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

[1] **Gordon R. Keller** is a geotechnical engineer currently with Genesee Geotechnical, 5506 Genesee Road, Taylorsville, CA 95983; **Leslie J. Boak** is a regional transportation engineer, Pacific Southwest Region, 1323 Club Drive, Vallejo, CA 94592; **Micahel J. Furniss** is a hydrologist (retired), Pacific Northwest Research Station, Redwood Sciences Laboratory, 1700 Bayview Street, Arcata, CA 95521.

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

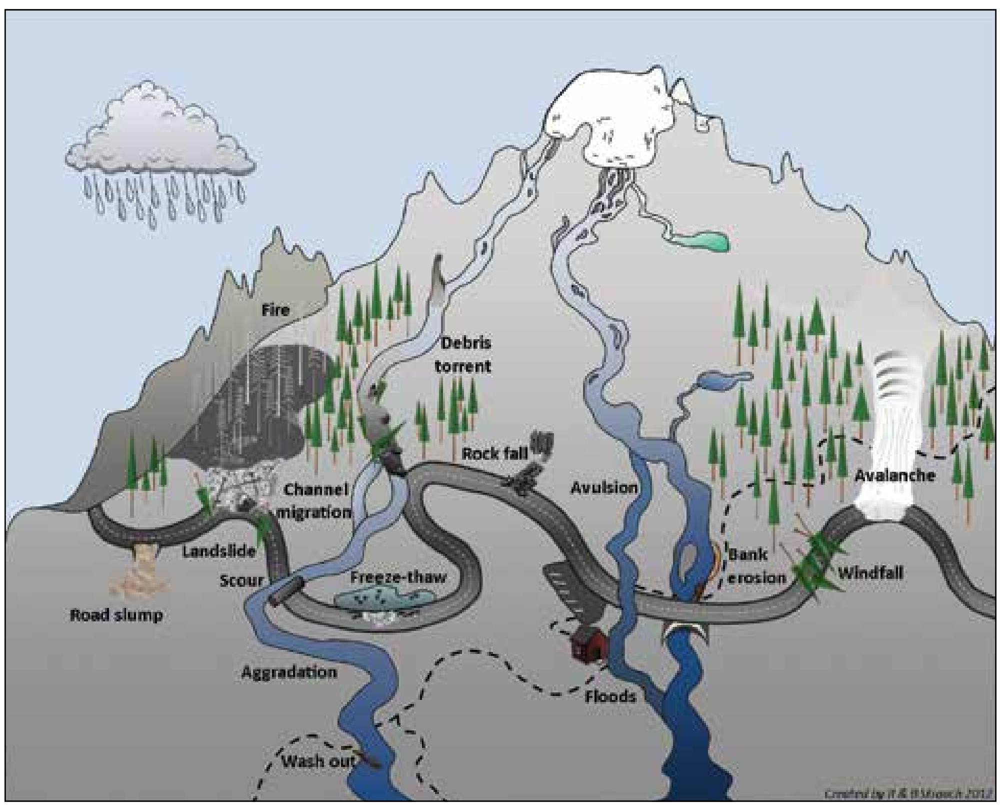


Figure 4.1—Many pathways exist for the effects of climate stressors, climate change, and other disturbances on roads and other infrastructure. Multiple pathways are common. (Figure from Strauch et al. 2014)

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,

Gordon Keller

Gordon Keller

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.

Gordon Keller
Gordon Keller
Gordon Keller
Gordon Keller

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

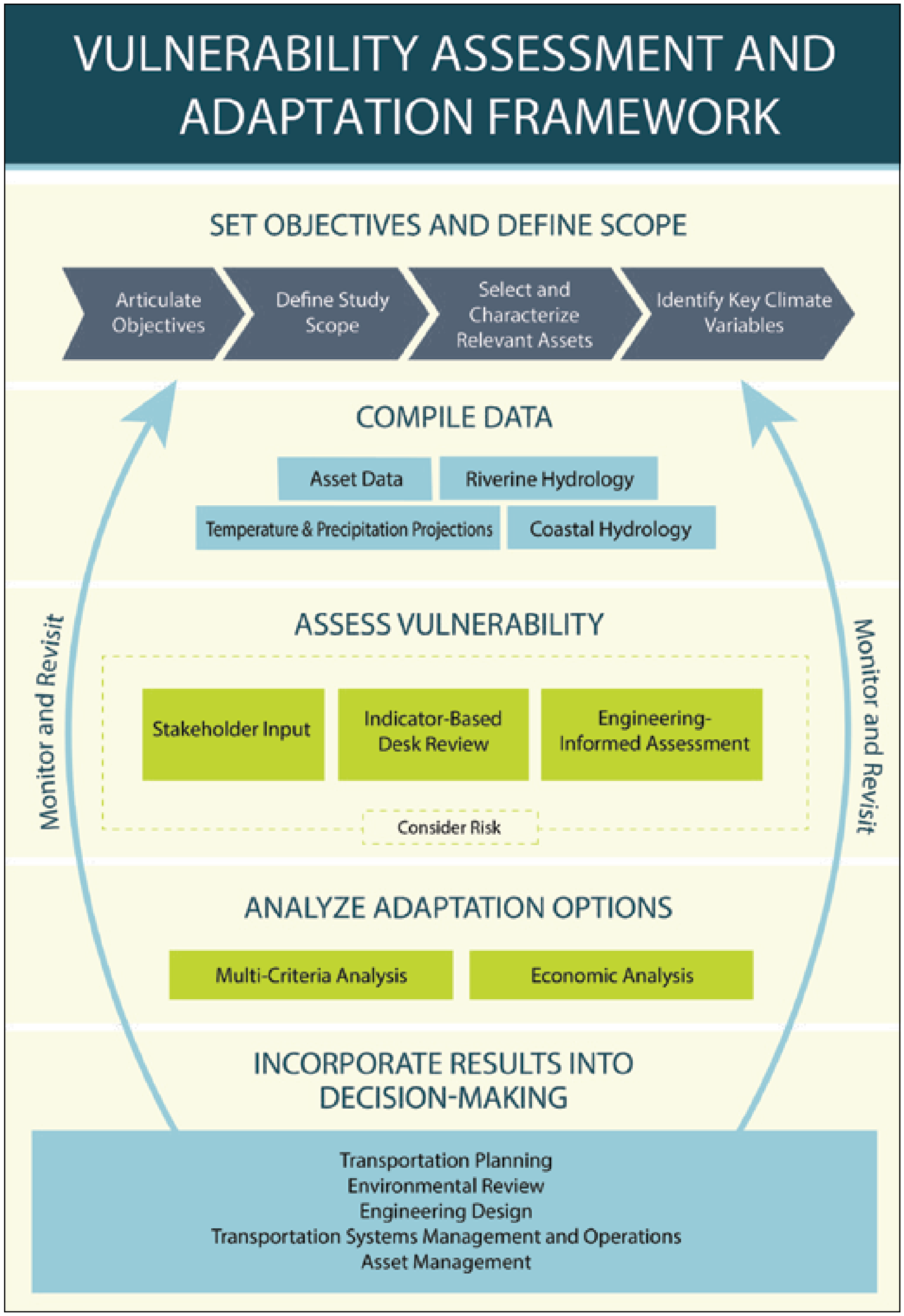


Figure 4.4—A framework for assessing the effects of climate change and extreme weather on infrastructure can be used for both high-level planning and on-the-ground project implementation. This structured approach ensures thoroughness and consistency in designing and maintaining infrastructure in a changing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

Likelihood of damage or loss[b]	Magnitude of consequences[c]		
	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.

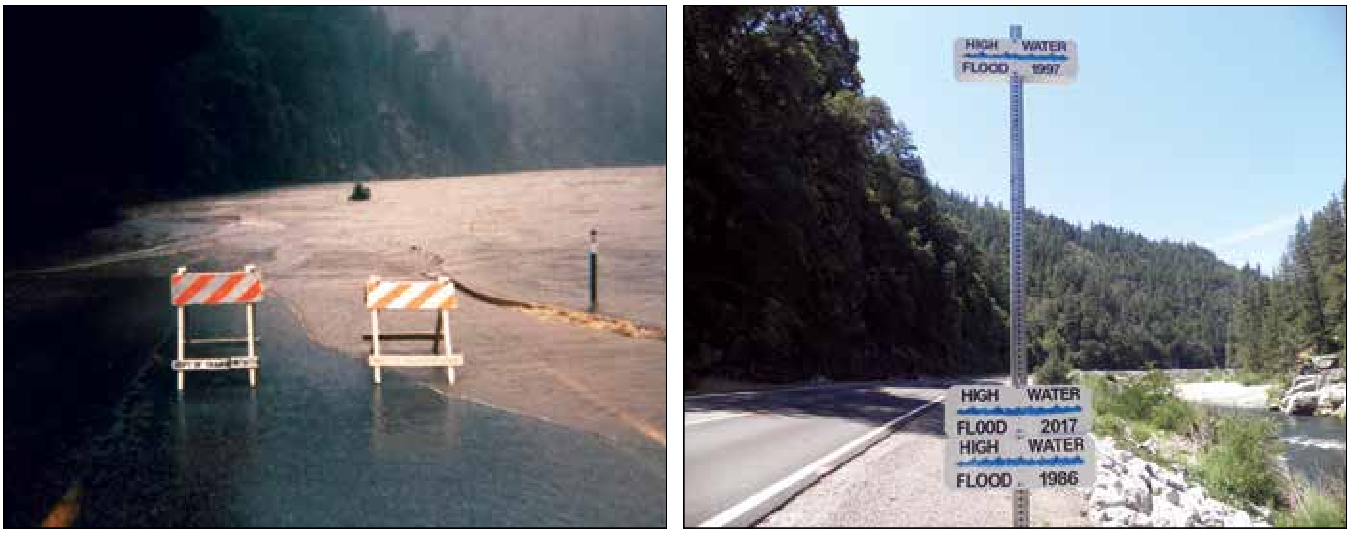
Examples of the climatic variability impacts facing the Sierra Nevada were observed in northern California in 2017 and 2018. In 2017, record flooding created a crisis at the Oroville Dam where the primary spillway was extensively damaged (repair costs exceeded $1.1 billion), and possible use of the untested 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.

Gordon Keller



Gordon Keller

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.

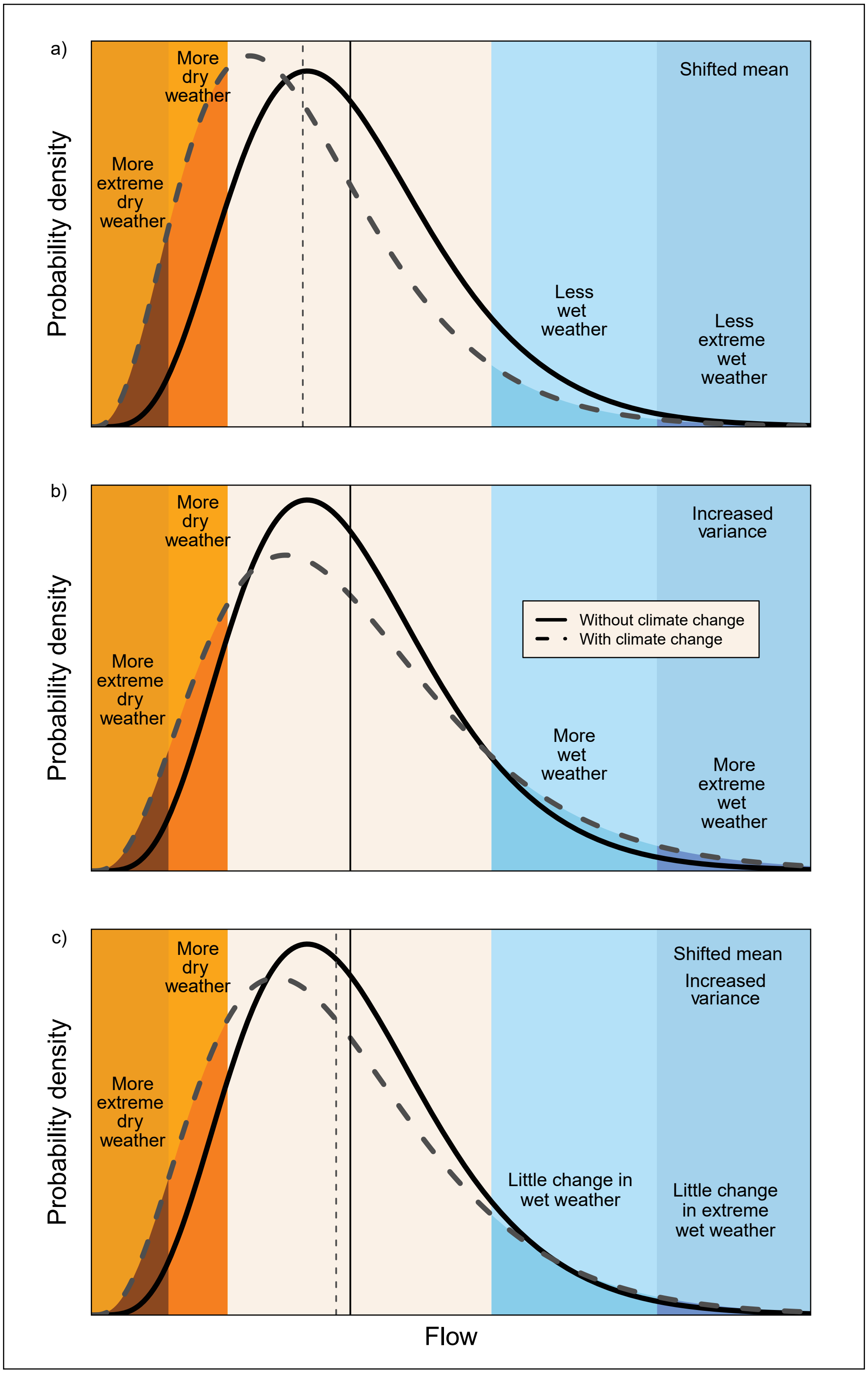


Figure 4.7—Conceptual diagram of how hydrologic flow can be affected by both a change in the mean and change in the variance of climate and weather. Climate change is expected to increase the frequency and magnitude of peak flows and flooding in winter, and to shift peak flows earlier in the season.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

Gordon Keller

Gordon Keller

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

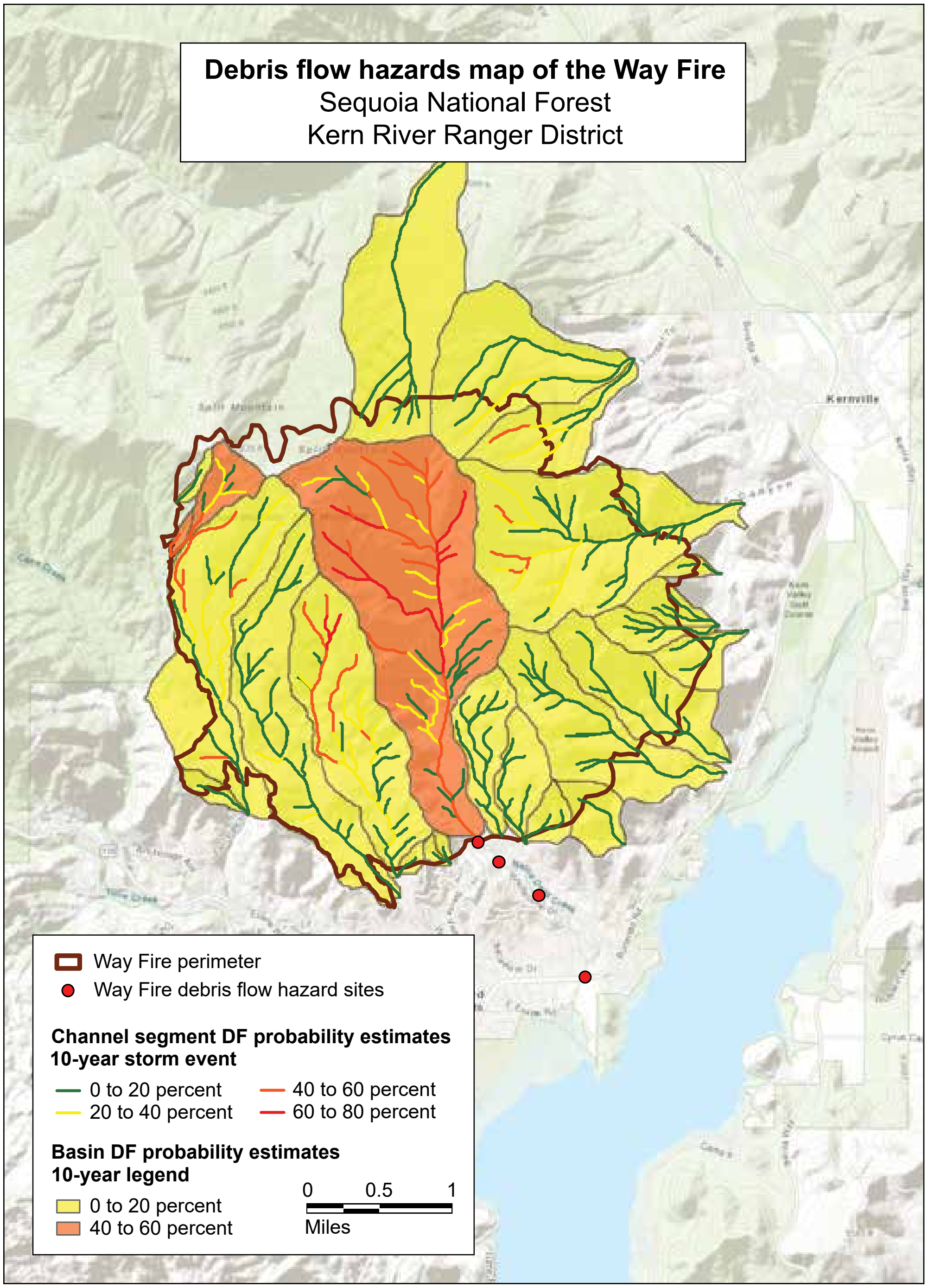


Figure 4.9—Example of a U.S. Geological Survey and U.S. Forest Service debris flow (DF) hazard map with channel and basin slide probabilities for the Way Fire, Sequoia National Forest, 2014.

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

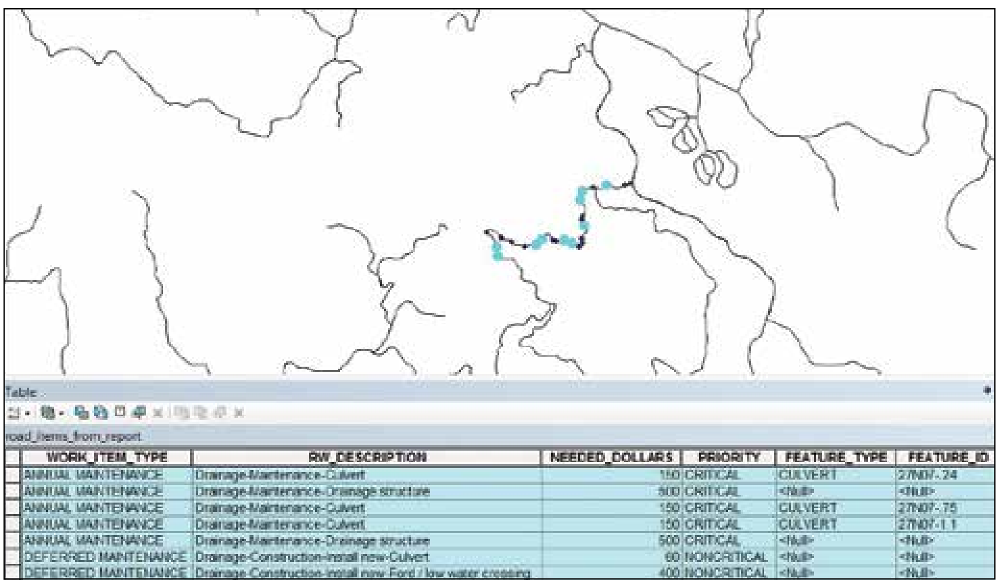
Routine maintenance is important for roads to function properly any time of year, and particularly when large storms occur. This protects the investment and adjacent resources. Figure 4.11 shows roads badly in need of road maintenance and roads that are vulnerable to additional damage from a storm. When 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).

Gordon Keller

Gordon Keller

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

Roger Nichols

Gordon Keller

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 undersized 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.

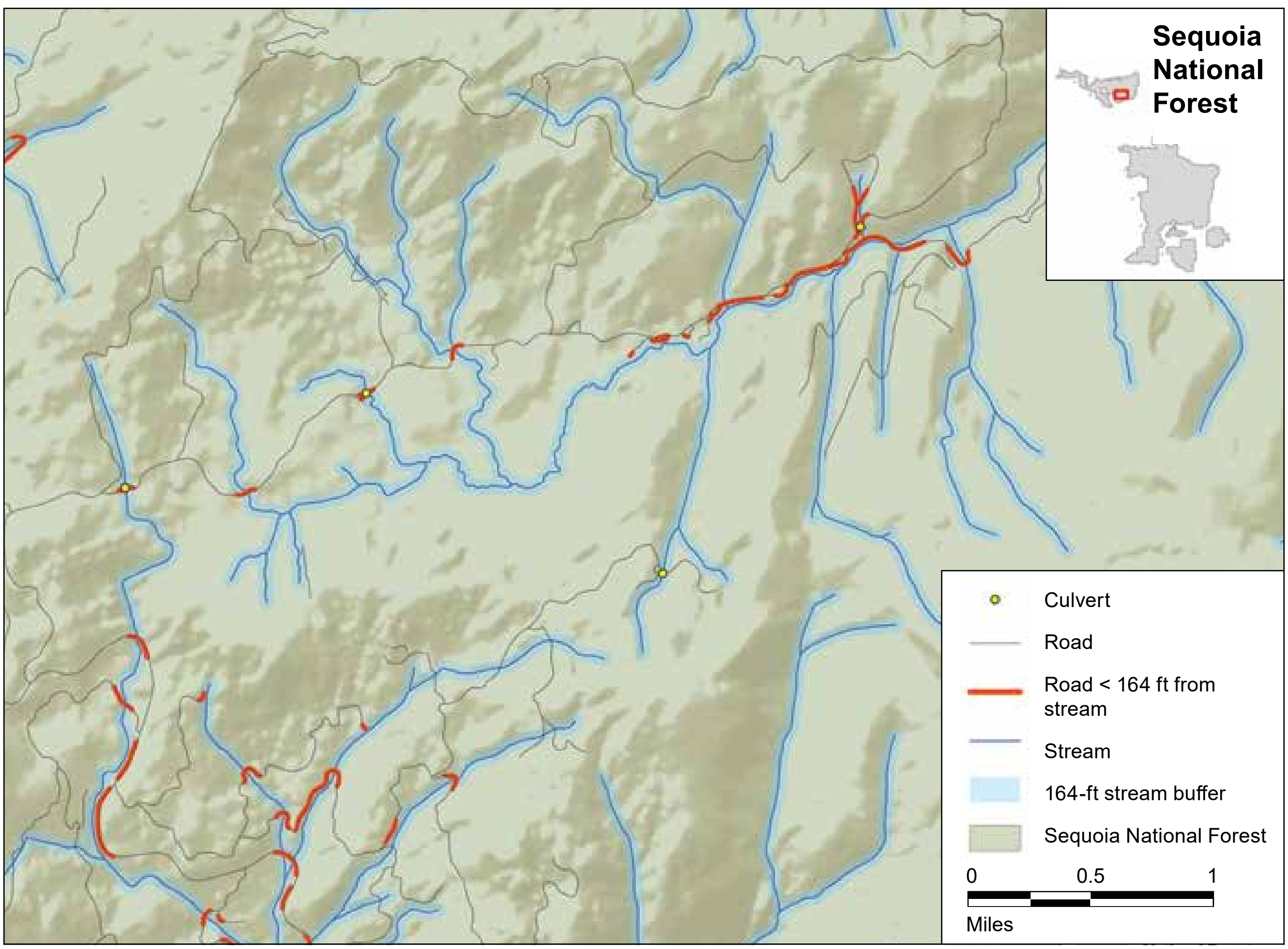


Figure 4.15—Map created using INFRA database showing locations where existing main roads are within 164 ft (50 m) of a stream and may be vulnerable to increased streamflows, road-stream crossing failure, stream diversion, and channel migration.

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.

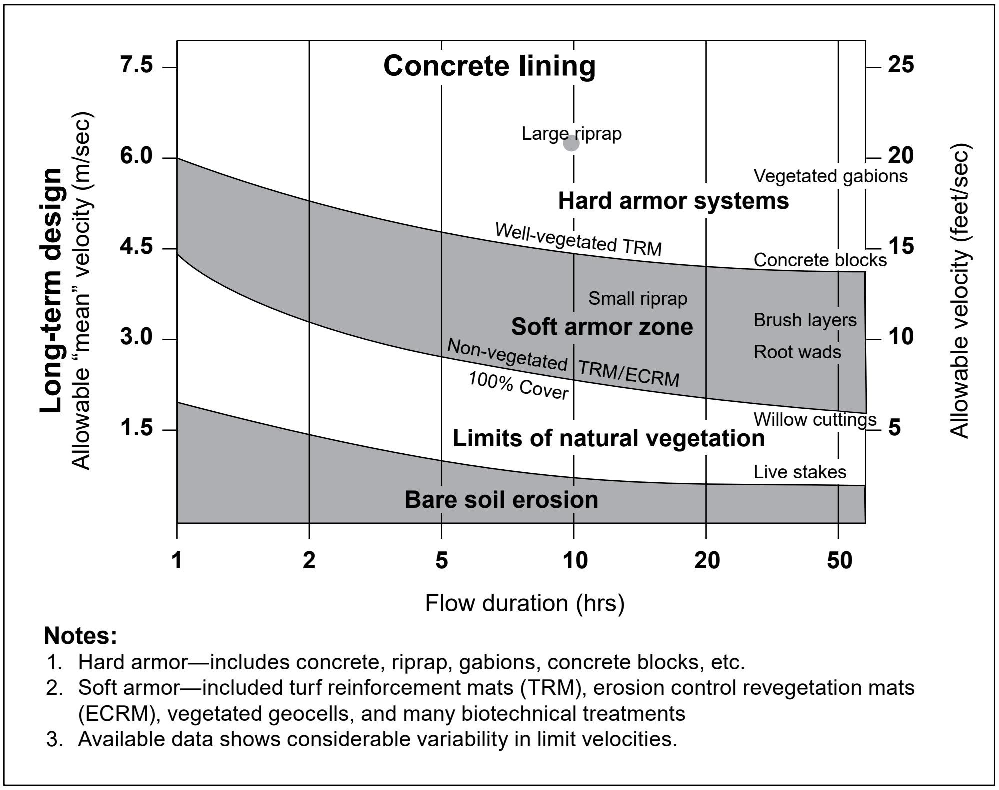


Figure 4.16—Allowable velocities and flow duration for various erosion and bank protection measures. (Figure adapted from Fischenich [2001], with information from Theisen [1992] and McCullah and Gray [2005])

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.

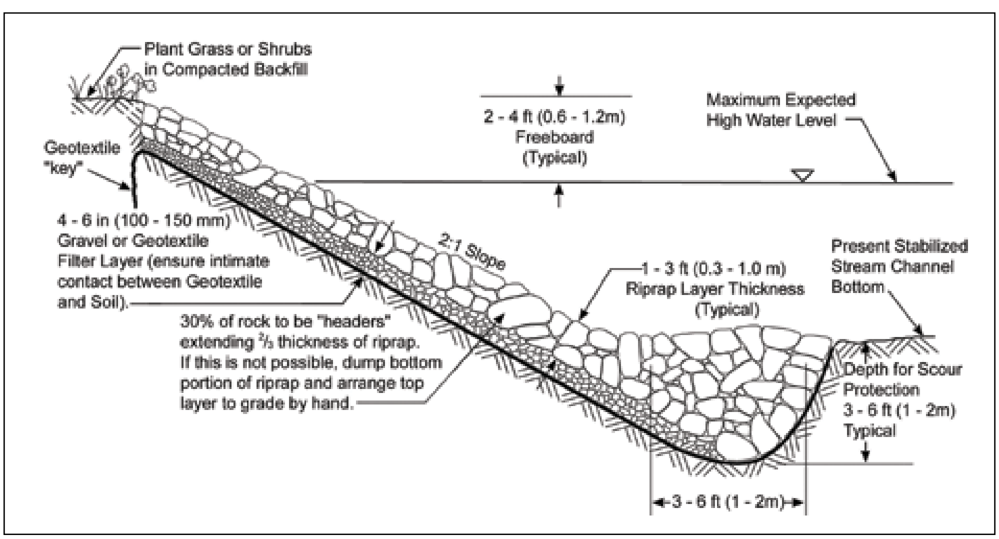


Figure 4.17—Typical riprap installation details for streambank protection. (Figure from Keller et al. [2011])

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.

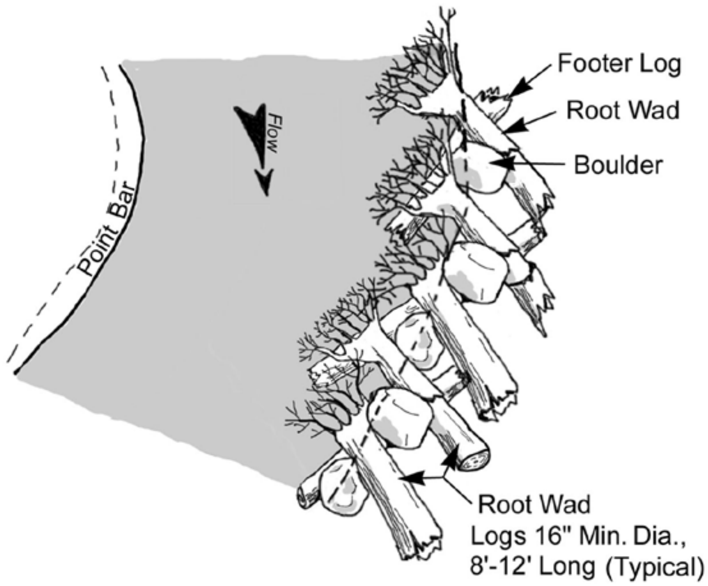
Examples of ways to increase local resistance to erosion include:

- 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

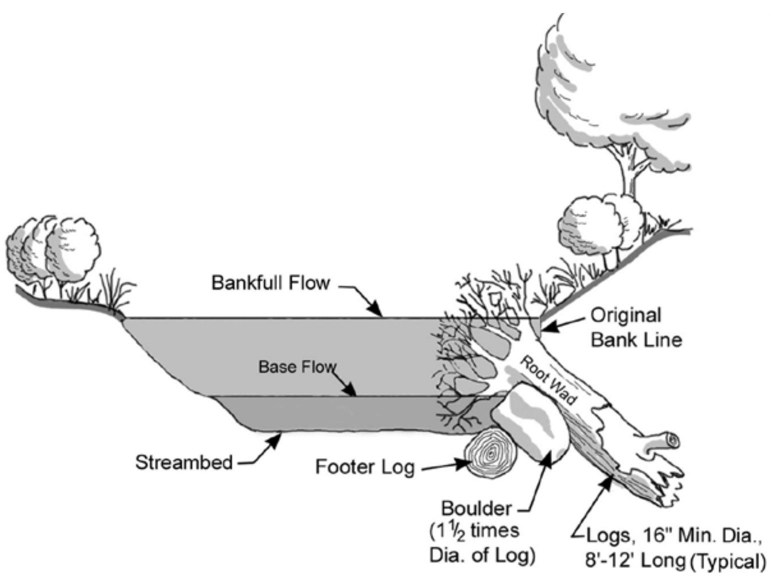
The force of water can be reduced by river training structures such as spur dikes, groins, vanes, J-hooks, jetties, barbs, weirs, drop structures, in-channel logs (large woody debris) and boulders, increasing channel sinuosity, and vegetated floodways. A combination of methods is often used. Treatments 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.

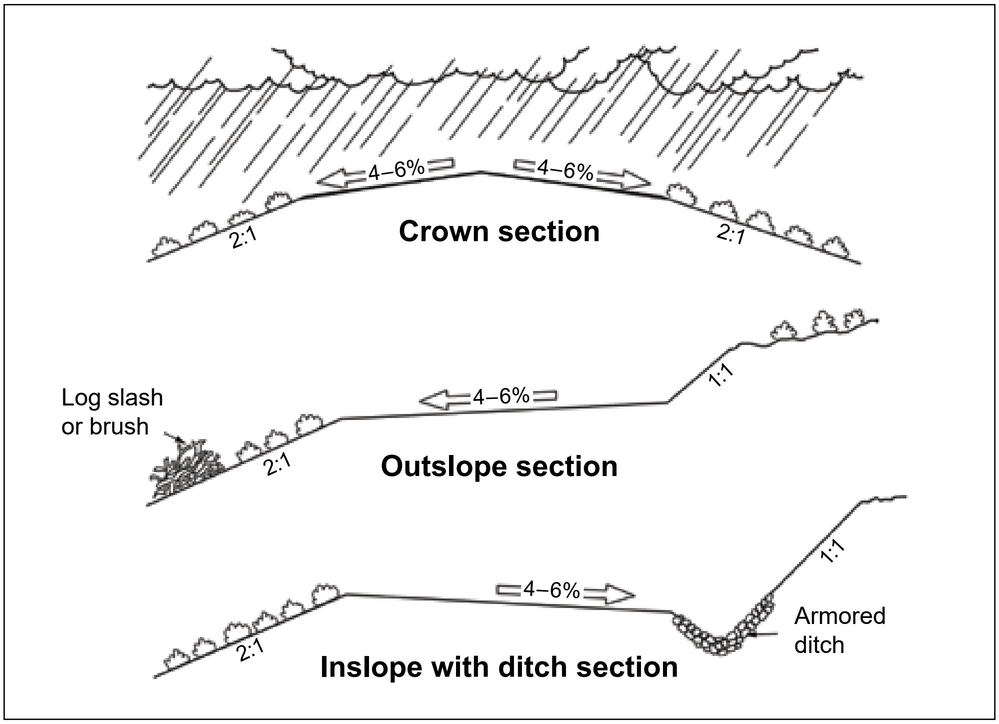


Figure 4.21—Basic road surface drainage options based on the shape of the road surface in cross-section: crown, outslope, and inslope sections. (Figure from Keller and Sherar [2003])

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.

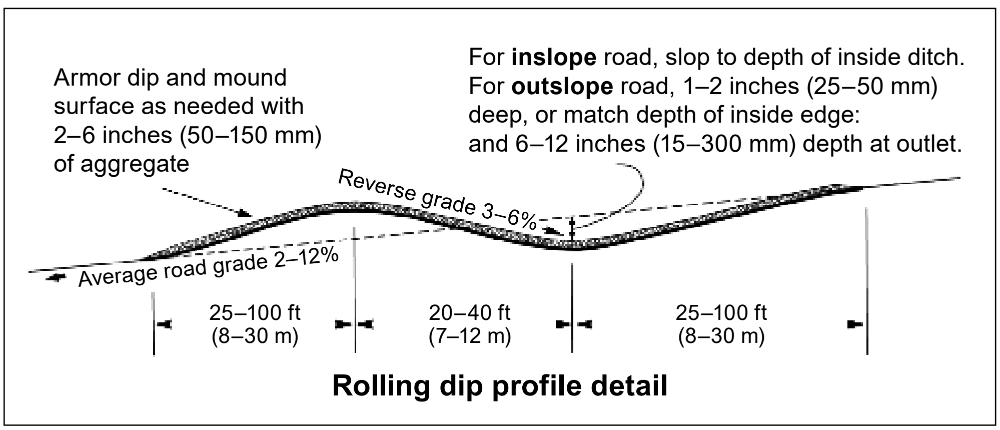


Figure 4.22—The form of a rolling dip, with a mound and reverse grade to prevent water from going past the dip. (Figure from Keller and Ketcheson [2015])

Gordon Keller

Gordon Keller

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.

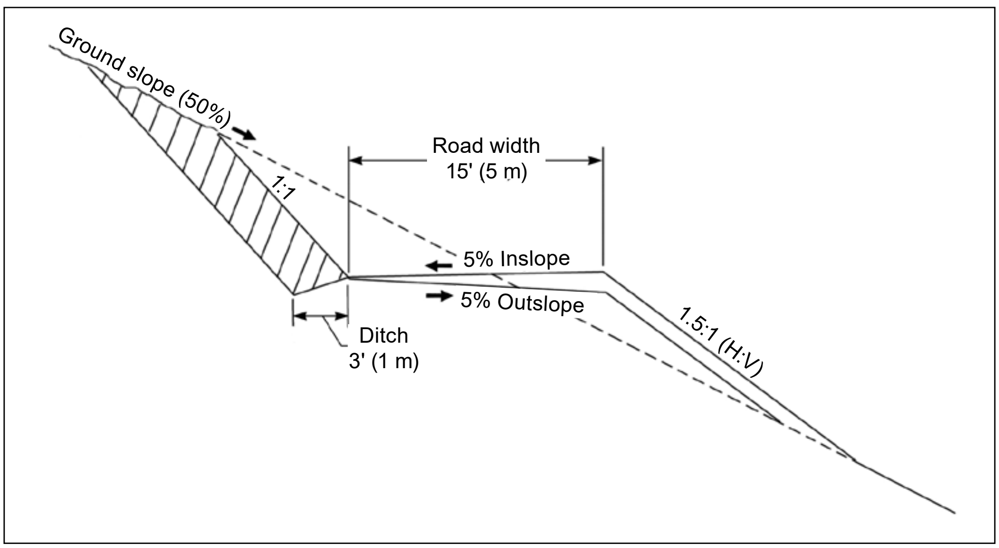


Figure 4.24—Road template of an inslope versus outslope road. The outslope requires less earthwork, less overall road width and loss of productive land, and best prevents water concentration. Backup cross-drains are usually needed in case the outslope road develops ruts. (Figure from Keller and Ketcheson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

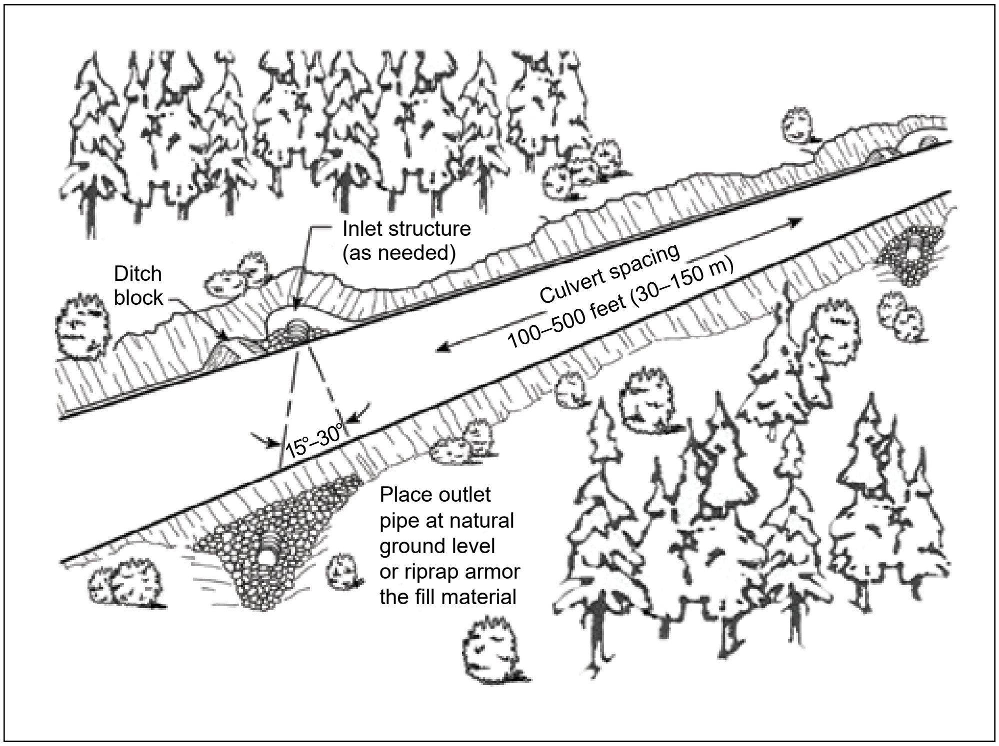


Figure 4.25—A typical culvert cross-drain installation. (Figure from Keller et al. [2011])

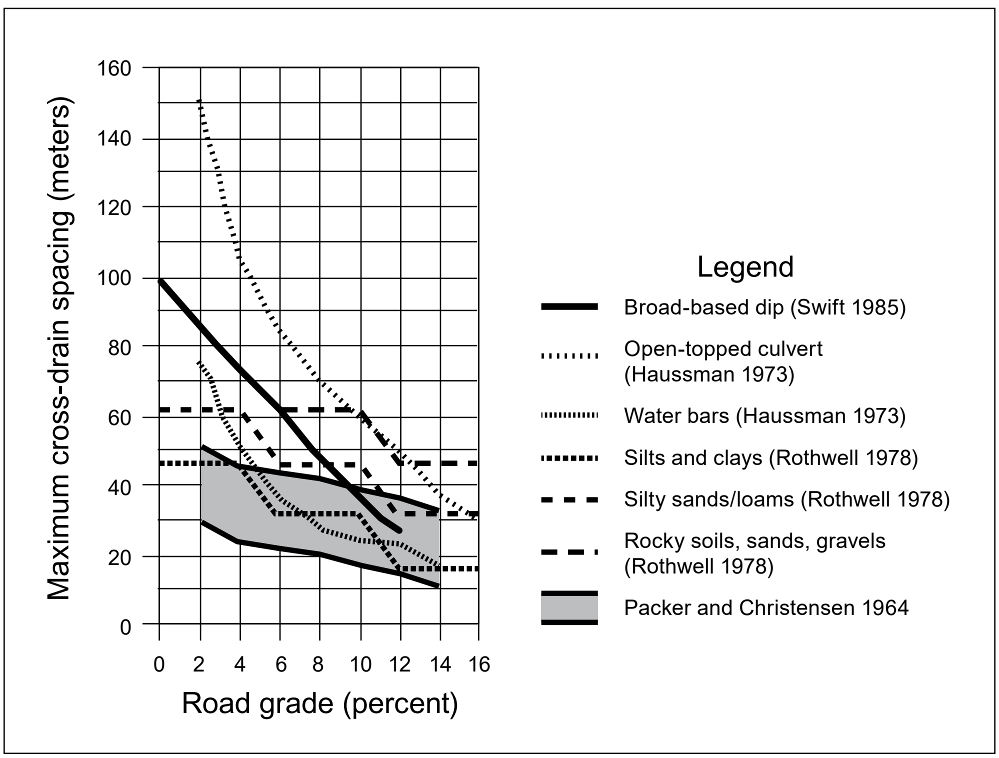


Figure 4.26—Range of recommended cross-drain spacing, as a function of road grade. Note: Conversion 1 m = 3.28 ft. (Figure from Copstead et al. [1998])

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

Gordon Keller

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

Gordon Keller

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.

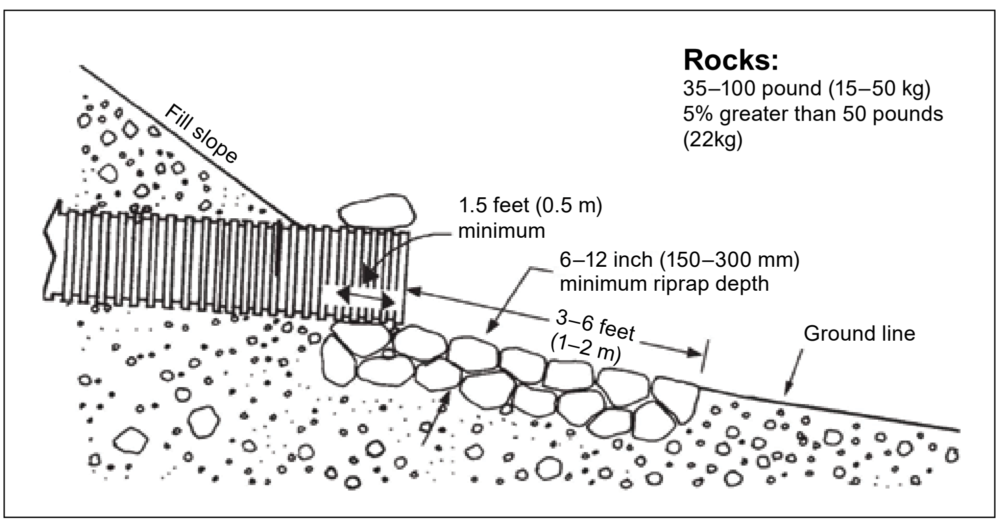


Figure 4.29—Detail of culvert-pipe outlet protection using small rock for riprap. (Figure from Keller and Sherar [2003])

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).

San Dimas Technology Development Center

Gordon Keller

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.

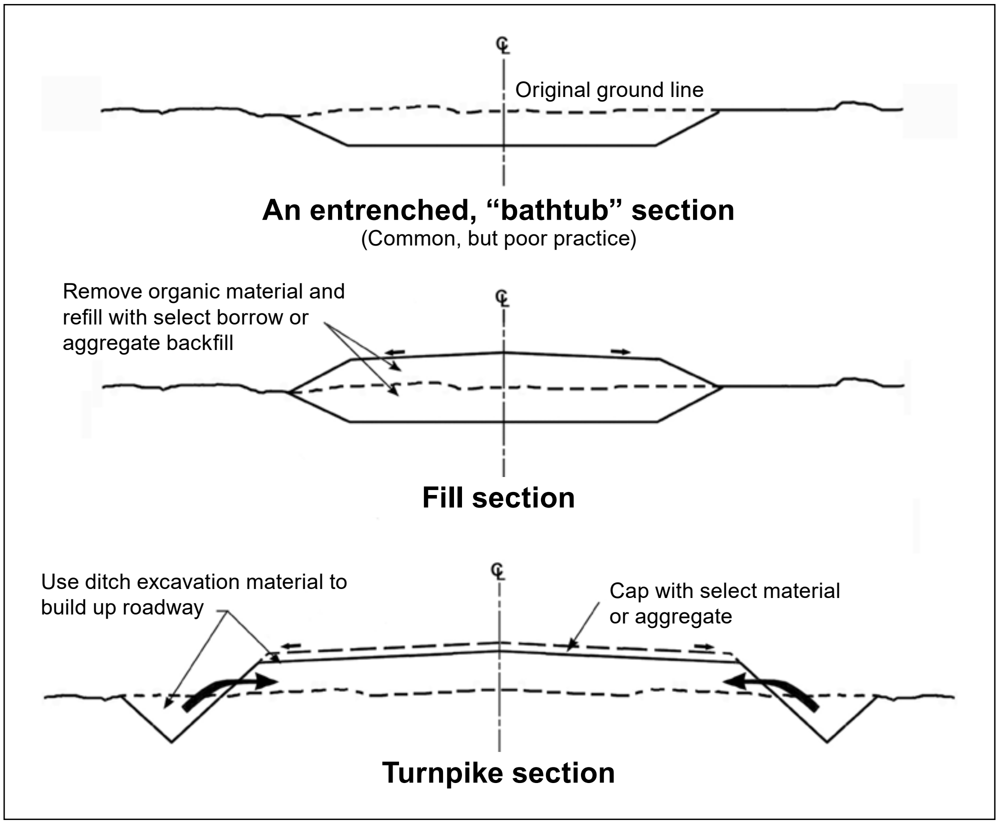


Figure 4.31—Road options in wet, flat terrain to elevate and drain the roadway surface. (Figure from Keller et al. [2011])

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.

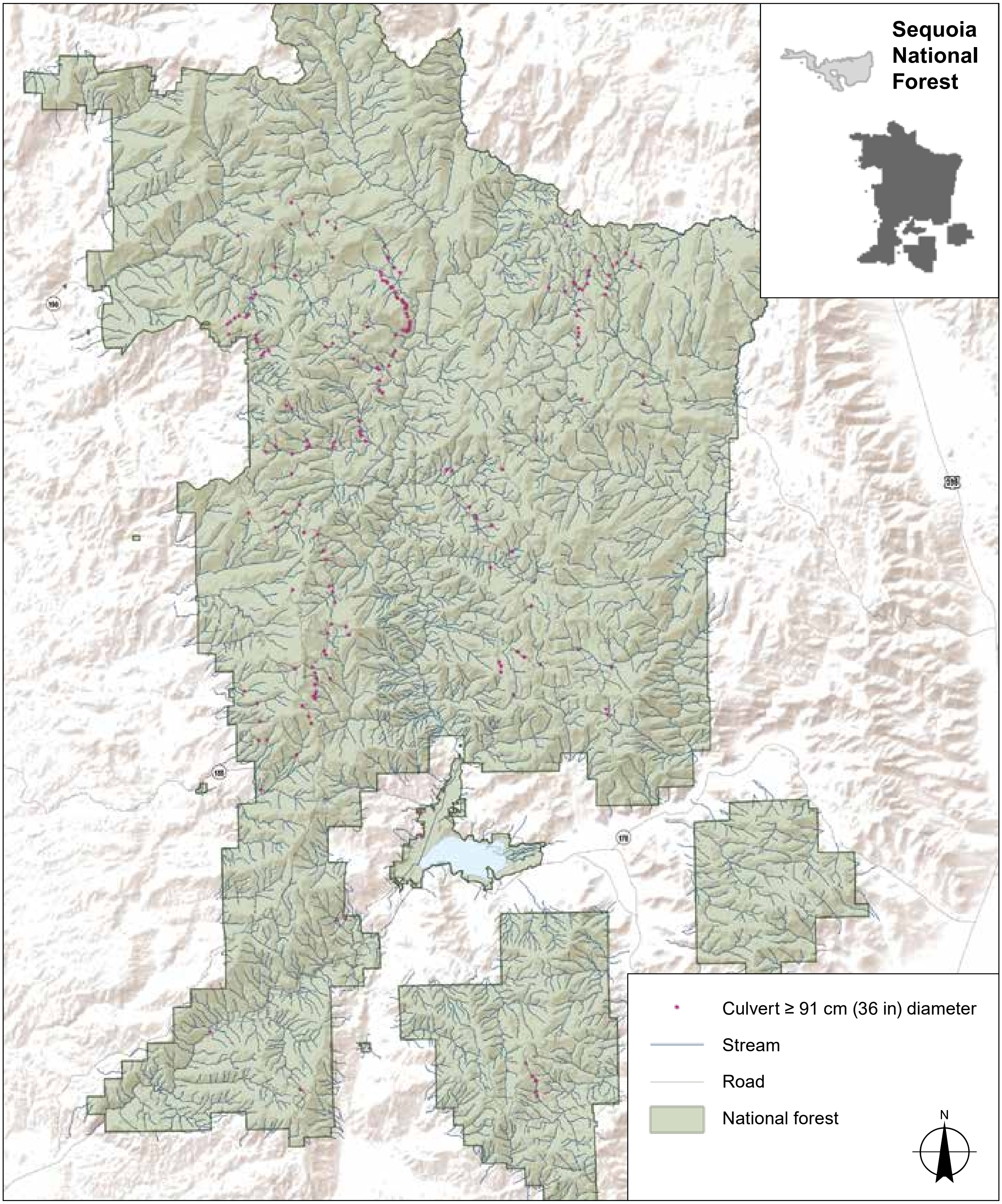


Figure 4.32—Example of forest INFRA data showing 36-inch or larger culverts on the road system, Sequoia National Forest.

Gordon Keller

Gordon Keller

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.

Gordon Keller

Gordon Keller

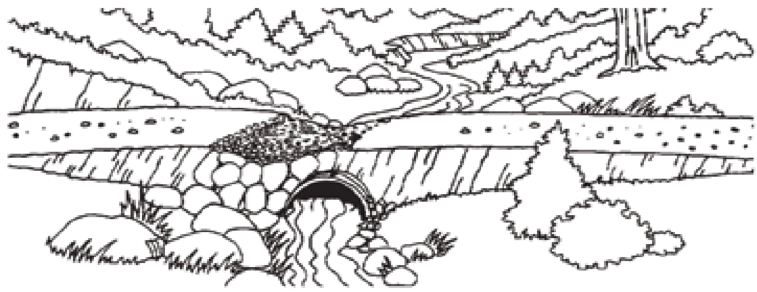
Figure 4.34—Culverts needing maintenance and with a high risk of plugging and failure because of logs across the inlet (left) and damage to the inlet (right).

- 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).

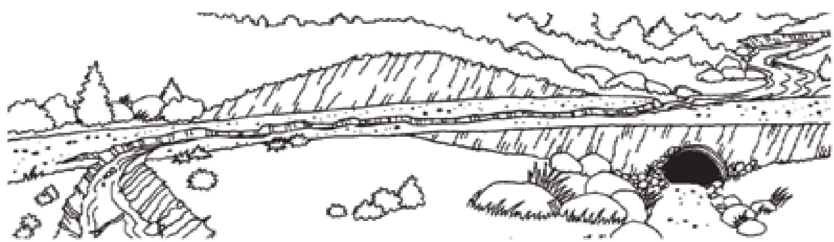
If the low point is over the pipe, or an armored dip is constructed in the roadway near the structure, water will flow across the road and return quickly to the channel (fig. 4.35a). Armoring of the dip or low point prevents erosion, downcutting, and additional damage to the road and fill. Also, in fire 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

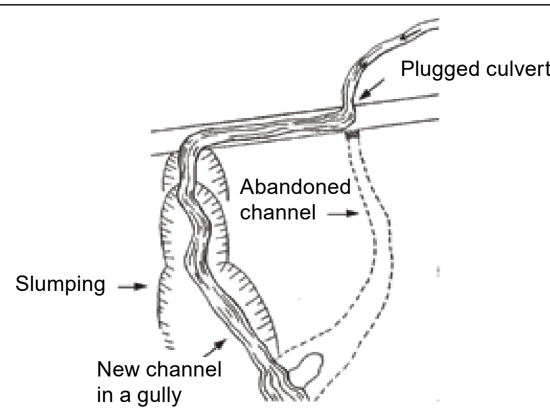


a. Armored dip over a low fill to prevent stream diversion

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).

[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

[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.

Gordon Keller

Gordon Keller

Gordon Keller

Gordon Keller

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).

Gordon Keller

Gordon Keller

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).

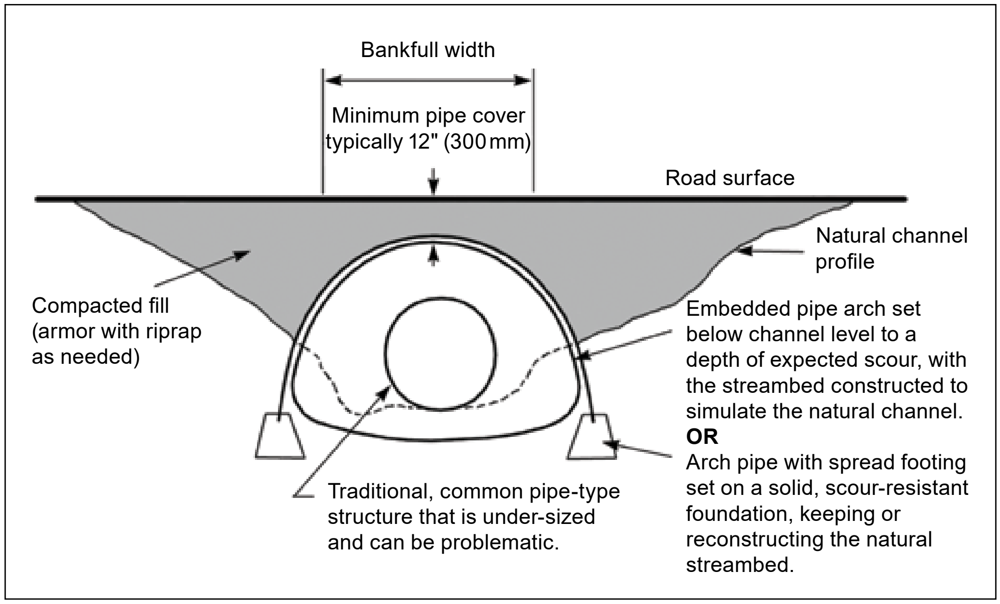
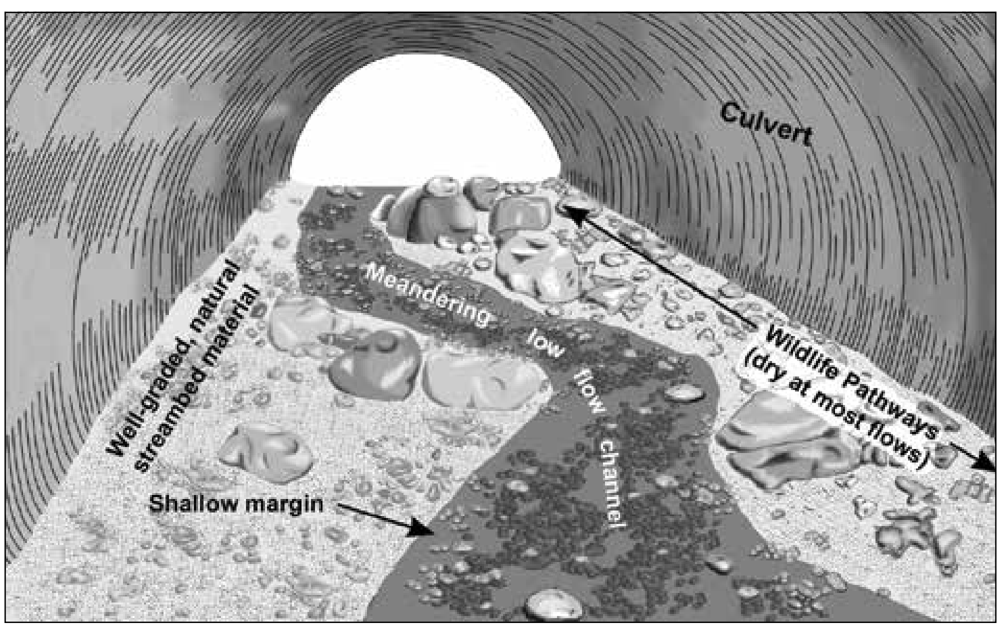


Figure 4.40—An improved or stream-simulation culvert installation compared to traditional culvert installations. (Figure from Keller and Ketcheson [2015])

Gordon Keller

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.

Gordon Keller

Gordon Keller

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).

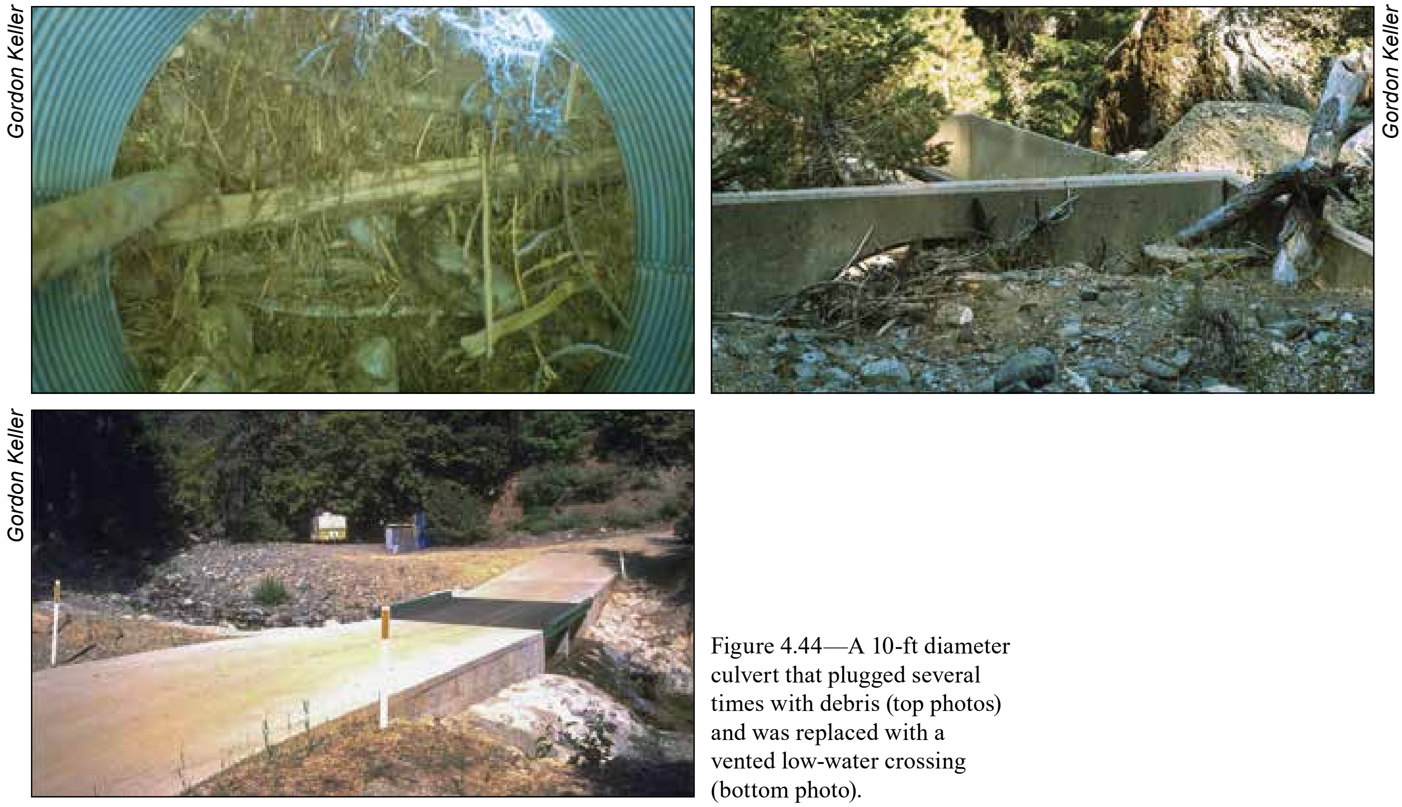


Figure 4.44—A 10-ft diameter culvert that plugged several times with debris (top photos) and was replaced with a vented low-water crossing (bottom photo).

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.

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.

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.

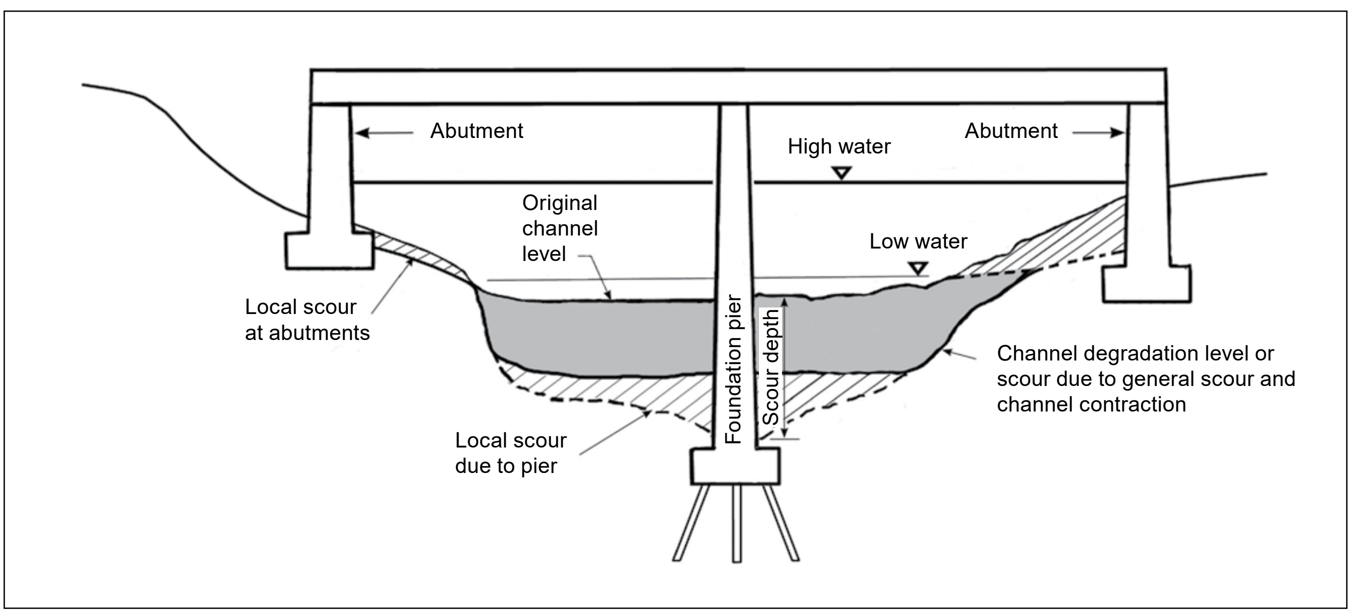


Figure 4.49—Scour types and common scour problem areas around a bridge. (Adapted and reproduced with the written authority of the Transportation Association of Canada, from Neill [1973])

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).

Gordon Keller

Gordon Keller

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.

Gordon Keller

Gordon Keller

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.

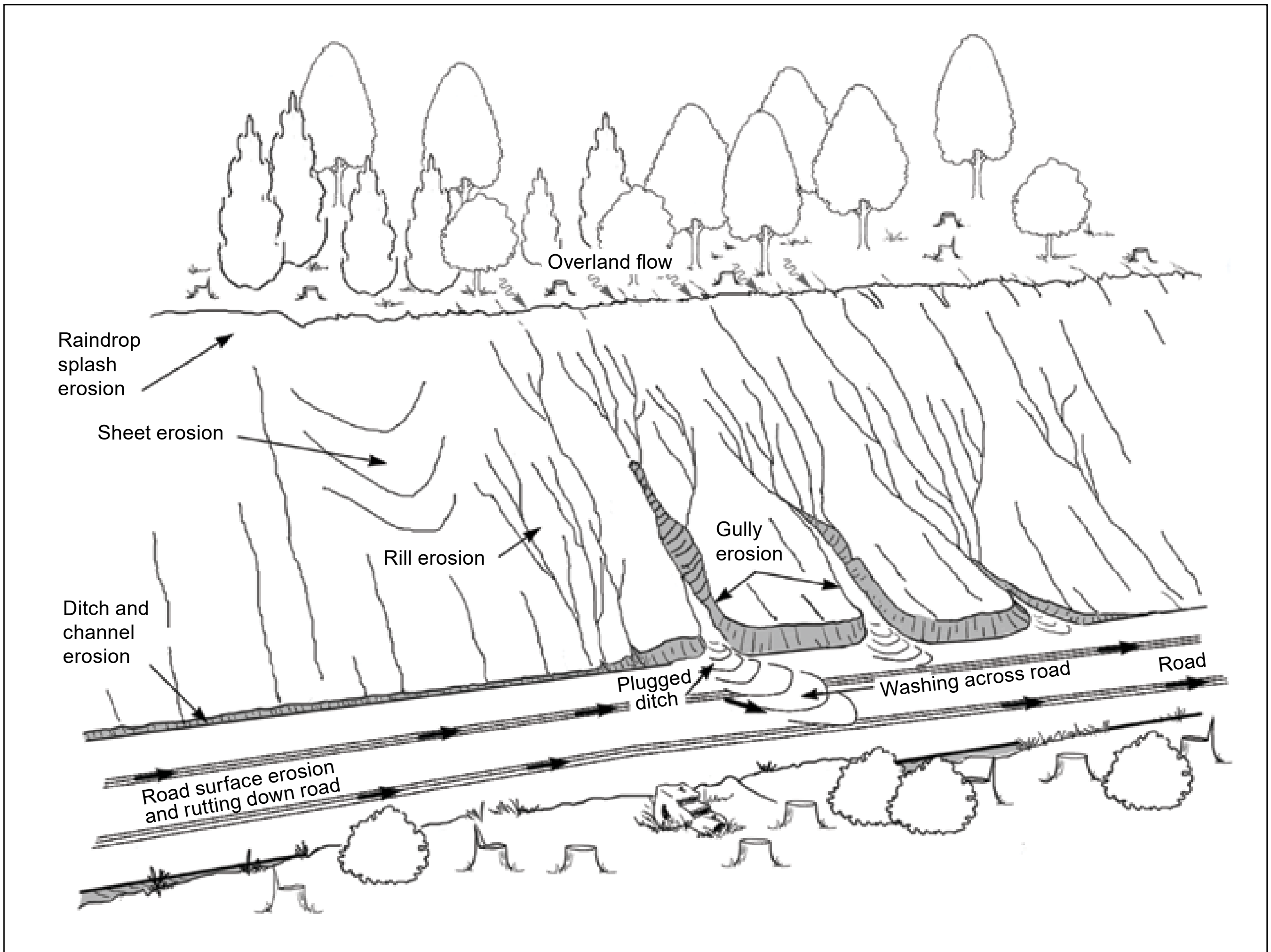


Figure 4.52—Common types and sources of erosion along a road. (Figure from Keller et al. [2011])

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

Gordon Keller

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

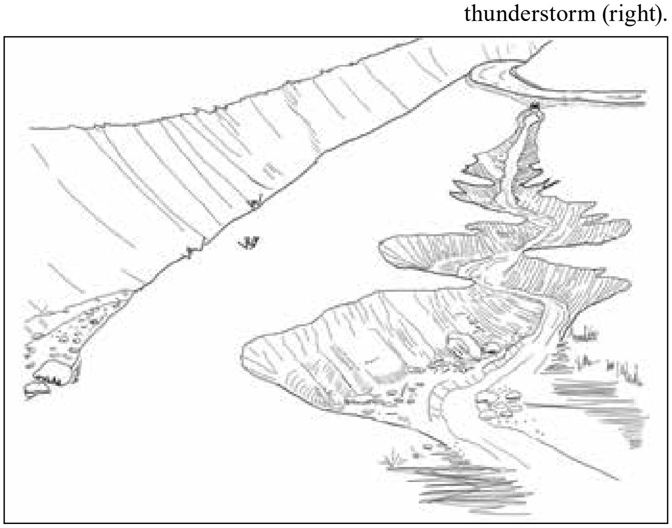
John McCullah

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

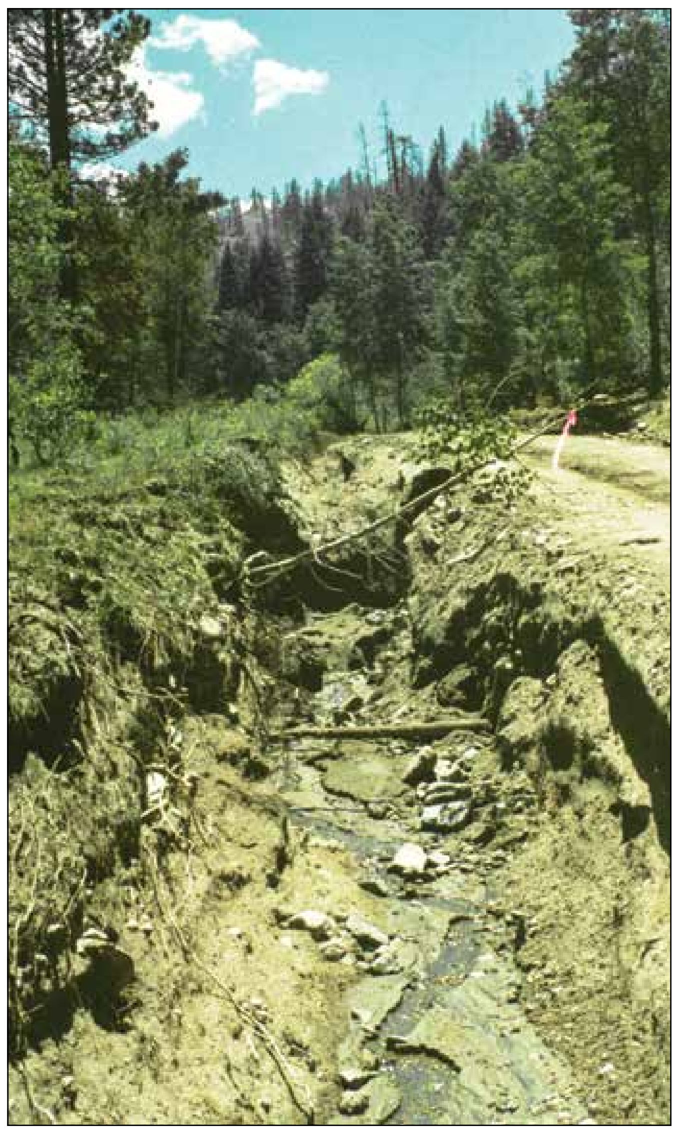
USDA NRCS (1992) and Lewis (2000) described bioengineering techniques, providing field personnel with basic soil bioengineering concepts and examples of techniques especially effective in stabilizing and revegetating upland roadsides.

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.



Heather Ross



Gordon Keller

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).

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

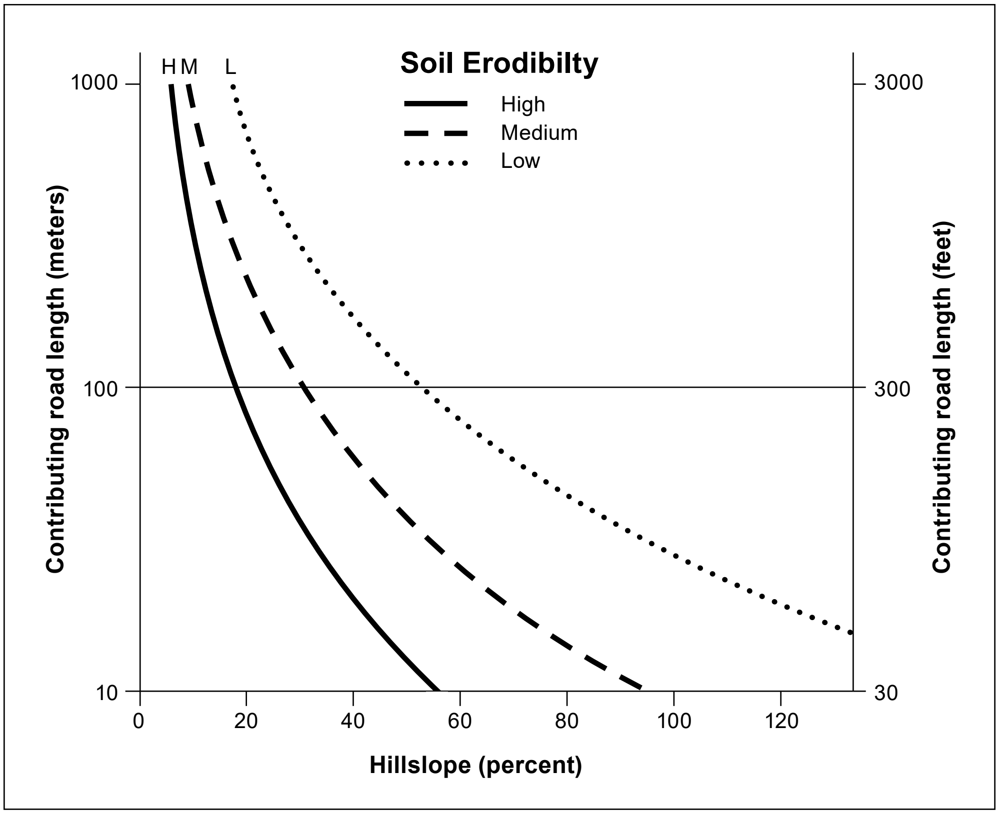


Figure 4.58—Gully initiation data from the contributing road length as a function of hillslope for various soil erodibility categories. (Adapted from Cissel et al. 2012a.)

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.

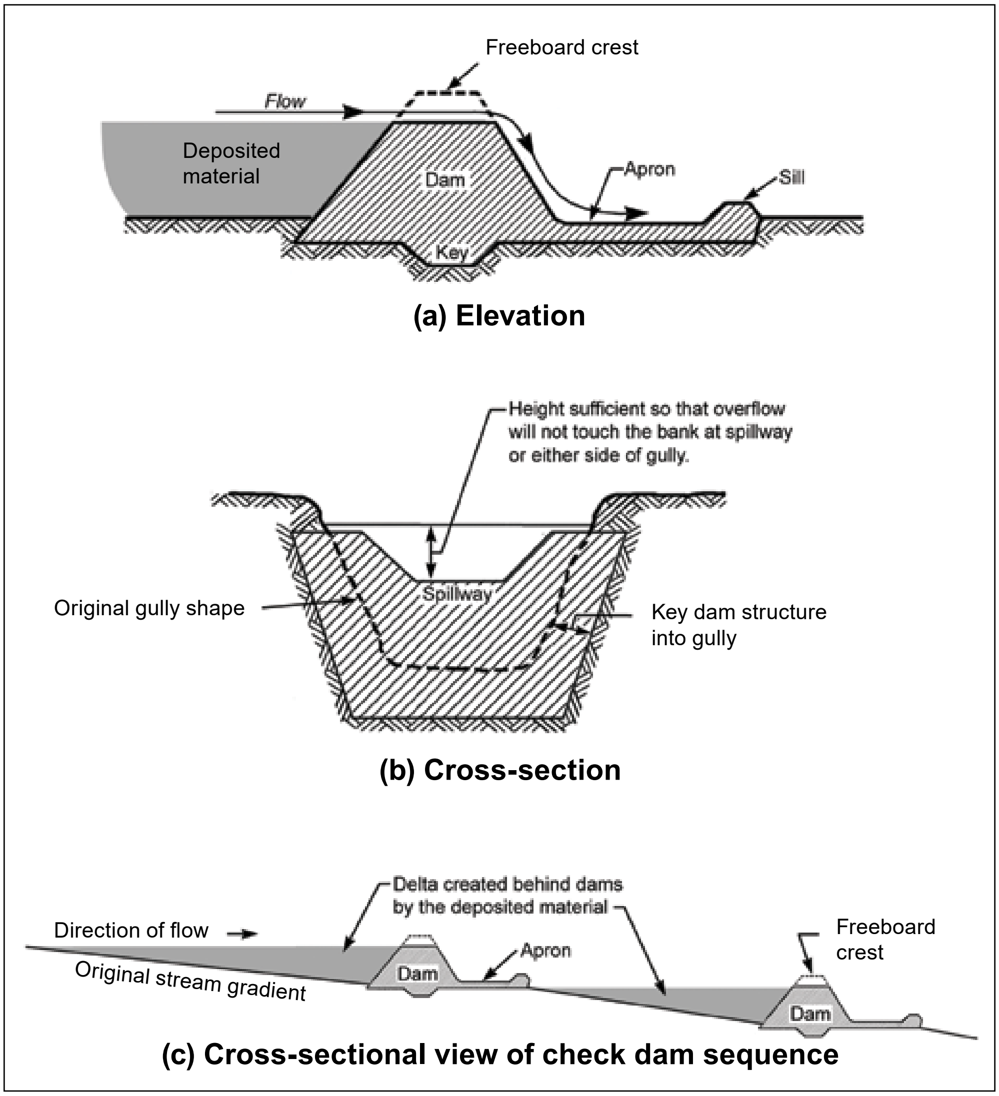


Figure 4.60—Check-dam design used to control or stabilize a gully. Note the details for keying the structure into the gully, having a U-shaped weir, and protecting the toe area against scour with other downslope structures. (Figure from Keller and Ketcheson [2015])

- 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

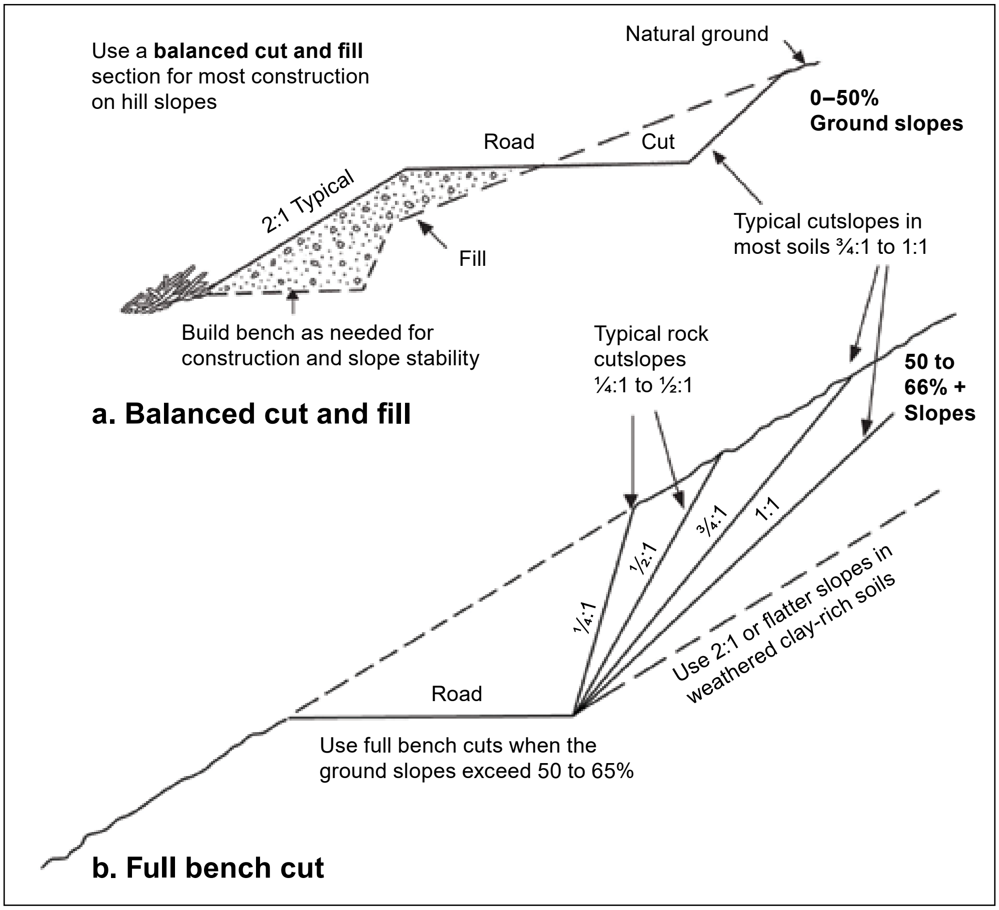


Figure 4.61—A balanced cut and fill, and commonly used stable cutslope angles. (Figure from Keller et al. [2011])

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).

Gordon Keller

Gordon Keller

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.

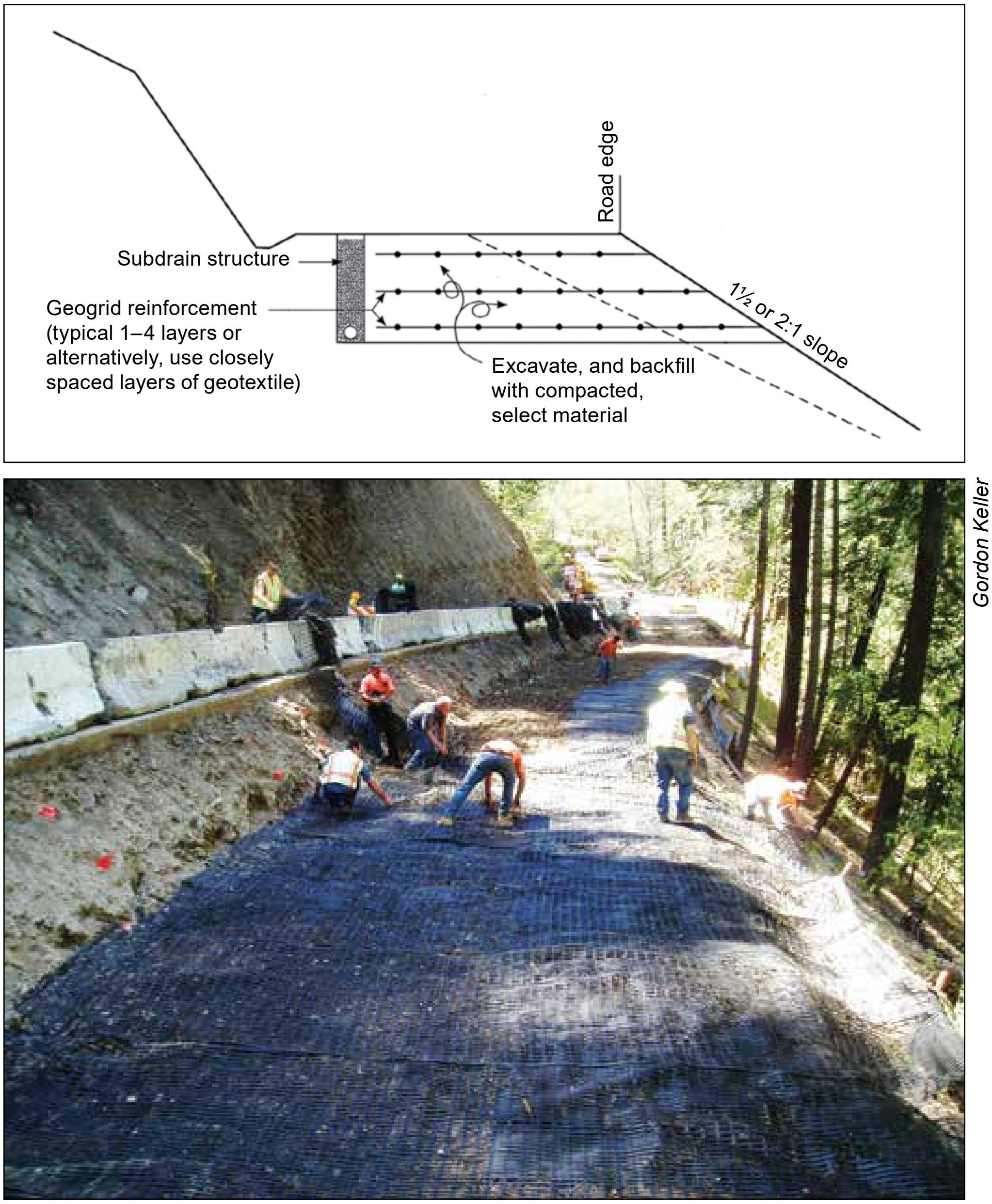


Figure 4.64—Cross section and installation of a typical deep-patch road-embankment repair. (Figure from Keller et al. [2011])

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.

Don Lindsay, CGS

Gordon Keller

Alan Gallegos

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

Jerome DeGraff

Gordon Keller

Gordon Keller

Gordon Keller

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).

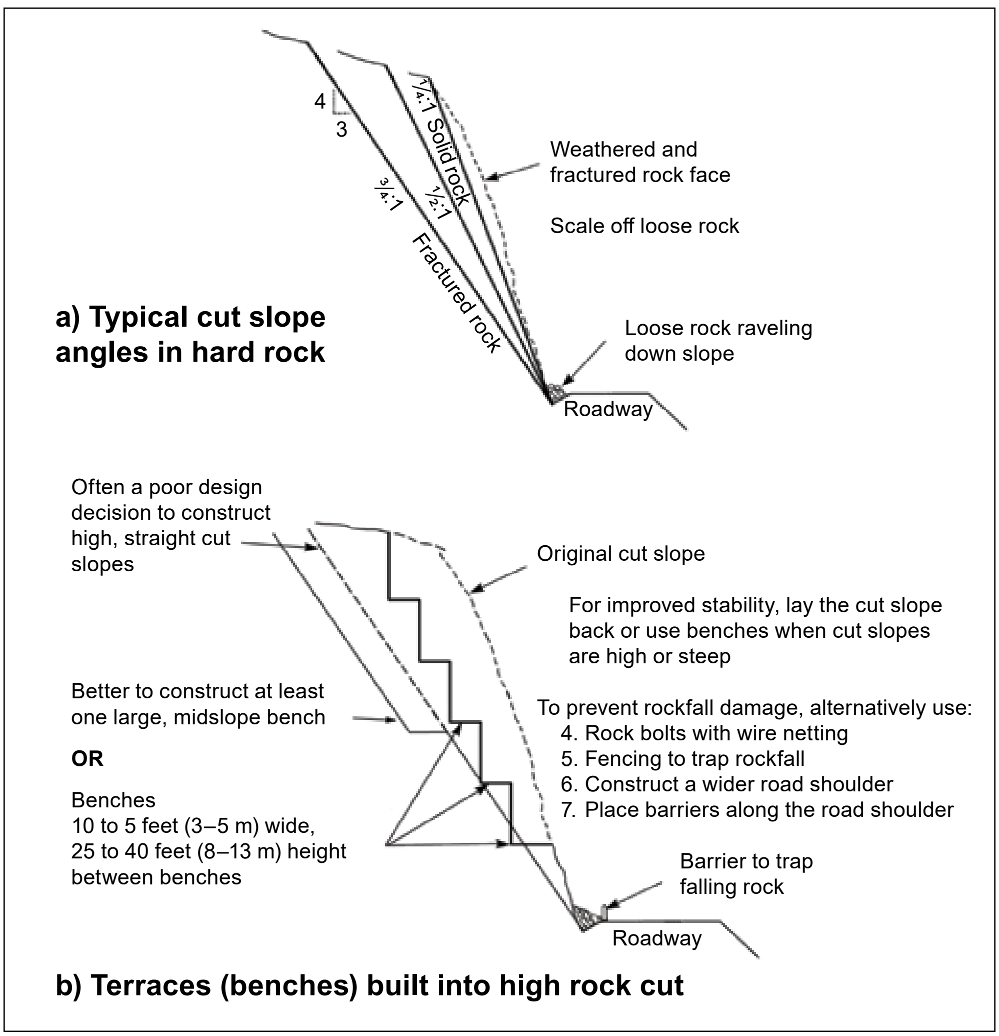


Figure 4.68—Rockfall prevention and protection measures. (Figure from Keller et al. [2011])

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

---

[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

Gordon Keller

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).

Gordon Keller

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.

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.

Continued on next page

Continued from page 163

- **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.

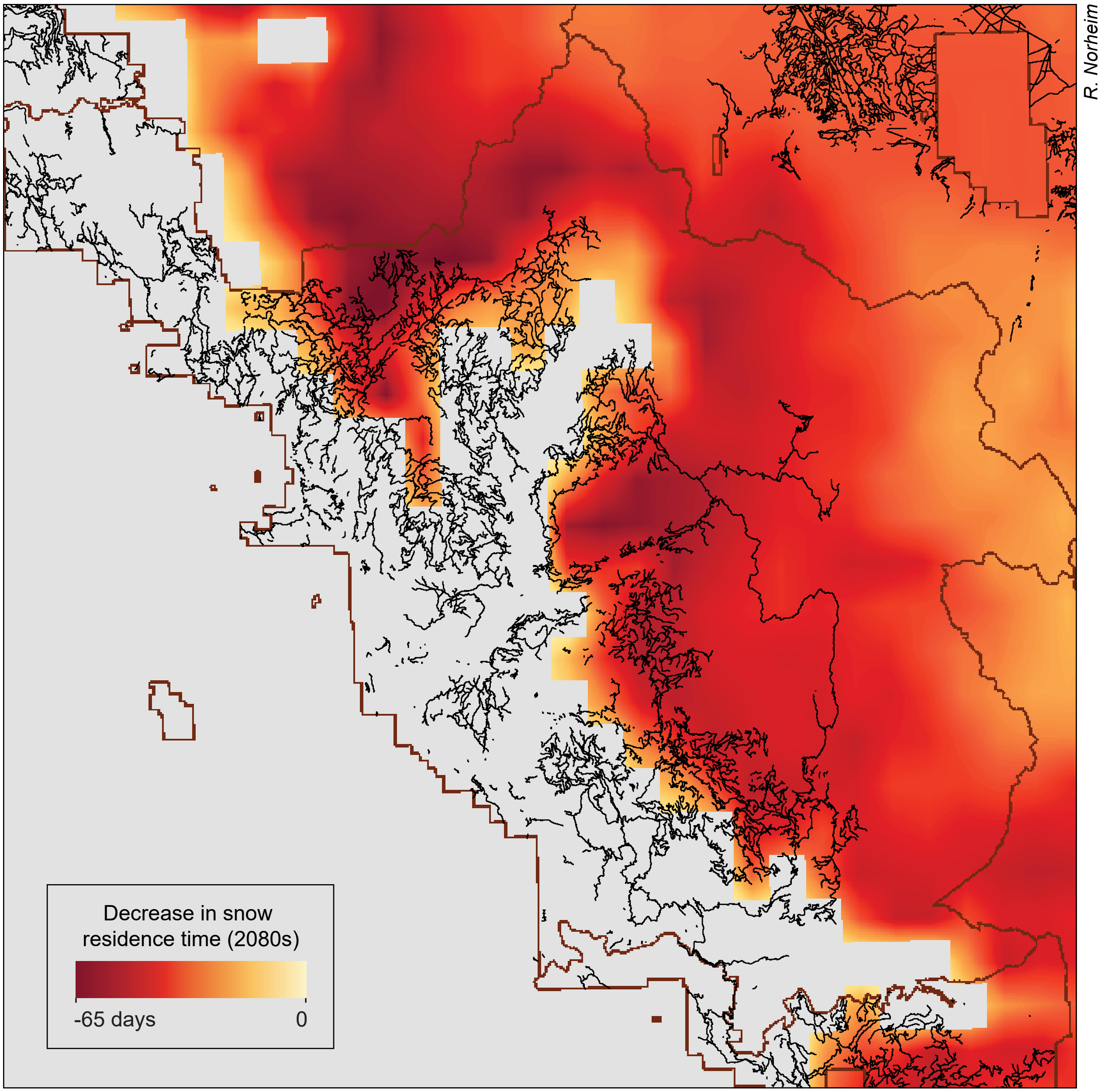


Figure 4.77—Map showing the forest road system (black lines) and decrease in projected snow residence time in the central Sierra Nevada.

Literature Cited

Benda, L.; Miller, D.; Andras, K. [et al.]. 2007. NetMap: a new tool in support of watershed science and resource management. Forest Science. 53: 206–219.

Berg, R.; Christopher, B.; Samtani, N. 2009. Design of mechanically stabilized earth walls and reinforced soil slopes, Volume 1 and 2. FHWA-NHI-10-024 and 025. Washington, DC: U.S. Department of Transportation, Federal Highway Administration. 378 p.

Black, T.A.; Cissel, R.M.; Luce, C.H. 2012. The Geomorphic Road Analysis and Inventory (GRAIP) package. Volume 1: data collection method. Gen. Tech. Rep. RMRS-GTR-280WWW. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 110 p.

Bolander, P.; Yamada, A. 1999. Dust palliative selection and application guide. Gen. Tech. Rep. 9977 1207- SDTDC. San Dimas, CA: U.S. Department of Agriculture, Forest Service, San Dimas Technology and Development Center. 19 p.

Briaud, J.; Maddah, L. 2016. Minimizing roadway embankment damage from flooding—a synthesis of highway practice. Washington, DC: Transportation Research Board. 120 p.

Brown, S.A.; Clyde, E. 1989. Design of riprap revetments. Hydraul. Engin. Circ. 11, FHWA-IP-89-016. Washington, DC: U.S. Department of Transportation, Federal Highway Administration. 169 p.

Cafferata, P.; Lindsay, D.; Spittler, T. [et al.]. 2017. Designing watercourse crossings for passage of 100-year flood flows, wood, and sediment. Calif. Forestry Rep. 1 (revised). Sacramento, CA: State of California, Department of Forestry and Fire Prevention. 137 p.

California Department of Transportation [Caltrans]. 2018a. Caltrans climate change vulnerability assessment. Summ. rep. Sacramento, CA: District 2. 29 p.

California Department of Transportation [Caltrans]. 2018b. Caltrans climate change vulnerability assessment. Summ. rep. Sacramento, CA: District 6. 55 p.

Chen, C., ed. 1997. Debris flow hazards mitigation: mechanics, prediction, and assessment. Proceedings of the first international conference on debris flows. New York, NY: American Society of Civil Engineers. 817 p.

Cissel, R.; Black, T.; Luce, C. [et al.]. 2012a. Erosion sensitivity index for gullies, hillslope, and road segment length for storm damage risk reduction treatments. Boise, ID: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station and Portland, OR: Pacific Northwest Region. 5 p.

Cissel, R.M.; Black, T.A.; Schreuders, K.A.T. [et al.]. 2012b. The Geomorphic Road Analysis and Inventory (GRAIP) package. Volume 2: office procedures. Gen. Tech. Rep. RMRS-GTR-281WWW. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 160 p.

Clarkin, K.; Connor, A.; Furniss, M.J. [et al.]. 2005. National inventory and assessment procedure for identifying barriers to aquatic organism passage at road-stream crossings. San Dimas, CA: U.S. Department of Agriculture, Forest Service, San Dimas Technology and Development Center. 62 p.

Clarkin, K.; Keller, G.; Warhol, T.; Hixson, S. 2006. Low-water crossings: geomorphic, biological and engineering design considerations. 0625-1801-SDTDC. San Dimas, CA: U.S. Department of Agriculture, Forest Service, San Dimas Technology and Development Center.

Collins, T. 2008. Debris flows caused by failure of fillslopes: early detection, warning, and loss prevention. Landslides. 5: 107–120.

Committee on Adaptation to a Changing Climate. 2018. Climate-resilient infrastructure: adaptive design and risk management. ASCE Manuals and Reps. on Engin. Prac. 140. Reston, VA: American Society of Civil Engineers. 294 p.

Copstead, R.; Johansen, K.; Moll, J. 1998. Introduction to surface cross-drains. 9877-1806-SDTDC. San Dimas, CA: U.S. Department of Agriculture, Forest Service, San Dimas Technology and Development Center. 21 p.

Cramer, M.; Bates, K., eds. 2003. Integrated streambank protection guidelines. Olympia, WA: Washington State Department of Fish and Wildlife, Department of Transportation, and Department of Ecology; Washington, DC: U.S. Army Corps of Engineers; and Washington, DC: U.S. Fish and Wildlife Service. 625 p.

Croke, J.; Hairsine, P. 2006. Sediment delivery in managed forest: a review. Environmental Reviews. 14: 59–87

Das, T.; Maurer, E.P.; Pierce, D.W. [et al.]. 2013. Increases in flood magnitudes in California under warming climates. Journal of Hydrology. 501: 101–110.

DeGraff, J. 1994. The geomorphology of some debris flows in the southern Sierra Nevada, California. Geomorphology. 10: 231–252.

DeGraff, J.; Wagner, D.; Gallegos, A. [et al.]. 2011. The remarkable occurrence of large rainfall-induced debris flows at two different locations on July 12, 2008, southern Sierra Nevada, CA, USA. Landslides. 8: 343–353.

Dettinger, M.D. 2011. Climate change, atmospheric rivers and floods in California—a multi-model analysis of storm frequency and magnitude changes. Journal of the American Water Resources Association. 47: 514–523.

Dettinger, M.; Alpert, H.; Battles, J. [et al.]. 2018. Sierra Nevada summary report. California's fourth climate change assessment. Pub. SUM-CCCA4-2018-004. Sacramento, CA: State of California.

Durrell, C. 1987. Geologic history of the Feather River Country, California. Berkeley, CA: University of California Press. 45 p.

Engineering Canada. 2016. PIEVC engineering protocol for infrastructure vulnerability assessment and adaptation to a changing climate—principles and guidelines. Version PG-10.1. Ottawa, Ontario, Canada.

Eubanks, E.; Meadows, D. 2002. A soil bioengineering guide for streambank and lakeshore stabilization, FS-683. San Dimas, CA: U.S. Department of Agriculture, Forest Service, San Dimas Technology and Development Center. 187 p.

Fay, L.; Akin, M.; Shi, X. 2012. Cost-effective and sustainable road slope stabilization and erosion control. NCHRP Synth. 430 (NCHRP Proj. 20-5, Topic 42-09). Bozeman, MT: Montana State University, Western Transportation Institute; Washington, DC: Transportation Research Board. 70 p.

Field, C.B.; Barros, V.; Stoecker, T.F., eds. 2012. Managing the risks of extreme events and disasters to advance climate change adaptation: special report of the intergovernmental panel on climate change. A special report of working groups I and II of the Intergovernmental Panel on Climate Change. New York, NY: Cambridge University Press.

Fischenich, C. 2001. Stability thresholds for stream restoration materials. Technical Notes Collection ERDC TN-EMRRP-SR-29. Vicksburg, MS: U.S. Army Engineer Research and Development Center. https://apps.dtic.mil/dtic/tr/fulltext/u2/a392430.pdf. (16 March 2020).

Flanagan, D.C.; Nearing, M.A., eds. 1995. USDA–Water Erosion Prediction Project: hillslope profile and watershed model documentation. Nat. Soil Erosion Res. Lab. Rep. 10. Lafayette, IN: U.S. Department of Agriculture, National Soil Erosion Research Laboratory.

Furniss, M.J.; Howe, C. 2016. Regional-scale climate change vulnerability assessment for infrastructure in the national forests and grasslands of the Rocky Mountain Region: including roads, trails, and recreational facilities. Golden, CO: U.S. Department of Agriculture, Rocky Mountain Region. 117 p.

Furniss, M.J.; Little, N.J.; Peterson, D.L. 2018. Effects of climate change on infrastructure. In: Halofsky, J.E.; Peterson, D.L.; Ho, J.J., eds. Climate change vulnerability and adaptation in the Intermountain Region [part 2]. Gen. Tech. Rep. RMRS-GTR-375. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 339–362.

Furniss, M.J.; Roby, K.B.; Cenderelli, D. [et al.]. 2013. Assessing the vulnerability of watersheds to climate change: results of national forest watershed vulnerability pilot assessments. Gen. Tech. Rep. PNW-GTR-884. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 32 p. plus appendix.

Furniss, M.; Ledwith, T.; Love, M. [et al.]. 1998. Response of road- stream crossings to large flood events in Washington, Oregon, and Northern California. 9877-1806-SDTDC. San Dimas, CA: U.S. Department of Agriculture, Forest Service, San Dimas Technology and Development Center. 14 p.

Furniss, M.; Love, M.; Flanagan, S. 1997. Diversion potential at road-stream crossings. Water-Road Interaction Tech. Ser. 9777 1814-SDTDC. San Dimas, CA: U.S. Department of Agriculture, Forest Service, San Dimas Technology and Development Center. 12 p.

Gillespie, N.; Unthank, A.; Campbell, L. [et al.]. 2014. Flood effects on road–stream crossing infrastructure: Economic and ecological benefits of stream simulation designs. Fisheries. 39: 2, 62–76

Gillies, C. 2007. Erosion and sediment control practices for forest roads and stream crossings—a practical operations guide. Vancouver, BC: Forest Engineering Research Institute of Canada, Western Region. 87 p.

Gray, D.; Leiser, A. 1982. Biotechnical slope protection and erosion control, New York, NY: Van Nostrand Reinhold Company. 271 p.

Groenier, J.S.; Gubernick, R.A. 2009. Locating your trail bridge for longevity. 0971-2810-MTDC. Missoula, MT: U.S. Department of Agriculture, Forest Service, Missoula Technology and Development Center.

Gubernick, R. 2011. White Mountain National Forest flood damage assessment: river, slope, and infrastructure damage assessment and recommendations. Intern. rep. Berlin, NH: U.S. Department of Agriculture, Forest Service, White Mountain National Forest.

Gucinski, H.; Furniss, M.J.; Ziemer, R.R.; Brookes, M.H. 2001. Forest roads: a synthesis of scientific information. Gen. Tech. Rep. PNW-GTR-509. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 103 p.

Halofsky, J.; Peterson, D.; Ho, J. [et al.], eds. 2018a. Climate change vulnerability and adaptation in the Intermountain Region. Gen. Tech. Rep. RMRS-GTR-375. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. Part I.

Halofsky, J.; Peterson, D.; Ho, J. [et al.], eds. 2018b. Climate change vulnerability and adaptation in the Intermountain region. Gen. Tech. Rep. RMRS-GTR-375. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. Parts II.

Hayhoe, K.; Wuebbles, D.J.; Easterling, D.R. [et al.]. 2018. Our changing climate. In: Reidmiller, D.R.; Avery, C.W.; Easterling, D.R. [et al.], eds. Impacts, risks, and adaptation in the United States: fourth national climate assessment, volume II. Washington, DC: U.S. Global Change Research Program: 72–144.

Intergovernmental Panel on Climate Change [IPCC]. 2007. Summary for policymakers. In: Parry, M.L.; Canziani, O.F.; Palutikof, J.P. [et al.], eds. Climate change 2007: impacts, adaptation and vulnerability. Contribution of working group II to the fourth assessment report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom: Cambridge University Press: 7–22.

Intergovernmental Panel on Climate Change [IPCC]. 2014. Climate change 2014: mitigation of climate change. Contribution of working group III to the fifth assessment report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom: Cambridge University Press.

Kattell, J.; Eriksson, M. 1998. Bridge scour evaluation: screening, analysis, and countermeasures. 9877-1207-SDTDC. San Dimas, CA: U.S. Department of Agriculture, Forest Service, San Dimas Technology and Development Center. 35 p.

Keller, G.; Ketcheson, G. 2015. Storm damage risk reduction guide for low-volume roads. Tech. Rep. 1277-1814. San Dimas, CA: U.S. Department of Agriculture, Forest Service, San Dimas Technology and Development Center.

Keller, G.; Sherar, J. 2003. Low-volume roads engineering: best management practices field guide. Washington, DC: U.S. Department of Agriculture, Forest Service, Office of International Programs; U.S. Agency for International Development. 158 p.

Keller, G.; Wilson Musser, S.; Bolander, P.; Barandino, V. 2011. Stabilization and rehabilitation measures for low-volume forest roads. 1177-1801-SDTDC. San Dimas, CA: U.S. Department of Agriculture, Forest Service, San Dimas Technology and Development Center. 333 p.

Kestler, M.A. 2003. Techniques for extending the life of low-volume roads in seasonal frost areas. Volumes 1819, 1819B. Washington, DC: Transportation Research Board.

Kestler, M.; Berg, R.; Miller, H. [et al.]. 2011. Keeping springtime low-volume road damage to a minimum: toolkit of practical low-cost methods for road managers. Transport. Res. Rec. 2205. Washington, DC: Transportation Research Board.

Kilgore, R.; Herrmann, G.; Thomas, W.; Thompson, D. 2016. Highways in the river environment: floodplains, extreme events, risk, and resilience. Hydraul. Engin. Circ. 17. 2nd ed. FHWA-HIF-16-018. Washington, DC: U.S. Department of Transportation, Federal Highway Administration, Office of Bridges and Structures. 157 p.

Kunkel, K.; Karl, T.; Easterling, D. [et al.]. 2013. Probable maximum precipitation and climate change. Geophysical Research Letters. 40: 1402–1408.

Lagasse, P.; Clopper, P.; Pagan, G. [et al.]. 2009. Bridge scour and stream instability countermeasures. 3rd ed. FHWA-NHI-09-111. Washington, DC: U.S. Department of Transportation, Federal Highway Administration, Office of Bridge Technology, and National Highway Institute. 256 p. Volumes 1 and 2.

Lewis, L. 2000. Soil bioengineering: an alternative for roadside management (a practical guide). 0077-1801-SDTDC. San Dimas, CA: U.S. Department of Agriculture, Forest Service, San Dimas Technology and Development Center. 43 p.

Louter, D. 2006. Windshield wilderness: cars, roads, and nature in Washington's national parks. Seattle, WA: University of Washington Press. 288 p.

Luce, C.; Black, T. 2001. Effects of traffic and ditch maintenance on forest road sediment production. In: Proceedings of the seventh federal interagency sedimentation conference. Washington, DC: U.S. Interagency Committee on Water Resources, Subcommittee on Sedimentation: V67–V74.

Luce, C.H.; Rieman, B.E.; Dunham, J.B. [et al.]. 2001. Incorporating aquatic ecology into decisions on prioritization of road decommissioning. Water Resources Impact. 3: 8–14.

Luce, C.; Morgan, P.; Dwire, K. [et al.]. 2012. Climate change, forests, fire, water, and fish: building resilient landscapes, streams, and managers. Gen. Tech. Rep. RMRS-GTR-290. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 207 p.

Macdonald, G. 1966. Geology of the Cascade Range and Modoc Plateau. Bull. 190. In: Geology of Northern California. Bulletin 190: 65-95. San Francisco, CA: California Division of Mines and Geology.

McCullah, J.; Gray, D. 2005. Environmentally sensitive channel and bank protection measures, NCHRP Rep. 544. Washington, DC: Transportation Research Board, National Cooperative Highway Research Program. 50 p. plus CD.

Meyer, R.S.; Nicholls, D.L.; Patterson, T.M.; White R.E. 2013. Energy efficiency in U.S. Forest Service facilities: a multiregion review. Gen. Tech. Rep. PNW-GTR-886. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 28 p.

Mohney, J. 1994. Retaining wall design guide. EM-7170-14 (and FHWA-FLP-94-006). Washington, DC: U.S. Department of Agriculture, Forest Service, Engineering Staff and Federal Highway Administration. 535 p.

Mote, P.W.; Li, S.; Lettenmaier, D.P. [et al.]. 2018. Dramatic declines in snowpack in the western US. npj Climate and Atmospheric Science. 1: 2.

Muhunthan, B.; Shu, S.; Sasiharan, N. [et al.]. 2005. Design guidelines for wire mesh/cable net slope protection. WA-RD 612.2. Olympia, WA: Washington State Department of Transportation, Research Office. 60 p.

Napper, C. 2006. Burned Area Emergency Response treatments catalog. 0625-1801-SDTDC, San Dimas, CA: U.S. Department of Agriculture, Forest Service, San Dimas Technology and Development Center. 254 p.

Neill, C.R., ed. 1973. Guide to bridge hydraulics. Toronto, Canada: University of Toronto Press. 191 p.

Nelson, N.; Clifton, C.; Black, T. [et al.]. 2010. Wall Creek watershed GRAIP roads assessment, North Fork John Day subbasin, Umatilla National Forest. Boise, ID: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 71 p. http://www.fs.fed.us/GRAIP/downloads/case_studies/WallCreekWatershed2010.pdf. (26 October 2016).

Olsen, J.R. 2015. Adapting infrastructure and civil engineering practice to a changing climate. Reston, VA: American Society of Civil Engineers, Committee on Adaptation to a Changing Climate. 93 p.

Partington, M.; Bradley, A.; Durand-Jézéquel, M.; Forrester, A. 2017. Adapting resource road infrastructure to climate change. Tech. Rep. 61. Pointe Claire, Quebec, Canada: FP Innovations.

Partington, M.; Bradley, A.; Durand-Jézéquel, M.; Forrester, A. 2018. Analysis of a British Colombia resource road's vulnerability to climate change: Tum Tum Forest Service Road PIEVC case study. Tech. Rep. 35. Pointe Claire, Quebec, Canada: FP Innovations.

Peterson, D.L.; Millar, C.I.; Joyce, L.A. [et al.]. 2011. Responding to climate change in national forests: a guidebook for developing adaptation options. Gen. Tech. Rep. PNW-GTR-855. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 109 p.

Peterson, D.L.; Vose, J.M.; Patel-Weynand, T., eds. 2014. Climate change and United States forests. Dordrecht, The Netherlands: Springer.

PIARC World Roads Association (PIARC). 1999. Natural disaster reduction for roads. Final Rep. 72.02B. Paris, France: PIARC Working Group 2G. 275 p.

Piton, G. 2016. Sediment transport control by check dams and open check dams in alpine torrents. Doctoral dissertation. Grenoble, France: Université Grenoble.

Polade, S.; Gershunov, A.; Cayan, D. [et al.]. 2017. Precipitation in a warming world: assessing projected hydro-climate changes in California and other Mediterranean climate regions. Nature Scientific Reports. 7: 10783.

Potyondy, J.P.; Geier, T.W. 2011. Watershed condition classification. Tech. Guide FS-978. Washington, DC: U.S. Department of Agriculture, Forest Service.

Prellwitz, R.T.; Steward, J., coords. 1994. Slope stability reference guide for national forests in the United States. EM-7170-13. Washington, DC: U.S. Department of Agriculture, Forest Service, Engineering Staff. 1091 p. Volumes 1–3.

Rapp, C.; Abbe, T. 2003. A framework for delineating channel migration zones. Ecol. Pub. 03-06-027. Olympia, WA: Washington State Department of Ecology and Washington State Department of Transportation.

Reidmiller, D.R.; Avery, C.W.; Easterling, D.R. [et al.]. 2018. Impacts, risks, and adaptation in the United States: fourth national climate assessment, volume II. Washington, DC: U.S. Global Change Research Program. 1515 p.

Richardson, E.V.; Davis, S.R. 2001. Evaluating scour at bridges. 4th ed. HEC 18, FHWA_NHI-01-001. Washington, DC: U.S. Department of Transportation, Federal Highway Administration, National Highway Institute, Office of Bridge Technology. 378 p.

Ritter, M.A.; Skog, K.; Bergman, R. 2011. Science supporting the economic and environmental benefits of using wood and wood products in green building construction. Gen. Tech. Rep. FPL-GTR-206. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 9 p.

Rivas, T. 2006. Erosion control treatment selection guide. 0677-1203-SDTDC. San Dimas, CA: U.S. Department of Agriculture, Forest Service, San Dimas Technology and Development Center. 66 p.

Rosgen, D. 1996. Applied river morphology. 2nd ed. Pagosa Springs, CO: Wildland Hydrology.

Schmidt, K.M.; Roering, J.J.; Stock, J.D. [et al.]. 2001. The variability of root cohesion as an influence on shallow landslide susceptibility in the Oregon Coast Range. Canadian Geotechnical Journal. 38: 995–1024.

Schuster, R.L.; Highland, L.M. 2003. Impact of landslides and innovative landslide-mitigation measures on the natural environment. In: Lee, C.F.; Tham, L.G., eds. Proceedings of the international conference on slope engineering. Hong Kong, China: University of Hong Kong: 64–74.

Schwartz, M.; Hall, A.; Sun, F. [et al.]. 2017. Significant and inevitable end-of-twenty-first-century advances in surface runoff timing in California's Sierra Nevada. Journal of Hydrometeorology. 18: 3181–3197.

Sergent, J.; Petras, G.; Gelles, K.; Bacon, J. 2018. Three startling facts about California's Camp Fire. USA Today**,** November 20.

Sotir, R.B. 2001. Integration of soil bioengineering techniques for watershed management. In: Hayes, D.F., ed. Proceedings of the 2001 wetlands engineering and river restoration conference. Reston, VA: American Society of Civil Engineers.

Steinferld, D.; Riley, S.; Wilkinson, K. [et al.]. 2007. Roadside revegetation: an integrated approach to establishing native plants. FHWA-WFL/TD-07-005. Vancouver, WA: U.S. Department of Transportation, Federal Highway Administration, Western Federal Lands Highway Division; U.S. Department of Agriculture, Forest Service, Umatilla National Forest. 424 p.

Strauch, R.L.; Raymond, C.L.; Hamlet, A.F. 2014. Climate change, hydrology, and access in the North Cascade Range. In: Raymond, C.L.; Peterson, D.L.; Rochefort, R.M., eds. Climate change vulnerability and adaptation in the North Cascades region. Gen. Tech. Rep. PNW-GTR-892. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 45–112.

Stream Simulation Working Group. 2008. Stream simulation: an ecological approach to providing passage for aquatic organisms at road-stream crossings. 7700–Transport. Manage. 0877-1801-SDTDC. San Dimas, CA: U.S. Department of Agriculture, Forest Service, San Dimas Technology and Development Center.

Swanston, D.N. 1971. Principal mass movement processes influenced by logging, road building and fire. In: Krygier, J.T.; Hall, J.D., eds. Forest land uses and stream environment: proceedings of a symposium. Corvallis, OR: Oregon State University: 29–40.

Theisen, M.S. 1992. The expanding role of geosynthetics in erosion and sediment control. In: Hassel, W.G.; Nordstrom, S.K.; Keammerer, W.R.; Todd, J., eds. Proceedings: high altitude revegetation workshop No. 10. Fort Collins, CO: Colorado State University, Colorado Water Resources Research Institute: 150–170.

Tillery, A.; Matherne, A.M. 2013. Post-wildfire debris flow hazard assessment of the area burned by the 2012 Little Bear Fire, south-central New Mexico. Open-File Rep. 2013-1108. Reston, VA: U.S. Department of the Interior, Geological Survey. 15 p.

Turner, K.; Schuster, R., eds. 1996. Landslides: investigation and mitigation. Spec. Rep. 247. Washington, DC: National Academy of Sciences, Transportation Research Board. 673 p.

Turner, K.; Schuster, R., eds. 2012. Rockfall: characterization and control. Washington, DC: National Academy of Sciences, Transportation Research Board. 400 p.

U.S. Department of Agriculture, Forest Service [USDA FS]. 2000. Water/road interaction technology series. San Dimas, CA: San Dimas Technology and Development Center.

U.S. Department of Agriculture, Forest Service [USDA FS]. 2012. National best management practices for water quality management on National Forest System lands. Volume 1. Nat. Core BMP Tech. Guide. FS-990a. Washington, DC.

U.S. Department of Agriculture, Forest Service [USDA FS]. 2014. National visitor use monitoring program. http://www.fs.fed.us/recreation/programs/nvum. (4 September 2016).

U.S. Department of Agriculture, Forest Service [USDA FS]. 2018. USDA Forest Service transportation resiliency guidebook: addressing climate change impacts on USDA Forest Service transportation assets. Washington, DC.

U.S. Department of Agriculture, Forest Service [USDA FS]. [In press]. National best management practices for water quality management on National Forest System lands. Volume 2. National Core BMP Monit. Tech. Guide. FS-990b. Washington, DC.

U.S. Department of Agriculture, Natural Resources Conservation Service [USDA NRCS]. 1992. Soil bioengineering for upland slope protection and erosion reduction. Engin. Field Handb. part 650. Washington, DC. 143 p. Chapter 18.

U.S. Department of Agriculture, Natural Resources Conservation Service [USDA NRCS]. 1996. Streambank and shoreline protection. Engin. Field Handb. part 650. Washington, DC. Chapter 16.

U.S. Department of Transportation, Federal Highway Administration [USDOT FHWA]. 2009. Stream instability, bridge scour, and countermeasures: a field guide for bridge inspectors. FHWA-NHI-08-106. Washington, DC. 47 p.

U.S. Department of Transportation, Federal Highway Administration [USDOT FHWA]. 2012. Climate change and extreme weather vulnerability handbook. Washington, DC.

U.S. Department of Transportation, Federal Highway Administration [USDOT FHWA]. 2014. Emergency relief for federally owned roads: disaster assistance manual. FHWA-FLH-15-001. Washington, DC. 115 p.

U.S. Department of Transportation, Federal Highway Administration [USDOT FHWA]. 2017a. Synthesis of approaches for addressing resilience in project development. FHWA-HEP-17-082. Washington, DC. 224 p.

U.S. Department of Transportation, Federal Highway Administration [USDOT FHWA]. 2017b. Vulnerability assessment and adaptation framework. 3rd ed. FHWA-HEP-18-020. Washington, DC. 86 p.

Varnes, D. 1978. Slope movement types and processes. In: Schuster, R.; Kirzek, R. eds. Landslides—analysis and control. Transport. Res. Board Spec. Rep. 176. Washington, DC: National Academy of Sciences, Transportation Research Board: 11–33.

Vose, J.M.; Clark, J.S.; Luce, C.H.; Patel-Weynand, T., eds. 2016. Effects of drought on forests and rangelands in the United States: a comprehensive science synthesis. Gen. Tech. Rep. WO-93b. Washington, DC: U.S. Department of Agriculture, Forest Service, Washington Office. 289 p.

Vose, J.M.; Peterson, D.L.; Domke, G.M. 2018. Forests. In: Reidmiller, D.R.; Avery, C.W.; Easterling, D.R. [et al.], eds. Impacts, risks, and adaptation in the United States: fourth national climate assessment, volume II. Washington, DC: U.S. Global Change Research Program: 232–267.

Vose, J.; Peterson, D.L.; Patel-Weynand, T., eds. 2012. Effects of climatic variability and change on forest ecosystems: a comprehensive science synthesis for the U.S. forest sector. Gen. Tech. Rep. PNW-GTR-870. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 265 p.

Warner, M.D.; Mass, C.F. 2017. Changes in the climatology, structure, and seasonality of Northeast Pacific atmospheric rivers in CMIP5 climate simulations. Journal of Hydrometeorology. 18: 2131–2141.

Wikipedia. 2017. The Oroville dam crisis. https://en.wikipedia.org/wiki/Oroville_Dam_crisis. (12 April 2019).

Wilhere, G.; Atha, J.; Quinn, T. [et al.]. 2016. Incorporating climate change into the design of water crossing structures. Final proj. rep. Olympia, WA: Washington Department of Fish and Wildlife. 48 p.

Wilson-Musser, S.; Denning, C. 2005. Deep patch road embankment repair application guide. 0577-1204-SDTDC. San Dimas, CA: U.S. Department of Agriculture, Forest Service, San Dimas Technology and Development Center. 21 p.