Infrastructure, Flood Risk, and Sustainable Operations in Front Range National Forests

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Infrastructure, Extreme Events, Climate Change, and Management Concerns

Infrastructure refers to a collection of facilities and services, typically encompassing energy, water and wastewater, waste management, transportation, public health, food and agriculture, telecommunications, and banking (National Research Council 1993). Systems of public buildings, known as public works, contribute important governmental functions and may be incorporated as infrastructure. The U.S. Department of Agriculture, Forest Service considers infrastructure to comprise structures and facilities for administrative, transportation, recreation, or special uses, such as dams and camping concessions (OIG 2017a). The complete Forest Service infrastructure portfolio contains 40,000 buildings, 27,000 recreational sites such as campgrounds, 370,000 miles of roads, 13,000 road and trail bridges, and 3,000 dam structures (OIG 2017a). Public utilities and corridors and privately owned structures, such as oil and gas wells, also occur on National Forest System lands. Infrastructure typically consists of socioeconomic development, but natural areas and hydrologic features also may be considered infrastructure with functions in supplying clean air and water (National Research Council 1993).

Infrastructure is vulnerable to extreme weather events and stresses from changing climate through flooding, drought, wildfire, landslides and debris flows, extreme heat, ice, strong winds, freeze-thaw cycles, and snowmelt (Mora et al. 2018). Multiple outcomes result from extreme events, including interactions (Hanberry 2020). Drought and warming may stress water supplies and indoor cooling systems, create tree mortality and hazard trees, and increase road dust (Hanberry 2020). Drought and warming may increase probability of wildfire, which threatens infrastructure and natural resources, exacerbates flooding, and generates smoky and low visibility conditions (Karau et al. 2024; Rangwala 2024). After vegetation is removed by fire, the likelihood of flooding and debris flow may increase following rain events (Keller et al. 2021). Flooding and associated soil erosion may generate infrastructure failure of administrative buildings, roads, bridges, and recreation sites near streams, steep slopes, and unstable soils (Furniss and Howe 2016; Furniss et al. 2018). Extreme events may cause road closures, emergency evacuation, disruption of livelihoods, injury and mortality, and breakdown of infrastructure networks, such as electrical and water supplies and emergency services (Hanberry 2020; Mora et al. 2018). Climate change likely will increase frequency of extreme events (Karau et al. 2024; Rangwala 2024).

Anticipation of potential infrastructure vulnerabilities due to exposure to natural hazards as a consequence of extreme weather and climate change can help inform management priorities and guide plans to increase infrastructure resilience (Keller et al. 2021). Infrastructure without ongoing maintenance or near its lifecycle end is more likely to fail due to structural weakness, under-design below minimum standards, or more demanding conditions than anticipated (Furniss et al. 2018). Many stream crossings with older culverts were designed to accommodate 25-year peak streamflows, whereas current standards typically require sizing for 100-year flows, resulting in older culverts that are failing due to inadequate culvert capacity and increased plugging hazards (Furniss et al. 2018). Current and future stream flows also may exceed the capacity of bridges and dams (Furniss et al. 2018). Extreme snowfalls can limit transportation and access, while warmer and less snowy winters reduce maintenance and snow removal costs and allow early access to facilities (Keller et al. 2021). Drought and warming above 90 °F may reduce bridge integrity and cause heaving, buckling, and cracking in roads, increasing maintenance costs (Klein et al. 2015). However, if roads are drier and warmer in the future, with reduced erosion and freeze-thaw episodes, weather may cause less damage than under current conditions (Neumann et al. 2015). Variable weather or seasonal changes create problems for scheduling of contracts and maintenance work (Keller et al. 2021). Consequences may be unknown and underestimated, even though infrastructure is vulnerable to extreme weather events.

The Front Range of central Colorado (fig. 1) already may be experiencing climate change and risks to infrastructure caused by design for historical climate conditions instead of current extreme events and future climate change (Lall et al. 2018). Managers and planners for the Rocky Mountain Region and the Arapaho-Roosevelt National Forests and Pike-San Isabel National Forests requested (1) delineation of 100-year-flood boundaries to identify infrastructure within 100-year-flood boundaries for future avoidance of these floodplains; (2) management guidelines for infrastructure that is resilient to climate change and extreme weather events; and (3) information about incorporation of sustainable operations. Based on these management concerns, we specifically assessed flood risk to infrastructure of recreational sites and buildings by developing a GIS layer of 100-year-flood inundation using modeled streamflow rates during 1994 to 2018 (Zheng and Hanberry 2020). However, more work with resource managers, hydrologists, and engineers is needed to assess both this model and risks to infrastructure. Roads, trails, and campgrounds near streams, which are a strong indicator of potential flood hazard, in national forests and grasslands of the Rocky Mountain Region were identified by Furniss and Howe (2016) and manager concerns about fire risk to national forests and the wildlands urban interface are addressed in this report (Karau et al. 2024). We also suggested management practices and sustainable operations for infrastructure and resources for detailed information. In particular, Keller et al. (2021) provided extensive treatments for adapting transportation infrastructure to the effects of climate change and additional national core best management practices are available for roads, trails, and recreation on National Forest System lands (USDA FS 2012).

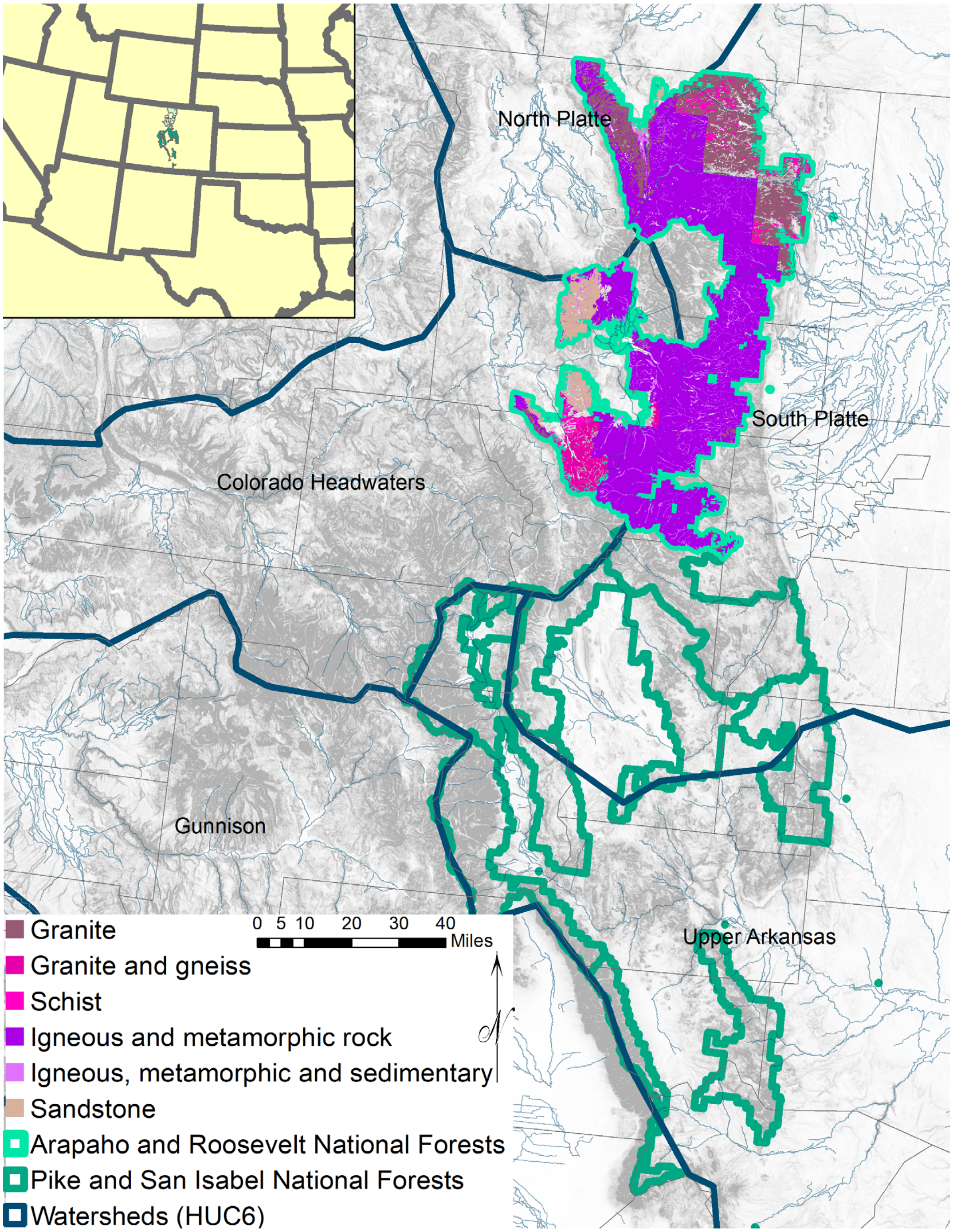

Figure 1—The setting for the Front Range region in central Colorado, including the Arapaho and Roosevelt National Forests and Pike and San Isabel National Forests, watersheds, and topographic roughness (darker gray has greater topographic difference). The Rocky Mountains are comprised primarily of igneous and metamorphic rock, as demonstrated in the Arapaho and Roosevelt National Forests.

Infrastructure and Flooding

Flooding is damaging through direct rainfall, overbank flow, channel scour, soil erosion, treefall, and landslide (Keller et al. 2021). Flooding stresses stream crossings of culverts and bridges, road and drainage systems, and unstable slopes through transportation of large volumes of water and debris, resulting in the potential for failure during high runoff periods (Keller et al. 2021). Consequences of failure include reduced water quality and loss of designated uses due to a range of limited, short-term impacts to severe, long-term impacts (Furniss and Howe 2016). Landslides, or movement of rock and soil due to saturated soil on steep slopes, often worsen flooding and roads commonly increase landslide risks (Furniss et al. 2018). Heavy rains after fire or drought, which reduce vegetation, may result in debris flows (Keller et al. 2021).

Flooding effects on infrastructure involve damage to structures and roads and failure of culverts, dams, and bridges, causing road and trail closures and millions of dollars in basic repairs (ARP 2013; Wobus et al. 2014). Costs consist of transportation disruption, infrastructure relocation or abandonment, and loss of property and even lives (Pralle 2019). In the early hours of June 11, 2010, a flash flood in the Albert Pike Recreation Area campground, Ouachita National Forest, Arkansas, claimed the lives of 20 people (USDA 2010). The area was flood-prone and in a 100-year floodplain. However, the event was judged to be beyond a 500-year return period magnitude, so most safety measures may have been ineffective except for avoidance of locating campgrounds in floodplains (USDA 2010). The 2013 Colorado Front Range Flood produced an estimated $16.8 million in damages to structures in the Arapaho-Roosevelt National Forests, and 10 fatalities, and $2.9 billion in damages for 18 counties in the Front Range (ARP 2013). Other historical peak discharge events in Colorado are recorded (USGS 2022a). Currently, flood events in the Upper Colorado River region average a cost of $27 million per year (Wobus et al. 2014). Flooding costs in the future are expected to average about $52 million per year (Wobus et al. 2014). Damage to infrastructure also can affect water quality and aquatic ecosystems (Furniss and Howe 2016). For example, spills from mine tailings dams on or near National Forest System lands may result in health risks from pollutants, such as at the Gold King Mine wastewater spill near Silverton, Colorado, during 2015 (OIG 2017a).

Current Flood Risk

Currently, data about flooding and their recurrence intervals are not publicly available in the United States (Hydrologic Engineering Center 2023). The Federal Emergency Management Agency (FEMA) ratings are the standard in flood risk (National Research Council 2009; OIG 2017b; Pralle 2019). Flood maps typically are based on a variety of methodologies, including field-intensive data, historical flooding information, and negotiation with 22,000 communities (Pralle 2019). Less populated areas often are excluded from mapping (Pralle 2019). Maps are updated when new flooding events occur (Pralle 2019; Wing et al. 2017). That is, these flood maps are not able to provide accurate assessments of current flood risk for the United States due to varying quality, incompleteness, and lack of funds (estimated at billions of dollars) to revise maps with new information (National Research Council 2009; OIG 2017b; Pralle 2019). For example, after September 2013 flooding in Colorado, Colorado's Legislature funded the Colorado Hazard Mapping Program to determine flood hazard area (Colorado Water Conservation Board 2019).

Flood hazard mapping and modeling in the United States is in a developmental stage (Hydrologic Engineering Center 2023). Global flood models that are openly accessible do not provide detailed information for smaller streams (Bernhofen et al. 2018). A variety of proprietary flood risk models have proliferated in recent years (Risk & Investment 2017). However, due to lack of open access and transparency, the completeness and accuracy of these maps generally is unknown but likely to provide flood risk to houses in urban areas for insurance purposes, with a focus on urban storm water drainage based on impervious surface area and localized storm water drainage infrastructure (Risk & Investment 2017). A national 30-m flood hazard model is available, at a cost, even though flow of urban storm water may not be modeled as accurately as other proprietary flood risk maps (Wing et al. 2017).

Given lack of available model information, Furniss and Howe (2016) evaluated vulnerability of roads, trails, and campgrounds in national forests and grasslands of the Rocky Mountain Region by using road, trail, and campground proximity of 100 feet and 300 feet to streams, thus indicating potential flood hazard. The Arapaho-Roosevelt National Forests and Pawnee National Grasslands contained 812 road miles and 21 recreational sites within 100 feet of streams and 1,219 road miles and 32 recreational sites within 300 feet of streams, out of 5,106 road miles and 79 recreational sites, with 7,786 road and motor trail stream crossings (Furniss and Howe 2016). The Pike and San Isabel National Forests and Cimarron and Comanche National Grasslands contain 1,111 road miles and 35 recreational sites within 100 feet of streams and 1,617 road miles and 66 recreational sites within 300 feet of streams, out of 5,880 road miles and 180 recreational sites, with 8,962 road and motor trail stream crossings (Furniss and Howe 2016).

To provide information about 100-year flood discharge, or a 1 percent chance of being equaled or exceeded during any year under current stationary conditions, we used the following method (documented in Zheng et al. 2018). The National Water Model (NWM version 2.0) is a new tool that simulates hourly water flow for 2.7 million stream locations (National Hydrography Dataset; NHDPlusV2) based on more than 8,000 U.S. Geological Survey gauges in the contiguous United States (Office of Water Prediction 2019). We used the retrospective (1994 to 2018) simulation to extract the maximum flow rate for each stream reach. We then applied the USGS bulletin 17B flood frequency analysis method to determine discharge rates, from the log-Pearson Type III frequency distribution (IACWD 1982). We supplied discharge rates at multiple intervals, including the 100-year recurrence interval, for about 5,000 stream reaches. To determine area and height of inundation, we used the height above nearest drainage (HAND) method (Rennó et al. 2008; Rodda 2005) and HAND data (Liu et al. 2018; Zheng et al. 2018), based on hydrologic terrain, to estimate inundation rather than more computationally intensive modelling. We applied synthetic rating curves from the HAND raster to convert the 100-year flow rates to corresponding water levels (Zheng et al. 2018), using the Manning's equation with a predefined channel roughness value of 0.05.

An approximate flood mapping approach with simplified hydraulic assumptions is not likely to generate products as accurate as locally detailed engineering models, but this modeling approach is realizable at a continental scale and provides information about floodplains where other models are not available. Caveats include multiple sources of error that may affect these models, although after identification of problems, models will improve. Bias may occur in the National Water Model simulations, NHD stream locations, and digital elevation models. For example, obstructions such as bridges, roads, and river intersections may interfere with determination of hydrologic terrain. Validation shows that the HAND models may be comparable with observed floods and computationally intensive hydrological models (Afshari et al. 2018; Johnson et al. 2019; Nobre et al. 2016). A challenge for flood modeling is depicting stormwater drainage in urban areas when heavy rainfall overwhelms local drainage capabilities, which this model will not represent well (Zhang et al. 2018), albeit urban modeling may not be relevant to forested lands.

Facilities Within 100-Year Flood Zones

Of the approximately 200 open recreational areas (all GIS layers from the USDA Forest Service Enterprise Data Warehouse) that may be high risk due to overnight stays (that is, campgrounds, camping areas, horse camps, group campgrounds, hotels, lodges, lookout/cabins, resorts, and recreation residences), 62 were within 300 feet of 100-year flood zones (table 1; resource managers and engineers will need to evaluate accuracy and implications of the results). Seventeen of these recreational areas were in the Arapaho-Roosevelt National Forests and 45 were in the Pike-San Isabel National Forests (fig. 2). The GIS points do not represent dimensions and also may not be centered on the recreational area sites, and thus we applied a large 300-foot buffer around the points signifying recreational sites. Some recreational areas may extend well into the flood zones. For example, the Dutch George Campground of Arapaho-Roosevelt National Forests was inundated by the 100-year flood zone (fig. 3).

Table 1—Overnight stay recreational areas and associated wastewater sites likely at greatest risk of inundation during a 100-year flood based on 100 (wastewater) to 300 (recreational areas) foot proximity to GIS point locations to a modeled flood zone. The model is not an engineered design and point locations are imprecise.

Arapaho and Roosevelt National Forests		
Site name	**Type**	**Capacity**
Ansel Watrous	Campground	90
Big Bend	Campground	45
Big South	Campground	20
Browns Park	Campground	120
Camp Dick	Campground	255
Chambers Lake	Campground	305
Dutch George	Campground	120
Kelly Flats	Campground	150
Lower Narrows	Campground	40
Mountain Park	Campground	320
North Fork Poudre	Campground	45
Peaceful Valley	Campground	90
Sleeping Elephant	Campground	75
Stove Prairie Landing	Campground	45
Tom Bennett	Campground	60
Tunnel	Campground	245
Upper Narrows	Campground	40
Peaceful Valley Host Site	Holding Tank	0
Camp Dick Host Site #2	Holding Tank	0
Camp Dick Host Site #1	Holding Tank	0

Pike and San Isabel National Forests		
Site name	**Type**	**Capacity**
Blue Lake	Campground	75
Buffalo	Campground	205
Cascade	Campground	105
Chalk Lake	Campground	105
Coaldale	Campground	40
Cottonwood Lake	Campground	125

Table 1 continued.

Pike and San Isabel National Forests		
Site name	**Type**	**Capacity**
Cove	Campground	20
Davenport	Campground	60
Deer Creek	Campground	65
Dexter	Campground	75
Fourmile	Campground	70
Geneva Park	Campground	125
Goose Creek	Campground	50
Green Mountain	Campground	30
Halfmoon East	Campground	30
Halfmoon West	Campground	80
Happy Meadows	Campground	40
Iron City	Campground	75
Jefferson Creek	Campground	90
Kite Lake	Campground	78
Lodgepole	Campground	175
May Queen	Campground	135
Monarch Park	Campground	264
Mt. Princeton	Campground	95
Ophir Creek	Campground	155
Osprey	Campground	65
Ouzel	Campground	65
Parry Peak	Campground	130
Platte River	Campground	50
Purgatoire	Campground	115
Riverside	Campground	95
Spillway	Campground	120
Springer Gulch	Campground	75
St. Charles	Campground	75
Weston Pass	Campground	70
Winfield	Camping Area	35
Ponderosa	Group Campground	120
Spruce	Group Campground	60

Table 1 continued.

Pike and San Isabel National Forests		
Site name	**Type**	**Capacity**
Crescent Mining Camp	Lookout/Cabin	6
Clyde	Recreation Residence	0
Fox Lake	Recreation Residence	0
Rock Creek	Recreation Residence	0
Stage Road	Recreation Residence	0
Vicksburg	Recreation Residence	0
Weston Pass	Recreation Residence	70
Blue Mtn	Toilet-Vault	0
Spruce Grove Cement	Toilet-Vault	0
Whiteside	Toilet-Vault	0
Spruce Grove Stick Built	Toilet-Vault	0
Spillway	Toilet-Vault	0
Elevenmile	Toilet-Vault	0

Of the approximately 800 active buildings, six were within 50 feet of flood zones, which were in the Pike and San Isabel National Forests (table 1). These buildings were vaulted toilets, and thus represent potential water pollution sources, and also may indicate campgrounds that extend into flood zones. Three wastewater holding tanks in the Arapaho-Roosevelt National Forests were within 100 feet of flood zones. No oil or gas wells were within 50 feet of flood zones. There were 363 road intersections within the flood zone, of which 191 were in the Arapaho-Roosevelt National Forests and 172 were in the Pike-San Isabel National Forests.

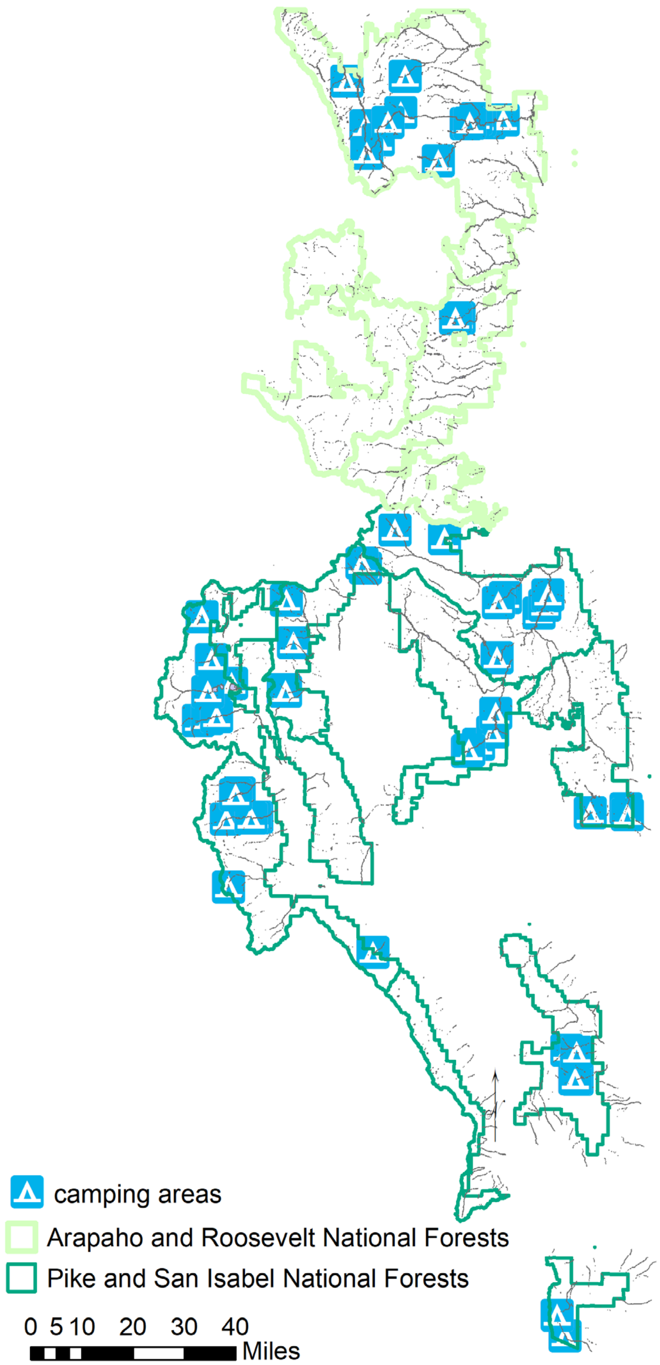

Figure 2—Location of 17 camping areas within 300 feet of 100-year flood zones in the Arapaho and Roosevelt National Forests and 45 camping areas within 300 feet of 100-year flood zones in the Pike and San Isabel National Forests. These areas may be at greatest risk of inundation based on proximity of GIS point locations indicating overnight stay recreational areas to a model. However, the model is not an engineered plan and point locations are dimensionless and may be imprecise.

Figure 3—Example of a campground area in comparison to a GIS point location for the Dutch George campground of Arapaho and Roosevelt National Forests and inundation of the campground during 100-year flood (green zone).

Future Flood Risk and Infrastructure

Current flood risk is not well-established and future flood risk due to climate warming is even more uncertain. Flood risk based on current stream flows may not remain stable under future stream flows and stream channels (Rangwala 2024; Wenger et al. 2010). Therefore, "100-year" flood risk is a misnomer and instead represents a 1 percent chance of flooding under current conditions. Stream geometry also may change over time along with other hydroclimate changes.

Greater frequency of intense precipitation events likely will increase risks of flooding, landslides, and infrastructure damage to roads, dams, bridges, and culverts (Furniss et al. 2018). Winter flooding events and peak flows may increase as precipitation shifts from snow to rain and greater winter soil moisture may increase landslide risk (Furniss et al. 2018). One coarse method of identifying areas at greater risk in the future is to locate areas that have increases in realized precipitation during the past 30 years and areas that are expected to increase in precipitation, runoff, or extreme rainfall events in the future, which overall indicate potentially increasing flooding (Rangwala 2024).

Percent change in 1.5-year flood (F1.5, percent), 25-year flood (F25, percent), and absolute change in center of flow mass timing (CFM, days) between historical data (1977–2006) and end of century (2071–2099) projections were produced from daily runoff and baseflow from the Variable Infiltration Capacity (VIC) macroscale hydrologic model (Liang et al. 1994). The F1.5, F25, and CFM stream metrics are based on the ensemble mean of 10 general circulation models associated with a scenario that assumes balanced use of fossil fuels and renewable energy sources (Wenger et al. 2010). Data are available for each stream segment in the 1:100,000 scale National Hydrography Dataset (NHDPlus version 2) of the western United States (https://data.fs.usda.gov/geodata/edw/datasets.php?xmlKeyword=Hydro+Flow+Metrics+West). F1.5 and F25 represent flood levels that are expected to occur every 1.5 and 25 years, respectively, and CFM represents the day of the water year when half of the total annual stream flow has been exceeded.

Over two-thirds of streams within the Arapaho-Roosevelt and Pike-San Isabel National Forests are projected to experience decreases in 1.5-year floods (bankfull flows) by the end of the century (fig. 4). The remaining streams are projected to remain constant or experience moderate increases (10 to 20 percent) in bankfull flows. Stream flows that can lead to larger floods (F25) may increase in over one-third of Arapaho-Roosevelt and Pike-San Isabel National Forests streams (fig. 5). The largest of these increases (> 25 percent change in 25-year floods) is projected to occur within tributaries of large Front Range canyons and the Upper Arkansas River. The timing of peak flows (CFM) may occur 2 to 6 weeks earlier by the end of the century due to snow melting earlier in the year (fig. 6). These changes in the frequency and timing of floods may intensify damage to roads, bridges, and other infrastructure near perennial streams.

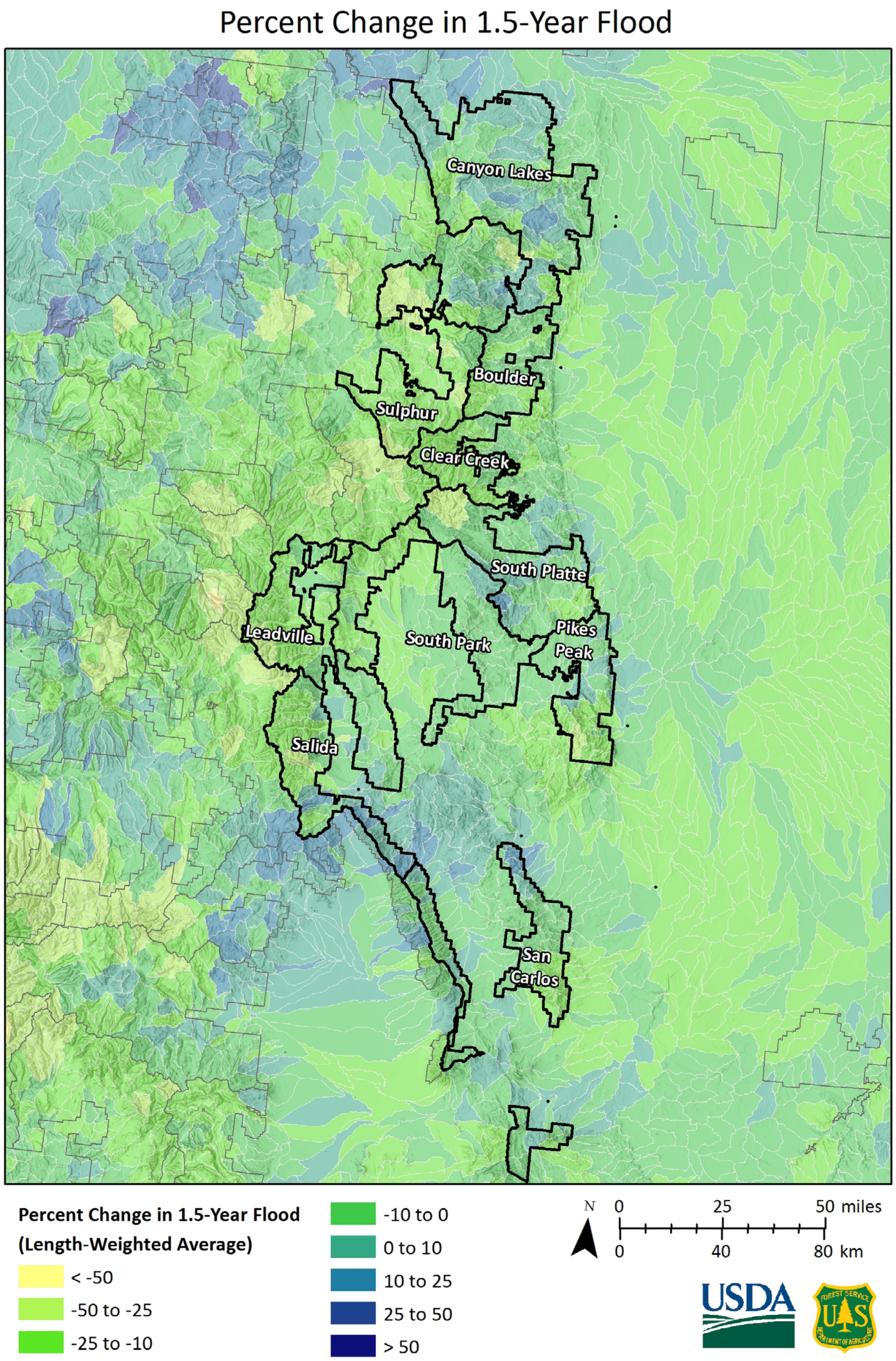

Figure 4—Percent change in 1.5-year flood between historical data (1977–2006) and future (2071–2099) projections.

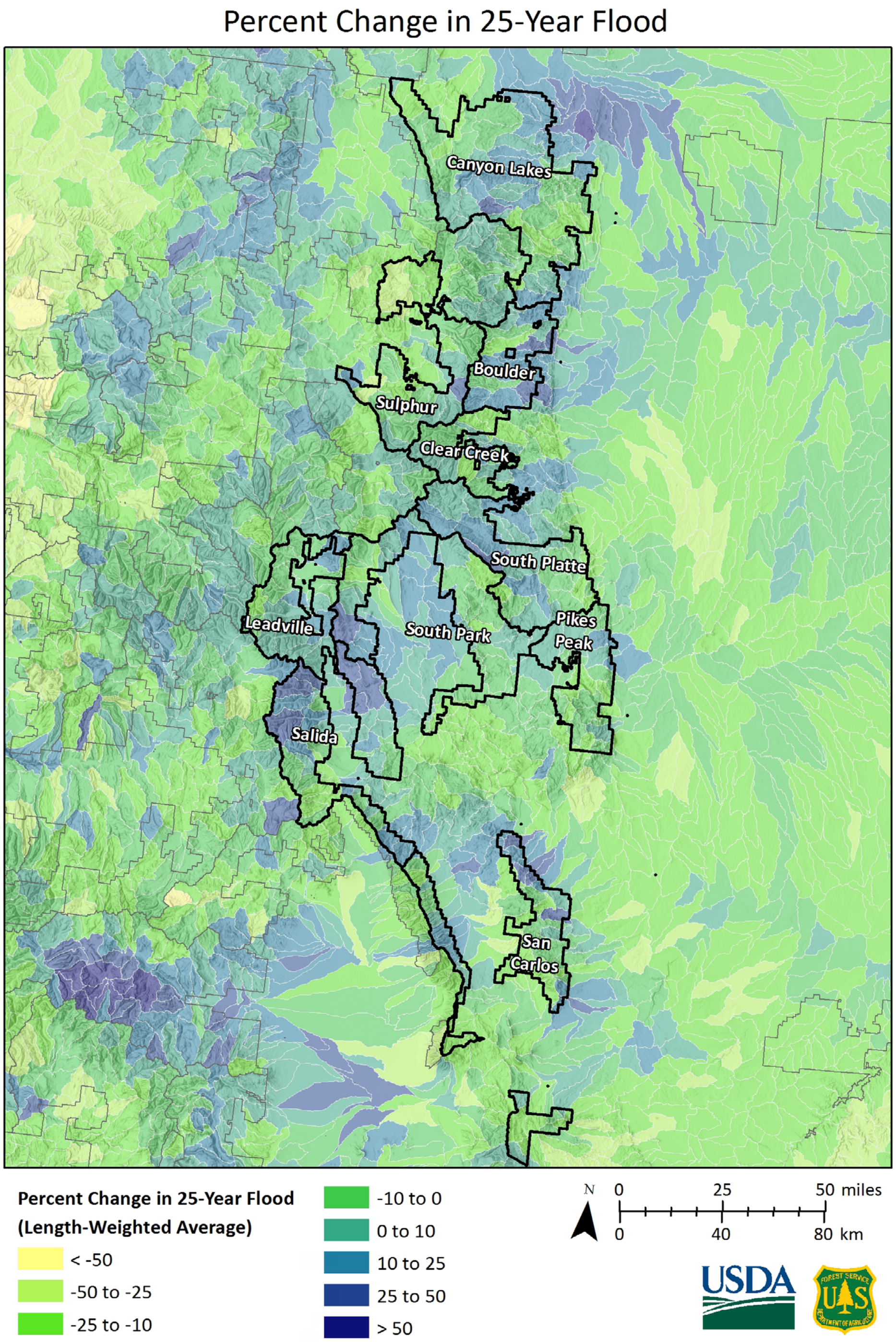

Figure 5—Percent change in 25-year flood between historical data (1977–2006) and future (2071–2099) projections.

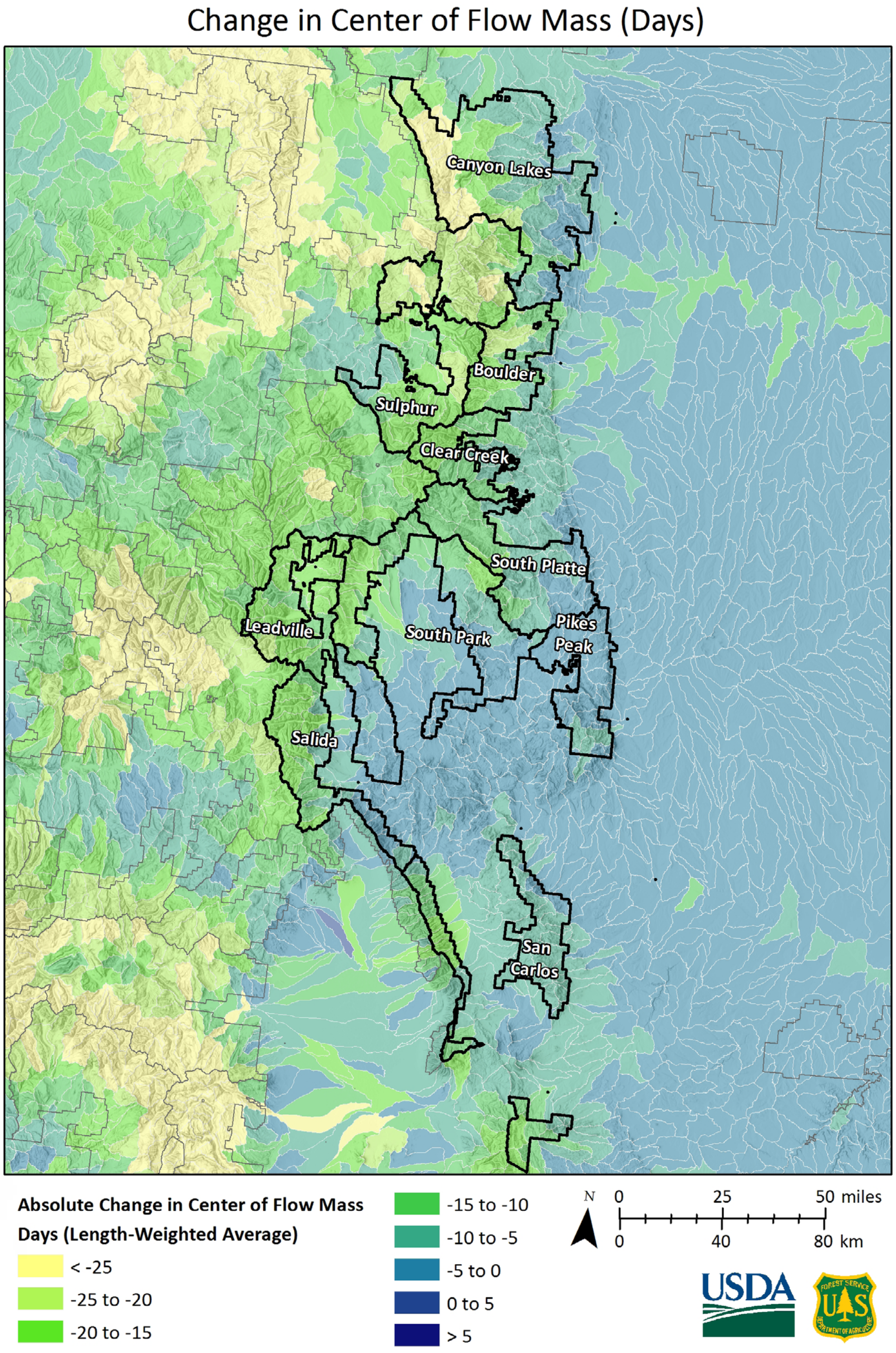

Figure 6—Absolute change in center of flow mass days between historical data (1977–2006) and future (2071–2099) projections.

Infrastructure Management For Extreme Weather Events and Climate Change

More resilient infrastructure designs and implementing best management practices are central to adapting to climate change. First, risks to the infrastructure can be assessed and consequences of failure evaluated. Then, specific structural mitigations require an engineered plan. Keller et al. (2021) presented a thorough range of infrastructure adaptation treatments for road maintenance, management, and closure; road-stream encroachment; road surface drainage improvements; culvert and stream-crossing structure protection and improvements; fords and low-water crossings; bridge protection and improvements; erosion prevention and erosion control; slope stabilization measures; roadway freeze-thaw effects; and fire detours (table 2). Simple strategies involve regularly cleaning out culverts, maintaining roads and ensuring surface drainage measures are functional, modifying bridge and culvert designs to accommodate greater flows, preventing culvert plugging, avoiding potential stream diversion at road-stream crossings, and correcting scour problems at bridges (Keller et al. 2021). Stabilization treatments, planned by engineers and specialists, are intended to minimize susceptibility of structures, streambanks, and steep slopes to failure and erosion. Measures can be taken to reduce flow velocity and concentration of flow and redirect water flow as needed. Erosion control, streambank protection, and scour protection encompass the use of materials such as vegetation, soil bioengineering with plants and woody debris, or conventional engineering elements of rock riprap, gabions, concrete, and turf-reinforcing mats (Keller et al. 2021). Closing and relocating roads or other infrastructure from flood zones is sometimes the best solution in terms of risk and cost-effectiveness (Keller et al. 2021). Keller and Sherar (2003) summarized many of the key best management practices for engineering design and function of roads and Furniss and Howe (2016) listed numerous ways to make road systems more resilient.

Table 2—Vulnerabilities and adaptation actions (modified from Keller et al. 2021).

Infrastructure Type	Vulnerability	Adaptation Action
Facilities	Damage from fires, floods, and wind	• Move vulnerable buildings and facilities • Develop evacuation plans • Use fire-resistant materials (e.g., metal roofs) and cover holes to protect from embers (e.g., gutters) • Thin for defensible space around structures
	Depleted water systems	Drill or deepen water wells
	Lack of available water during droughts	Increase water efficiency, decrease water use, plan for droughts
	Slope failures	Construct stable cut and fill slopes
	Rockfall	Add drainage and deep-rooted vegetation
	Debris flows	Add slope stabilization measures as needed
	Erosion	• Maintain adequate ground cover • Diffuse concentrated water • Armor eroding sites
Roads	Damage from fires, floods, and wind	• Inspect, maintain, repair • Decommission unneeded roads • Designate detour routes • Remove hazard trees
	Road-stream encroachment	Move vulnerable sections of roads out of channel migration zone
	Landslide prone areas	• Redirect streamflow away from stream bank • Stabilize unstable slopes
	Erosion/sedimentation	• Outslope roads • Maintain adequate ground cover • Improve drainage • Armor weak streambanks
	Water quality degradation	Use frequent rolling dips, cross-drains, and leadoffs
	Gully formation	• Armor pipe and dip outlets • Armor eroding ditches
	Pavement freeze-thaw damage	Use springtime road use restrictions

Table 2 continued.

Infrastructure Type	Vulnerability	Adaptation Action
Culverts	Culvert failures	Keep channel clear
	Washout from poor installation	Repair damaged culvert sections
	Lack of capacity	Add stream-diversion protection dips
	Plugging with debris, logs, and sediment	• Add trash racks to trap debris • Use stream simulation designs
Bridges	Bridge failure	Keep channel clear of debris and vegetation
	Foundation scour	Armor foundations and areas of scour potential
	Loss of clearance or capacity	Redirect channel flow away from abutments
	Timber bridges burned by wildfire	• Remove vegetation near bridges • Remove aggradation deposits • Increase clearance

National core best management practices are available for roads, trails, and recreation on National Forest System lands; these practices particularly are effective due to the requirement that road storm damage surveys be conducted shortly after storms (USDA FS 2012). Surveying roads after storms is critical to detect and prevent problems from insufficient drainage, unstable slopes, or vulnerable infrastructure. Understanding causes of failure and designs and prescriptions that reduce likelihood of future failures are discussed by Furniss and Howe (2016). Additionally, it is important to assess damage or potential for damage to water bodies to establish causes of failures and determine mitigation at damaged sites and preventive actions at similar sites.

The *Transportation Resiliency Guidebook* (USDA FS 2018) supplies a conceptual framework for practitioners at a local level to consider climate change and prepare for effects on the transportation system. New Forest Service bridges and bridge replacements, as well as culverts, are designed in accordance with the agency's aquatic organism passage stream simulation guide, making bridges and culverts substantially more resilient to climate change (Furniss et al. 2018). The Forest Service Transportation Analysis Process is intended to maintain a sustainable road network in accordance with best management practices, integrating a map of the recommended minimum road system and lists of unneeded roads and key issues with a road risk assessment to prioritize road infrastructure (Furniss and Howe 2016; USDA FS 2012). The Program for Emergency Relief for Federally Owned Roads was established to assist Federal agencies with repairing Federal roads that have incurred serious damage from a natural disaster (USDOT FHWA 2014). The Federal Highway Administration (USDOT FHWA 2012 and 2017) and the Transportation Resiliency Guidebook (USDA FS 2018) both provide a climate change and extreme weather vulnerability assessment framework for assessing vulnerability to climate change and extreme weather events.

Interactive with the Transportation Analysis Process, the Watershed Condition Framework model rated various factors that influence watershed condition (Keller et al. 2021). Every national forest in the United States completed a Watershed Condition Assessment at the sub-watershed scale (HUC-6; 10,000–40,000 acres) during 2010 (Keller et al. 2021). The model is based on 12 watershed condition indicators, for which road density, condition, and proximity to streams contributed to the ratings.

Sustainable Operations

Recommendations about sustainable operations incorporate reducing water and energy consumption and increasing water and energy efficiency, purchasing sustainable goods and services, reducing waste generation, and reusing and recycling materials for sustainable resource use and reducing greenhouse gas emissions (USDA FS 2014). The USDA has a Sustainable Buildings Implementation Plan with lists of resources available at other agencies (USDA 2011). The Leadership in Energy and Environmental Design (LEED) Green Building Rating System was developed by the U.S. Green Building Council (USGBC) for sustainable building and development practices (USDA 2015). The LEED rating systems are available for new construction and existing building operations and maintenance (USDA 2015).

Sustainable operations involve a shift toward renewable energy for climate change mitigation. Embarking on atmospheric carbon drawdown and net-zero carbon emissions is possible through existing technologies of rapid electrification based on renewable energy, such as rooftop solar, electric vehicles, and heat pumps (Griffith et al. 2020). Solar systems on buildings are one option to consider. Although buildings differ in size, grid-tied inverter systems cost about $2 to $3 per watt (S. Rivers, Black Hills Solar, Inc., personal communication). Average capacity installed for a residence typically is 4 kW to 6 kW and larger office buildings may use at minimum 10 kW (that is, $20,000 to $30,000; EnergySage 2019). Battery systems will increase the price compared to a grid-tied only solar system. In addition, depending on location, electrician costs may range from $500 to $2000 for connecting the inverter to the solar and electric panels (S. Rivers, Black Hills Solar, Inc., personal communication).

Conclusions and Future Assessments

Management concerns included identifying infrastructure within 100-year-flood boundaries. Before preparing for future flooding risk, current flood risk first needs to be established, albeit flood risk may change over time because stream flows are not stationary (Wenger et al. 2010). We modeled 100-year-flood floodplain boundaries to identify infrastructure potentially vulnerable to current flooding, based on 1994 to 2018 water flows. We used a method to approximate current flood risk that, while comprehensive, is not likely to identify all 100-year floodplains and vulnerable camping areas. Other models and confirming evidence such as a known history of floods and hydric soils will help detect 100-year floodplains and vulnerable infrastructure. Work conducted by resource managers, hydrologists, and engineers is needed to evaluate this model and assess flood risk at recreational areas.

Based on the identified 100-year floodplains and vulnerable camping areas, more intensive local assessments can be made, incorporating modeling, field assessment, and engineered plans. Avoiding identified areas in 100-year floodplains for future development is prudent, particularly for campgrounds. For already built recreational areas, river camping is enjoyable to many visitors, but it may be necessary to balance demand for recreation against risks to human lives due to catastrophic flash floods, which are unpredictable in time and space, and sometimes offer little warning. To communicate flood risks of infrastructure to the public, posted signs should provide a visible warning of probable flood heights near infrastructure in inventoried 100-year floodplains (USDA FS 2010). Early warning systems of sirens, visitor safety communication, and evacuation plans and training are other effective safety practices (USDA FS 2010). Closing access during some seasons or removing infrastructure is an option where risks to public safety are great, such as where flooding events and 100-year floodplains are documented and recreation use occurs.

Flooding risks are likely to change with a warming climate because both precipitation and stream channels are not stationary in time (Rangwala 2024; Wenger et al. 2010). A simple strategy to identify future risk may be to identify infrastructure near streams that will receive greater precipitation in the form of extreme rainfall events or runoff in the future (Furniss and Howe 2016). Stream flows that can lead to larger floods may increase in over one-third of Arapaho-Roosevelt and Pike-San Isabel National Forests streams, with greatest increases (> 25 percent change in 25-year floods) projected to occur within tributaries of large Front Range canyons and the Upper Arkansas River. However, any areas may be vulnerable to extreme events, which are difficult to predict (Hydrologic Engineering Center 2023; Karau et al. 2024; Mora et al. 2018).

Future work ideally will continue to develop a comprehensive risk assessment of exposure and vulnerability of infrastructure, integrating a complete portfolio of infrastructure at risk, such as roads, bridges, and water supplies, to climate-related events such as floods, landslides, drought, and other natural hazards at national forest scales. Assessments are key to evaluating risk and setting priorities for work that can or needs to be done for resilience. This process involves forming an interdisciplinary team of resource managers and engineers to examine site data and history, compile available models, and rank infrastructure risk using a risk matrix to prioritize needed work or adaptation measures (Keller et al. 2021). Detailed information about environmental and administrative context, infrastructure condition and alternative options, biological resources, climate projections, and values likely are needed for accurate determinations of risk. Although models may not exist for current or future natural hazard exposure, a comprehensive assessment, along with development of a database, will help identify risks that can be known now and information needs for risk management.

Similarly, detailed information typically is not available at larger extents, but site scale inventories can be developed and combined, for example, to map potential for landslides and high debris flow hazards after fires (USGS 2022b). Preferably, a map of all infrastructure in relation to potential hazards will be produced, with an associated risk rating, although such a map has not yet been produced for any National Forest.

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