Chapter 11: Effects of Climate Change on Infrastructure

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Introduction

Climatic conditions, particularly extreme rainfall, snowmelt, and flooding, pose substantial risks to infrastructure in and near public lands in the Intermountain Adaptation Partnership (IAP) region (box 11.1). Minor floods happen frequently in the region, and large floods happen occasionally. These events can damage or destroy roads and other infrastructure and affect resource values and ecosystem services (Murray and Ebi 2012) (fig. 11.1). Drought (extended periods of heat and low precipitation) can also affect resource values, especially as it influences fuel moisture and wildfire, soil moisture, drying road conditions, low streamflow, exposed streambanks and facilities, and interactions among drought, fire, and flooding.

These are familiar problems and risks because infrastructure has always been vulnerable to climatic stresses (Gucinski et al. 2001). Climate warming is very likely to increase the magnitude and frequency of these climate stressors, thereby increasing hazards and risk to infrastructure, people, and ecosystems of the region. Anticipating changes in risk and consequences can enable managers to respond by helping to set priorities and implement projects that increase resilience (Peterson et al. 2011; Vose et al. 2012).

Human population growth and demand for water and other natural resources have resulted in cumulative effects to forest resources, particularly near populated areas. Climate change adds to these effects, and in some cases exacerbates the risks (e.g., washouts, landslides, culvert failure, local

Box 11.1—Summary of Climate Change Effects on Roads and Infrastructure in the Intermountain Adaptation Partnership Region

Broad-scale climate change effect: Increase in magnitude of winter and spring peak streamflows.

Resource entity affected: Infrastructure and roads near perennial streams, which are valued for public access.

Current condition, existing stressors: Many roads with high value for public access and resource management are located near streams. A large backlog of deferred maintenance exists because of decreasing budget and maintenance capacity. Many roads are in vulnerable locations subject to high flows.

Sensitivity to climatic variability and change: Roads in near-stream environments are periodically exposed to high flows. Increased magnitude of peakflows increases susceptibility to effects ranging from minor erosion to complete loss of the road prism. These effects influence public safety, access for resource management, water quality, and aquatic habitat.

Expected effects of climate change: Projections for increased magnitude of peakflows indicate that more miles of road and more facilities will be exposed to higher flow events and greater impacts.

Adaptive capacity: Knowing the extent and location of potentially vulnerable road segments will help with prioritizing scarce funding, treatments to reduce storm damage risk, and communicating potential hazard and risk to the public.

Risk assessment:

<u>*Potential magnitude of climate change effects*</u>

- For those watersheds determined to be sensitive
  - Moderate magnitude by 2040
  - High magnitude by 2080

<u>*Likelihood of climate change effects*</u>

- For those watersheds determined to be sensitive
  - Moderate likelihood by 2040
  - High likelihood by 2080

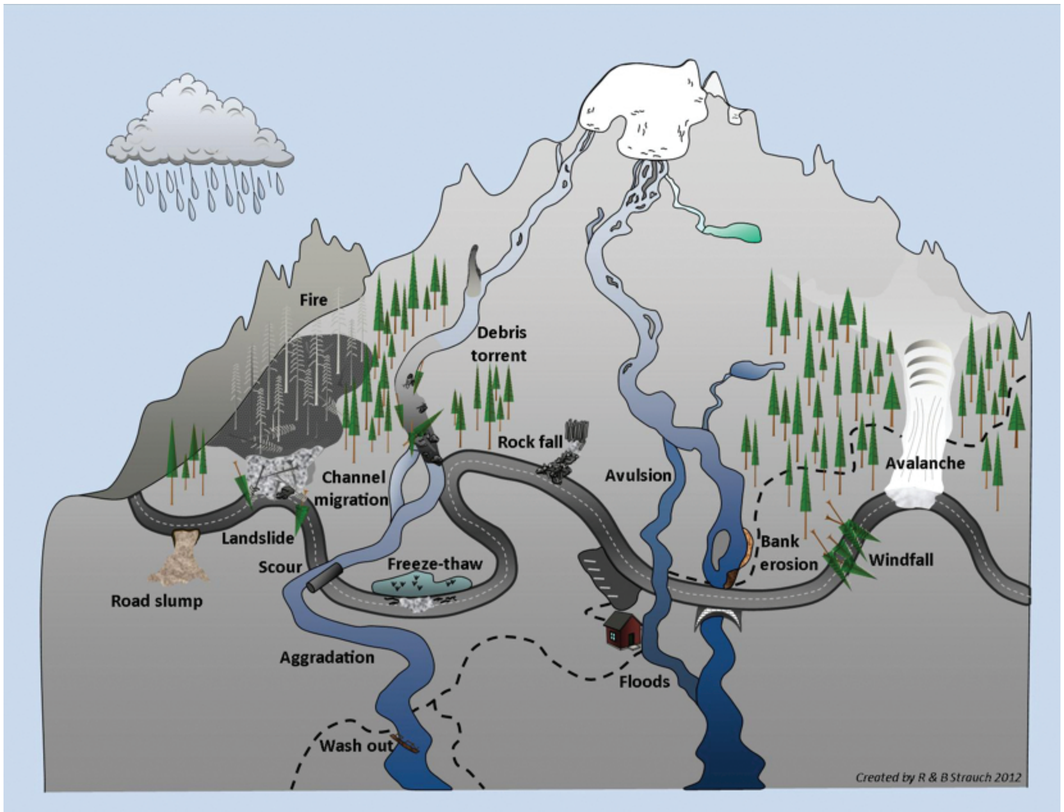

Figure 11.1—Schematic depicting the many geomorphic, hydrological, and weather-related disturbances that can damage roads and other infrastructure (from Strauch et al. 2014).

flooding, road closures) (Furniss et al. 2013; Strauch et al. 2014). The importance of particular infrastructure, and probability of damage, may vary. By anticipating changes that a rapidly warming climate may bring, resource managers can be proactive in making infrastructure more resilient, safe, and reliable on Federal lands, thus reducing negative consequences for public land, water, and ecosystem services.

This chapter is a review of vulnerable infrastructure, namely roads, trails, structures, developed recreation facilities, and dams. The focus is primarily within the boundaries of national forests and grasslands in the U.S. Department of Agriculture Forest Service (USFS) Intermountain Region, although the methods and inferences can be applied to infrastructure systems throughout the IAP region and other geographic areas.

Assessment Approach

The following three-level assessment approach can be used to systematically analyze the vulnerability of infrastructure to climate change. Assessment Level 1 (the top level) simply documents the type and quantity of infrastructure. Assessment Level 2 examines infrastructure investments at the regional level. Assessment Level 3 considers infrastructure at local or smaller scales.

Assessment Level 1—Inventory

The presence of an infrastructure feature is a first approximation of vulnerability. Although exposures and risks differ greatly from place to place, all infrastructure is vulnerable, so an inventory of the amount and spatial distribution of infrastructure is also a first approximation of vulnerability. A description of infrastructure by quantity, type, and feature within Federal lands shows the investments that are potentially affected by climatic forces. Assessment units, such as national forests, ranger districts, or subwatersheds, with higher infrastructure density or higher levels of infrastructure investment, can be considered more vulnerable than those with little or no infrastructure (fig. 11.2).

Assessment Level 2—Regional Scales

Two indicators of vulnerability can be discerned at the regional scale via simple geographic information system (GIS) queries: (1) proximity of infrastructure to streams, and (2) trail and road-stream crossings. Together, these two indicators depict components associated with moving water that may be vulnerable to extreme climatic events (fig. 11.3). Although some errors may exist in spatial resolution and mapping, the indicators reliably capture hydrological connectivity and vulnerability to fluvial processes, which are of greatest concern and potential consequence. Slope steepness and soil type may also be indicators of vulnerability discerned at broad spatial scales, but the relationships to vulnerability can be more context dependent and require local knowledge about potential effects of hydrological events. The ecological disturbance of wildfire can also be a significant impact to infrastructure.

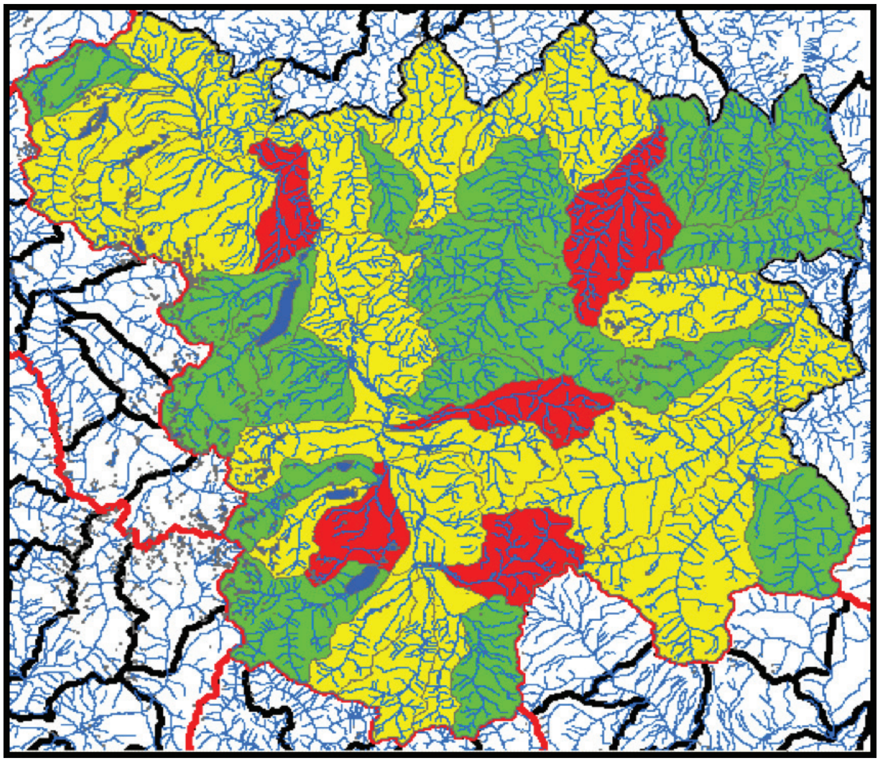

Figure 11.2—An example of using the presence of infrastructure as an indicator of vulnerability. This map shows the amount of infrastructure in Sawtooth National Recreation Area in Idaho by subwatersheds (Hydrologic Unit Code 6). Red-shaded subwatersheds have high amounts of infrastructure; yellow, moderate amounts; and green, low amounts (from Furniss et al. [2013]).

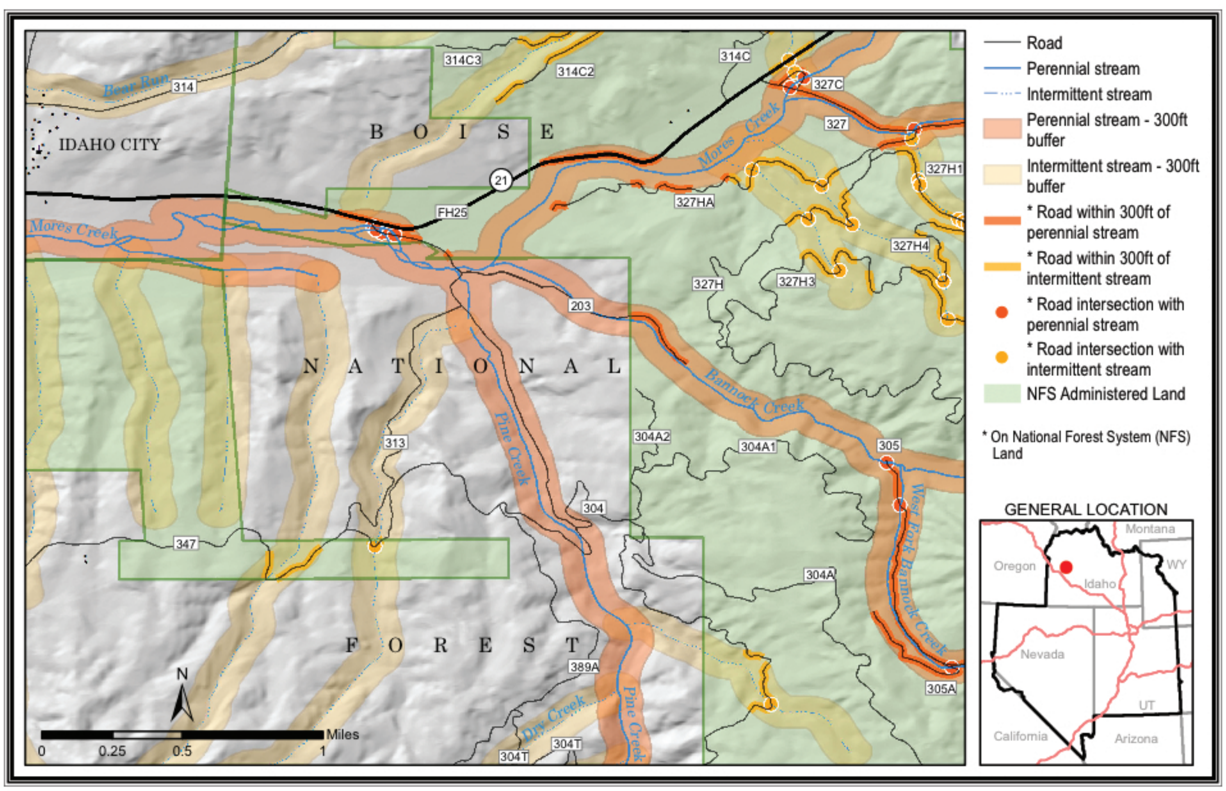

Figure 11.3—Map of an area from Upper Morse Creek and adjacent watersheds in Boise National Forest, Idaho, depicting 300-foot buffers around streams (map created by Teresa Rhoades, U.S. Forest Service). Mapping buffers around streams can be used to identify current roads that are potentially at risk from flooding, and to preclude the placement of new roads in vulnerable locations. Mapping the intersection of streams with roads can be used to identify road sections and culverts that are potentially vulnerable to flooding. These are locations that can be prioritized for infrastructure improvement.

Assessment Level 3—Local Scales

Many vulnerability indicators are best derived at smaller scales—national forests and parks, ranger districts, subbasins, watersheds, subwatersheds—where specific data about context and conditions are usually available. These indicators are not included in this assessment but can be incorporated into smaller-scale assessments and forest planning efforts. These indicators may include:

- Presence of vulnerable communities that rely on Federal roads for access;
- Local population density and land development patterns;
- Infrastructure value information, such as alternate road routes for community access, investment levels, and historical maintenance costs;
- Road assessments, such as Geomorphic Road Analysis and Inventory Package (GRAIP) surveys and flood damage surveys;
- Landslides and landslide-prone terrain;
- Steep terrain that can lead to rockfall, debris slides, and drainage failures;
- Stream channels with high probability of avulsion (sudden cutting off of land by flood, currents, or change in course of water);
- Areas of high wildfire risk and postfire flood risk;
- Presence of sensitive aquatic systems, terrestrial systems, and cultural resources that may be affected by damage, failure, or destruction of infrastructure; and
- Past Emergency Relief of Federally Owned Roads projects (box 11.2); these roads are sometimes called "repeat offenders."

Infrastructure that is costly to maintain and has high usage is generally considered more vulnerable. For example, roads and road drainage structures are major investments, facilitate many valued uses, and can be costly to repair if damaged by storms. In contrast, trailheads are often easily repaired if damaged by wind, water, or heat, and may be of little consequence to resource management if they are out of service for a short time.

Box 11.2—Emergency Relief for Federally Owned Roads

The **Emergency Relief for Federally Owned Roads program** (ERFO) was established to assist Federal agencies with the repair or reconstruction of tribal transportation facilities, Federal lands transportation facilities, and other Federally owned roads that are open to public travel and are found to have suffered serious damage by a natural disaster over a wide area or by a catastrophic failure (FHWA n.d.). The intent of the ERFO is to pay the unusually heavy expenses for the repair and reconstruction of eligible facilities.

The Emergency Relief for Federally Owned Roads program is not intended to cover all repair costs but to supplement repair programs of Federal land management agencies. Repairs are classified as either emergency or permanent. Emergency repairs are those repairs undertaken during or immediately after a disaster to restore essential traffic, to minimize the extent of damage, or to protect the remaining facilities. Prior approval is not required, although all other eligibility requirements of the program still apply. Permanent repairs are undertaken after the occurrence of the disaster to restore facilities to their pre-disaster conditions. Prior approval is required.

The Emergency Relief for Federally Owned Roads program provides assistance to Federal agencies whose roads meet the definition of "open to public travel." The Federal share payable for the repair of tribal transportation facilities, Federal lands transportation facilities, and other Federally owned roads is 100 percent. Funds for the ERFO are provided from the Highway Trust Fund and the General Fund through the Emergency Relief Program for Federal-aid Highways. The ERFO funds are not to duplicate assistance under another Federal program or compensation from insurance, cost share, or any other source.

The Office of Federal Lands Highway is responsible for efficient and effective management of public funds entrusted by Congress and for ensuring that the ERFO is administered consistent with laws, regulations, and policies. Applicants are expected to prioritize the repair of the ERFO projects that are in the public's best interest, based on available funds. Federal agencies and local government entities have the responsibility to perform emergency repairs, shift project and program priorities, give emergency relief work prompt attention and priority over nonemergency work, and assist the Office of Federal Lands Highway in its stewardship and oversight responsibilities.

Current ERFO regulations require that roads be "replaced in kind" in most circumstances, that is, with a similar type of road in the same location. This is not a climate-smart practice if the road is at risk to climate-induced changes in hydrological regimes, including extreme events (e.g., floods, landslides). This is especially true for roads already in high-risk locations, such as floodplains. Resolving this issue between the Federal Highway Administration and Federal agencies will improve climate resilience, ensure good investments, and promote a sustainable transportation system on Federal lands.

Risk Assessment

Infrastructure risk can be proactively addressed by identifying assets that have a high likelihood of being affected by future climatic conditions and significant consequences if changes do occur. The connection between likelihood and consequences can be addressed through a formal or informal risk assessment that can assist land managers with anticipating and responding to future conditions (Ojima et al. 2014). For example, a two-dimensional matrix can be used to determine an integrated risk factor (Keller and Ketcheson 2015) (fig. 11.4) for infrastructure or other resources.

Knowing that storm events will occur, a storm damage risk reduction (SDRR) approach can help minimize effects from natural disasters. Infrastructure system management should be comprehensive and address basic questions such as: (1) Is the infrastructure needed? (2) Should it be decommissioned? (3) Should it be relocated? and (4) Can it be adapted to future climatic conditions? Storm damage risk reduction methods incorporate design to minimize road damage and associated environmental impacts from storm events. The principles can be transferred to other types of infrastructure. Key SDRR storm-proofing principles (Keller and Ketcheson 2015) include:

- Identify areas of documented or potential vulnerability;
- Avoid local problematic and high-risk areas;
- Use appropriate minimum design standards;
- Employ self-maintaining concepts in the selection and implementation of treatments; incorporate relevant, cost-effective technology;
- Perform scheduled maintenance;
- Use simple, positive, frequent roadway surface drainage measures and use restrictions;

Likelihood of damage or loss	**Magnitude of consequences**		
	RISK		
	Major	**Moderate**	**Minor**
Very likely	Very high	Very high	Low
Likely	Very high	High	Low
Possible	High	Intermediate	Low
Unlikely	Intermediate	Low	Very low

Likelihood of damage or loss

Very likely: Nearly certain occurrence (>90%)

Likely: Likely occurrence (50-90%)

Possible: Possible occurrence (10-50%)

Unlikely: Unlikely occurrence (<10%)

Magnitude of consequences

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

Figure 11.4—Example of a risk rating matrix that can be used to evaluate the likelihood and consequences of climate change effects for infrastructure or other resources. The location of conditions within the matrix can vary over time, allowing for an ongoing assessment of risk and development of potential responses for reducing the risk of storm damage (from Keller and Ketcheson 2015).

- Properly size, install, and maintain culverts to pass water as well as debris and sediment;
- Design culverts based on stream simulations;
- Use simple fords or vented low-water crossings;
- Stabilize cut slopes and fill slopes;
- Use deep-rooted vegetation to “anchor” soils;
- Design high-risk bridges and culverts with armored overflows;
- Eliminate diversion potential at culverts;
- Use scour prevention measures for structures on questionable foundation material; and
- Consider channel morphology and stream channel changes near a bridge, culvert, ford, or road along a stream.

Risk assessment can also focus on storm damage as a factor by assessing (1) probability of a climatic event and subsequent infrastructure failure, and (2) expected consequences, which can include safety, loss of life, cost of infrastructure damage, and environmental damage (Keller and Ketcheson 2015) (fig. 11.4). Ideally, roads and other infrastructure determined to be at high risk would be improved, closed, or relocated.

Other Assessment and Resilience Efforts

This assessment is informed by other assessments and activities that have been conducted for Federal lands (Peterson et al. 2014; Vose et al. 2012, 2016). Much of the work done on transportation systems can aid in the development of assessment of other infrastructure types. National forests can efficiently complete more localized analyses by building on this existing work.

Watershed Condition Assessment

In 2010, every national forest and grassland in the United States completed a Watershed Condition Assessment (WCA) at the subwatershed scale (Hydrologic Unit Code 6, 10,000–40,000 acres). This was conducted by using a national Watershed Condition Framework (WCF) model that rated various factors that influence watershed condition. This 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 for the Intermountain Region, road density, condition, and proximity to streams contributed significantly to the ratings.

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. National forests in the Intermountain Region are currently identifying a sustainable road network in accordance with the rule. 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: (1) road improvement and decommissioning, (2) establishing a framework to set annual maintenance costs, and (3) identifying and improving the ability to meet agreement and Best Management Practice (BMP) requirements with regulatory agencies. Consideration of climate change is not currently 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. Costs and transportation requirements need to be balanced to arrive at a sustainable and suitable transportation system. This climate change vulnerability assessment is best integrated with the TAP reports and updates as appropriate, including analyses identified in the USFS Travel Planning Handbook (Forest Service Handbook 7709.55). Analysis includes:

- 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; and
- List of proposed changes to current travel management designations, including proposed additions to or deletions from the forest transportation system.

This vulnerability assessment can be used to help set priorities for improving roads to increase their resilience and reduce their environmental effects. The TAP should be interactive with the WCF process and vice versa. Every national forest in the Intermountain Region has completed a Travel Analysis Report that differentiates roads likely to be needed from those that are likely to be unneeded and recommended for decommissioning.

Best Management Practices

Implementing, monitoring, and improving practices for 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. 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, should be used in new planning efforts, National Environmental Policy Act (NEPA) analysis, design, implementation, maintenance, and evaluation of proposed activities, particularly if projects affect water resources.

Federal Highway Administration

The Federal Highway Administration vulnerability assessment framework consists of three primary components: (1) defining objectives and scope, (2) assessing vulnerability, and (3) integrating vulnerability into decisionmaking (FHWA 2012). This approach is important in all aspects of infrastructure management in order to efficiently and effectively utilize funding. A comprehensive approach helps to determine relevant objectives, identify and categorize assets, and identify appropriate climatic factors to track. Developing a clear approach minimizes data collection and analyses, streamlines the evaluation process for complex climate change issues, and saves land managers and engineers time and money (fig. 11.5).

For transportation and other infrastructure systems, the kinds of climatic changes that can cause the most significant damage or be the most disruptive to operations are often extreme events of relatively short duration, as opposed to annual or seasonal averages. Heat waves, drought, and flooding affect infrastructure over short timescales (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).

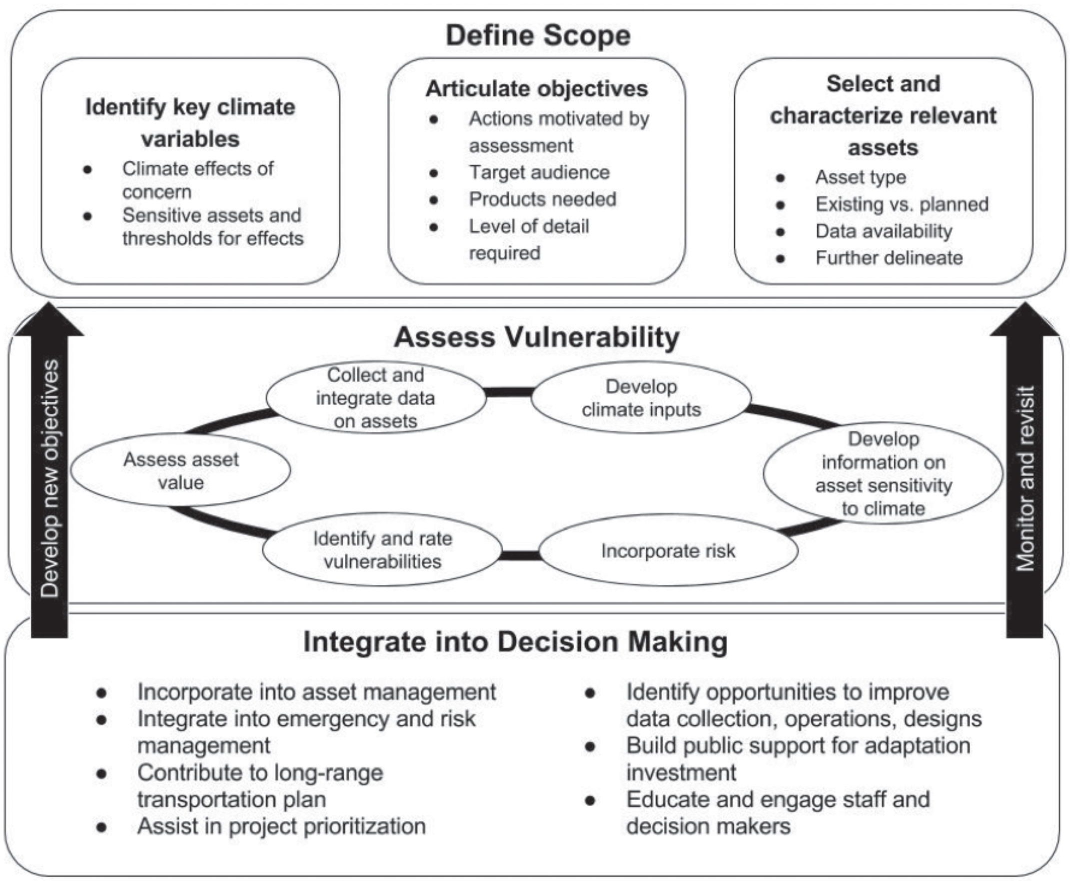

Figure 11.5—A framework for assessing the effects of climate change and extreme weather vulnerability on infrastructure. This framework can be used for both high-level planning and on-the-ground project implementation. This structured approach ensures thoroughness and consistency in designing and maintaining infrastructure in a changing climate (modified from Federal Highway Administration [FHWA] 2012).

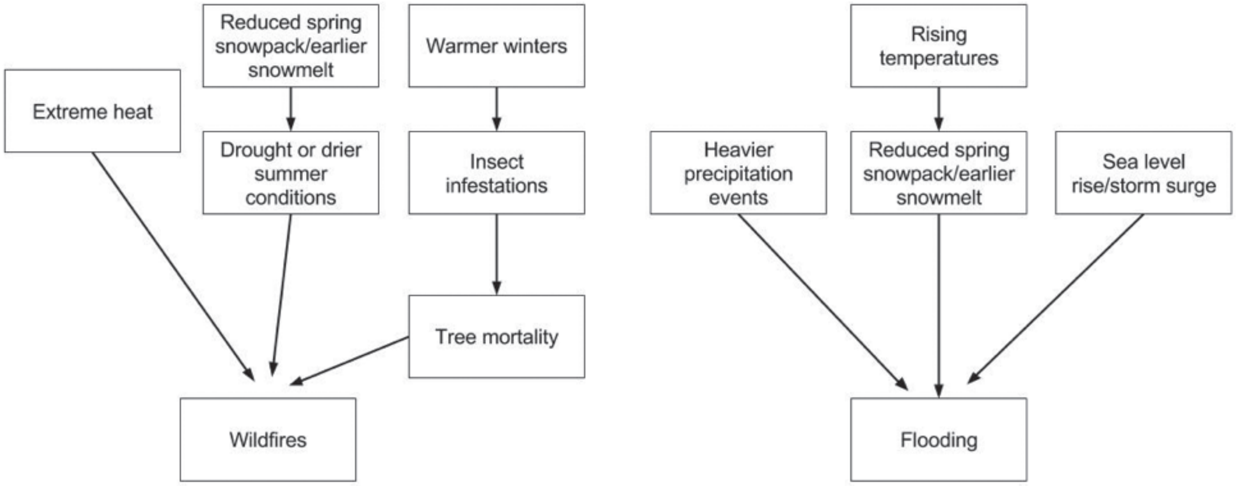

Figure 11.6—Conceptual framework of changes in climate- and weather-related stressors to flooding, wildfires, and tree mortality (modified from USDA FS n.d.).

Other Considerations

Although experienced engineers and maintenance personnel may be knowledgeable about historical and current storm system patterns, future climatic conditions may be underestimated. To build risk awareness, a Washington State Department of Transportation assessment asked staff, "What keeps you up at night?" and then used this information to help identify system vulnerabilities that may be exacerbated by future climatic changes. Local knowledge from specialists who have historical information about sites and trends can be particularly useful.

Similar to natural resource categories (e.g., vegetation, wildlife), infrastructure can be analyzed in a structured, detailed manner based on the vulnerability components: exposure, sensitivity, and adaptive capacity (IPCC 2007). Exposure is the potential for infrastructure to be adversely affected by a climate stressor, 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.

In order to complete a detailed assessment, an interdisciplinary team can be identified to determine key assets. Then, climate stressors are identified (fig. 11.6), and information is collected for key assets. For climate stressors, indicators or thresholds can be identified to categorize vulnerabilities. Ranking assets by defined values and risks will help prioritize planning, funding, replacement, and maintenance activities. For example, roads and recreation sites that are heavily used and are likely to be exposed to multiple stressors (e.g., wildfire, flooding) are key assets that may require significant investment to ensure resilience in a warmer climate.

Assessing the Effects of Climate Change

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

The 12 national forests in the Intermountain Region contain 45,769 miles of roads (table 11.1) and 31,074 miles of trails (tables 11.2, 11.3). Of the existing roads, only 2,007 miles are paved. Road density is typically higher at low elevations or adjacent to mountain passes near major highways. Roads and trails cross many streams and rivers because of rugged mountain topography. Most known road-stream crossings are culverts or bridges that were installed decades ago. Some crossings have been replaced, but many culverts have not been inventoried and conditions are unknown. In many landscapes, historical road locations are more likely to be adjacent to streams, greatly increasing risk of road damage and degraded aquatic resources.

There are 862 USFS-owned bridges in the Intermountain Region that are regularly inspected per Federal Highway Administration criteria, which include waterway

Table 11.1—Road length for different maintenance levels in national forests in the U.S. Forest Service Intermountain Region (INFRA USFS n.d.).

	Operational maintenance level					
National forest	Basic custodial care (closed)[a]	High-clearance vehicles[b]	Suitable for passenger cars[c]	Moderate degree of user comfort[d]	High degree of user comfort[e]	Total
	Miles					
Ashley	34	1,159	364	221	248	2,027
Boise	1,685	3,107	1,121	126	457	6,496
Bridger-Teton	617	995	407	248	358	2,624
Caribou-Targhee	1,554	1,538	593	199	23	3,908
Dixie	1,050	2,118	483	64	539	4,254
Fishlake	308	2,094	195	30	42	2,669
Humboldt-Toiyabe	826	5,837	1,338	118	47	8,165
Manti-La Sal	346	1,914	454	133	1	2,848
Payette	968	1,888	444	36	11	3,347
Salmon-Challis	1,241	2,316	388	41	2	3,987
Sawtooth	320	1,519	404	46	53	2,342
Uinta-Wasatch-Cache	234	1,979	491	171	226	3,102
Total	9,182	26,465	6,682	1,433	2,007	45,769

[a] Roads placed in storage (more than 1 year) between intermittent uses, basic custodial maintenance is performed, and 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] Moderate degree of user comfort and convenience at moderate travel speeds.
[e] High degree of user comfort and convenience.

capacity and stream channel characteristics and condition. Approximately 70 percent of them are constructed of timber, and the remaining are constructed of concrete and steel. Many timber bridges, which were constructed during the 1960s when timber sales were common, are too short, resulting in scour near bridge abutments. Most timber bridges are nearing the end of their intended lifespan, whereas most concrete and steel bridges were designed adequately for flows and are in good condition. The Regional Bridge Engineer may determine whether a specific bridge is particularly vulnerable to climatic events. 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 significantly more resilient to climate change.

Determining the effects of construction, maintenance, operations, decommissioning, or abandoning roads and trails is crucial, because each of these actions affects the environment in many ways (Gucinski et al. 2001). Geotechnical evaluation of proposed road locations, which is essential for stable roads, was not done in the early years of road construction. Roads constructed several decades ago often have culverts and bridges (table 11.4) that are at

Table 11.2—Summary of trail distance and trail bridges in national forests in the U.S. Forest Service Intermountain Region (INFRA USFS n.d.).

National forest	Distance	Trail bridges
	Miles	*Number*
Ashley	1,219	41
Boise	2,251	67
Bridger-Teton	3,500	47
Caribou-Targhee	4,016	52
Dixie	2,004	23
Fishlake	2,559	3
Humboldt-Toiyabe	3,647	9
Manti-La Sal	1,035	5
Payette	1,885	103
Salmon-Challis	3,448	53
Sawtooth	2,574	84
Uinta-Wasatch-Cache	2,936	95
Total	31,074	542

Table 11.3—Summary of Watershed Condition Framework criteria used to classify road and trail function in the U.S. Forest Service Intermountain Region.

Attribute	Good: functioning properly[a]	Fair: functioning at risk[b]	Poor: impaired function[c]
Open road density	Road/trail density is <1 mile per square mile or a locally determined threshold for good conditions supported by forest plans or analysis and data.	Road/trail density is 1–2.4 miles per square mile, or a locally determined threshold for fair conditions supported by forest plans or analysis and data.	Road/trail density is >2.4 miles per square mile, or a locally determined threshold for poor conditions supported by forest plans or analysis and data.
Road and trail maintenance	Best Management Practices (BMPs) for maintenance of designed drainage features are applied to >75% of roads, trails, and water crossings.	BMPs for maintenance of designed drainage features are applied to 50–75% of roads, trails, and water crossings.	BMPs for maintenance of designed drainage features are applied to <50% of roads, trails, and water crossings.
Proximity to water	<10% of road/trail length is located within 300 feet of streams and water bodies or hydrologically connected to them.	10–25% of road/trail length is located within 300 feet of streams and water bodies or hydrologically connected to them.	>25% of road/trail length is located within 300 feet of streams and water bodies or hydrologically connected to them.
Mass wasting	Very few roads are on unstable landforms or rock types subject to mass wasting with little evidence of active movement or road damage. No danger of large quantities of debris being delivered to the stream channel.	A few roads are on unstable landforms or rock types subject to mass wasting with moderate evidence of active movement or road damage. Some danger of large quantities of debris being delivered to the stream channel, although this is not a primary concern.	Most roads are on unstable landforms or rock types subject to mass wasting with extensive evidence of active movement or road damage. Mass wasting that could deliver large quantities of debris to the stream channel is a primary concern.

[a] Density and distribution of roads and linear features indicate that the hydrological regime (timing, magnitude, duration, and spatial distribution of runoff flows) is substantially intact and unaltered.
[b] Density and distribution of roads and linear features indicate that there is a moderate probability that the hydrological regime is substantially altered.
[c] Density and distribution of roads and linear features indicate that there is a higher probability that the hydrological regime is substantially altered.

the end of their design life, making them more susceptible to damage by extreme hydrological events. Many stream crossings with culverts were designed to accommodate 25-year peakflows, whereas current standards typically require sizing for 100-year flows. Many older culverts have reached or passed their design life and are failing. Until recently, culvert sizing was generally expected to last 25 years, representing a surprisingly 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 (Gucinski et al. 2001). Although engineering knowledge is greater now than when most roads and other infrastructure were built, geotechnical skills are still in short supply at many locations in the USFS and other land management agencies.

The relationship between vulnerability and the current value of roads and other infrastructure may not be clear in some cases. For example, some roads constructed for timber purposes are now used for public recreation and access to small rural communities. Therefore, road standards and risk of the loss of continuity are not consistent with the value of the access or consequences of loss. Many administrative and recreation sites are vulnerable because they are located near streams and geomorphically unstable areas (table 11.5). Although exposures and risks differ from place to place, many roads and trails are vulnerable, and as noted earlier, documentation of the amount and spatial distribution of infrastructure is a first approximation of vulnerability (figs. 11.2, 11.5). In general, units of analysis (e.g., subwatersheds) that have extensive infrastructure are more vulnerable than those that have little or no infrastructure.

Road Management and Maintenance

The condition of roads and trails differs widely across the IAP region (tables 11.1, 11.3), as do the effects of roads on watersheds and aquatic ecosystems. Road construction has declined since the 1990s, with few new roads being added. Road maintenance is primarily the responsibility of Federal agencies, but County road maintenance crews maintain some roads. The Federal Highway Administration is also involved with the management, design, and funding of highways within national forests and national parks, as well as the State highway system.

Roads vary in level of environmental impact. They tend to accelerate runoff rates, decrease late season flows, increase peakflows, and increase erosion rates and sediment

Table 11.4—Summary of bridge conditions in national forests in the U.S. Forest Service Intermountain Region (INFRA USFS n.d.).

National forest	Adequate	Structurally deficient	Total
	---------------------*Number*-------------------		
Ashley	30	7	37
Boise	90	9	99
Bridger-Teton	85	31	116
Caribou-Targhee	58	19	77
Dixie	38	13	51
Fishlake	15	0	15
Humboldt-Toiyabe	60	5	65
Manti-La Sal	26	4	30
Payette	60	2	62
Salmon-Challis	101	20	121
Sawtooth	95	12	107
Uinta-Wasatch-Cache	68	14	82
Total	726	136	862

delivery to stream systems (Furniss et al. 2000; Guckinski et al. 2001). These impacts are generally greater from roads near rivers and streams, although roads in uplands also affect surface flows, shallow groundwater flows, and erosion processes (Trombulak and Frissell 2000). The effects of stream proximity and terrain slope on road failures can be discerned from data on road damage and failures, although these data are uncommon in most areas.

Each national forest develops a road maintenance plan for the fiscal year, primarily based on priorities by operational maintenance level, then by category and priority. Roads for passenger cars are subject to National Traffic and Motor Vehicle Safety Act standards (23 USC chapter 4, section 402), receiving priority for appropriated capital maintenance, road maintenance, and improvement funds over roads maintained for high-clearance vehicles. Activities that are critical to health and safety receive priority for repair and maintenance, but are balanced with demands for access and protection of aquatic habitat.

Given current and projected funding levels, national forest staff are examining tradeoffs associated with providing access, and maintaining and operating a sustainable transportation system that is safe, affordable, and responsive to public needs while causing minimal environmental impact. Management actions being implemented to meet these objectives include reducing road maintenance levels, stormproofing roads, upgrading drainage structures and stream crossings, reconstructing and upgrading roads, decommissioning roads, converting roads to alternative modes of transportation, and developing more comprehensive access and travel management plans. Unfortunately, current levels of funding for maintenance are generally insufficient to reduce the risk of climate-related damage to roads.

Major transportation projects in national forests, such as reconstruction of roads and trails or decommissioning, must comply with NEPA, which often requires an environmental assessment and public involvement. Decommissioning or obliteration of roads is a process of restoring roads to a more natural state by 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).

Spatial and terrain analysis tools developed to assess road risks, such as the Water and Erosion Predictive model (Flanagan and Nearing 1995), GRAIP (Black et al. 2012; Cissel et al. 2012), and NetMap (Benda et al. 2007), are often used to identify hydrological effects and guide management on projects. For example, a recent analysis on the Payette National Forest determined that 8 percent of the road system contributes 90 percent of the sediment; analysis results help to prioritize treatment plans by identifying the most critical sites (Nelson et al. 2014). Similar findings have been observed with GRAIP modeling on other national forests in the Intermountain Region.

Climate Change Effects on Transportation Systems

Most effects of high temperatures on roads and associated infrastructure are indirect, through the influence of altered snowpack dynamics, wildfire, and extreme events. However, some direct effects of high temperature exist, including softening and buckling of pavement, thermal expansion of bridge-expansion joints, rail-track deformities related to heating, limitations on periods of construction activity due to health and safety concerns, lengthening of the construction season in cold areas, and vehicle overheating (resulting in roadway incidents and safety issues) (INFRA n.d.).

Climate change is expected to significantly alter hydrological regimes, especially in the latter half of the 21st century (Chapter 4) (fig. 11.7). Specifically, climate and hydrology may affect the transportation system in the IAP region through reduced snowpack and earlier snowmelt and runoff, resulting in a longer season of road use, higher peakflows and flood risk, and increased landslide risk on steep slopes associated with more intense precipitation and elevated soil moisture in winter (Strauch et al. 2014). Increased drought and wildfire disturbance (chapters 6, 7), in combination with higher peakflows, may also lead to increased erosion and landslide frequency. Proximity of roads and other infrastructure to streams provides an approximation of hydrological connectivity (Furniss et al. 2000), indicating the hazard of sedimentation, pollutants, and peakflow changes. Changes in climate and hydrology

Table 11.5—Developed recreation sites in national forests in the U.S. Forest Service Intermountain Region (INFRA USFS n.d.).

National forest	Boating site	Campground	Camping area	Group campground	Interpretive site	Interpretive visitor	Lookout/ cabin	Picnic site	Trailhead
Ashley	15	60	8	12	26	1	9	6	11
Boise	20	68	7	8	4	0	18	5	88
Bridger-Teton	18	40	3	4	15	3	11	12	110
Caribou-Targhee	14	47	6	5	2	2	14	3	31
Dixie	5	23	6	3	0	2	4	2	45
Fishlake	3	27	14	4	8	0	8	2	52
Humboldt-Toiyabe	2	60	7	6	4	1	5	11	49
Manti-La Sal	4	34	3	9	17	1	8	1	51
Payette	1	36	23	0	29	0	3	1	31
Salmon-Challis	2	50	24	2	5	0	2	7	30
Sawtooth	10	74	1	5	9	2	0	12	35
Uinta-Wasatch-Cache	8	109	11	7	7	4	10	42	158
Total	102	628	113	65	126	16	92	104	691

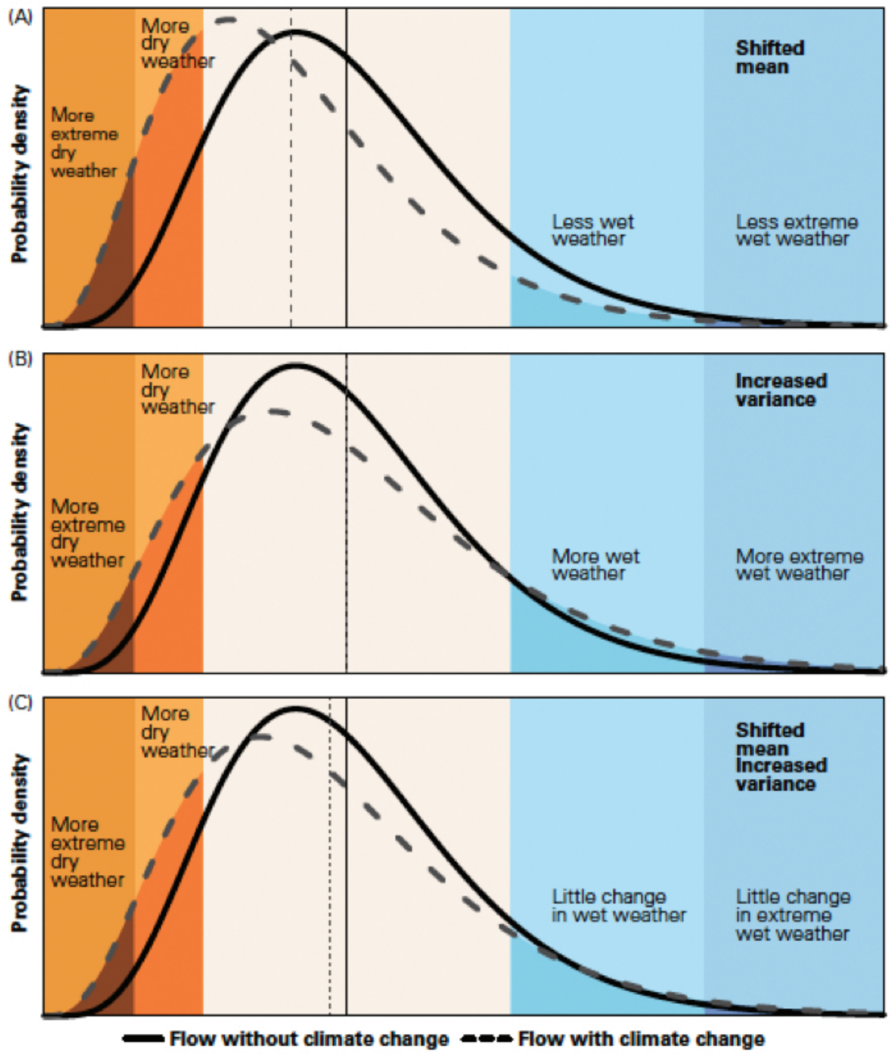

Figure 11.7—Conceptual diagram of how hydrological flow can be affected by both a change in the mean and change in the variance of climate and weather. Climate change is expected to increase the frequency and magnitude of peakflows and flooding in winter (from Field et al. 2012).

can have direct and indirect effects on infrastructure and access, and damage can be chronic or sudden (Bisson et al. 1999; Goode et al. 2012). Direct effects are those that physically alter the operation or integrity of transportation facilities (figs. 11.8–11.10). These include effects related to floods, snow, landslides, extreme temperatures, and wind. Indirect effects include secondary influences of climate change on access that can increase threats to public safety and change visitor use patterns. For hydrological extremes such as flooding, the effect on access may be related more to weather events (e.g., the effects of a single storm) than to climate trends (Keller and Ketcheson 2015). But the expansion of future extremes outside the historical range of frequency or intensity is likely to have the greatest impacts, for example by exceeding current design standards for infrastructure.

Projected changes in soil moisture and form of precipitation with climate change may locally accelerate mass wasting. Shallow, rapid debris slides may become more frequent, impacting infrastructure and access. Climate projections indicate that the conditions that trigger landslides will increase because more precipitation will fall as rain rather than snow, and more winter precipitation will occur in intense storms (Goode et al. 2012; Salathé et al. 2014). These effects will probably differ with elevation because higher elevation areas typically have steeper slopes and more precipitation during storms. Flooding can also be exacerbated by increased basin size during rain events because elevation at which snow falls is projected to move higher (Hamlet et al. 2013). Furthermore, reduced snowpack is expected to increase antecedent soil moisture in winter (Clifton et al. 2017; Goode et al. 2012; Luce 2018).

Elevated soil moisture and rapid changes in soil moisture can affect slope stability and are responsible for triggering more landslides than any other factor (Crozier 1986). Antecedent moisture, geology, soil conditions, land cover, and land use also affect landslides (Kim et al. 1991; Strauch et al. 2014), and areas with projected increases in antecedent soil moisture (coupled with more intense winter storms) will have increased landslide risk (box 11.3). Although the Variable Infiltration Capacity (VIC) model (Chapter 4) does not directly simulate slope stability failures or landslides, VIC model projections of December 1 total column soil moisture can be used as an indicator of landslide risk.

Figure 11.8—Damage caused by a small stream. Proximity to streams affects the vulnerability of roads and associated infrastructure to high streamflows. Even small streams can cause road damage and failure during large storms and where slopes are unstable (photo: S. Hines, U.S. Forest Service).

Figure 11.9—Erosion next to a forest road. Extreme rainfall and flooding can cause severe gully erosion adjacent to forest roads (photo from Keller and Ketcheson 2015, used with permission).

Figure 11.10—Washout of a road in a floodplain as a result of channel widening during high river flow (photo from Keller and Ketcheson 2015, used with permission).

Box 11.3—Factors Related to Vulnerability of Infrastructure to Climate Change

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 or insufficient funds, or both, 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

- Are located near streams and rivers
- Cross streams and rivers
- Are built on steep, unstable slopes
- Are 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 probably cause failures down-road)
- Have unstable fills and side cast
- Are subject to diverted drainage from other roads and facilities
- Are 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

- Are located near streams and rivers
- Have facilities that attract public use in areas subject to flooding or landslides, or both
- Are reached by roads or trails that are vulnerable
- Are 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

- Are reached by roads or trails that are vulnerable
- Are located near streams or rivers and subject to flooding
- Are in areas subject to landslide hazards
- Have high risk of damage or destruction by wildfire
- Are poorly insulated
- Have inadequate ventilation
- Have substandard plumbing or plumbing not protected from the weather
- Are in locations that are subject to loss or changes due to climatic extremes

Box 11.3 (*continued*)—Factors Related to Vulnerability of Infrastructure to Climate Change

Dams

- Have inadequate safety provisions
- Have inadequate safety inspection frequency
- Have inadequate spillways for extreme storms
- Have inadequate structural integrity against aging and extreme events
- Are subject to cracking or failure caused by earthquakes, extreme flooding, or landslides
- Are subject to new hydrological regimes in areas where snowfall and snowpack are declining

Ecosystems associated with streams that are subject to impacts from infrastructure

- Have rare species that are 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., side casting) periodically disturb habitats
- Multiple crossings or road or trail segments in near-stream locations remove shade and may reduce large-wood recruitment
- Other factors are stressing communities and habitats
- Have lotic habitats that are fragmented by road-stream crossings or other barriers that restrict migration and movement (connectivity) of aquatic organisms

Projections from the VIC model indicate that December 1 soil moisture will be higher as the climate warms, and thus there will be higher landslide risk in winter on unstable land types at higher elevations (Goode et al. 2012).

Vulnerability of roads to hydrological change (Chapter 4) varies based on topography, geology, slope stability, design, location, and use. To assess vulnerability of the transportation system and infrastructure in the IAP region, we identified traits of the transportation system most sensitive to projected climatic changes (box 11.3) in order to inform transportation management and long-range planning (Flanagan and Furniss 1997; Flanagan et al. 1998).

Roads and trails built decades ago have increased sensitivity because of age and declining condition. Many infrastructure components are at or near the end of their design lifespan. Culverts were typically designed to last 25 to 75 years, depending on structure and material. Culverts remaining in place beyond their design life are less resilient to high flows and bed load movement and have a higher likelihood of structural failure. Underdrains can clog with time and retaining structure components can corrode, degrade, and weaken. As roads and trails age, their surface and subsurface structure deteriorates, and less intense storms can cause more damage than storms of high intensity would have caused when the infrastructure was new.

Advanced material design, alignment, drainage, and subgrade that are required standards today were generally not available or were not required when much of the travel network was developed. Consequently, newer or replaced infrastructure will generally have higher resilience to climate change, especially 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 fish passage and stream function, using open-bottomed arch structures that are less constricted during high flows and accommodate aquatic organism 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 effectively at these crossings (Gillespie et al. 2014). In addition, culverts on nonfish-bearing streams are being upgraded as funding and opportunities become available.

The location of roads and trails can increase vulnerability 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 peakflows, which can affect road crossing structures (Croke and Hairsine 2006; Schmidt et al. 2001; Swanston 1971). Many roads and trails were also constructed in valley bottoms near streams to take advantage of gentle grades, but proximity to streams increases sensitivity to flooding, channel migration, bank erosion, and shifts in alluvial fans and debris cones. Most road-stream crossings use culverts rather than bridges, and culverts are generally more sensitive to increased flood peaks and associated debris.

Roads currently in the rain-on-snow zone, typically in mid-elevation basins, may be increasingly sensitive to warmer temperatures because this is where significant snowpack accumulation is subject to warm storms. Increased peakflow magnitudes can be modeled with some accuracy for changes in snowpack and effects on rain-on-snow runoff mechanisms (Safeeq et al. 2014). Although temperature-induced changes in snowpack dynamics will be manifested in the Pacific Northwest sooner than in most of the Intermountain Region, some areas of the western IAP region are considered vulnerable to increased peakflows. In addition, if total precipitation and intensity increase, peakflows in subalpine watersheds may increase significantly (Muzik 2002). Management of roads and trails (planning, funding, maintenance, and response) affects sensitivity of the transportation system, and the condition of one road or trail segment can affect the function of connected segments. Major highways within the IAP region, built to higher design standards and maintained more frequently, will be less sensitive to climate change than unpaved roads in national forests that were built with lower design standards. Lack of funding can limit options for repairing infrastructure, as well as result in less maintenance, which can affect the short- and long-term vulnerability of the transportation system. For example, replacing a damaged culvert with an "in kind" culvert that was undersized for the current streamflow conditions leads to continued sensitivity to both current flow regime and projected higher flows.

Climate Change Effects on Trails

Land managers can follow a similar assessment process for trail systems as for roads. The IAP region has an extensive trail system in a variety of ecosystems managed and maintained in collaboration with various partners (table 11.2) (Chapter 10). To respond to expected changes in hydrological regimes (Chapter 4), trails will need to be increasingly resilient to higher peakflows and flood frequency, so design changes may need to accommodate projected peakflows rather than historical peakflows (Strauch et al. 2014). With declining agency budgets, increasing the resilience of trail systems will require creative approaches. Partnerships are helping national forests in the Intermountain Region to maintain parts of the trail system.

Climate Change Effects on Developed Recreation Sites

Although trails make up a significant proportion of the recreation system, developed recreation sites are also common assets that are often vulnerable to climate-related stresses (table 11.6). Damaged recreation sites reduce access and services for visitors (Chapter 10) and may incur considerable economic loss. Camping is one of the most popular warm-weather activities in the IAP region (Chapter 10). Many campgrounds are located near streams, often in floodplains, locations that are particularly vulnerable because climate change will increase the frequency and magnitude of flooding (Chapter 4), potentially damaging infrastructure and creating safety problems. Similar issues may affect boating sites along streams, and some lakeshore sites may become less accessible if water levels decrease during droughts. Additional drought-related impacts include erosion and soil compaction of shorelines, decreased water quality from algal blooms, and exposure to invasive species. Dump sites can also be affected by water-related disturbance.

Recreation infrastructure in upland areas will be vulnerable to wildfire damage. 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 adjacent to vegetation with high fuel loadings, and access for fire suppression may be difficult. Downhill ski areas, and, to a lesser extent, cross-county ski areas and snowparks, typically have dense clusters of recreational infrastructure and lodging, with the potential for large economic losses.

Climate Change Effects on Facilities

The Intermountain Region has 2,195 fire, administrative, and other facilities that encompass a structural footprint of over 2 million square feet (table 11.7). The facilities serve many purposes, ranging from administrative offices in urban areas to backcountry cabins. In 2017, the total current replacement value for these facilities was $440 million.

Since 2004, every national forest in the Intermountain Region has had a facility master plan (FMP), and some forests have done updates. 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. Future revisions of FMPs can incorporate components of climate change assessment and adaptation.

The USFS has a Capital Improvement Program (CIP), which is a national-level funding mechanism that funds top-ranked CIP 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 (ESPCs), which seek to reduce energy requirements, have been implemented. These utilize third-party financers and contractors to develop large-scale (>$1 million) energy efficiency measures. The Intermountain Region is currently paying on a 25-year ESPC that funded small projects such as light and sink fixture replacement.

Increased use of wood in building projects links USFS facilities with healthy forests. Wood products in building systems tend to have lower environmental burdens than functionally equivalent products, and require less energy if used in wall systems (Ritter et al. 2011). Replacing other materials with wood products reduces the rate of carbon

Table 11.6—Relative vulnerability to climate change of administrative and recreation infrastructure in the U.S. Forest Service Intermountain Region (see table 11.5). Ratings are approximate and relative, based on coarse generalizations of value of the type of feature, typical exposures to climatic stresses, typical sensitivity to climatic stresses, and consequences of loss.

Type	Feature	Relative vulnerability
Administrative	Documentary site	Moderate
Administrative	Information site/fee station	Moderate
Administrative	Interpretive site	Moderate
Administrative	Interpretive site–administrative	High
Administrative	Interpretive visitor center (large)	High
Administrative	Interpretive visitor center (small)	Moderate
Picnic	Day use area	Moderate
Picnic	Group picnic site	Moderate
Picnic	Picnic site	Low
Camp	Campground	Moderate
Camp	Camping area	Low
Camp	Group campground	Moderate
Recreation	Boating site	High
Recreation	Fishing site	Moderate
Recreation	Horse camp	Low
Recreation	Hotel, lodge, resort	High
Recreation	Lookout/cabin	High
Recreation	Observation site	Low
Recreation	Other recreation concession site	Moderate
Recreation	Swimming site	Moderate
Recreation	Trailhead	Low
Recreation	Wildlife viewing site	Low
Other	Dump station	High
Other	Off-highway vehicle staging area	Moderate
Other	Organization site	Moderate
Snow	Nordic ski area	High
Snow	Snowpark	High
Snow	Snowplay area	Moderate

emissions to the atmosphere. However, increased use of wood structures also increases exposure and potential damage from wildfires.

Potential adjustments in building design to accommodate a warmer climate include modified roof design with respect to snow load, and modified footing depth with respect to the frost protection line (Olsen 2015). In addition, water facilities can be designed to improve efficiency and conserve water, especially in arid locations. Although the USFS uses current building standards for structures, a warmer climate may motivate future changes in design.

Climate Change Effects on Dams

The Intermountain Region contains 317 dams distributed among 12 national forests (table 11.8). Dams are typically sized to withstand the probable maximum flood (PMF, or 10,000-year flood flow). Such a high standard reflects the severe consequences of dam failure in terms of loss of human life and property, as well as damage to aquatic and riparian ecosystems. If climate change causes an increased frequency and magnitude of peakflows as expected, the PMF may increase, although it will be difficult to project the occurrence of rare, extreme events.

Table 11.7—Summary of fire, administrative, and other buildings in national forests in the U.S. Forest Service Intermountain Region (INFRA USFS n.d.).

National forest	Buildings	Total deferred maintenance	Current replacement value
	-----*Number*-----	---------------------*Dollars*---------------------	
Ashley	117	3,209,244	27,992,597
Boise	278	7,694,875	70,596,571
Bridger-Teton	220	1,697,102	35,884,205
Caribou-Targhee	170	1,222,776	40,343,855
Dixie	98	3,583,176	21,397,194
Fishlake	89	364,549	8,811,909
Humboldt-Toiyabe	255	8,190,928	52,857,539
Manti-La Sal	79	920,872	9,516,946
Payette	237	14,095,341	54,471,482
Salmon-Challis	278	18,677,939	44,905,880
Sawtooth	142	7,781,721	25,255,776
Uinta-Wasatch-Cache	227	7,151,204	45,857,589
Regional	5	396,713	1,656,011
Total	2,195	74,986,439	439,547,553

Increasing temperature in future decades is expected to reduce water supplies for agriculture, industrial uses, human consumption, and fisheries (Chapter 4). Dams are usually a buffer to water shortages, so there may be increased emphasis on maintaining current dams and new applications for additional dams on public lands, particularly upstream from areas where private uses of water have a significant impact on streamflow during critical water-need seasons. Federal agencies will need to respond to these applications and associated environmental assessments, which are typically complex and time consuming.

Table 11.8—Summary of dams in national forests in the U.S. Forest Service Intermountain Region (INFRA USFS n.d.).

National forest	Active	Inactive/disposed	Total
	-----------------------------*Number*------------------------		
Ashley	29	0	29
Boise	4	0	4
Bridger-Teton	16	4	20
Caribou-Targhee	11	0	11
Dixie	39	6	45
Fishlake	36	12	48
Humboldt-Toiyabe	28	1	29
Manti-La Sal	35	7	42
Payette	13	0	13
Salmon-Challis	9	0	9
Sawtooth	3	0	3
Uinta-Wasatch-Cache	47	17	64
Total	270	47	317

Box 11.4—Exposure to Climate Change of Transportation Systems and Access in the Intermountain Adaptation Partnership Region

Current and short-term exposures (less than 10 years)

- Roads and trails will be damaged by floods and inundation because of mismatches between existing designs and current flow regimes.
- Landslides, debris torrents, and sediment and debris movement will block access routes and damage infrastructure.
- Traffic will be affected by temporary closures to clean and repair damaged roads and trails.
- Frequent repairs and maintenance from damages and disruption will incur higher costs and resource demands.

Medium-term exposures (intensifying or emerging in about 10–30 years)

- Flood and landslide damage is likely to increase in late fall and early winter, especially in watersheds with mixed rain and snow.
- Current drainage capacities may become overwhelmed by additional water and debris.
- Increases in surface material erosion are expected.
- Backlogged repairs and maintenance needs will grow with increasing damages.
- Demand for travel accommodations, such as easily accessible roads and trails, is projected to increase.
- Increased road damage will challenge emergency response units, making emergency planning more difficult.

Long-term exposures (emerging in 30–100 years)

- Fall and winter storms are expected to intensify, greatly increasing flood risk and infrastructure damage and creating a greater need for cool-season repairs.
- Higher streamflows will expand channel migration, potentially beyond recent footprints, causing more bank erosion, debris flows, and wood and sediment transport into streams.
- Changes in hydrological response may affect visitation patterns by shifting the seasonality of use.
- Shifts in the seasonality of visitation may cause additional challenges to visitor safety, such as increased use in areas and during seasons prone to floods and avalanches.
- Managers will be challenged to provide adequate flexibility to respond to uncertainty in impacts to access.

Rain-on-snow events, which can intensify peakflows, may become more common at higher elevations, and less common at lower elevations. Flow hydrographs in the lower-elevation snow zones will change from snowmelt dominated to rainfall dominated, thereby increasing peakflows substantially (Chapter 4). Dams that are in the rain-snow transition snow zone and lower-elevation snow zones will be increasingly subject to flows that were not characteristic during their design and construction. Evaluating dams for safety hazards, a responsibility of national forests, may become even more important in the future.

Projected Climate Change Effects

Near-Term Climate Change Effects

Assessing the vulnerability and exposure of infrastructure in the IAP region to climate change requires evaluating projected changes in hydrological processes (boxes 11.3, 11.4). The integrity and operation of the transportation network may be affected in several ways.

Higher streamflow in winter (October through March) and higher peakflows, in comparison to historical conditions, will increase the risk of flooding and impacts on structures, roads, and trails. Many transportation professionals consider flooding and inundation to be the greatest threat to infrastructure and operations because of the damage that standing and flowing water cause to transportation structures (MacArthur et al. 2012; Walker et al. 2011). Floods also transport logs and sediment that block culverts or are deposited on bridge abutments. Isolated intense storms can overwhelm the vegetation and soil water holding capacity and concentrate high velocity flows into channels that erode soils and remove vegetation. During floods, roads and trails can become preferential paths for flood waters, reducing operational function and potentially damaging infrastructure not designed to withstand inundation. If extreme peakflows become more common, they will have a major effect on roads and infrastructure.

In the short term, flooding of roads and trails may increase, threatening the structural stability of crossing structures and subgrade material. Roads near perennial streams are especially vulnerable (fig. 11.3), and many of these roads are located in floodplains and are used for recreation access. Increases in high flows and winter soil moisture may also increase the amount of large woody debris delivered to streams, further increasing damage to culverts and bridges, and in some cases making roads impassable or requiring road and facility closures. Unpaved roads with limited drainage structures or minimal maintenance are likely to undergo increased surface erosion and gully formation, requiring additional repairs or grading.

Increasing incidence of more intense precipitation and higher soil moisture in early winter could increase the risk of landslides in some areas. Landslides also contribute to flooding by diverting water, blocking drainage, and filling channels with debris (Chatwin et al. 1994; Crozier 1986; Schuster and Highland 2003). Increased sedimentation from landslides also causes aggradation within streams, thus elevating flood risk. Culverts filled with landslide debris can cause flooding, damage, or complete destruction of roads and trails (Halofsky et al. 2011). Landslides that connect with waterways or converging drainages can transform into more destructive flows (Baum et al. 2007). Roads themselves also increase landslide risk (Swanson and Dyrness 1975; Swanston 1971), especially if they are built on steep slopes and through erosion-prone drainages. In the western United States, the development of roads increased the rate of debris avalanche erosion by 25 to 340 times the rate found in forested areas without roads (Swanston 1976), and that number of landslides is directly correlated with total miles of roads in an area (Chatwin et al. 1994; Montgomery 1994). Consequently, areas with high road or trail density and projected increases in soil moisture may be vulnerable to increased landslide risks, especially if an area already experiences frequent landslides.

Short-term changes in climate may affect safety and access in the IAP region. Damaged or closed roads reduce agency capacity to respond to emergencies or provide detour routes during emergencies (Olsen 2015). Increased flood risk could make conditions more hazardous for river recreation and campers. More wildfires (Chapter 8) could reduce safe operation of some roads and require additional emergency response to protect recreationists and communities (Strauch et al. 2014). Furthermore, damaged and closed roads can reduce agency capacity to respond to wildfires.

Longer-Term Climate Change Effects

Many of the short-term effects of climate change are likely to increase in the medium (10–30 years) and long term (>30 years) (Strauch et al. 2014) (box 11.4). In the medium term, natural climatic variability may continue to affect outcomes in any given decade, whereas in the long term, the cumulative effects of climate change may become a dominant factor, particularly for temperature-related effects. Conditions thought to be extreme today may be averages in the future, particularly for temperature-related changes (MacArthur et al. 2012).

Flooding in winter is projected to continue to intensify in the long term (Huntington 2006), particularly in mixed rain-and-snow basins, but direct rain-and-snow events may diminish in importance as a cause of flooding (McCabe et al. 2007). At mid- to high elevations, more precipitation falling as rain rather than snow will continue to increase winter streamflow. By the 2080s, peakflows are anticipated to increase in magnitude and frequency (Chapter 4). In the long term, higher and more frequent peakflows are likely to continue to increase sediment and debris transport within waterways. These elevated peakflows could affect stream-crossing structures downstream as well as adjacent structures because of elevated stream channels. Even as crossing structures are replaced with wider and taller structures, shifting channel dynamics caused by changes in flow and sediment may affect lower elevation segments adjacent to crossings, such as bridge approaches. Flooding can cause stream aggradation and degradation. With stream degradation, bridge footings may become exposed, undercut, and possibly unstable.

Projected increases in flooding in fall and early winter will shift the timing of peakflows and affect the timing of maintenance and repair of roads and trails. More repairs may be necessary during the cool, wet, and dark time of year in response to damage from fall flooding and landslides, challenging crews to complete necessary repairs before snowfall. If increased demand for repairs cannot be met, access may be restricted until conditions are suitable for construction and repairs. Delayed repairs have the potential effect of further damaging ecosystems.

Over the long term, higher winter soil moisture may increase landslide risk, especially in areas with tree mortality from fire and insect outbreaks, because tree mortality reduces soil root cohesion and decreases interception and evaporation, further increasing soil moisture (Martin 2007; Montgomery et al. 2000; Neary et al. 2005; Schmidt et al. 2001). Thus, soils may become more saturated and vulnerable to slippage on steep slopes during winter. Although floods and landslides will continue to occur near known hazard areas (e.g., because of high forest road density), they may also occur in new areas (e.g., those areas which are currently covered by deep snowpack in midwinter) (MacArthur et al. 2012). Thus, more landslides at increasingly higher elevations (with sufficient soil) may be a long-term effect of climate change.

Climate change effects on access may create public safety concerns for Federal lands (Olsen 2015). A longer snow-free season may extend visitor use in early spring and late fall at higher elevations (Rice et al. 2012) (Chapter 10). Lower snowpack may lead to fewer snow-related road closures for a longer portion of the year, allowing visitors to reach trails and campsites earlier in the season. However, warmer temperatures and earlier snowmelt may encourage use of trails and roads before they are cleared. Trailheads, which are located at lower elevations, may be snow-free earlier, but hazards associated with melting snow bridges, avalanche chutes, or frozen snowfields in shaded areas may persist at higher elevations along trails. Whitewater rafters may encounter unfavorable conditions from lower streamflows in late summer (Hand and Lawson 2018; Mickelson 2009) and hazards associated with deposited sediment and woody debris from higher winter flows. Warmer winters may shift river recreation to times of year when risk of extreme weather and flooding is higher. In addition, less water may be available for water-based recreation at lakes. Some activities may increase use of unpaved roads in the wet season, which can increase damage and associated maintenance costs.

Climate change may also benefit access and transportation operations in the IAP region over the long term. For example, less snow cover will reduce the need for and cost of snow removal. Earlier access to roads and trails will create opportunities for earlier seasonal maintenance and recreation. Temporary trail bridges installed across rivers may be installed earlier in spring as spring flows decline. A longer snow-free season and warmer temperatures may allow for a longer construction season at higher elevations. Less snow may increase access for summer recreation, but it may reduce opportunities for winter recreation, particularly at low and moderate elevations (Joyce et al. 2001; Morris and Walls 2009) (Chapter 10). The highest elevations will retain relatively more snow than other areas, which may create higher local demand for winter recreation and summertime river rafting over the next several decades.

References

Baum, R.; Harp, E.; Highland, L. 2007. Landslide hazards in the Seattle, Washington, area. Fact Sheet 2007-3005. Denver, CO: U.S. Geological Survey. http://pubs.usgs.gov/fs/2007/3005/pdf/FS07-3005_508.pdf [Accessed September 4, 2016].

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.

Bisson, P.A.; Cleaves, D.A.; Everest, F.H.; [et al.]. 1999. Roads analysis: Informing decisions about managing the National Forest transportation system. Misc. Rep. FS-643. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Black, T.A.; Cissel, R.M.; Luce, C.H. 2012. The geomorphic road analysis and inventory package (GRAIP). 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.

Chatwin, S.C.; Howes, D.E.; Schwab, J.W.; [et al.]. 1994. A guide for management of landslide-prone terrain in the Pacific Northwest. Land Manage. Handbk. 18. 2nd ed. Victoria, BC, Canada: Ministry of Forests, Research Program.

Cissel, R.M.; Black, T.A.; Schreuders, K.A.T.; [et al.]. 2012. The geomorphic road analysis and inventory package (GRAIP). Volume 2: Office procedures. Gen. Tech. Rep. RMRS-GTR-281WWW. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Clifton, C.F.; Day, K.T.; Dello, K.; [et al.]. 2017. Climate change and hydrology in the Blue Mountains. In: Halofsky, J.E.; Peterson, D.L., eds. Climate change vulnerability and adaptation in the Blue Mountains region. Gen. Tech. Rep. PNW-GTR-939. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

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

Crozier, M.J. 1986. Landslides: Causes, consequences, and environment. Dover, NH: Croom Helm Limited.

Federal Highway Administration [FHWA]. 2012. Climate change and extreme weather vulnerability handbook. Washington, DC: U.S. Department of Transportation, Federal Highway Administration. http://www.fhwa.dot.gov/environment/climate_change/adaptation/publications/vulnerability_assessment_framework [Accessed September 4, 2016].

Federal Highway Administration [FHWA]. [n.d.]. Emergency relief for Federally owned roads (ERFO). Washington, DC: U.S. Department of Transportation, Federal Highway Administration, Office of Federal Lands Highway. https://flh.fhwa.dot.gov/programs/erfo [Accessed September 3, 2016].

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.

Flanagan, S.; Furniss, M.J. 1997. Field indicators of inlet controlled road-stream crossing capacity. San Dimas, CA: U.S. Department of Agriculture, Forest Service, San Dimas Technology and Development Center.

Flanagan, D.C.; Nearing, M.A., eds. 1995. USDA–Water Erosion Prediction Project: Hillslope profile and watershed model documentation. NSERL Rep. No. 10. Lafayette, IN: U.S. Department of Agriculture, National Soil Erosion Research Laboratory.

Flanagan, S.A.; Furniss, M.J.; Ledwith, T.S.; [et al.]. 1998. Methods for inventory and environmental risk assessment of road drainage crossings. Res. Pap. 9877-1809-SDTDC. San Dimas, CA: US Department of Agriculture, Forest Service, San Dimas Technology and Development Center.

Furniss, M.J.; Flanagan, S.; McFadin, B. 2000. Hydrologically-connected roads: An indicator of the influence of roads on chronic sedimentation, surface water hydrology, and exposure to toxic chemicals. Stream Notes. July 2000: 1–2.

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.

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: 62–76.

Goode, J.R.; Luce, C.H.; Buffington, J.M. 2012. Enhanced sediment delivery in a changing climate in semi-arid mountain basins: Implications for water resource management and aquatic habitat in the northern Rocky Mountains. Geomorphology. 139–140: 1–15.

Gucinski, H.; Furniss, M.J.; Ziemer, R.R.; [et al.]. 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.

Halofsky, J.E; Shelmerdine, W.S.; Stoddard, R.; [et al.]. 2011. Climate change, hydrology, and road management at Olympic National Forest and Olympic National Park. In: Halofsky, J.E; Peterson, D.L.; O'Halloran, K.A.; Hoffman, C.H. Adapting to climate change at Olympic National Forest and Olympic National Park. Gen. Tech. Rep. PNW-GTR-844. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 21–42.

Hamlet, A.F.; Elsner, M.M.; Mauger, G.S.; [et al.]. 2013. An overview of the Columbia Basin climate change scenarios project: Approach, methods, and summary of key results. Atmosphere-Ocean. 51: 392–415.

Hand, M.S.; Lawson, M. 2018. Effects of climate change on recreation. In: Halofsky, J.E.; Peterson, D.L.; Dante-Wood, S.K., eds. Climate change vulnerability and adaptation in the northern Rocky Mountains. Gen. Tech. Rep. RMRS-GTR-374. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Huntington, T.G. 2006. Evidence for intensification of the global water cycle: Review and synthesis. Journal of Hydrology. 319.1: 83–95.

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, UK: Cambridge University Press: 7–22.

Joyce, L.; Abers, J.; McNulty, S.; [et al.]. 2001. Potential consequences of climate variability and change for the forests of the United States. In: Melillo, J.; Janetos, A.; Karl, T., chairs. Climate change impacts on the United States: The potential consequences of climate variability and change. Cambridge, UK: Cambridge University Press: 489–524.

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.

Kim, S.K.; Hong, W.P.; Kim, Y.M. 1991. Prediction of rainfall-triggered landslides in Korea. Landslides. 2: 989–994.

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

Luce, C.H. 2018. Effects of climate change on snowpack, glaciers, and water resources in the Northern Rockies. In: Halofsky, J.E.; Peterson, D.L.; Dante-Wood, S.K., eds. Climate change vulnerability and adaptation in the northern Rocky Mountains. Gen. Tech. Rep. RMRS-GTR-374. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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.

MacArthur, J.; Mote, P.; Ideker, J.; [et al.]. 2012. Climate change impact assessment for surface transportation in the Pacific Northwest and Alaska. Res. Rep. WA-RD 772. Olympia, WA: State of Washington, Department of Transportation, Office of Research and Library Services. OTREC-RR-12-01. Salem, OR: Oregon Transportation Research and Education Consortium.

Martin, Y.E. 2007. Wildfire disturbance and shallow landsliding in coastal British Columbia over millennial time scales: A numerical modeling study. Catena. 69: 206–219.

McCabe, G.J.; Clark, M.P.; Hay, L.E. 2007. Rain-on-snow events in the western United States. Bulletin of the American Meteorological Society. 88: 319–328.

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.

Mickelson, K.E.B. 2009. Impacts of regional climate change on the Pacific Northwest white water recreation industry. Master's thesis. Seattle, WA: University of Washington.

Montgomery, D.R. 1994. Road surface drainage, channel initiation, and slope instability. Water Resources Research. 30: 1925–1932.

Montgomery, D.R.; Schmidt, K.M.; Greenberg, H.M.; [et al.]. 2000. Forest clearing and regional landsliding. Geology. 28: 311–314.

Morris, D.; Walls, M. 2009. Climate change and outdoor recreation resources for the future: Background. Washington, DC: Resources for the Future. http://www.rff.org/RFF/Documents/RFF-BCK-ORRG_ClimateChange.pdf [Accessed September 4, 2016].

Murray, V.; Ebi, K.L. 2012. IPCC special report on managing the risks of extreme events and disasters to advance climate change adaptation (SREX). Journal of Epidemiology and Community Health. 66: 759–760.

Muzik, I. 2002. A first-order analysis of the climate change effect on flood frequencies in a subalpine watershed by means of a hydrological rainfall–runoff model. Journal of Hydrology. 267: 65–73.

Natural Resource Manager-Infra [INFRA]. n.d. Infrastructure corporate database (not accessible to public). Washington, DC: USDA Forest Service. [Accessed April 13, 2017].

Neary, D.G.; Ryan, K.C.; DeBano, L.F., eds. 2005. Rev. 2008. Wildland fire in ecosystems: Effects of fire on soils and water. Gen. Tech. Rep. RMRS-GTR-42-vol.4. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Nelson, N.; Cissel, R.; Black, T.; [et al.]. 2014. GRAIP roads assessment: Upper East Fork Weiser River and Boulder Creek, Payette National Forest. Boise, ID: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Ojima, D.S., Iverson, L.R.; Sohngen, B.L.; [et al.]. 2014. Risk assessment. In: Peterson, D.L.; Vose, J.M.; Patel-Weynand, T., eds. Climate change and United States forests. Dordrecht, The Netherlands: Springer: 233–244.

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.

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.

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

Potyondy, J.P.; Geier, T.W. 2011. Watershed condition classification technical guide. FS-978. Washington, DC: United States Department of Agriculture, Forest Service.

Rice, J.; Tredennick, A.; Joyce, L.A. 2012. Climate change on the Shoshone National Forest, Wyoming: A synthesis of past climate, climate projections, and ecosystem implications. Gen. Tech. Rep. RMRS-GTR-274. Fort Collins, CO; U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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 Lab.

Safeeq, M.; Grant, G.E.; Lewis, S.L.; [et al.]. 2014. A hydrogeologic framework for characterizing summer streamflow sensitivity to climate warming in the Pacific Northwest, USA. Hydrology and Earth System Sciences. 18: 3693–3710.

Salathé, E.P.; Hamlet, A.F.; Mass, C.F.; [et al.]. 2014. Estimates of twenty-first-century flood risk in the Pacific Northwest based on regional climate model simulations. Journal of Hydrometeorology. 15: 1881–1899.

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.

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–Transportation Mgmt. 0877 1801–SDTDC. San Dimas, CA: U.S. Department of Agriculture, Forest Service, National Technology and Development Program.

Swanson, F.J.; Dyrness, C.T. 1975. Impact of clear-cutting and road construction on soil erosion by landslides in the western Cascade Range, Oregon. Geology. 3: 393–396.

Swanston, D.N. 1971. Principal mass movement processes influences 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, School of Forestry and Department of Fisheries and Wildlife: 29–40.

Swanston, D.N. 1976. Erosion processes and control methods in North America. In: Proceedings: 16. IUFRO World Congress, Div. I: Forest environment and silviculture. Aas, Norway: Norwegian IUFRO Congress Committee: 251–275.

Trombulak, S.C.; Frissell, C.A. 2000. Review of ecological effects of roads on terrestrial and aquatic communities. Conservation Biology. 14: 18–30.

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

USDA Forest Service [USDA FS]. 2014. National visitor use monitoring program. Washington, DC: U.S. Department of Agriculture, Forest Service, Recreation, Heritage & Wilderness Resources. http://www.fs.fed.us/recreation/programs/nvum [Accessed September 4, 2016].

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

USDA Forest Service [USDA FS]. [In press]. National best management practices for water quality management on National Forest System lands. Volume 2: National core BMP monitoring technical guide. FS-990b. Washington, DC: U.S. Department of Agriculture, Forest Service.

Vose, J.M.; Clark, J.S.; Luce, C.H.; [et al.], 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.

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.

Walker, L.; Figliozzi, M.; Haire, A.; [et al.]. 2011. Identifying surface transportation vulnerabilities and risk assessment opportunities under climate change: Case study in Portland, Oregon. Transportation Research Record: Journal of the Transportation Research Board. 2244: 41–49.