activities	$1,276,397,182

[a] Considers only main recreation activity.

paired with a consideration of distances typically traveled by visitors to each forest/unit in the assessment area, where patterns of willingness to travel for each forest align with distances traveled by a majority. These patterns intersect, and many people can adapt by moving to different areas for similar activities, although effects on the recreation experience, benefits derived, and relationships to perceptions of place are not well understood.

Climate Change Vulnerability Assessment

Northern Sierra Zone

The Northern Sierra Zone of the assessment area includes Modoc (fig. 5.8), Lassen (fig. 5.9), and Plumas National Forests (fig. 5.10). Primary recreation visits in this zone (table 5.6) involve many warm-weather activities (40.3 percent); developed camping (13.5 percent) and viewing natural features (13.5 percent) represent the majority of visits. Wildlife-related activities account for the next highest recreation visits (21.0 percent), especially fishing (15.8 percent). Gathering forest products is the third highest category of main activity during forest visits at 10.0 percent of the total.

Modoc National Forest provides a broad range of recreational opportunities, including niche experiences for this forest and the Northern Zone. Devil's Garden Ranger District is home to a number of marshy reservoirs and the highest diversity of breeding waterfowl in the state (Audubon, n.d.). The area is remote and sees light recreation use. If climate change reduces bird viewing in other areas of the state, this area may see an increase in use in the future. However, climate shifts could reduce the value of marshy reservoirs as bird habitat.

Modoc National Forest is also home to the South Warner Wilderness, which provides opportunities for backpacking, horseback riding, hunting, wildlife viewing, and fishing. Ash Creek and a number of lakes on this forest are stocked by the California Department of Fish and Wildlife. Higher water temperatures may degrade habitat, and access to preferred water sources may decrease. Therefore, it will be important to monitor trends in quality fishing opportunities, and administrative decisions to shift stocking practices may be needed in some cases.

Gathering forest products is a larger proportion of recreation use in this zone than in the Central and Southern Zones. On Modoc National Forest, forest products requiring permits for gathering include obsidian, Christmas trees, and mushrooms. The effect of climate change on gathering forest products is uncertain (Hand and Lawson 2018b).

The Northern Zone is host to the Hat Creek Rim section of the Pacific Crest Trail (PCT) on Lassen National Forest. Owing to a 26-mi stretch of trail without water, the section has been named "a legendary stretch on a trail of legends"

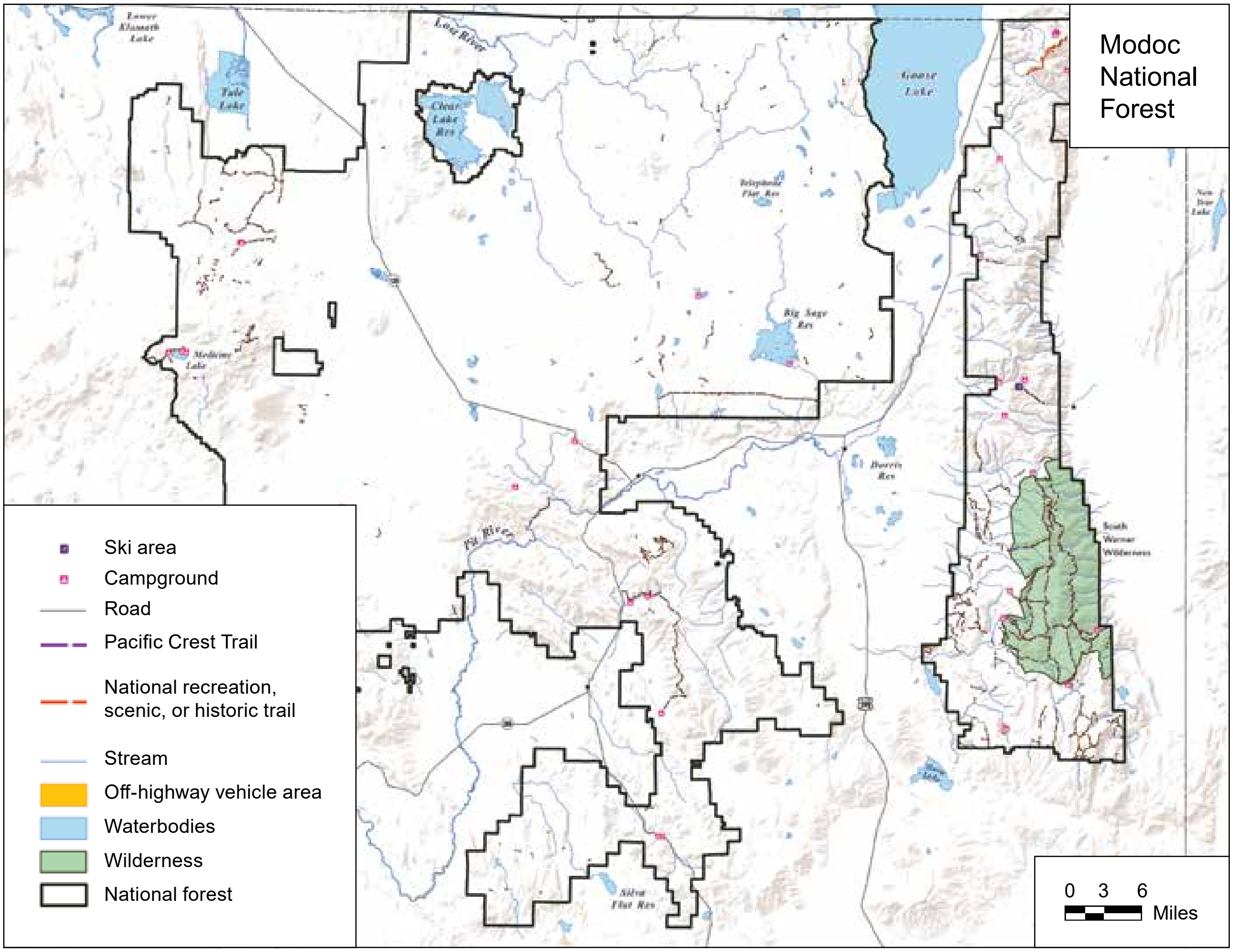

Figure 5.8—Recreation niche map of the Northern Sierra Zone, Modoc National Forest.

by Cheryl Strayed, the author of "Wild" (https://wild.pcta.org/hike-from-wild/hat-creek-rim-california). In 2017, a large water tank was installed, replacing a community-sourced water cache for hikers. Although this section of trail dictates that prudent hikers remember to bring water and that they hike in the cooler months, other sections can be impassable owing to deep snow or flooding.

Extended warm-weather seasons, increased temperatures, or more high-heat days are likely to affect the experience along this section of the PCT and increase the importance of the partnership between the USFS and recreation partners in maintaining access to water and providing clear messaging to enhance visitor safety. Collaborating with the PCT Association and other groups may increase visitor awareness of risks in advance of a trip, and increase preparedness, visitor safety, and enjoyment.

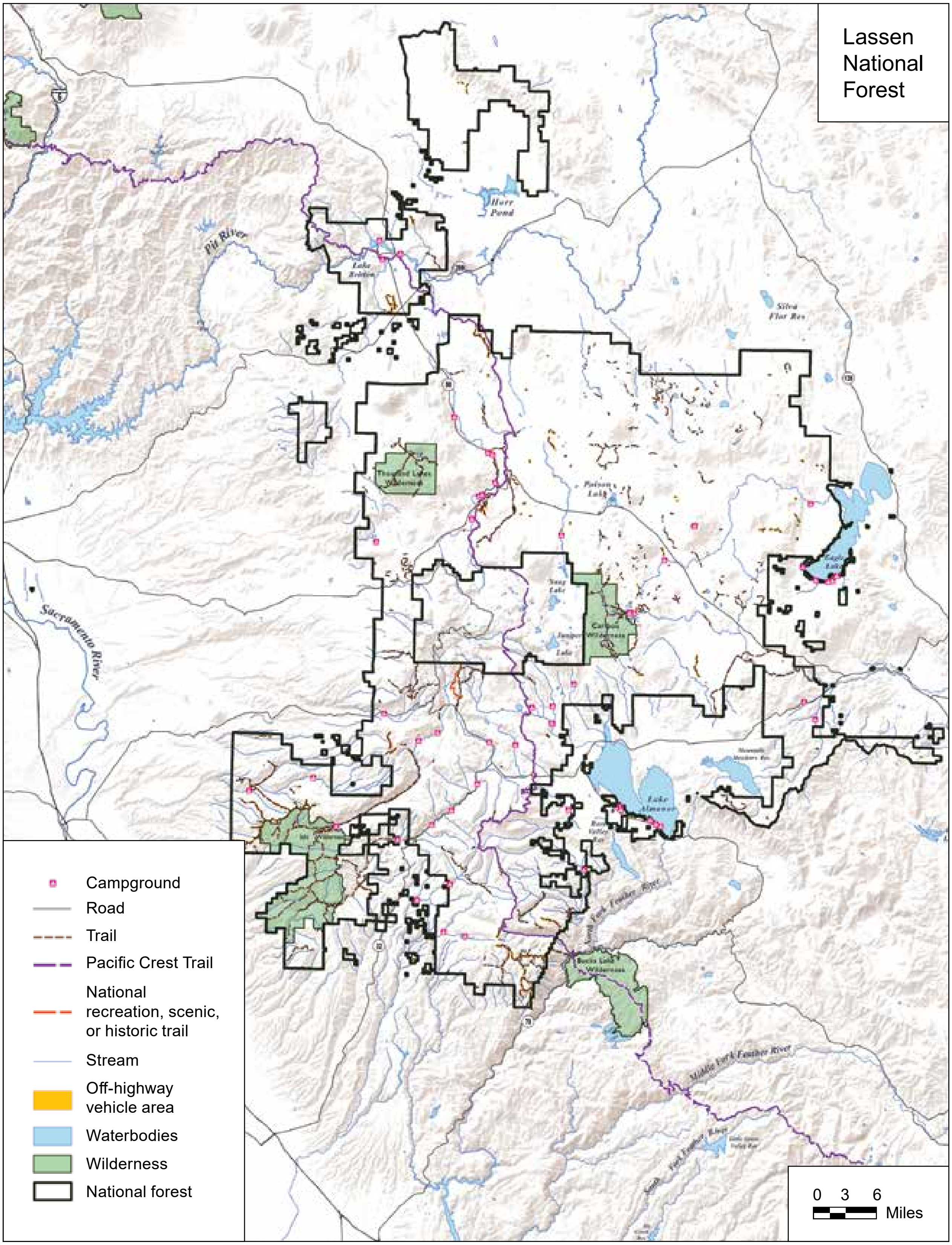

Figure 5.9—Recreation niche map of the Northern Sierra Zone, Lassen National Forest.

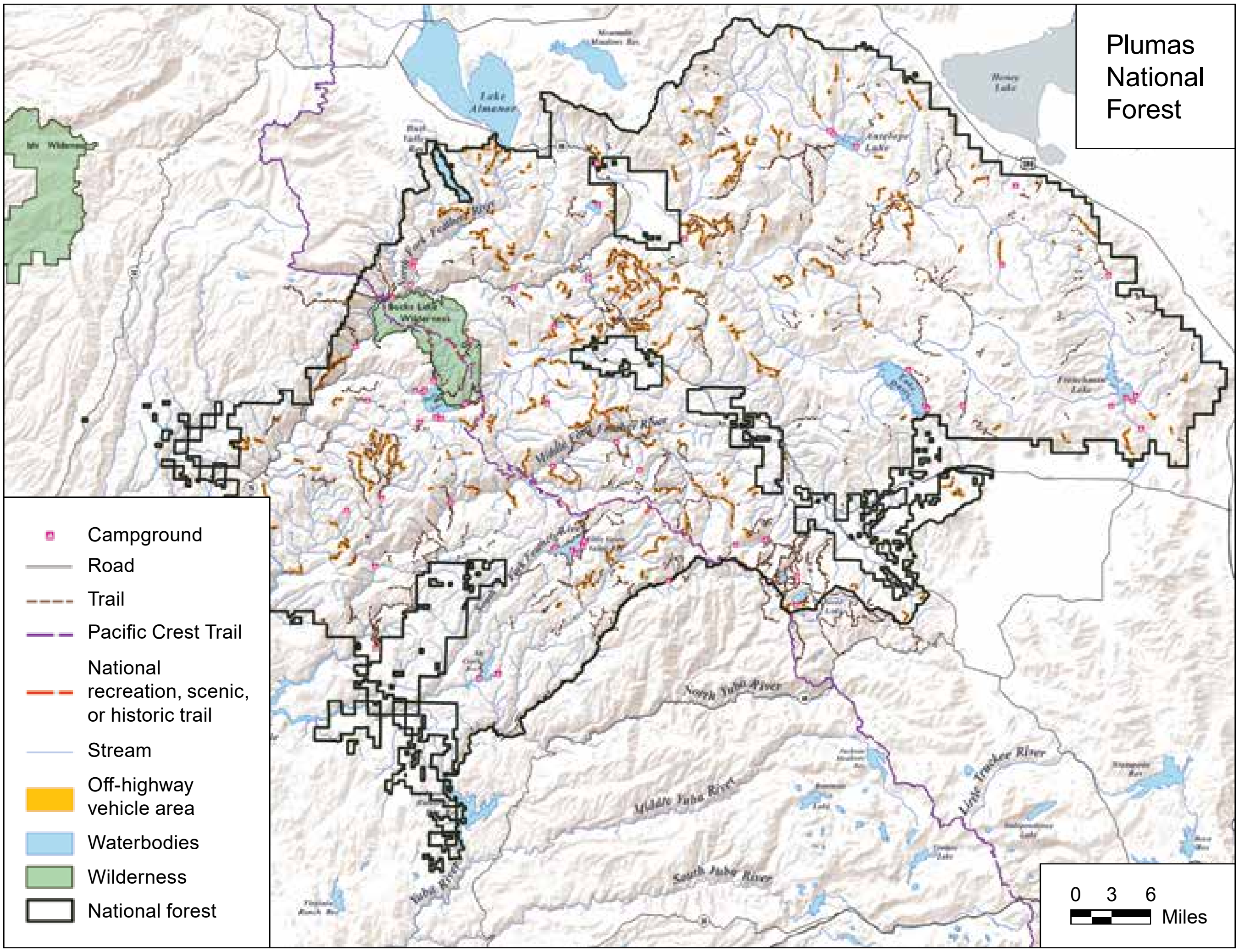

Figure 5.10—Recreation niche map of the Northern Sierra Zone, Plumas National Forest.

In Lassen National Forest, a self-guided interpretive trail guides visitors along a route where they can see spatter cones, craters, and the Hat Creek Valley, all centered around the Hat Creek Lava Flow. As of the writing of this report, the Spattercone Day Use area where this trail is accessed was closed because of recent damage from a severe storm. This example highlights the potential of extended effects from storm damage, which reduces access and opportunities for recreation use.

The PCT extends about 75 mi across Plumas National Forest, crossing the Middle and North Fork canyons of the Feather River. Under climate change, the Feather River is projected to have a decrease in mean annual flow of 2.2 to 8.8 percent, depending on the modeled increase in temperature (Hunsaker et al. 2014). In addition, the Feather Falls National Recreation Trail takes hikers to the 640-ft falls, identified as a special place. Decreased waterflow may alter these recreational opportunities in the future.

Table 5.6—Main recreation activities for the Northern Sierra Zone (2015–2017)

Main activity	Frequency	Percentage of total
Warm-weather activities:		
Developed camping	98,382	13.5
Viewing natural features	98,291	13.5
Hiking/walking	49,298	6.8
Picnicking	15,848	2.2
Other nonmotorized	11,031	1.5
Bicycling	10,337	1.4
Backpacking	4,606	0.6
Horseback riding	3,923	0.5
Primitive camping	983	0.1
Total	292,698	40.3
Winter activities:		
Downhill skiing	13,763	1.9
Snowmobiling	6,075	0.8
Cross-country skiing	315	0.0
Total	20,153	2.8
Wildlife activities:		
Fishing	114,825	15.8
Viewing wildlife	22,037	3.0
Hunting	15,570	2.1
Total	152,432	21.0
Gathering forest products:		
Gathering forest products	72,357	10.0
Water-based activities, not including fishing:		
Motorized water activities	22,713	3.1
Nonmotorized water	11,913	1.6
Total	34,627	4.8
Other activities:		
Relaxing	64,363	8.9
Driving for pleasure	54,900	7.6
Some other activity	23,176	3.2
Resort use	3,983	0.5
Motorized trail activity	2,799	0.4
Off-highway vehicle use	2,477	0.3
Nature center activities	1,606	0.2
Nature study	1,376	0.2
Visiting historic sites	113	0.0
Other motorized activity	0.0	0.0
Total	154,792	21.3
Total for all activities	727,058	100

Spending associated with local visitation in the Northern Zone forests is about 44 percent of that expended for nonlocal visitation. Among local visitation, gas/oil and groceries account for the largest portion of expenditures (table 5.7).

Table 5.7—Total annual expenditures within 50 mi of the survey site by nonlocal and local visitors to the Northern Sierra Zone, by spending category

	Nonlocal spending[a b]		Local spending	
Spending category	**Total annual expenditures**	**Spending for each category**	**Total annual expenditures**	**Spending for each category**
	Thousands of dollars ($2017)[c]	*Percent*	*Thousands of dollars ($2017)*[c]	*Percent*
Lodging	6,802	22.1	510	3.8
Camping fees	1,846	6.0	1,084	8.0
Restaurant	4,670	15.1	1,313	9.7
Groceries	5,393	17.5	3,823	28.3
Gas and oil	7,110	23.0	4,487	33.2
Local transportation	175	0.6	32	0.2
Entry fees	1,093	3.5	637	4.7
Recreation and entertainment	1,392	4.5	273	2.0
Sporting goods	1,325	4.3	1,168	8.6
Souvenirs and other expenses	1,039	3.4	197	1.5
Total	30,845	100	13,524	100

Note: Spending totals were calculated using the procedures outlined in White (2017) and parameters and spending averages used by the U.S. Forest Service office of Ecosystem Management Coordination.
[a] Nonlocal refers to trips that required traveling more than 50 mi to the survey site.
[b] Data source is the fourth round of the National Visitor Use Monitoring (NVUM) surveys.
[c] NVUM data, 2015–2017.

The estimated annual economic benefit for recreation participation associated with the Northern Zone is about $60.3 million (table 5.8), or 4.7 percent of the overall estimated value for the three zones ($1.3 billion). Plumas National Forest has the highest annual economic benefit (47.7 percent of total Northern Zone value), followed by Lassen National Forest (33.8 percent), and Modoc National Forest (18.5 percent). Highest economic benefits for the entire Northern Zone are associated with fishing, developed camping, relaxing, and viewing natural features. Hiking/walking and gathering forest products also provide substantial economic benefits. It should be noted that gathering forest products is considered in the recreation context as captured by NVUM data but may also represent maintenance of traditional tribal and cultural values (Lake and Long 2014). Gathering forest products represents a higher percentage of overall recreation use in the Northern Zone than in the Central and Southern Zones.

Table 5.8—Estimate of annual aggregate economic benefit for the Northern Sierra Zone

Activity participation[a]	Economic benefit
	2016 dollars
Warm-weather activities:	
Hiking/walking	4,693,572
Viewing natural features	6,737,356
Bicycling	1,050,758
Developed camping	8,670,423
Other nonmotorized	902,349
Backpacking	395,144
Picnicking	897,528
Horseback riding	270,080
Primitive camping	70,829
Total	23,688,039
Winter activities:	
Downhill skiing	1,090,578
Cross-country skiing	17,707
Snowmobiling	308,095
Total	1,416,380
Wildlife activities:	
Fishing	10,299,748
Hunting	1,766,215
Viewing wildlife	1,389,336
Total	13,455,299
Gathering forest products:	
Gathering forest products	4,760,588
Water-based activities, not including fishing:	
Nonmotorized water	1,918,378
Motorized water activities	1,780,401
Total	3,698,779
Other activities:	
Relaxing	6,088,460
Some other activity	1,577,315
Driving for pleasure	3,555,733
Resort use	824,446
Off-highway vehicle use	153,597
Motorized trail activity	188,071
No activity reported	659,108
Visiting historic sites	6,795
Other motorized activity	0.0
Nature center activities	121,498
Nature study	101,921
Total	13,276,944
Total for all activities	60,296,029

[a] Main recreation activity.

When asked what the forest visit would be substituted with if the current forest visited was not available, the most common response from visitors to Modoc, Lassen, and Plumas National Forests was they would have gone elsewhere for the same activity (46.5, 35.9, and 69.5 percent, respectively) (fig. 5.11). However, more than one-fourth of Lassen National Forest visitors indicated they would have stayed at home, and another fifth would have come back another time. Modoc National Forest visitors split their remaining options between coming back another time, staying at home, or going elsewhere for a different activity. Plumas National Forest visitors indicated they would be more likely to stay at home or come back another time.

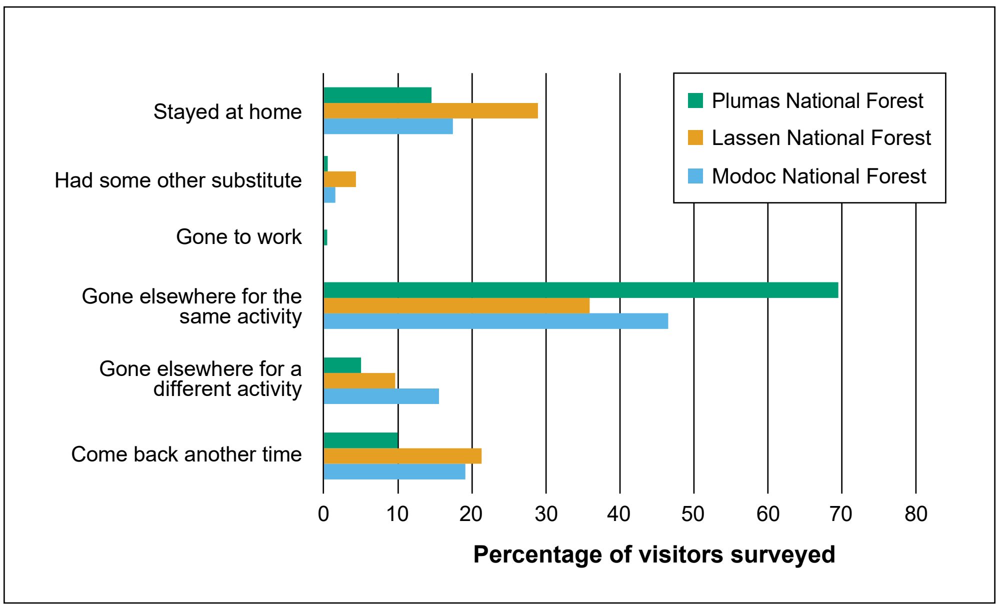

Figure 5.11—Alternative location or option that Northern Sierra Zone forest visitors would choose if unable to visit the national forest where they were surveyed.

When traveling to another location to recreate as a substitute for Modoc and Plumas National Forests, just over half would travel between 26 and 50 mi (52.5 and 51.2 percent, respectively) (USDA FS 2018e, 2018f), whereas nearly half (49.6 percent) of Lassen National Forest visitors would travel between 0 and 50 mi (USDA FS 2018d) (fig. 5.12). In each case, visitors to the Northern Sierra Zone indicated they were most likely to stay local (within a 50-mi radius). This finding seems reasonable, given that NVUM reports show a near majority or majority of recreation visitors originate from within a 50-mi radius of their recreation destination.

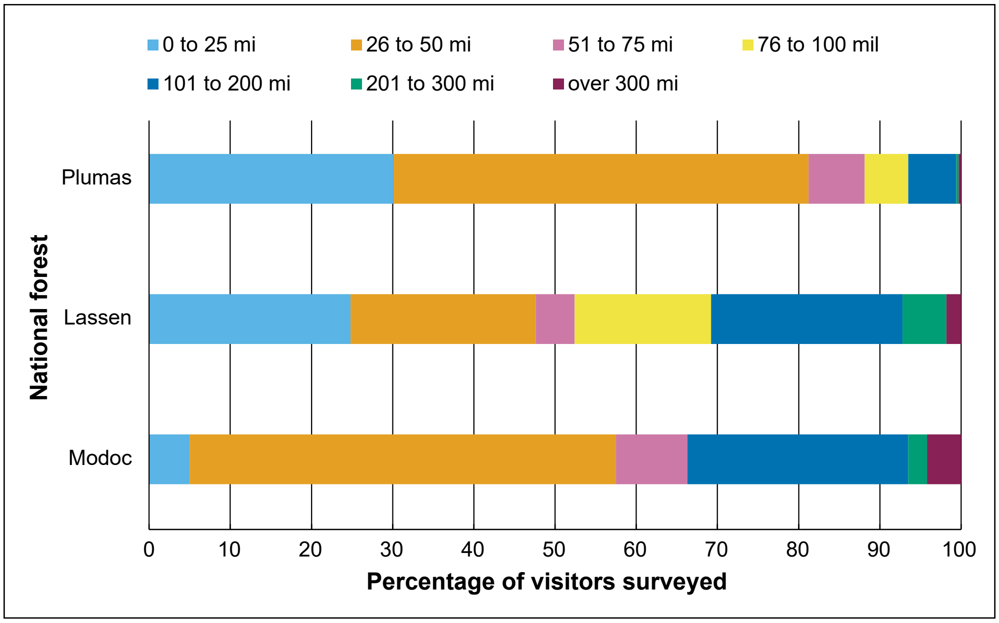

Figure 5.12—Distance that Northern Sierra Zone forest visitors would travel if they could not visit the national forest where they were surveyed.

Central Sierra Zone

The Central Sierra Zone encompasses four national forests/units, including Tahoe National Forest (fig. 5.13), LTBMU (fig. 5.14), Eldorado National Forest (fig. 5.15), and Stanislaus National Forest (fig. 5.16). Warm-weather activities represent the largest portion of activities in this zone, with viewing natural features (16 percent) and hiking/walking (15.1 percent) the largest share of activities in this category (table 5.9). Winter activities accounted for 37.1 percent of recreational activities in the Central Zone, with downhill skiing the predominant recreation use (35.8 percent). Winter activities were almost equal in economic benefit to warm-weather activities in the Central Zone.

Tahoe National Forest is a popular forest, situated within a 1- to 2-hour drive of San Francisco, Sacramento, and Reno. Special places are numerous on this forest, including the Donner Camp Picnic Site and Interpretive Trail of historical interest. The North Fork American River, also on Tahoe National Forest, was designated as a wild and scenic river in 1978. It provides recreation opportunities in the late fall and spring when other sections of the forest are still covered in snow. Extended warm-weather seasons may affect these patterns of use in ways that will require future monitoring and assessment for sustainable recreation delivery.

LTBMU and Eldorado National Forest jointly manage the Desolation Wilderness, covering 63,960 ac of lakes, subalpine forests, and alpine habitat. The Desolation Wilderness is among the most popular in the National Wilderness

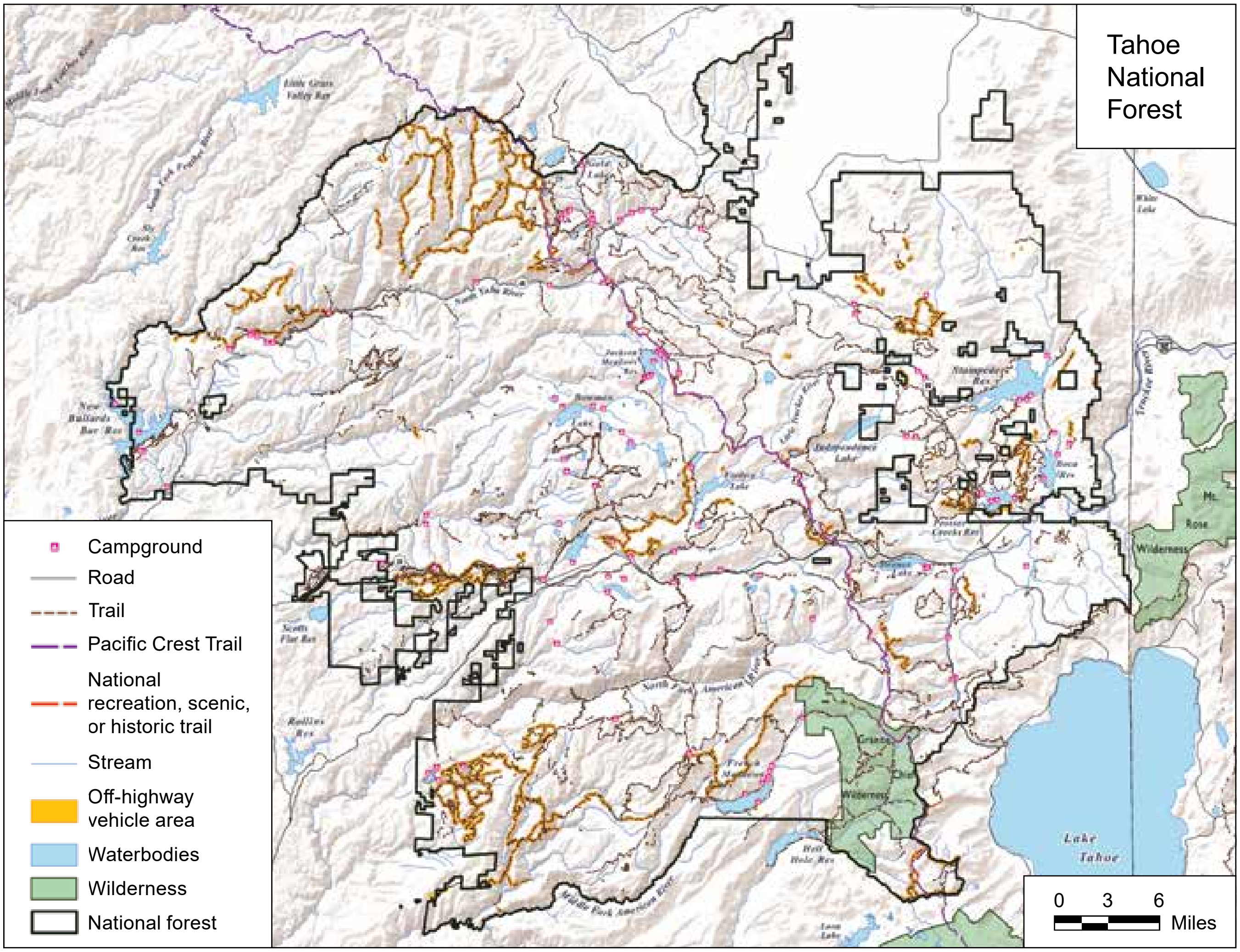

Figure 5.13—Recreation niche map of the Central Sierra Zone, Tahoe National Forest.

Preservation System, and visitors must obtain a permit for day or overnight use year-round. As a Class I Wilderness Area, air quality and visibility are monitored with specific targets for improvement. Viewsheds contribute to the wilderness visitor experience. Good air quality is important to the recreationist experience related to these viewsheds as well as the overall benefits to physical health gained during outdoor recreation. If climate change increases the frequency and extent of wildfire, air quality may be diminished significantly by smoke.

The basin is also home to the Tallac Historic Site, hosting three estates that are maintained for historical interest. These locations are open from late spring through early fall for hiking and sightseeing, with summer-season heritage tours. An extended warm-weather season may increase interest in this location, which is already heavily used during the summer peak season.

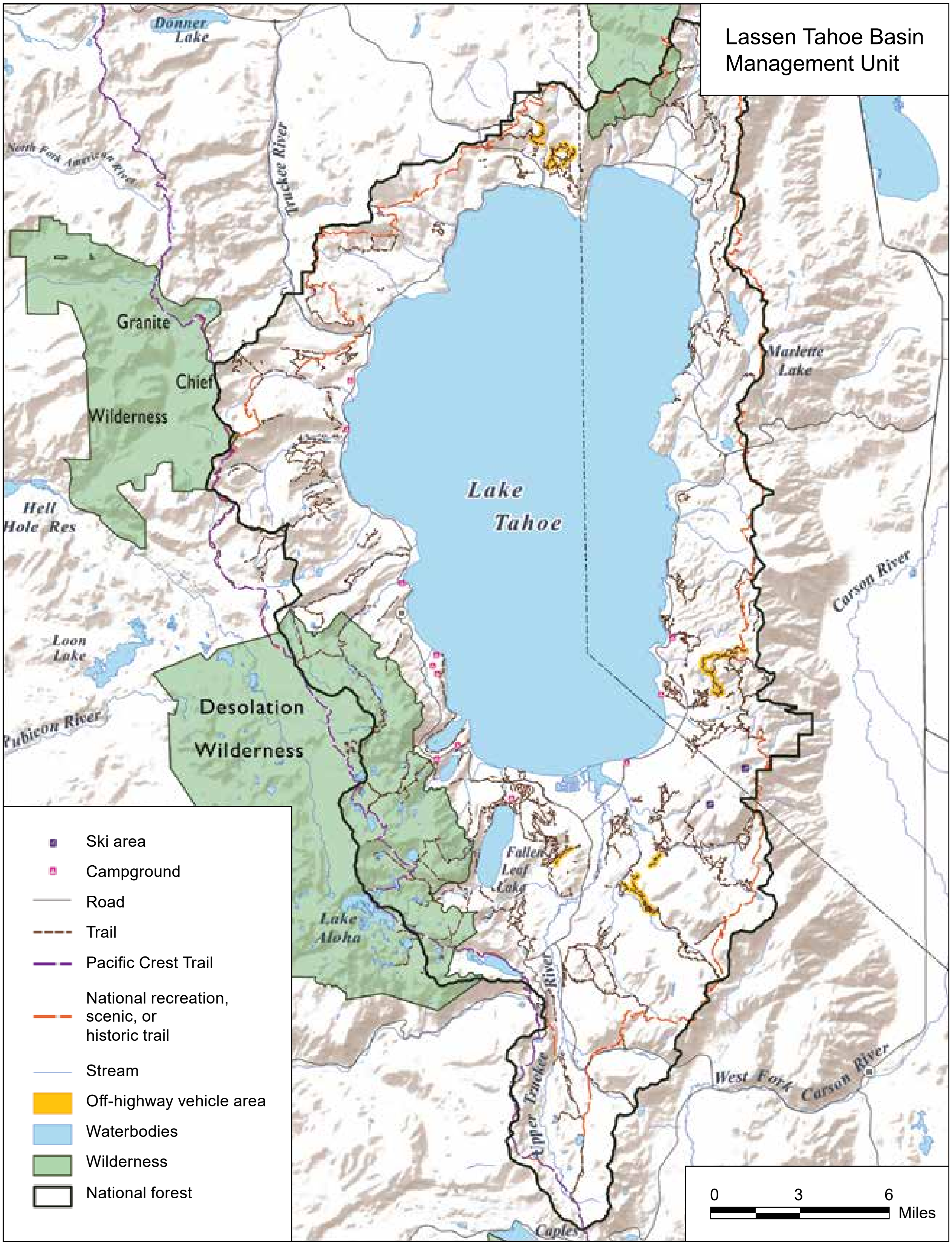

Figure 5.14—Recreation niche map of the Central Sierra Zone, Lake Tahoe Basin Management Unit.

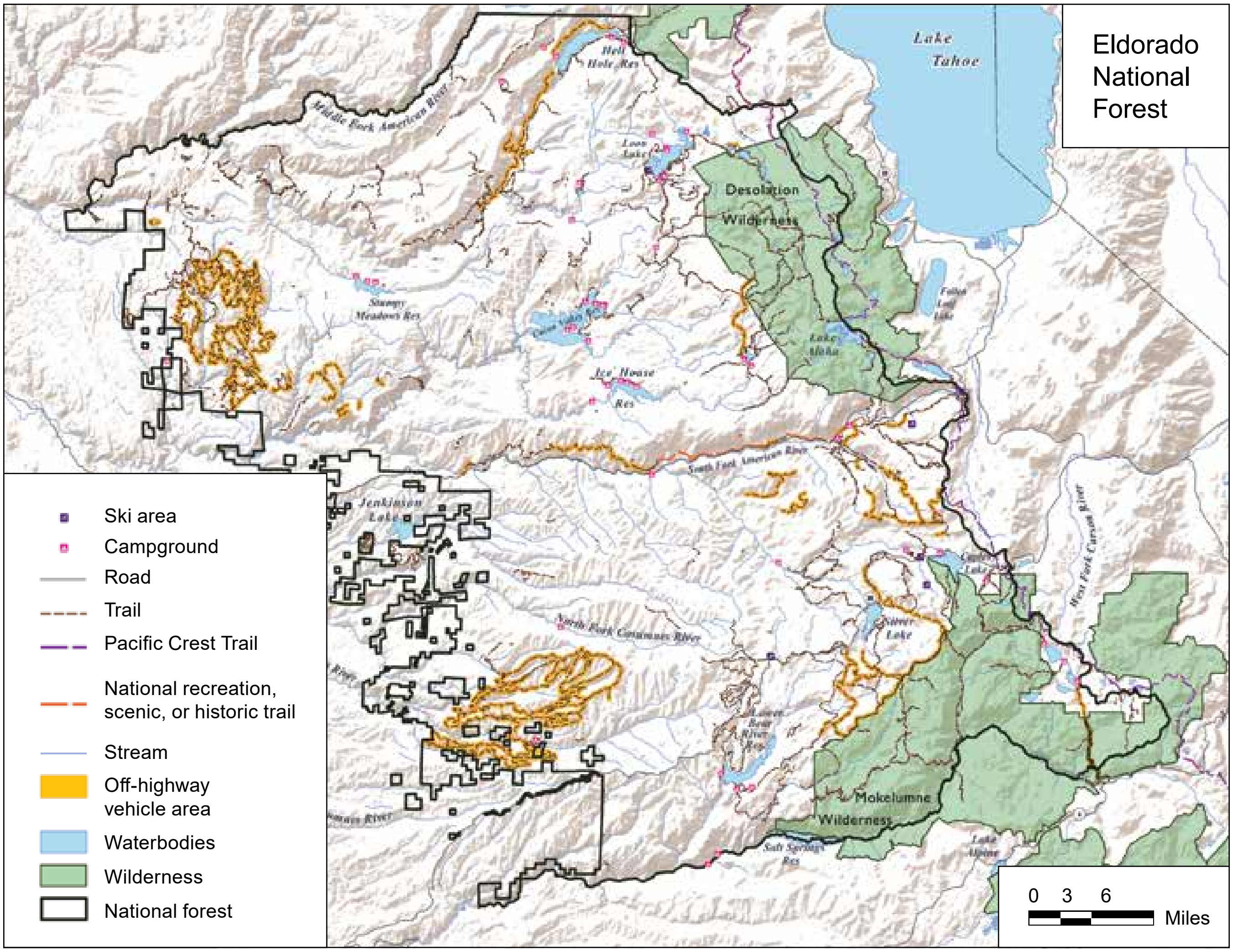

Figure 5.15—Recreation niche map of the Central Sierra Zone, Eldorado National Forest.

Eldorado National Forest is considered an urban forest, owing to its proximity to multiple large metropolitan centers. The forest ranges from 1,000 to 10,000 ft elevation. The Pony Express National Historic Trail is 19 mi long. The renowned Rubicon Trail supports off-highway vehicles (OHVs) and four-wheel drive vehicles. In most cases, the trail is kept open, although observing fire restrictions is strongly encouraged year-round. According to the Rubicon Trail Foundation, (1) wet trails should be avoided to reduce erosion damage, (2) winter travel is inadvisable because of snow cover and constrained options for rescue, (3) summer brings increased fire danger and crowding, and (4) fall brings fast-moving storms (https://www.rubicontrailfoundation.org/trailinfomation/conditions). Although this foundation is part of a robust volunteer and partnership network that works to maintain and restore trail access, climate change may bring more extreme storm events that would require strengthening of these supporting networks.

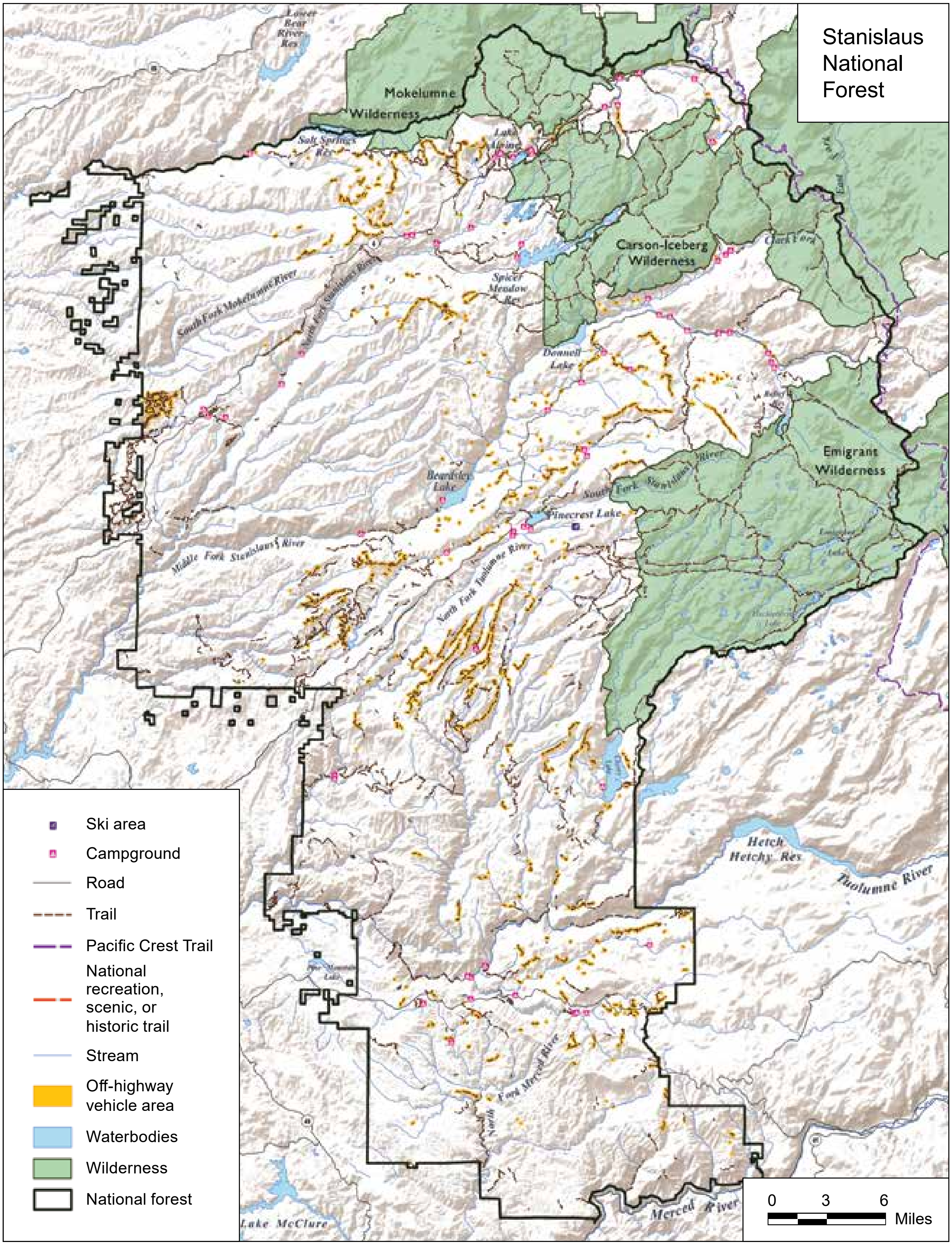

Figure 5.16—Recreation niche map of the Central Sierra Zone, Stanislaus National Forest.

Table 5.9—Main recreation activities for the Central Sierra Zone (2015–2017)

Main activity	Frequency	Percentage of total
Warm-weather activities:		
Viewing natural features	1,907,080	16.0
Hiking/walking	1,791,801	15.1
Other nonmotorized	454,480	3.8
Bicycling	268,538	2.3
Developed camping	213,408	1.8
Picnicking	136,859	1.1
Backpacking	101,462	0.9
Horseback riding	44,926	0.4
Primitive camping	21,377	0.2
Total	4,939,930	41.5
Winter activities:		
Downhill skiing	4,257,643	35.8
Cross-country skiing	136,189	1.1
Snowmobiling	21,417	0.2
Total	4,415,250	37.1
Wildlife activities:		
Fishing	275,531	2.3
Viewing wildlife	135,573	1.1
Hunting	63,318	0.5
Total	474,422	4.0
Gathering forest products:		
Gathering forest products	8,990	0.1
Water-based activities, not including fishing:		
Motorized water activities	133,174	1.1
Nonmotorized water	104,298	0.9
Total	237,472	2.0
Other activities:		
Relaxing	1,078,350	9.1
Driving for pleasure	256,649	2.2
Some other activity	172,636	1.5
Nature center activities	89,582	0.8
Off-highway vehicle use	68,306	0.6
Nature study	59,224	0.5
Motorized trail activity	49,259	0.4
Visiting historic sites	28,937	0.2
Resort use	19,754	0.2
Other motorized activity	2,372	0.0
Total	1,825,068	15.3
Total for all activities	11,901,133	100

Stanislaus National Forest provides a variety of recreation opportunities and settings. The Tuolumne Wild and Scenic River and the North Fork of the Stanislaus offer whitewater boating, and fishing opportunities are abundant in lakes, streams, and rivers (Three Forests Interpretive Association 2017). Although increased temperatures may draw more visitors to these water activities, reduced flows may adversely affect experiences offered, and increased water temperatures may adversely affect suitable conditions for fish.

Changes in winter activities associated with climate change effects are of concern in the Central Sierra Zone. In the Lake Tahoe region, the onset of adequate snow depth to provide for over-snow recreation has been shifted by about 2 weeks since 1985 (Hatchett and Eisen 2018). This shift is significant, given the economic contributions from over-snow use, expected increase in other types of winter recreation, and need for more accurate quantification of adequate snow depth to protect long-term ecosystem sustainability. Additional loss of Sierra snowpack is anticipated (Huang et al. 2018) (chapter 2).

As was the case for the Northern Zone, nonlocal visitors have much higher total annual expenditures within a 50-mi radius of the survey site (table 5.10). Overall annual expenditures among nonlocals bring approximately $1.1 billion to local

Table 5.10—Total annual expenditures within 50 mi of the survey site by nonlocal and local visitors to the Central Sierra Zone, by spending category

	Nonlocal spending[a b]		Local spending	
Spending category	**Total annual expenditures**	**Spending for each category**	**Total annual expenditures**	**Spending for each category**
	Thousands of dollars ($2017)[c]	*Percent*	*Thousands of dollars ($2017)*[c]	*Percent*
Lodging	294,085	26.9	3,065	3.2
Camping fees	14,736	1.3	3,285	3.4
Restaurant	227,749	20.8	14,151	14.9
Groceries	123,787	11.3	16,539	17.4
Gas and oil	135,978	12.4	28,093	29.5
Local transportation	5,654	0.5	359	0.4
Entry fees	95,918	8.8	13,758	14.4
Recreation and entertainment	120,340	11.0	8,409	8.8
Sporting goods	35,582	3.3	5,861	6.2
Souvenirs and other expenses	40,821	3.7	1,711	1.8
Total	1,094,650	100	95,231	100

Note: Spending totals were calculated using procedures outlined in White (2017) and parameters and spending averages used by the U.S. Forest Service office of Ecosystem Management Coordination.

a Nonlocal refers to trips that required traveling more than 50 mi to the survey site.

[b] Data source is the fourth round of the National Visitor Use Monitoring (NVUM) surveys.

[c] NVUM data, 2015–2017.

economies. Nonlocal visitors have the largest proportion of expenditures in the lodging and restaurants categories.

The estimated annual economic benefit for recreation participation associated with the Central Zone is about $923 million (table 5.11), 72.3 percent of the overall estimated value for the three zones ($1.2 billion). The LTBMU has the highest annual economic benefit (65.5 percent of total Central Zone value), followed by Tahoe (14.2 percent), Eldorado (10.8 percent), and Stanislaus (9.6 percent). In the Central Zone, warm-weather activities and winter activities are more similar in economic benefit than in any other zone (table 5.11). The largest estimated economic benefit is from downhill skiing, representing about 38 percent of the overall economic benefit from forest recreation activities.

Comparison of several NVUM surveys over time shows how recreation benefits have changed for downhill skiing on the LTBMU. California experienced drought conditions from 2007 to 2009 (California Department of Water Resources 2010) and more recently from 2011 to 2017 (National Integrated Drought Information System 2019). Some recreation activities that depend on water and winter conditions, including downhill skiing, were significantly affected.

In the LTBMU, downhill skiing is by far the most popular outdoor recreation activity. Prior to the 2007–2009 California drought, 2005 NVUM data showed there were more than 3.8 million annual visits for downhill skiing. Data from the subsequent NVUM surveys (2010 and 2015) showed a decrease of annual visits by 19 percent and 21 percent, respectively, despite an overall population increase in California and Nevada for the same time period. Applying the economic benefits methodology, the predrought (2005) estimated economic benefit for downhill skiing was $321.6 million (based on 2016 dollars). The drought conditions were associated with fewer snow-use days, resulting in fewer visits and an associated decline in economic benefit to $269.4 million in 2010 and $265.9 million in 2015 (based on 2016 dollars). The actual economic losses may be larger than these reported values, because the estimates do not include other revenue streams (e.g., special use fees). Similar results can be found for Inyo and Tahoe National Forests, both also highly dependent on water conditions and supply, and the activities they support.

When asked what the forest visit would be substituted with if the current forest visited was not available, the most common response from visitors to Tahoe, Eldorado, and Stanislaus National Forests, and LTBMU was they would have gone elsewhere for the same activity (59.8, 54.9, 41.2, and 37.8 percent, respectively; USDA FS 2018j, 2018a, 2018i, and 2018c, respectively) (fig. 5.17). Almost a fifth of LTBMU visitors indicated they would have gone elsewhere for a different activity (18.1 percent) or come back another time (17.1 percent).

Table 5.11—Estimate of annual aggregate economic benefit for the Central Sierra Zone

Activity participation[a]	Economic benefit
	2016 dollars
Warm-weather activities:	
Hiking/walking	150,986,676
Viewing natural features	122,384,578
Bicycling	23,711,367
Developed camping	16,637,376
Other nonmotorized	31,308,533
Backpacking	7,167,298
Picnicking	6,726,514
Horseback riding	3,112,378
Primitive camping	1,285,243
Total	363,319,963
Winter activities:	
Downhill skiing	351,748,822
Cross-country skiing	7,285,442
Snowmobiling	1,005,763
Total	360,040,027
Wildlife activities:	
Fishing	21,679,079
Hunting	6,207,997
Viewing wildlife	7,931,485
Total	35,818,561
Gathering forest products:	
Gathering forest products	511,664
Water-based activities, not including fishing:	
Nonmotorized water	14,042,193
Motorized water activities	8,965,903
Total	23,008,096
Other activities:	
Relaxing	91,700,178
Some other activity	10,670,568
Driving for pleasure	16,271,581
Resort use	3,424,770
Off-highway vehicle use	3,379,153
Motorized trail activity	2,689,409
No activity reported	621,402
Visiting historic sites	1,671,347
Other motorized activity	110,016
Nature center activities	5,847,377
Nature study	3,905,714
Total	140,291,515
Total for all activities	922,989,827

[a] Main recreation activity.

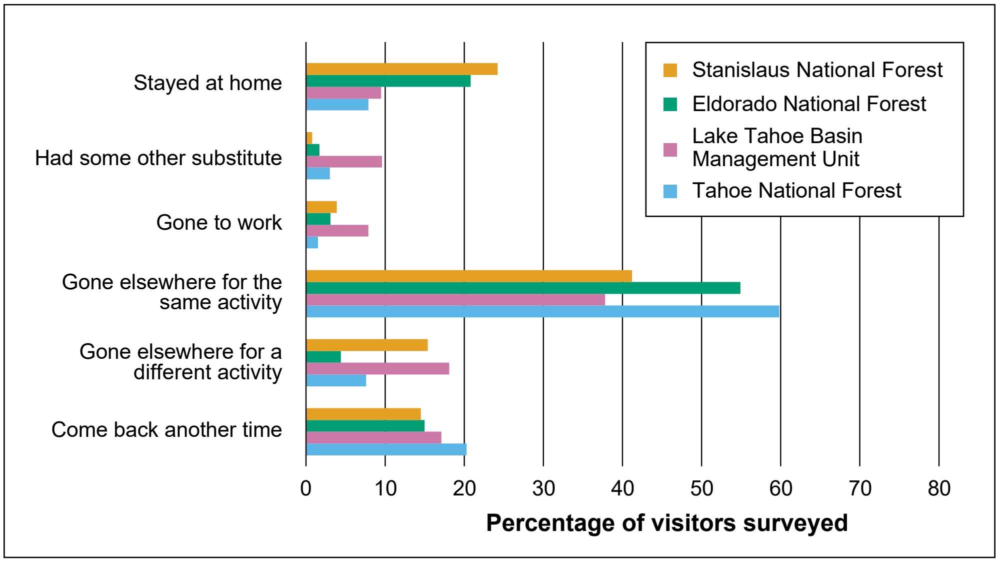

Figure 5.17—Alternative location or option that Central Sierra Zone forest/unit visitors would choose if unable to visit the forest/unit where they were surveyed.

The distance that respondents would have traveled to an alternate location varied by forest/unit. The largest proportion of visitors to Tahoe National Forest would have traveled between 0 and 25 mi (thus staying local), whereas on Eldorado and Stanislaus National Forests, more than one-fourth would have traveled between 101 and 200 mi (fig. 5.18). Visitors to the LTBMU were unique in that more than one-third indicated they would travel over 300 mi to an alternate location.

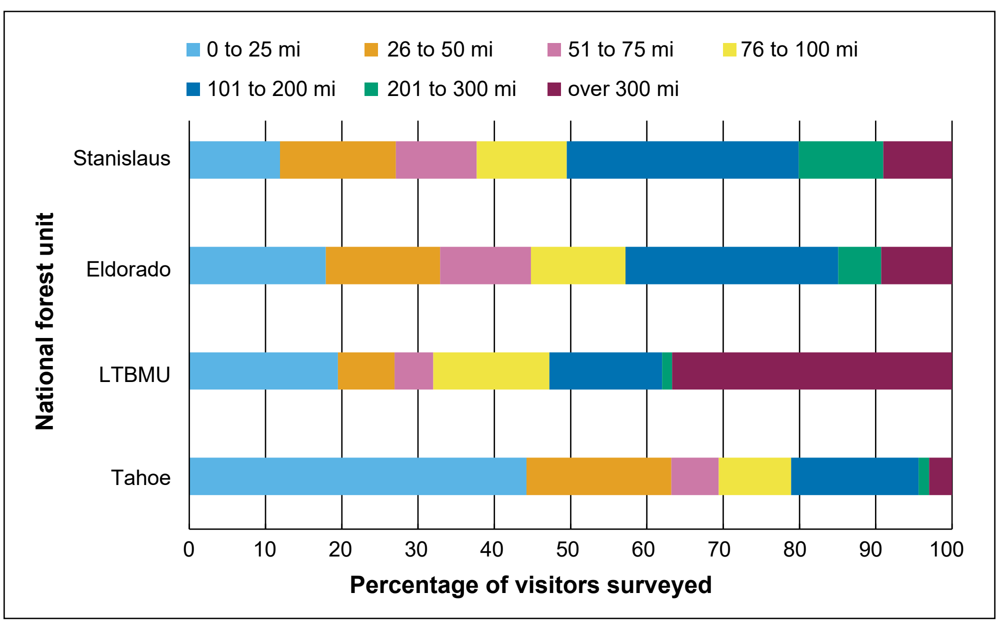

Figure 5.18—Distance that Central Sierra Zone forest/unit visitors would travel if they could not visit the national forest/unit where they were surveyed. LTBMU = Lake Tahoe Basin Management Unit.

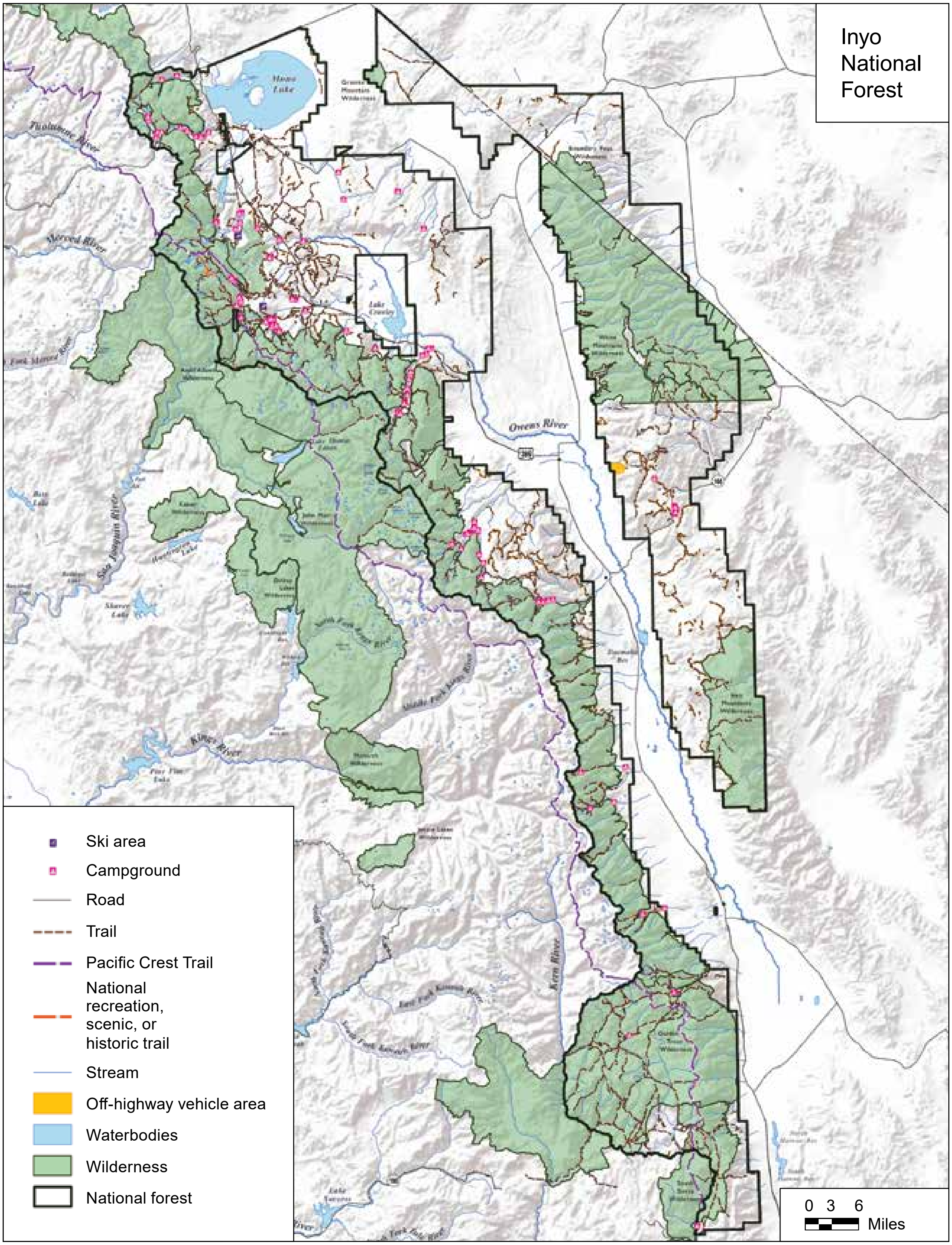

Figure 5.19—Recreation niche map of the Southern Sierra Zone, Inyo National Forest.

NVUM data provide useful insight into these responses. A majority of visitors to Stanislaus National Forest reportedly traveled more than 100 mi to arrive at their recreation destination, similar to LTBMU visitors for whom more than half traveled more than 200 mi.

Southern Sierra Zone

The Southern Sierra Zone of the assessment area contains Inyo (fig. 5.19), Sierra (fig. 5.20), and Sequoia (fig. 5.21) National Forests. Warm-weather activities represent the largest share of recreation use in the Southern Zone, followed by winter activities, with downhill skiing the largest single type of use reported (table 5.12). Inyo National Forest is home to two ski areas, 100 mi of snowmobile trails, and 25 mi of Nordic ski trails. The town of Mammoth Lakes is central to the Mammoth

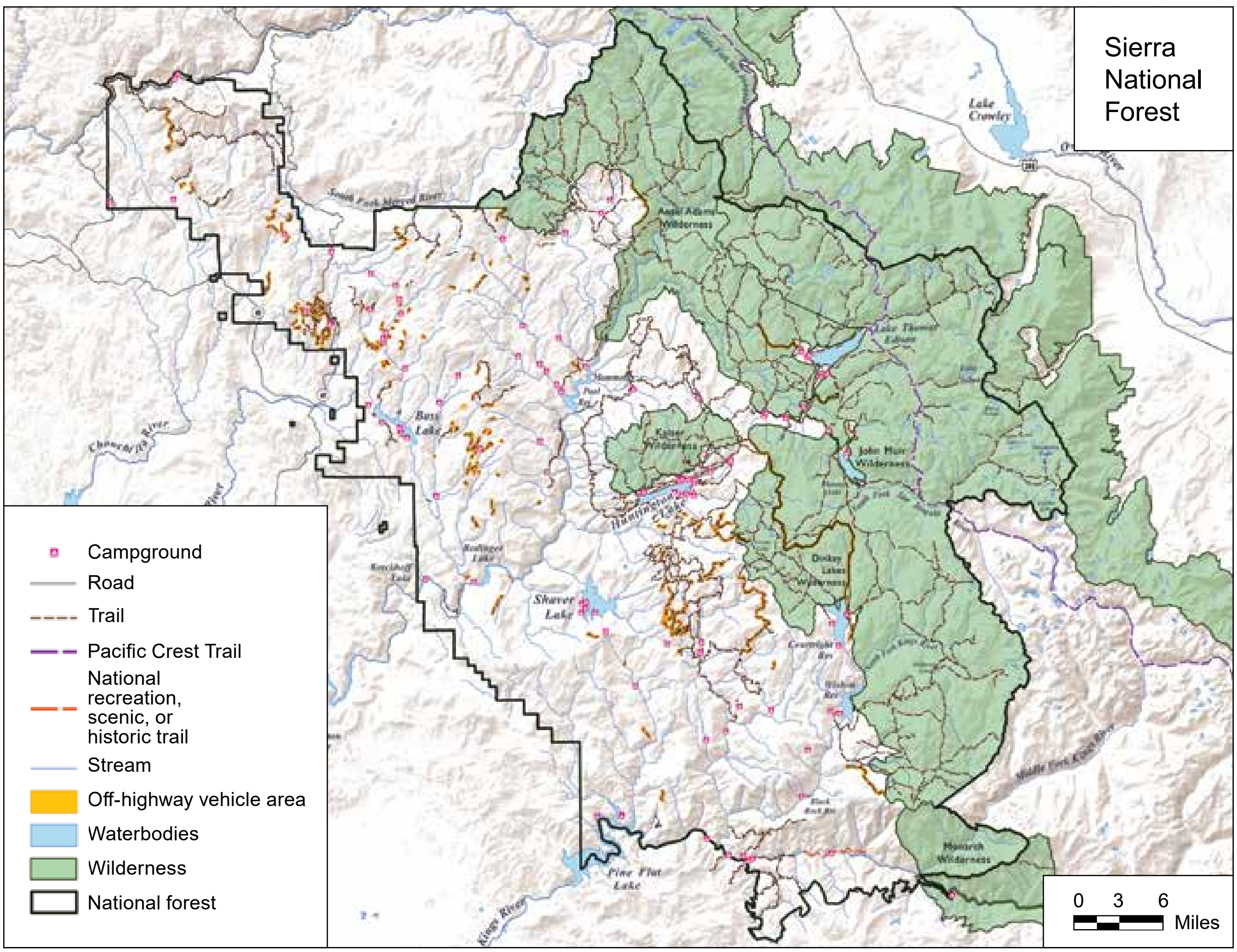

Figure 5.20—Recreation niche map of the Southern Sierra Zone, Sierra National Forest.

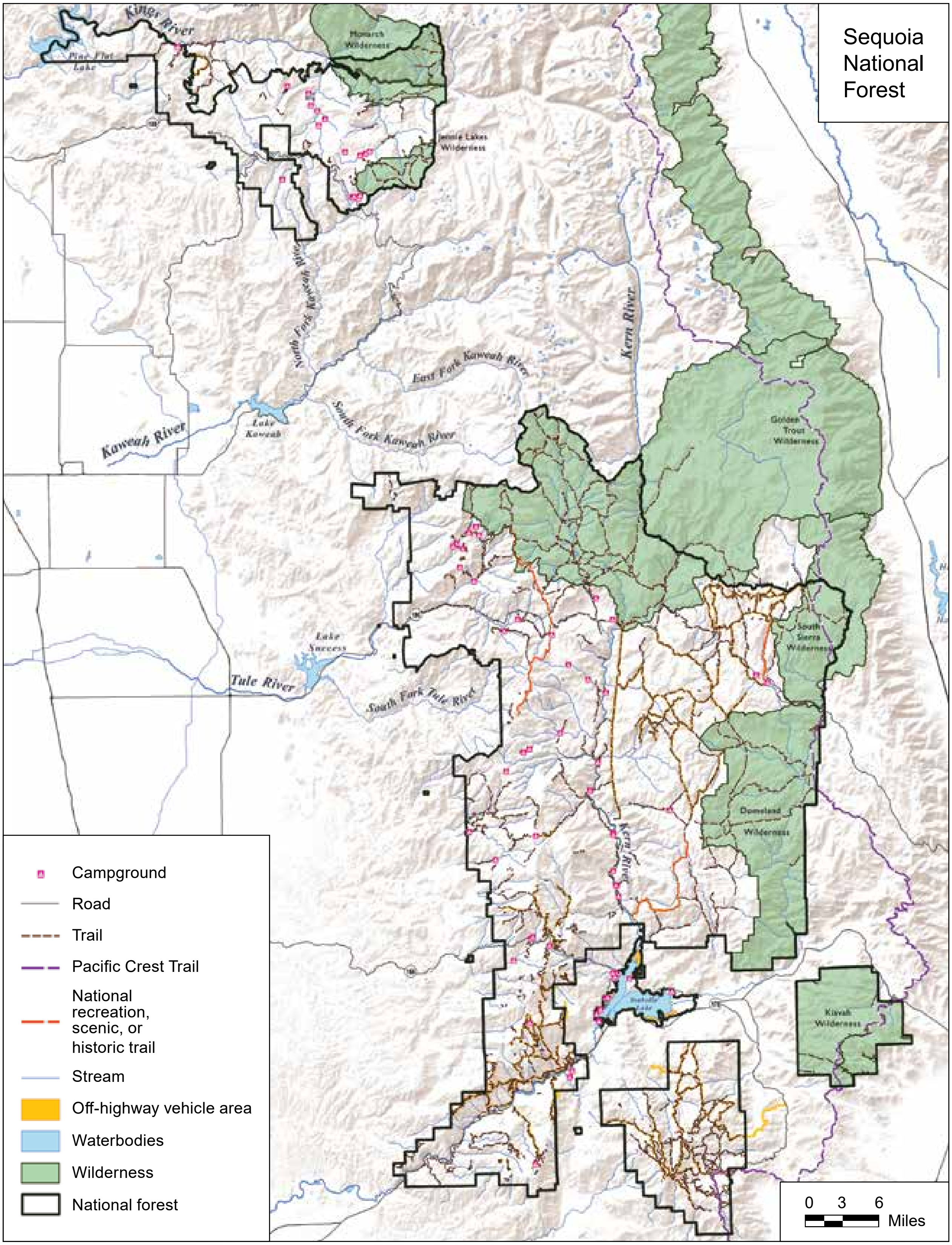

Figure 5.21—Recreation niche map of the Southern Sierra Zone, Sequoia National Forest.

Table 5.12—Main recreation activities for the Southern Sierra Zone (2015–2017)

Main activity	Frequency	Percentage of total
Warm-weather activities:		
Hiking/walking	742,375	16.0
Viewing natural features	439,942	9.5
Bicycling	281,004	6.1
Other nonmotorized	177,741	3.8
Developed camping	172,388	3.7
Backpacking	81,886	1.8
Picnicking	80,291	1.7
Horseback riding	11,829	0.3
Primitive camping	8,740	0.2
Total	1,996,193	43.1
Winter activities:		
Downhill skiing	1,076,619	23.3
Cross-country skiing	173,079	3.7
Snowmobiling	3,775	0.1
Total	1,253,472	27.1
Wildlife activities:		
Fishing	239,276	5.2
Hunting	103,538	2.2
Viewing wildlife	27,315	0.6
Total	370,129	8.0
Gathering forest products:		
Gathering forest products	18,437	0.4
Water-based activities, not including fishing:		
Nonmotorized water	39,389	0.9
Motorized water activities	19,885	0.4
Total	59,274	1.3
Other activities:		
Relaxing	369,777	8.0
Some other activity	242,984	5.3
Driving for pleasure	136,564	3.0
Off-highway vehicle use	42,367	0.9
Motorized trail activity	33,147	0.7
Visiting historic sites	28,466	0.6
Other motorized activity	26,032	0.6
Resort use	22,575	0.5
Nature center activities	20,255	0.4
Nature study	7,762	0.2
Total	929,929	20.1
Total for all activities	4,627,435	100

Lakes Ranger District, a home to winter sports and popular in the summer for mountain biking and fishing. Although snowmaking capabilities can likely sustain some winter sports, uses outside of developed runs may be affected by reduced snow.

Nine federally designated wilderness areas are on Inyo National Forest covering approximately 1 million ac. Hiking to the top of Mount Whitney is popular and requires a permit. This forest is home to long-lived Great Basin bristlecone pines (*Pinus longaeva* D.K. Bailey) at high elevation. The scenic byway offers opportunities to view these trees, and a visit to the Schulman Grove visitor's center offers an opportunity to learn more about them. The center is closed during the winter season, although travel along the route may increase if warm-weather use increases. An increased visitor season could increase impacts and require expansion of parking lots and overlooks.

Sierra National Forest is home to groves of giant sequoia (*Sequoiadendron giganteum* [Lindl.] J. Buchh.) (e.g., the McKinley Grove) and five wilderness areas (including the John Muir and Ansel Adams Wildernesses), providing year-round recreation use. A standing forest order was issued for the Kaiser Wilderness to increase camping setbacks to 200 ft from lakes within the wilderness to allow for recovery of vegetation and mitigation of impacts from camping. Further restrictions include limits on stock use within 100 ft of the lakes, and a decreased length of stay. These measures were attributed in part to the continued high level of recreation use, a reminder that increases in the number of visitors or length of seasons may result in ecological effects that require changes in management. Wildfires have likewise had considerable impacts on this forest (e.g., the Kaiser and Thomas Fires). Nelder Grove was severely affected by the Railroad Fire (fig. 5.5).

Positioned between two wilderness areas is the Dusy Ershim OHV trail, a 30-mi point to point trail known for its considerable challenges to the OHV rider, camping, fishing, and a lake (https://www.alltrails.com/trail/us/california/dusy-ershim-4x4-trail).

Sequoia National Forest is home to whitewater rafting and other uses on the Kern and Kings Rivers, and Lake Isabella offers the only motorized boating opportunity. The Kern River can become hazardous when the flow of water is increased, a likely event in some years as mentioned previously in this report, and may result in injury or loss of life (see Lin 2017).

Giant Sequoia National Monument on Sequoia National Forest contains 33 giant sequoia groves or grove complexes (USDA FS 2012). Recent research suggests the giant sequoias are being affected by extended drought as well as increased temperature (Su et al. 2017). Impacts on this iconic species are of concern for current and future generations of visitors and the managers addressing social and ecological change in the region.

The South Zone includes two federally designated iconic places: Mono Basin National Forest Scenic Area on Inyo National Forest and Giant Sequoia National Monument on Sequoia National Forest. Site managers of 41 U.S. Forest Service iconic places were surveyed during 2016–2017 (Ellison et al. 2018). Managers of these places (including the two in the South Zone) identified scenic value as a primary reason for designation as an iconic place. Additional values were biophysical features and unique recreation opportunities. Ratings of current conditions and resource condition trends were not always reassuring, with some areas in impaired or deteriorated condition.

Although current levels of recreation use were believed to be sustainable by a majority of respondents, future trends in use were not believed sustainable by a majority. The largest perceived challenges for sustainable management among survey respondents were internal funding, staffing shortages, and competing demands on staff time. Recreation use demands were noted as challenges by more than half of the respondents, and climate change was cited by less than a third of respondents (Ellison et al. 2018). Noteworthy is the likely impact on scenic value and recreation opportunities from climate change, as well as increased pressures in the form of deteriorated conditions, increased demands in selected areas, and funding issues. Although climate change was less often cited as a concern, the main issues of concern to respondents are likely to intersect with climate change effects. Monitoring of current and expected effects on recreation sustainability as viewed by managers would be an interesting focus for ongoing information gathering to inform development and modification of adaptation strategies.

Southern Sierra forests are home to endemic native trout, with other native species confined to smaller areas of forests, owing to stocking practices and their effects on habitat (Hunsaker et al. 2014). Limited habitat and projected climate change effects leave native trout species vulnerable (Hunsaker et al. 2014).

Increased average annual and winter temperatures along with decreased snowpack are of concern in the Southern Zone forests (Gonzalez 2012). Projections show a continuing increase in extreme temperatures as well as extreme precipitation events where a 1-in-20-year storm is projected to occur every 8 to 10 years (Gonzalez 2012). Of further concern in the Southern Zone forests is the well-documented relationship among wildfire, intense rainstorms, and debris flows that threaten recreation sites and access as well as surrounding communities (Hunsaker et al. 2014) (fig. 5.22).


James D. Absher

Figure 5.22—Postfire erosion, Sierra National Forest.

The majority of dollars expended in the Southern Zone are for lodging costs for nonlocal visitation. Nonlocal visitation expenditures are the vast majority of recreation expenditures in the zone (table 5.13). The estimated annual economic benefit for recreation participation associated with the Southern Zone is about $293 million (table 5.14), about 22.9 percent of the overall estimated value for the three zones ($1.3 billion). Inyo National Forest has the highest annual economic benefit (62.3 percent of total Southern Zone value), followed by Sequoia National Forest (21.6 percent), and Sierra National Forest (16.1 percent). The largest estimated economic benefit for recreation in the Southern Zone is from downhill skiing, although as a group, warm-weather activities provide the larger share of estimated benefits by category of activity (table 5.14).

When asked what the forest visit would be substituted with if the current forest visited was not available, the most common response from visitors to Inyo, Sierra, and Sequoia National Forests was that they would have gone elsewhere for the same activity (45.6, 34.7, and 44.3 percent respectively; USDA FS 2018b, 2018h, and 2018g, respectively) (fig. 5.23). Almost a third of Sierra National Forest visitors would have come back another time.

Distance respondents would have traveled to an alternate location varied by forest (fig. 5.24). More than a third of visitors (43.4 percent) to Inyo National Forest

Table 5.13—Total annual expenditures within 50 mi of the survey site by nonlocal and local visitors to the Southern Sierra Zone, by spending category

	Nonlocal spending[a b]		Local spending	
Spending category	Total annual expenditures	Spending for each category	Total annual expenditures	Spending for each category
	Thousands of dollars ($2017)[c]	*Percent*	*Thousands of dollars ($2017)*[c]	*Percent*
Lodging	105,182	27.4	615	2.4
Camping fees	10,156	2.6	984	3.8
Restaurant	76,375	19.9	3,688	14.2
Groceries	47,301	12.3	5,371	20.7
Gas and oil	54,456	14.2	8,815	33.9
Local transportation	2,220	0.6	98	0.4
Entry fees	25,287	6.6	2,483	9.6
Recreation and entertainment	34,841	9.1	1,469	5.7
Sporting goods	12,399	3.2	1,988	7.6
Souvenirs and other expenses	15,453	4.0	474	1.8
Total	383,672	100	25,985	100

Note: Spending totals were calculated using the procedures outlined in White (2017) and parameters and spending averages used by the U.S. Forest Service office of Ecosystem Management Coordination.

[a] Nonlocal refers to trips that required traveling more than 50 mi to the survey site.

[b] Data source is the fourth round of the National Visitor Use Monitoring (NVUM) surveys.

[c] NVUM data, 2015–2017.

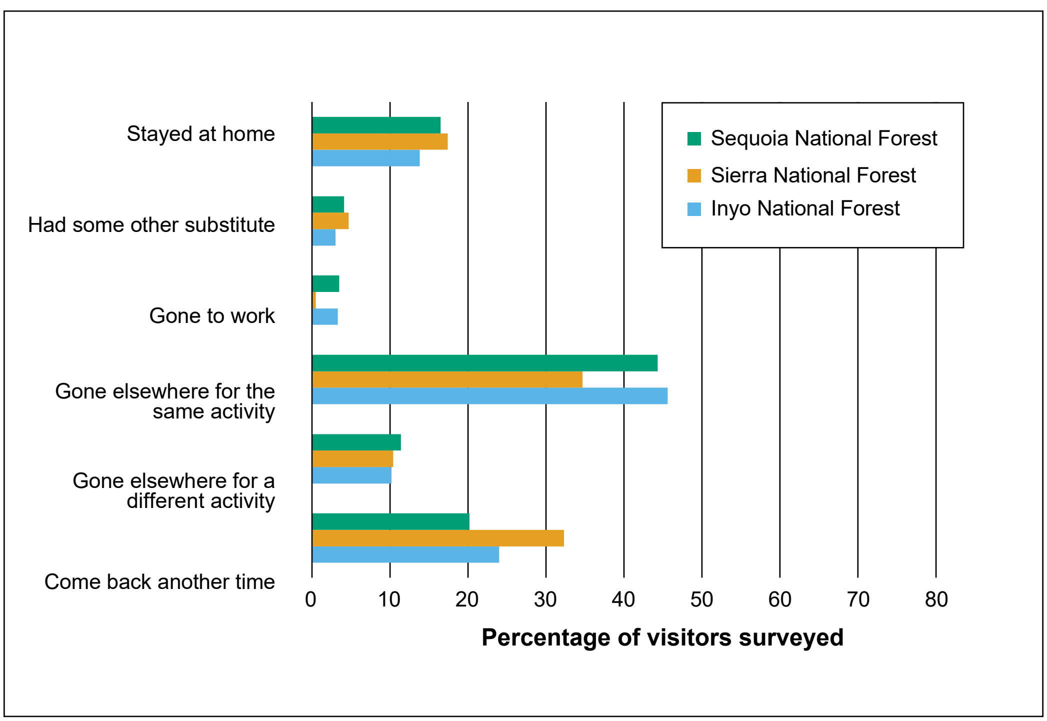

Figure 5.23—Alternative location or option that Southern Sierra Zone forest visitors would choose if unable to visit the national forest where they were surveyed.

Table 5.14—Estimate of annual aggregate economic benefit for the Southern Sierra Zone

Activity participation[a]	Economic benefit
	2016 dollars
Warm-weather activities:	
Hiking/walking	51,228,248
Viewing natural features	23,023,280
Bicycling	19,601,081
Developed camping	11,120,155
Other nonmotorized	9,707,842
Backpacking	4,832,305
Picnicking	3,167,638
Horseback riding	688,375
Primitive camping	437,875
Total	123,806,799
Winter activities:	
Downhill skiing	69,678,740
Cross-country skiing	7,414,831
Snowmobiling	147,795
Total	77,241,366
Wildlife activities:	
Fishing	16,154,748
Hunting	9,570,599
Viewing wildlife	1,290,172
Total	27,015,519
Gathering forest products:	
Gathering forest products	1,028,903
Water-based activities, not including fishing:	
Nonmotorized water	4,456,506
Motorized water activities	1,075,878
Total	5,532,384
Other activities:	
Relaxing	26,126,424
Some other activity	12,662,536
Driving for pleasure	7,178,301
Resort use	3,712,182
Off-highway vehicle use	1,877,566
Motorized trail activity	1,634,048
No activity reported	1,500,034
Visiting historic sites	1,293,849
Other motorized activity	1,081,565
Nature center activities	1,018,422
Nature study	401,426
Total	58,486,353
Total for all activities	293,111,326

[a] Main recreation activity.

indicated they would travel over 300 mi to an alternate location. Following similar patterns for prior sections in this report, Inyo visitors traveled a considerable distance to recreate at their final destination according to the latest NVUM survey results, with almost three-fourths reporting distances of more than 200 mi.

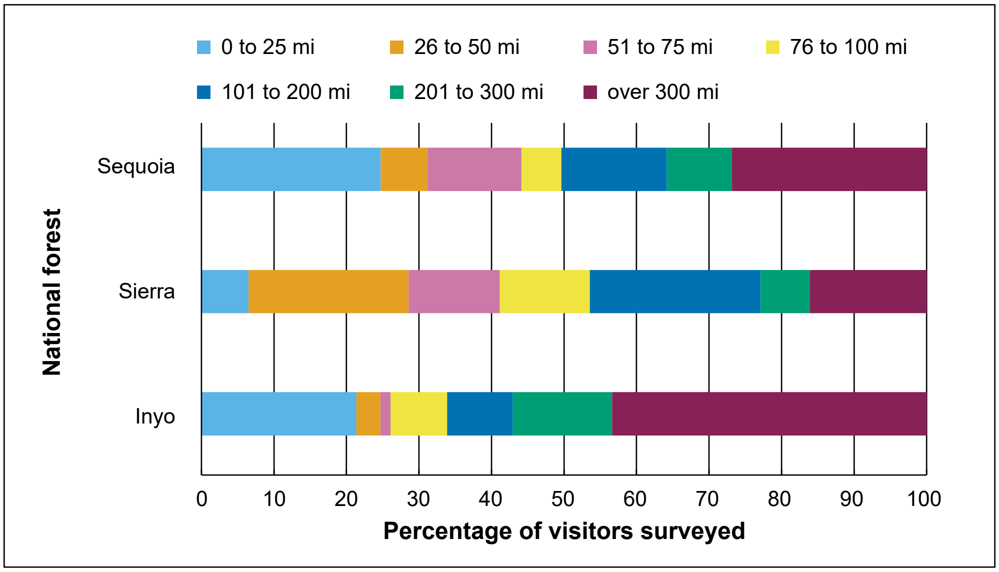

Figure 5.24—Distance that Southern Sierra Zone forest visitors would travel if they could not visit the national forest where they were surveyed.

Adapting Recreation to the Effects of Climate Change

Although many effects from climate change are anticipated, and some have already occurred to varying degrees, many strategies will likely be effective in adapting to climate change effects. We consider a few of these in this chapter and give a place-based view of their consideration in the chapter exploring adaptation strategies and tactics (chapter 6). To promote climate change resilience, Jardine and Long (2014) outlined several approaches, including a focus on longer time horizons for planning, setting of adaptable objectives, and ability to revisit and modify as needed; and use of valuation tools, monitoring, and research.

The Interagency Visitor Use Management Council's resources, particularly the "Indicators, Thresholds, and Monitoring Guidebook" (IVUMC 2019a) and the "Visitor Use Capacity Guidebook" (IVUMC 2019b) may be helpful toward planning for and monitoring of recreation use levels and selection of indicators. Additional resources that address concerns such as recreation use impacts under different social and ecological conditions and approaches to monitoring include Marion's work (see Marion et al. 2016), and a handbook for managers developed by Burn and Winter (Burn and Winter 2007, 2008; Winter and Burn 2010).

An additional strategy is to ensure a solid disciplinary mix in the consideration of socioecological linkages in assessment of impacts and development of tactics, monitoring, and adaptive responses. In other words, a robust systems approach and the willingness to incorporate complex and diverse sources of information are needed to develop appropriate climate change responses. Additional research focused on the intersection of climate change and recreation is needed, as the understanding of short and longer term direct and indirect effects is not sufficiently understood (Brice et al. 2017). Beyond the impacts, an improved understanding of the effectiveness of various adaptation strategies and tactics requires study over time. For example, impacts of substitution behaviors and their degree of effectiveness in maintaining the myriad benefits of recreation require additional study.

Adaptation to climate change effects is already evident in the assessment area. For example, messaging of air quality impacts from wildfires and smoke was widely shared across media during the summer of 2018 when multiple fires affected conditions on several forests and communities in the area. National forest websites list area and site closures, frequently along with a description of causes for the closures. These are also shared with relevant media. In April 2017, the Stanislaus National Forest announced closure of four roads and the recreation areas along the roads in response to damage from extreme snow levels and winter storms. The closure was expected to run through the end of 2018 (Peterson 2017).

Consideration of available technologies that may augment communication of associated risks as well as public actions is warranted (e.g., Ballew et al. 2015). For example, the U.S. Forest Service has a novel smartphone and iPhone® application that helps address:

- Agency strategic goal 2 (USDA FS 2015): Deliver benefits to the public.
    - Strategic objective F: Connect people to the outdoors—Utilize new and emerging technologies and techniques to reach nontraditional and diverse audiences in order to share recreational opportunities throughout the region.
- Agency strategic goal 3 (USDA FS 2015): Apply knowledge globally.
    - Strategic objective H: Transfer technology and applications—Further expand our use of technology to accomplish our work, manage our information, and share evolving knowledge (https://usdagcc.sharepoint.com/sites/fs-rhvr-mit/SitePages/Let%27s%20Get%20Started.aspx, drawn from the Salmon-Challis presentation posted to this site).

Because the app allows national forest staff to update messaging and information, areas that are affected by closures or reduced access could be noted for potential visitors, and the app could be used to identify locations nearby that would still be open for similar recreation opportunities.

Messaging itself benefits from use of the best available science. For example, a recent study reported that visitors to the Lower Klamath and Tule Lake National Wildlife Refuges would find messaging around climate change most relevant when framed as a quality of life issue (e.g., preserving recreation opportunities) or as an economic issue (e.g., maintaining revenues from recreation and tourism) (Sexton et al. 2012). The authors suggested placing science-based issues in a context that various audiences can relate to. The relevance of messaging for diverse audiences can be improved by addressing environmental issues from the context of importance to communities (Marcus et al. 2011).

Adaptation by Recreation Participants

Recreationists may benefit from searching information resources to plan forest visits (potential elevation of know-before-you-go messaging) and may need to develop alternative plans in case unexpected events render an area or opportunity unavailable. Substitution of alternative locations and activities is complex and may be less inviting to recreationists with a personal and or family connection to a location or activity, an identity associated with that place or activity, or a view that the activity and location are unique in a way that cannot be replaced elsewhere (Winter et al. 2014a). Although recreation visitors are most likely to adapt to short-term patterns where the primary forest location is not available for a planned recreation activity and visit, longer term impacts on recreation experience quality, recreation benefits, and place attachments are not well understood. Consideration may be given to implementing restoration and conservation engagement for visiting recreationists in the form of stewardship tourism given the considerable draw of some activities in the Sierra Nevada (Schild 2019, USDA FS 2010).

Adaptation by Public Land Managers

The U.S. Forest Service will likely need an expanded portfolio of approaches to address uncertainty surrounding climate change effects (Aplet et al. 2010). Projections overall show a continuing pattern of increased recreation use across the assessment area, suggesting the need to ensure adequate staffing and resources to continue to manage for a diversity of high-quality recreation opportunities. Increased staffing will be needed to aid delivery of recreation opportunities and to maintain visitor safety, as well as to aid protection and restoration of affected settings. Climate change will likely extend the season for warm weather activities, increase the variability of conditions for snow-dependent outdoor recreation activities, and consolidate outdoor recreation in remaining settings when outdoor

Projections overall show a continuing pattern of increased recreation use across the assessment area, suggesting the need to ensure adequate staffing and resources to continue to manage for a diversity of high-quality recreation opportunities.

recreation infrastructure and transportation systems are negatively affected by the extreme weather events and wildfire severity that climate change exacerbates.

Limits on visitation through determination of carrying and social capacity may be increasingly necessary, as will approaches that incorporate messaging around alternative areas and activities, and warnings about potential crowding and capacity issues. Strategies can be targeted to aid visitors in decision processes surrounding destinations and activities. Similarly, when environmental hazards may be higher (e.g., when air quality or water quality are degraded), messaging can inform visitors, particularly those with sensitivities, to avoid locations or activities until hazards are diminished or resolved.

Current platforms used to communicate availability of recreation opportunities, such as national forest websites, will increase in importance as messaging tools to maintain visitor awareness of specific seasons, closures, or limits to types of use. Social media platforms may be useful for a subset of interested parties seeking forest updates, although social media used and relied upon is diverse, changes rapidly, and requires investment and frequent updating to remain relevant (Ballew et al. 2015). Smartphone applications are a more recent innovation for the U.S. Forest Service and can be an essential tool in the agency's communication portfolio if updated in a timely way.

Partnerships and volunteer programs will continue to aid the U.S. Forest Service in providing and managing for its diverse recreation opportunities and settings. Partnerships and volunteers have been instrumental in providing recreation opportunities and in restoring areas, as was described earlier in this paper regarding the reopening of the Gabrielino Trail. These opportunities provide benefits to participating volunteers and partners, although considerable variation exists among national forests (Winter 2014b). Partnerships among agencies and institutions, resource management agencies, and others focused on resource sustainability are needed to support information needs and inform adaptive responses (CIRMOUNT Committee 2006). The examples of niche opportunities presented in this chapter included selected stories of how partners and volunteers contribute to sustainable recreation opportunities in the Sierra Nevada.

Monitoring of impacts from climate change that may disproportionally affect underrepresented groups will increase in importance as climate change effects continue to emerge.

As stated earlier in the chapter, monitoring of impacts from climate change that may disproportionally affect underrepresented groups will increase in importance as climate change effects continue to emerge. Where recreation access is of elevated benefit to populations otherwise at risk, preserving high-quality opportunities and access is a cornerstone of sustainable recreation delivery (Winter et al. 2019).

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Chapter 6: Adapting Infrastructure and Recreation in the Sierra Nevada to Climate Change

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Introduction

Climate change is currently affecting ecosystems and natural resources in forest ecosystems across the Western United States (Dettinger et al. 2018, Halofsky and Peterson 2017, Wuebbles et al. 2017). To prepare for the effects of increasing temperatures and shifts in precipitation, resource managers working for the U.S. Department of Agriculture, Forest Service (USFS) are currently mandated to integrate climate change information into decisionmaking during land management planning (USDA FS 2012). Climate change adaptation, or taking actions to reduce risks from changing climatic conditions and prepare for the effects of future changes (Lempert et al. 2018), will be necessary to maintain resilient ecosystems and sustainable natural resources on National Forest System lands. Implementing effective climate-informed management actions across large landscapes will require increased coordination between federal and state agencies, nongovernmental organizations, industry partners, and private landowners.

This chapter describes adaptation options that were developed to support sustainable management for recreation and infrastructure resources on National Forest System lands across the Sierra Nevada. We provide background on key climate sensitivities and discuss adaptation options identified during each of the workshops. Although the adaptation strategies and tactics presented here are not an exhaustive list, they represent diverse high-priority climate sensitivities and actions that are relevant for the Sierra Nevada, and, in many cases, other regions of the Western United States.

Adaptation strategies and tactics were developed over the course of three, 1-day workshops held at locations in the northern, central, and southern Sierra Nevada. During each workshop, climate change sensitivities and stressors were reviewed for infrastructure (chapter 4) and recreation (chapter 5). These workshops were designed to build the capacity of resource managers to adapt to climate change by having a focused dialogue on regional climatic patterns and projections, projected climate change effects, and potential adaptive responses. Workshops were attended by resource managers from national forests, national parks, and state agencies, as well as representatives from conservation organizations, utility and water providers, and industry. The three workshops were attended by a total of 75 participants.

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Following the review of climate change effects, breakout groups for each resource area identified a series of high-priority climate sensitivities and supporting adaptation strategies and tactics through facilitated discussion and worksheet exercises adapted from Swanston et al. (2016). Adaptation options for each resource area were then presented to the rest of the workshop group, and steps toward implementing them in future planning efforts and project designs were

Table 6.1—Adaptation options for infrastructure in the Sierra Nevada

Sensitivity to climate change	Adaptation strategy	Adaptation tactic
Increasing wildfires will pose a greater risk to infrastructure and communities in the wildland-urban interface (WUI).	Increase awareness of fire ecology and fuels management to reduce risk.	• Expand fuel reduction programs and increase fire-resilient communities and structures. • Increase public communication, education, outreach, and real-time alerts on fire safety. • Increase postfire hazard mitigation and education. • Collaborate with local communities to develop improved zoning, land use planning, safety zones, and evacuation routes in WUI areas.
	Manage vegetation to reduce fuel loads and increase defensible space around facilities, WUI communities, and other vulnerable sites.	• Use prescribed burns and thinning to reduce fuel loading and increase forest resilience to fire. • Restore natural forest processes and conditions (e.g., regeneration, disturbance, landscape heterogeneity) where ecosystem characteristics fall outside the range of desired conditions.
Warming temperatures, extreme weather events, and disturbances will alter public access into vulnerable areas with limited infrastructure.	Establish or improve egress, evacuation routes, and safety zones.	• Identify evacuation routes and safety zones in vulnerable locations. • Identify alternate routes (e.g., when closures are in place) to avoid high-risk areas. • Improve public communication to increase awareness of risks and emergency response protocols. • Plan on increased stabilization of needed alternate routes.
Reduced snowpack and earlier peak streamflows can lead to water shortages in late summer.	Increase watershed resilience to increased or more variable runoff events.	• Increase offstream water storage capacity (water outside river channels, water transported via irrigation canal networks). • Increase groundwater recharge in headwater/upper elevation watersheds. • Conserve and manage water storage for prolonged drought conditions.
	Increase management flexibility and reduce risk exposure when considering infrastructure use, construction, and maintenance.	• Control access and timing of use on vulnerable infrastructure. • Develop additional and more flexible maintenance options. • Relocate and improve access points and plan for increased access in the future (e.g., higher elevation sites where snowpacks are reduced). • Increase forecasting and monitoring programs to improve predictions of runoff volume and timing.

discussed. The adaptation strategies and tactics presented in this chapter reflect the responses from the three adaptation workshops (tables 6.1 and 6.2). As a result, certain adaptation approaches may be emphasized relative to others. For a more comprehensive overview of additional adaptation options, readers should refer to chapters 4 (infrastructure) and 5 (recreation).

Sensitivity to climate change	Adaptation strategy	Adaptation tactic
Climate change effects will occur across management boundaries, straining already limited resources for site and infrastructure maintenance.	Increase awareness of the need for an "all lands" approach to climate change adaptation.	• Increase public education and outreach around shared stewardship and collaborative land management. • Use the incident command structure to create rapid-response teams to respond to disturbances or extreme events. • Identify and prioritize high-value assets/ investments at risk of climate change effects.
Increasing tree mortality leads to more hazard trees.	Reduce safety risks associated with hazard trees.	• Limit access to high tree-mortality areas until hazard trees are removed. • Remove hazard trees near critical infrastructure and facilities, ingress/egress points, and transportation/utility corridors. • Preserve quality of developed recreation sites (e.g., build shade structures) by changing design features and managing user expectations.
Increased flooding from extreme precipitation events or increasing rain on snow events can damage infrastructure.	Incorporate future conditions into project design.	• Adjust infrastructure design to account for shifts in runoff and precipitation type (e.g., upsize culverts, change construction material). • Reassess recurrence intervals and risk levels for established infrastructure design, and define uncertainties in terms of climate change projections. • Stabilize and reinforce soils along streambanks and near crossings where higher streamflows can damage roads, bridges, and culverts. • Relocate vulnerable roads and infrastructure away from channels.
Shifting streamflows and increased winter rainfall will lead to increased debris movement (e.g., sediment and logs) in streams and channels.	Design infrastructure to withstand larger streamflow events and debris loading.	• Increase vegetation cover to slow water flow and decrease erosion. • Improve drainage structures to prevent concentration and displacement of water. • Install trash racks, do channel maintenance, and armor eroding streambanks. • At problematic culverts, consider a ford. • Restrict or control access to high-risk areas (via road and trail closures) to improve vegetation establishment and improve public safety.

Table 6.2—Adaptation options for recreation in the Sierra Nevada

Sensitivity to climate change	Adaptation strategy	Adaptation tactic
Increased tree mortality from fire, drought, insects increases hazard, damages infrastructure, and reduces landscape aesthetics and quality of visitor experiences.	Increase resilience of social recreation infrastructure to increasing disturbances.	• Mitigate risks (e.g., remove hazard trees). • Expand communication of current conditions, user expectations, and alternative sites. • Create and maintain climate-adaptive infrastructure (e.g., install shade structures). • Establish fast-growing tree species after disturbance to provide shade on recreation sites.
	Improve hazard response protocols.	• Communicate risks associated with climate change and potential responses to hazards. • Collaborate with first responders to increase visitor safety and response protocols. • Actively manage recreation resources to reduce risk exposure.
Warming temperatures and decreasing snowpack will lead to shifting recreational seasons and patterns of use.	Adjust staffing and management during variable shoulder seasons to accommodate changes in seasonal access and recreation locations.	• Leverage local partnerships to help manage recreation facilities. • Pursue additional funding and partnerships to increase staffing and maintenance capacity. • Provide or increase housing and other resources for seasonal employees.
	Adjust visitor management policies and practices to increase management flexibility and facilitate transitions to meet user demands and expectations.	• Integrate projected recreation shifts into resource planning efforts. • Develop infrastructure design and maintenance plans to sustainably accommodate increasing visitor demands. • Identify potential carrying capacity thresholds and incorporate them into management plans and projects.
Climate change may increase the closure of recreation sites due to staffing shortages, disturbances, extreme weather events, safety issues, and higher maintenance costs.	Increase resilience of recreation sites to changing conditions and/or increased demand to continue providing recreation opportunities.	• Identify substitute locations to manage use and user overflow; improve reservation flexibility and transfer protocols. • Develop a communication plan (internal, external) with respect to contingencies and protocols for openings/closures in order to manage expectations. • Rotate use of recreation sites to minimize degradation.
Warming temperatures and decreasing snowpack will alter the elevation and timing of recreation use.	Increase capacity to anticipate and respond to shifting seasonal recreation patterns.	• Increase staffing capacity in areas where visitation increases. • Increase cross-boundary collaboration to improve access to recreation sites. • Monitor use and mitigate over-use. • Provide transportation alternatives to reduce congestion.

Sensitivity to climate change	Adaptation strategy	Adaptation tactic
Changing habitat conditions and decreased connectivity can lead to increased wildlife-human interactions.	Reduce human-related pressures and increase wildlife habitat connectivity.	• Improve wildlife habitat by reducing nonnative and invasive plants. • Increase habitat connectivity by restoring degraded sites in key areas. • Use wildlife-deterrent systems near facilities and infrastructure to minimize encounters with humans. • Increase public education and outreach about wildlife, habitat connectivity, and climate change.
Climate change can result in increased wildfire and smoke problems that reduce recreation opportunities and create health issues.	Increase management flexibility and anticipate fire-related effects at a regional scale.	• Create contingency plans for unexpected shifts in recreational use and timing. • Support research on alternative activity selection by recreationists. • Establish thresholds and protocols for site closure due to air quality or health concerns.
	Standardize and unify cross-agency communications.	• Increase communication across agencies to support consistent messaging. • Develop better public communication tools for real-time updates on disturbances, site conditions, and recommended responses to mitigate risks. • Work with interagency and non-governmental partners to increase outreach to clients and specific users.
Increasing tree mortality creates more hazard trees.	Reduce safety risks associated with hazard trees.	• Limit access to high tree-mortality areas until hazard trees are removed. • Remove hazard trees near critical infrastructure and facilities, ingress/egress points, and transportation/utility corridors. • Preserve quality of developed recreation sites by changing design features (e.g., build shade structures in areas that may experience extreme heat or tree mortality).
Climate change stressors reduce resilience of iconic places and recreational opportunities.	Manage iconic places for resilience using an interdisciplinary approach to provide recreation opportunities.	• Increase resilience of iconic sites by reducing human impacts (e.g., reduced visitation, installing boardwalks). • Communicate and collaborate across management boundaries and land ownerships, and improve communication about recreation alternatives that provide similar recreational or cultural experiences. • Increase education and outreach about other recreation options, changing conditions, and collaborative stewardship.

Climate Change Adaptation on National Forest Lands

Climate change adaptation consists of four general steps: (Peterson et al. 2011):

- Synthesize and review current climate change science and integrate this information with local management and social conditions and contextual factors (review).
- Evaluate climate change sensitivities, future climate exposure, and adaptive capacities for key ecosystems or natural resource areas (evaluate).
- Develop and implement adaptation options (resolve).
- Monitor the effectiveness of adaptation actions (observe) and adjust as needed.

Information from each of these steps is often integrated into climate change vulnerability assessments that describe the exposure, sensitivity, and adaptive capacity of natural resources.

Vulnerability assessments are often synthesized as reports, decisionmaking tools, or peer-reviewed publications designed to support science-based resource management and decisionmaking (Timberlake and Schultz 2019). Adaptation options developed during the assessment process describe specific actions that can be taken in response to climate change stressors to increase the resiliency of natural resources, ecosystems, and natural processes to changing climatic conditions (Peterson et al. 2011). Adaptation options vary in their scope and specificity, whereas **adaptation strategies** are first identified in response to a climate change vulnerability for a specific resource or ecosystem. These strategies typically have a broader focus conceptually and geographically and are often associated with management planning efforts.

To support adaptation strategies, managers identify **adaptation tactics**. Tactics are more targeted and prescriptive actions implemented to improve resilience to climate change at a particular location. Tactics are typically associated with efforts taking place at the project level. Climate change adaptation actions developed as strategies and tactics can range from small adjustments to significantly revised management practices (e.g., upsizing a new culvert on a flood-prone stream) to extensive, long-term projects (e.g., development of new recreation infrastructure to support year-round recreation).

Previous vulnerability assessments conducted across the Western United States (Halofsky et al. 2018a, 2018b), and in the Sierra Nevada specifically (Kershner 2014), have primarily focused on a variety of resource areas including forest vegetation, aquatic ecosystems, water resources, and ecosystem services. There is growing awareness that public lands and the built infrastructure on them are critical for recreational opportunities (Hand et al. 2018). Climate change is interacting with infrastructure networks and growing recreational demands to create management challenges that deserve specific attention.

The Sierra Nevada provides an opportunity to concurrently assess the effects of climate change on recreation and infrastructure. With continued warming, significant shifts in hydrologic processes and snow-water resources are projected across the Sierra Nevada (chapter 3). These climate change effects will occur as populations grow and recreation increases (chapter 5). The vulnerability of key recreation and infrastructure resources was assessed in the previous chapters to help inform resource managers as they prepare for both climatic and socioecological changes across the region (chapters 4 and 5).

This climate change vulnerability assessment is unique in its focus on recreation and infrastructure. By assessing the vulnerabilities of two interconnected resource areas, the assessment team was able to increase the focus of the overall assessment to synthesize the most relevant climate change information, so that specific adaptation options could be developed in response to climate change stressors. The vulnerability assessment was initiated and developed through a science-management partnership with recreation managers and engineers across the Sierra Nevada. Through these partnerships, the assessment team (1) synthesized the best available regionally focused climate change science, (2) assessed regional and forest-level climate change vulnerabilities, (3) collaboratively developed locally relevant climate change adaptation options with managers and stakeholders, and (4) integrated those adaptation options into a spatially explicit and peer-reviewed assessment for the entire Sierra Nevada region (chapter 1), (fig. 1.1).

Overview of Climate Change Effects in the Sierra Nevada

The Sierra Nevada has a Mediterranean climate, with approximately 80 percent of annual precipitation falling during the winter months, with total incoming precipitation exhibiting high interannual variability across the region (chapter 2). Because the precipitation regimes of this region are winter dominated, precipitation predominantly falls as snow at higher elevations where temperatures are cooler. Water resources used by a large proportion of the state are generated from mountain snowpacks accumulated on national forest lands (Belmecheri et al. 2015, Dettinger et al. 2018).

Owing to the strong seasonality of incoming precipitation, current transportation infrastructure, hydroelectric networks, and recreational resources across the Sierra Nevada are coupled with hydrologic processes and fluctuations (chapters 3, 4, and 5). Roads and other infrastructure on national forests provide access to recreational opportunities across all seasons. Recreational demand and outdoor recreation economies are increasing with growing populations in California (chapter 5).

With projected warming temperatures and more intense precipitation events, higher demand for public access in national forests may coincide with increasing occurrence of floods, landslides, and fire hazards (chapters 3 and 4).

Shifting hydrologic conditions driven by warming temperatures will have complex effects on the function of Sierra Nevada forest ecosystems (chapter 3). However, shifts in precipitation type or phase (i.e., rain or snow) will be one of the most direct and widespread effects of warming temperatures on regional hydrologic regimes. Shifts in precipitation regimes from snow-dominated to rain-dominated will significantly reduce snowpack storage capacities, alter the timing and magnitude of streamflow, and alter the timing of soil moisture inputs and availability later in the summer (chapter 3). Overall, the amount of water stored in snowpacks across the Sierra Nevada is projected to decrease by 60 percent by the end of the 21st century (Dettinger et al. 2018), with middle elevations experiencing the biggest losses.

As precipitation regimes become increasingly rain-dominated, there will be subsequent changes in the timing and amount of streamflow (Regonda et al. 2005, Schwartz et al. 2017) (chapter 3). Large advances in the timing of spring streamflows are projected to follow earlier snowmelt, with peak flows occurring as much as 1 to 2 months earlier in streams across the Sierra Nevada by the end of the 21st century (chapter 3). With rainfall events occurring more frequently during the winter, the number of large winter streamflow events will also increase (Das et al. 2011). Earlier and larger spring streamflows will potentially lead to prolonged and lower summer low flows for many streams that deliver water resources and support aquatic ecosystems.

Shifts in hydrologic regimes can also affect disturbance regimes in forest ecosystems. Drier atmospheric conditions resulting from increased air temperatures can accelerate soil moisture use and increase drought stress in water-limited ecosystems. Trees have physiological limits to the amount and duration of drought stress they can tolerate, with some drought-intolerant species experiencing mortality in response to more severe drought, insects, and subsequent disturbance events like wildfire (Allen et al. 2010, Anderegg et al. 2015, Westerling et al. 2006).

Climate Change Effects on Infrastructure

Infrastructure on national forests provides access to a variety of natural resources and supports the use of many ecosystem services and recreational opportunities. The 10 national forests in the Sierra Nevada contain a combined 26,500 mi of roads, 9,300 mi of trails, 684 bridges, 169 dams, over 4,100 buildings and administrative sites, and over 50 campgrounds. Total infrastructure investments for facilities alone have an estimated value of $750 million (chapter 4). Many of the current transportation, water resource, and facility infrastructure networks are a legacy of a century of natural resource extraction, recreation, and human settlement. The primary use of infrastructure resources has shifted in recent decades toward increasing recreational use (chapter 5). However, the combined effects of increasing use, aging infrastructure design, and changing climatic and hydrologic conditions are increasing the vulnerability of infrastructure and increasing risk for users.

The vulnerability of transportation and water allocation infrastructure to climate change and extreme events is a concern for forest, recreation, and water resource managers in the Sierra Nevada (chapters 3, 4, and 5). Infrastructure can be affected by direct climate change effects, increased climatic variability (e.g., precipitation timing, extreme temperatures, drought severity and duration) and indirect climate change effects such as increased fire and insect outbreaks. Infrastructure networks are interrelated with other resource management programs, and the vulnerability of infrastructure to climate change can influence access to and quality of other natural resources and ecosystem services (e.g., recreation). For example, many of the extensive road networks in the Sierra Nevada have been constructed in complex terrain where the risk of disturbance and natural hazards is high, and maintenance and repairs are difficult and costly. Some transportation infrastructure may become nonfunctional or unsustainable, given its age, outdated design, increasing usage for recreation, and vulnerability to hydrologic changes (Black et al. 2012, Luce and Black 1999).

Water resource infrastructure, including dams and reservoirs, stores water, reduces flooding, and provides recreational opportunities (chapter 5). Future changes in timing, type (rain vs. snow), and amount of precipitation will create challenges when storing and allocating water for irrigation, flood prevention, and energy production (chapter 3). Innovative adaptation solutions will be needed to address climate change stressors, including an expanded spatial scale of management actions (especially in highly vulnerable landscapes) and coordination among resource management programs.

Climate change will affect infrastructure over short and long time scales. Extreme events occurring over the course of several hours to several weeks often cause the most significant damage or are the most disruptive to operations. For example, roads, bridges, and culverts are susceptible to increased runoff during storm events and failures resulting from washouts, plugging, overtopping, stream diversion, and scour (chapter 4). However, long-term climatic patterns that affect infrastructure over the course of multiple decades—altered freeze-thaw cycle, timing and length of suitable construction weather, and snowmelt and stream hydrology—can also affect the sustainability of transportation, recreation, and water resource infrastructure. Population growth and changes in infrastructure use and demand will also affect the sustainability of built infrastructure in the Sierra Nevada.

Climate Change Effects on Recreation

The Sierra Nevada supports the largest outdoor recreation economy in California owing to its extensive recreation opportunities and proximity to nearby population centers (chapter 5). Recreation opportunities are available every season of the year across the region and are enjoyed by users who travel from throughout the United States and beyond. With increasing recreation demands over the past several decades, smaller rural communities in the Sierra Nevada have grown seasonal economies that depend on recreation visitation and expenditures.

Altered temperature, precipitation, water resources, and seasonality of weather conditions will affect evolving recreation patterns in the Sierra Nevada over the course of the 21st century (chapter 5). Higher temperatures are expected to be a primary driver, because most recreational activities are seasonal and vulnerable to changing seasonal conditions and extreme events. Climate change will likely affect the availability, quality, and timing of recreation opportunities, creating additional challenges when managing recreation sites and infrastructure (Hand and Lawson 2017) (chapter 5). These include snow-dependent activities like skiing, snowboarding, and snowmobiling, and warm-weather activities like hiking and camping. As temperatures continue to increase, the economic effects of climate change are expected to occur earlier in communities near national forests, particularly those that have developed economies that depend on outdoor recreation (Wear et al. 2012) (chapter 5).

Adapting to Climate Change in the Sierra Nevada

Adapting Infrastructure to Climate Change

Adapting infrastructure to changing hydrologic regimes—
Warming temperatures will likely have direct effects on hydrologic regimes and water resources (chapter 3), potentially increasing the vulnerability of infrastructure built along rivers and streams, and of facilities located in floodplains. Shifts in precipitation regimes from snow dominated to rain dominated can lead to increased peak flows that accelerate scouring, erosion, and sedimentation. Reduced snowpack and increased rain-on-snow events can also lead to increased and more variable streamflows (chapter 3), potentially increasing erosion and leading to flows that exceed the design parameters of culverts, bridges, and flood prevention infrastructure. To prepare for these extreme events, financial resources and maintenance plans can be improved by risk assessments that identify and prioritize vulnerable roads and infrastructure (Strauch et al. 2015).

At vulnerable or flood-prone sites, resilience near stream crossings and in floodplains can be enhanced by designing future infrastructure to withstand more frequent and severe flood events, and by upsizing or upgrading existing infrastructure to withstand future flooding and erosion. In the most vulnerable locations, roads and other infrastructure can be decommissioned or moved to mitigate risks (table 6.1). For example, engineers can adapt design standards to account for altered streamflow in locations where future rain-on-snow events or shifts to rain-dominated precipitation regimes are expected (Halofsky et al. 2011). Future maintenance and repair operations should occur during periods when weather conditions are optimum and risks to worker safety and site integrity are low. However, altered seasonal conditions may result in closures or restricted public access until conditions are suitable for maintenance and repairs.

Although extreme events like flooding are projected to increase in frequency (chapter 3), they remain difficult to project at the watershed scale. To improve forecasting and response times, managers can expand monitoring efforts to increase their capacity to respond to uncertain and rapidly changing streamflow, snowpack, and weather conditions. Fortunately, expanding monitoring networks can inform decisionmaking processes for multiple resource management programs (e.g., recreation, transportation, reservoirs), and the benefits are frequently shared by neighboring federal and state partners and local communities.

Altered precipitation regimes will also create challenges for dam and water resource managers who allocate water resources to support flood control, energy production, and irrigation demands that fluctuate throughout the year. Adjusting management operations of water control and allocation infrastructure may be necessary as precipitation regimes become more rain dominated (chapters 3 and 4). For example, as streamflows become increasingly variable, shifting the timing and amount of water releases during spring and summer dam operations is an option for maintaining reservoir levels to minimize flood risk in the spring while maximizing water storage for longer periods across the year (Wood and Lettenmaier 2006). To supplement reservoir storage, managers can consider using offstream water delivery infrastructure (canals, ditches, holding ponds) to increase water storage or divert excess streamflows (table 6.1).

Information on the current state of snowpack has typically been more beneficial than climate or weather forecasts for predicting runoff in basins with substantial snowmelt contributions (Wood et al. 2015). However, as precipitation regimes continue to shift with warming, responding to changing hydrologic conditions may require investment in monitoring upstream snowpack, soil, and weather. In areas where snowpack may no longer be a reliable predictor of streamflow timing in a warmer climate, alternative monitoring techniques or protocols may be needed (Harrison and Bales 2016). Improving streamflow forecasting and expanding streamflow and snowpack monitoring networks will help managers respond to extreme events by ensuring water allocation for downstream municipalities, irrigation, riparian areas, and recreation opportunities (Broad et al. 2007) (table 6.1).

Adapting infrastructure to disturbance—
Nearly all infrastructure in the Sierra Nevada is vulnerable to wildfires, particularly outdoor recreation and administrative facilities (chapters 4 and 5). To prevent damage before and during wildfires, vegetation can be managed to reduce fuel loads and increase defensible space around vulnerable facilities and transportation corridors located in the wildland-urban interface (Halofsky and Peterson 2016, Spies et al. 2010) (table 6.1). In addition to the direct effects of wildfire, infrastructure in recently burned areas where vegetation cover has been reduced is often vulnerable to unstable soils and intense precipitation events following fire that can cause erosion, landslides, and debris flows (Guardiola-Claramonte et al. 2011). Following wildfires, managers can prioritize slope stabilization projects around infrastructure near unstable slopes and riverbanks, increase monitoring of soil and slope conditions, and restrict public access to sites where unstable soils create safety hazards (table 6.1).

Concurrently, improving the resilience of ecosystems, infrastructure, and ecosystem services to changing disturbance regimes will help maintain the functionality of ecological processes such as regeneration, productivity, and nutrient cycling. However, with warming temperatures and increasing drought, disturbances like fire will continue to affect large landscapes managed by a mix of federal, state, tribal, and private entities.

Collaborative adaptation efforts and an “all lands” approach are essential for effective responses to increasing disturbances. Expanding existing partnerships among federal, state, and local agencies will increase the capacity of national forests and other organizations to maintain functional ecosystems, water resources, and recreation and transportation infrastructure. Public awareness of the connections among infrastructure, forest ecosystems, and disturbance can be promoted through outreach and education programs with local communities and stakeholders. This will also allow national forests to obtain feedback from the public, which can in turn help identify and prioritize vulnerable infrastructure and collaboratively develop climate-smart actions (table 6.1)

Adapting Recreation to Climate Change

Managing public lands to provide access to sustainable recreational opportunities is a growing priority for land management agencies. Specifically, the USFS framework for sustainable recreation (USDA FS 2010) describes the importance of restoring and adapting recreation settings; implementing "green" operations; enhancing communities; investing in special places; forging strategic partnerships; promoting citizen stewardship; knowing visitors, community stakeholders, and other recreation providers; providing the right information; building a solid financial foundation; and developing the workforce (chapter 5). As forest ecosystems become more vulnerable to climate change, there will be increasing risks to human safety, as well as strained staffing and financial resources. Increasing efforts to make vulnerable infrastructure and recreation resources more resilient to climate change will be necessary under increasingly uncertain conditions.

Adapting winter recreation management—
Higher average and more extreme temperatures will drive changes in the timing and patterns of seasonal outdoor recreation, with some of the most direct effects occurring at elevations where precipitation regimes will shift from snow dominated to rain dominated (chapter 3). Decreasing snowpack and shifts in the availability of snow-dependent recreation opportunities are a concern for managers throughout the Sierra Nevada, where ski resorts and widespread access to winter recreation sites on national forests generate economic revenue (chapter 5). Reduced snowpack can have significant effects on winter recreation, with the most notable being a decrease in the season length for snow-dependent recreation (e.g., skiing and snowmobiling).

As snowpack and snow residence times continue to decrease with warming temperatures, recreationists will likely respond in a variety of ways, including changing the location of recreation (e.g., moving to higher, snow-dominated sites), reducing the duration of their recreation use, or choosing to not participate in snow-dependent recreation by either staying home or choosing an alternative form of recreation at a different location (O'Toole et al. 2019, Scott and McBoyle 2007) (chapter 5).

To adapt to changes in the patterns and timing of winter recreation, managers can increase staffing and provide transportation alternatives at higher elevation sites that will continue to retain snow and may experience increased use with warming temperatures and increased access (table 6.1). However, recreation facilities and infrastructure in newly accessible areas may be unable to support increased use. Managers can minimize site degradation by developing preemptive strategies to control visitation rates (e.g., altered permitting or site closures) or upgrading infrastructure and facilities at sites that will likely experience increased use in the future.

Adapting warm-weather recreation management—
Reduced snowpack and snow residence times will simultaneously affect warm-weather- dependent recreation, as warming temperatures will lead to increased

warm-weather recreational opportunities at elevations where snowpack historically limited access during the spring and fall shoulder seasons (e.g., hiking, camping, and driving for pleasure) (Mendelsohn and Markowski 2004). As warm-weather opportunities increase in some locations, prolonged or increased use throughout the year may lead to accelerated degradation and congestion at popular high-use sites (chapter 5). At low- and mid-elevation sites where warm-weather recreation use will occur across longer seasons, identifying site-specific user capacities, planning for increased use, and updating facilities to accommodate increased recreation demand and pressure will increase site resilience and support increasingly variable recreation patterns (table 6.2).

Iconic ecosystems and natural areas (e.g., giant sequoia [*Sequoiadendron giganteum* {Lindl.} J. Buchholz] groves) will also experience the combined stressors of increasing drought severity along with increased visitation rates and human pressures. To increase the resilience of vulnerable sites to changing climate, managers can consider taking actions that reduce human-related impacts. There are many tactics that can support this strategy. For example, managers can limit visitation through site closures, rotate the timing of access to sites, implement permitting or lottery programs, increase onsite education and awareness about human impacts, and work with conservation organizations to monitor site conditions and communicate about alternative sites (table 6.2). However, implementing many of these tactics may be controversial at popular sites. Working closely with local partners and recreation groups to develop plans, communicate goals and objectives, and implement tactics will be critical (chapter 5).

Adapting recreation management to extreme weather events and disturbance— Climate change will likely lead to an increase in the frequency of extreme precipitation and rain-on-snow events, which can exacerbate natural hazards such as flooding and landslides (Ren et al. 2014) (chapters 3 and 5). As population and recreation demands grow, extreme events can increase risk exposure to recreationists and damage recreational infrastructure on which users depend to access recreation destinations (e.g., roads, trails, bridges, and facilities). Decreasing snowpack and increasing rain intensity will also alter streamflow timing and magnitude (chapter 3), leading to increased safety risk to water-based recreation users and travelers near streams and river crossings.

To prepare for these hazards and mitigate risk, managers can develop adaptation strategies that increase flexibility during resource planning efforts and management operations (table 6.2). Tactics to support these strategies include improving or updating rapid communication and response protocols following extreme events, increasing planning and coordination with other agencies and nongovernmental recreation partners, and identifying alternative sites and contingency plans to continue providing recreation opportunities when there are site closures in response to extreme events (table 6.2).

Increasing drought severity and intensity can also lead to more frequent disturbance events like wildfire. Although these disturbances are natural processes and play a critical role in the function of Sierra Nevada forests, the increasing extent and severity of recent events has affected ecosystem services in recent years, including both short- and long-term effects on recreation and infrastructure. During wildfires and in their immediate aftermath, the availability and quality of recreational opportunities can be reduced (chapter 5). For example, smoke emissions can degrade air quality to levels that are hazardous to human health, affecting large regions downwind of a fire and the quality of recreation opportunities that require physical exertion such as hiking, trail running, and mountain biking. The availability of outdoor recreation opportunities is reduced under these conditions, and communities with recreation-dependent economies may experience financial losses as fire seasons increase in length and wildfires become more frequent.

To prepare recreation resources for changing disturbance regimes and increase social resilience to the effects of wildfire, managers can mitigate fire risk at popular sites and in high-use travel corridors, increase the resilience of recreational facilities to fire risk, and improve rapid-response protocols to facilitate efficient closures owing to health or safety concerns (table 6.2). Even in the absence of climate change, managers have limited capacity to control or prevent these disturbances. Regardless of management intervention, disturbances like wildfire will continue to influence forest ecosystems in the Sierra Nevada. Increasing public understanding of the role disturbance plays in forest ecosystems will be important as disturbance regimes continue to change (chapter 5). Managers can work with local partners to increase public awareness about the ecological role of fire by increasing communication and outreach efforts to help manage user expectations of landscape aesthetics and recreation following wildfires.

With shifting climatic regimes and increasing recreation demand, extreme events, and disturbance frequency, current approaches to maintaining or repairing seasonal recreational sites may be insufficient to ensure economically feasible or sustainable recreation opportunities. Responding to altered seasonal conditions and recreation patterns with limited staffing and financial resources will be challenging (chapter 5). Recreation managers can identify ways to increase staffing presence, particularly during the spring and fall shoulder seasons and at high-use sites where existing facilities may be overwhelmed by greater use (table 6.2). Identifying and prioritizing the most vulnerable locations based on climate change projections will inform management plans and improve how staff and resources are deployed.

Increasing management flexibility in order to rapidly respond to changing conditions is another strategy that can increase the efficiency and effectiveness of management responses (table 6.2). This strategy can be facilitated by developing or updating protocols for enforcing rapid closures or access restrictions; for example, site access can be rotated to minimize human pressures and ecological degradation. Implementation of these tactics can be expanded across management boundaries by increasing staffing capacity through partnerships with local conservation and recreation groups that have volunteers available. Leveraging these partnerships will be a critical component of adapting to disturbances and changing ecosystem conditions in national forests (chapter 5).

Connections Between Infrastructure and Recreation

Management of recreation and infrastructure resources needs to be considered concurrently, because the ability of the public to access outdoor recreational opportunities depends on sustainable infrastructure. Although climate change effects on recreation and infrastructure are typically managed as separate programs on national forests, areas of overlap exist in how climate change will affect the two resource areas (chapter 5). In addition, although water resource infrastructure like reservoirs are critical for flood control and water allocations (chapter 4), they also provide opportunities for water-based recreation and generate significant income for nearby communities.

Recreation Use and Infrastructure Degradation

Some of the social and economic benefits associated with outdoor recreation can come at the cost of strained infrastructure and degraded natural areas. As demand for recreation and access to public lands increases, conflicts about development, congestion, and degradation of overused or sensitive sites can be expected in some locations (chapter 5). The extensive transportation networks in the Sierra Nevada create access to many recreation opportunities, but ease of access can also create risks to users and natural resources. For example, increasing or concentrated use can exceed current infrastructure design tolerances, overwhelm site capacity, strain maintenance resources, and potentially reduce the quality of recreation experiences. To maintain the resilience of these areas, managers can consider limiting travel on vulnerable roads and trails and restricting access to high-use sites (tables 6.1 and 6.2).

Climate change, recreation, and infrastructure are linked relative to water resources such as alpine snowpack, rivers, and lakes. These resources are focal points for recreation but also support diverse ecosystems and provide storage and release of water.

Climate change, recreation, and infrastructure are linked relative to water resources such as alpine snowpack, rivers, and lakes. These resources are focal points for recreation but also support diverse ecosystems and provide storage and release of water. Altered hydrologic regimes are a primary concern for infrastructure and recreation management. Roads, bridges, trails, and facilities are often located in proximity to streams or in floodplains. Increasing maximum temperatures, precipitation intensity, disturbance frequency, and peak streamflows, as well as altered timing and amount of recreation can reduce the resilience of infrastructure and recreation resources (chapter 4).

Disturbance, Extreme Events, and Hazards

Warming temperatures and increasing precipitation intensity will likely increase the frequency of disturbances such as debris flows, landslides, and avalanches, creating challenges when providing access to recreation sites, maintaining transportation and recreation infrastructure, and minimizing risk to travelers and staff (Lazar and Williams 2008, Strauch et al. 2015). To increase coordination across resource programs and agencies, managers can consider developing rapid response plans with neighboring landowners, first responders, and recreation groups (table 6.2). At locations where infrastructure is damaged by natural hazards or other extreme events, there may be considerable losses or shifts in recreation opportunities (chapter 5). These effects can have socioeconomic effects that extend beyond a single site, and surrounding communities may incur loss of critical infrastructure, as well as recreation and tourism revenue.

Drought-driven forest disturbances such as fire and insect outbreaks (chapter 2) can rapidly alter recreation and infrastructure resources across large landscapes, with effects that can last for decades. During wildfires, fire and smoke can lead to dangerous conditions and health hazards that put recreationists at risk and limit access to recreation opportunities. Following wildfires, landslides and debris flows can damage roads and facilities and reduce recreational opportunities by damaging infrastructure or increasing sedimentation and debris that can obstruct roads and trails. To prepare for these events, managers can upsize culverts, upgrade stream crossing designs, stabilize slopes near high traffic routes, minimize human and infrastructure exposure in high-risk areas, and increase communication about alternative travel routes and recreation opportunities during and after disturbance events (tables 6.1 and 6.2) (chapter 4).

Other long-term effects following fire and insect outbreaks include reduced scenic values, decreased site capacity to support sustainable infrastructure and recreation, and large numbers of dead and dying trees. Hazard trees are a major concern in the assessment area, particularly in the southern Sierra Nevada where forest mortality has been particularly high since 2010. Hazard trees present risks to human safety that can last for decades. Removal of hazard trees to prevent damage to facilities and provide access to recreation sites increases maintenance and road clearing costs.

Hazard-tree management typically focuses on removal near high-use facilities, roads, and trails (tables 6.1 and 6.2). However, responding to a large number of hazard trees may not be timely and may have financial limitations. Recreation and infrastructure managers can consider working together to increase education and communication about the risks of hazard trees and to inform the public about traveling and recreating safely in disturbance-affected landscapes (tables 6.1 and 6.2). Given the size and severity of recent fires and insect outbreaks, managing public expectations about recreation opportunities and access following disturbances is an important communication issue (table 6.2).

Because of the complex nature of climate change effects on infrastructure and recreation and the limited time and resources available to managers, collaboration will be a necessity when increasing the scale and flexibility of management actions.

Coordinating efforts and resources with local communities, partners, and other agencies to better manage recreational resources and infrastructure was a key theme that emerged during the Sierra Nevada adaptation workshops. Because of the complex nature of climate change effects on infrastructure and recreation and the limited time and resources available to managers, collaboration will be a necessity when increasing the scale and flexibility of management actions. Coordination with adjacent landowners will be particularly critical when adapting infrastructure to climate change effects because many roads pass through multiple ownerships (table 6.1) (chapter 4). Changes in the amount and quality of recreational opportunities on national forest lands can also affect recreation on lands adjacent to national forests. Coordination with recreation managers from other agencies and local recreation groups will be important, because recreation opportunities span management boundaries, and users frequently travel across those boundaries (chapter 5). Based on the results of the Sierra Nevada adaptation workshops, leveraging partnerships to increase the scale of adaptation projects will be a critical first step when adapting recreation and infrastructure in the Sierra Nevada to climate change stressors.

Conclusions

Climate change adaptation is a four-step process:

- Synthesize and review climate change science in the context of local management and socioecological issues.
- Evaluate climate change exposure, sensitivities, and adaptive capacities for natural resources and ecosystems of interest.
- Identify and develop adaptation options that guide climate-smart resource management.
- Implement adaptation actions, monitor their effectiveness, and modify management approaches as needed.

The Sierra Nevada adaptation partnership for infrastructure and recreation produced climate change adaptation options that address climate change vulnerabilities across the 10 national forest units in the Sierra Nevada. Adaptation strategies developed from the collaborative science-management partnership focused primarily on increasing resilience of existing recreation and infrastructure resources, as well as leveraging partnerships to expand the scale of future adaptation actions. Integrating resilience-focused adaptation strategies into management, planning, and project design for infrastructure and recreation will have multiple benefits to forest ecosystems and communities that rely on natural resources and ecosystem services.

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Chapter 7: Conclusions

David L. Peterson[1]

The Sierra Nevada Infrastructure and Recreation Vulnerability Assessment and Adaptation Partnership (hereafter Sierra Nevada Partnership) contributed to our understanding of climate change vulnerabilities and responses to potential climate change effects in national forests in the Sierra Nevada (Modoc National Forest [NF], Lassen NF, Plumas NF, Tahoe NF, Lake Tahoe Basin Management Unit, Eldorado NF, Stanislaus NF, Sierra NF, Inyo NF, Sequoia NF). The effort synthesized the best available scientific information to assess climate change vulnerability for recreation and infrastructure, developed recommendations for adaptation options, and catalyzed a collaboration among land managers, scientists, and stakeholders seeking to address climate change issues. Furthermore, the vulnerability assessment and corresponding adaptation options provided information to support national forests in implementing agency climate change objectives described in the National Roadmap for Responding to Climate Change (USDA FS 2010a).

Relevance to Climate Change Strategies

The Sierra Nevada Partnership process is directly relevant to climate change strategy and accountability in the U.S. Department of Agriculture, Forest Service (USFS) (USDA FS 2010a, 2010b). Information presented in this report is also relevant for other land management entities and stakeholders in the Sierra Nevada Partnership assessment area. This process can be replicated and implemented by any organization, and the adaptation options are applicable beyond USFS lands. As in previous assessment and adaptation efforts (e.g., Halofsky and Peterson 2017; Halofsky et al. 2011, 2018a, 2018b, 2019, in press; Raymond et al. 2014), a science-management partnership was critical to success. Those interested in utilizing this approach are encouraged to pursue a partnership as the foundation for increasing climate change awareness, assessing vulnerability, and developing adaptation plans.

The Sierra Nevada Partnership fills a strategic gap for the USFS Pacific Southwest Region by focusing on recreation and infrastructure, which are critical ecosystem services provided by national forests, as well as major social and economic considerations in California. This assessment of recreation and infrastructure complements climate change assessments for other resources that are focused on Sierra Nevada national forests (Kershner 2014) or encompass national forests within the broader scope of the Sierra Nevada (Dettinger et al. 2018).

The Sierra Nevada Partnership includes strategic priorities and activities that help fulfill the Pacific Southwest Region vision for leadership in restoration

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(USDA FS 2015). The partnership also connects with other assessments and strategies in California that provide a broader context for documenting and responding to the effects of climate change. This broader context includes the "Natural and Working Lands Climate Change Plan" (State of California 2019), the "California forest carbon plan" (Forest Climate Action Team 2018), and "California's forest and rangeland assessment" (Brown et al. 2018). The USFS provides leadership in multiple collaborations of agencies and other institutions focused on natural and human resources in the Sierra Nevada.

Relationships developed through the Sierra Nevada Partnership process were as important as the products that were developed, because these relationships build the partnerships that are the cornerstone for successful agency responses to climate change. The partnership among USFS resource management, USFS research, other agencies, various stakeholders, and the University of Washington will remain relevant for future forest planning and management efforts. By working with stakeholders, the capability to respond effectively to climate change increases, especially in the context of shared stewardship of resources beyond National Forest System lands.

Climate change response is a relatively new and evolving aspect of land management, and the Sierra Nevada Partnership provided an opportunity for participants to effectively communicate their professional experiences with respect to climate change and resource management in a collaborative and supportive environment. The workshops were especially valuable because they covered a broad range of topics, and multidisciplinary group discussions resulted in conceptual breakthroughs across disciplines and land management boundaries.

Communication, Education, and Organizational Capacity

Organizational capacity to address climate change requires building institutional capacity in management units through information exchange and communication. Information sharing and education were built into the Sierra Nevada Partnership process through webinars, face-to-face meetings of the assessment team (resource managers and scientists), and a series of workshops convened at three locations at Sierra Nevada national forests. At the workshops, scientists presented results of the vulnerability assessment, focused on climate change projections and on the effects of climate change on hydrology, recreation, and infrastructure. Resource managers and stakeholders then developed adaptation options in response to climate sensitivities identified in the assessment, including options relevant at the subregional scale and national forest scale. This hands-on approach allowed resource managers to both participate in the process and contribute directly to information and outcomes, thus increasing organizational capacity to address climate change.

Assessing Vulnerability and Adaptation

A science-based climate change vulnerability assessment requires units to identify the most vulnerable resources, assess the expected effects of climate change on vulnerable resources, and identify management strategies to improve the adaptive capacity of national forest lands. The Sierra Nevada Partnership vulnerability assessment described the climate change sensitivity of recreation and infrastructure in national forests located in the Sierra Nevada. Adaptation options developed for each resource area can be incorporated into resource-specific management plans.

Dialogue among groups of resource managers and scientists identified management practices that are useful for increasing resilience and reducing stressors to on-the-ground and organizational components of recreation and infrastructure. Although implementing all adaptation options developed in the Sierra Nevada Partnership process may not be feasible, resource managers can draw from the menu of options (chapter 6) as needed. Some adaptation options can be implemented now, whereas others may require revised management plans or policies, or may become more appropriate as climate change effects become more apparent.

Science and Monitoring

Current monitoring programs that provide information for detecting climate change effects were identified for some components of the vulnerability assessment. Information gaps and uncertainties important to understanding climate change vulnerabilities and management influences on vulnerabilities were also identified. These information gaps can help determine where monitoring and research would reduce uncertainties inherent in management decisions. Working across multiple jurisdictions and boundaries will allow Sierra Nevada Partnership participants to potentially increase collaborative monitoring on climate change effects and effectiveness of adaptation actions. Scientific documentation in the assessment can also be incorporated into large landscape assessments such as national forest land management plans, environmental analysis for National Environmental Policy Act (NEPA) projects, and specific project design criteria and mitigations.

Implementation

Although challenging, implementation of adaptation options will gradually occur with time, often motivated by extreme weather and large disturbance events, and facilitated by changes in policies, programs, and land management plan revisions. It will be especially important for ongoing restoration programs to incorporate considerations for climate change adaptation to ensure effectiveness. A focus on thoroughly vetted strategies may increase ecosystem and organizational function and resilience while minimizing implementation risk. Land management agencies, American Indian tribes, and private landowners working together will make implementation effective, particularly across boundaries.

Implementation of climate-informed management practices is often motivated by the occurrence of extreme weather events. For example, the storms of 2016–17 in the Sierra Nevada and beyond caused widespread damage to roads and other infrastructure (USDA FS 2017). Extensive drought-related tree mortality in the Sierra Nevada and severe wildfires throughout California over the past decade have captured the attention of federal land managers and the general public. Fortunately, the USFS has access to both internal sources of science-based options that address weather- and climate-related phenomena (e.g., USDA FS 2018) (chapter 3) and external programs focused on adaptation in California (e.g., Cal-Adapt).

Integration Across Resources

This report discusses climate sensitivities in separate chapters for recreation and infrastructure. In practice, overlap exists between these resource areas in terms of biophysical function, socioeconomic implications, and management responses (chapter 6). For example, water, infrastructure, and recreation are all sensitive to winter soil saturation that can lead to erosion and landslides. Higher temperatures, lower snowpack, earlier snowmelt, lower summer streamflow, and increased disturbances are prominent stressors. The compound influence of multiple stressors leading to larger and more frequent disturbances affects recreation, infrastructure, and many other resource areas. Identifying common concerns across resource areas may provide opportunities to coordinate adaptation efforts, thus improving effectiveness and efficiency.

Adaptation options are generally designed to protect individual resources, and reorganizing adaptation strategies and tactics by sensitivity may provide insight on opportunities for coordination. In some cases, adaptation options were identified that are relevant for both recreation and infrastructure, suggesting a need to coordinate and integrate adaptation planning. It is also important to consider adaptation options that are relevant for other resource issues included in previous climate change assessments for the Sierra Nevada (e.g., vegetation, water resources) (Dettinger et al. 2018, Kershner 2014). Adaptation options that yield benefits to more than one resource are likely to have the greatest overall benefit (Halofsky and Peterson 2017; Halofsky et al. 2011, 2018a, 2018b, 2019, in press; Peterson et al. 2011; Raymond et al. 2014). Some adaptation options involve tradeoffs and uncertainties that need further exploration. Assembling an interdisciplinary team to tackle this issue will be critical for assessing risks and developing risk management options.

Information in this assessment can be incorporated into everyday work through climate-informed thinking, assist in planning, and influence management priorities such as public safety. Flooding, wildfires, and insect outbreaks may all be exacerbated by climate change, affecting both recreation and infrastructure, and increasing the frequency and extent of hazards faced by federal employees and the public. Resource management can help minimize these hazards by restoring hydrologic function and reducing fuels. These management activities are commonplace, demonstrating that in many cases, current resource management is already preparing for a warmer climate.

Operations

Implementation of adaptation actions may be limited by insufficient human resources, insufficient funding, and conflicting priorities. However, climate-influenced effects are already apparent for some resource areas, such as altered hydrologic regimes and increased area burned by wildfires. Some adaptation options may be precluded and resources may be compromised if actions are not implemented soon. This creates an imperative for timely inclusion of climate change considerations in resource management and agency operations.

The climate change vulnerability assessment and adaptation approach developed by the Sierra Nevada Partnership can be used by the USFS and other organizations in many ways. From the perspective of federal land management, this information can contribute to the following aspects of agency operations:

- **Landscape and resource assessments:** The vulnerability assessment can be used to inform the assessment phase of planning, providing information on departure from desired conditions and best available science on climate change effects on resources. In addition, adaptation options describe desired conditions and management objectives for inclusion in planning documents.
- **Resource management strategies:** The vulnerability assessment and adaptation options can be used in forest resilience and restoration plans, conservation strategies, fire management plans, infrastructure planning, and State Wildlife Action Plans.
- **Project NEPA analysis:** The vulnerability assessment provides best available science for documentation of resource conditions, climate change effects analysis, and development of alternatives. Adaptation options provide project design recommendations for specific locations.
- **Monitoring plans:** The vulnerability assessment identifies knowledge gaps that can be addressed by monitoring.

- **National forest land management plan revision process:** The vulnerability assessment provides a foundation for understanding key resource vulnerabilities caused by climate change for the assessment phase of forest plan revision. Information from vulnerability assessments can be applied in assessments required under the USFS 2012 Planning Rule, describe potential climatic conditions and effects on key resources, and identify and prioritize resource vulnerabilities to climate change in the future. Climate change vulnerabilities and adaptation strategies can inform forest plan components such as desired conditions, objectives, standards, and guidelines.
- **Project design/implementation:** The vulnerability assessment and adaptation options provide recommendations for mitigation and project design at specific locations. A Story Map tool (https://arcg.is/q8GGf0), typically integrated with geospatial information, can further aid land managers in applying the vulnerability assessment and adaptation options at a local scale.

We are optimistic that climate change awareness, climate-informed management and planning, and implementation of climate change adaptation options in the Sierra Nevada Partnership assessment area will continue to evolve. We anticipate that within a few years:

- Climate change will become an integral component of federal agency operations.
- The effects of climate change on natural and human systems will be continually assessed.
- Monitoring activities will include indicators to detect the effects of climate change on recreation and infrastructure.
- Agency planning processes will provide more opportunities to manage across boundaries.
- Organizational capacity to manage for climate change will increase within federal agencies and with local stakeholders.
- Resource managers will implement climate-informed practices in long-term planning and management.

This assessment provides a foundation for understanding potential climate change effects and implementing adaptation options that help reduce the negative impacts of climate change and transition resources and management organizations to a warmer climate. We hope that by building on existing partnerships, the assessment will foster collaboration in climate change adaptation and resource management planning in the Sierra Nevada and beyond.

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Metric Equivalents

When you know:	Multiply by:	To find:
Inches	2.54	Centimeters
Feet (ft)	.305	Meters
Miles (mi)	1.609	Kilometers
Acres (ac)	.405	Hectares
Degrees Fahrenheit	.56 (ºF – 32)	Degrees Celsius

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