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Mark Twain National Forest Climate Change Impact Assessment and Vulnerability Framework for Recreation

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Abstract

Climate change will have profound effects on recreation, infrastructure, and related opportunities over the 21st century. This assessment evaluates how changes in climate, hydrology, and ecosystems influence the overall vulnerability of the Mark Twain National Forest's recreation opportunities and related infrastructure under a range of future climates. We synthesized and summarized information on the contemporary landscape (physiography and recreation assets), provided information on observed climate trends (including extreme events and hydrologic changes), described a range of projected future climates (including trends in potential extreme disturbances, hydrologic changes, and impacts to ecosystems and subsequent recreation opportunities), and provided a framework for land managers to assess local risk and vulnerability of recreation and infrastructure assets to climate change. We developed summaries of climate projections from statistically downscaled climate models that represent four distinct climate scenarios (MRI RCP 4.5, MRI RCP 8.5, IPSL RCP 4.5, IPSL RCP 8.5) in order to provide a range of plausible conditions that could impact forest hydrology and ecosystems, infrastructure, and recreation activities on the Mark Twain National Forest. We provided a synthesis of the scientific literature on climate impacts to tree species, invasive species, insects and pathogens, wildfires, wildlife, infrastructure, public health and safety, and implications for recreation management.

To help address these impacts, we also developed a vulnerability framework for recreation that builds on the Adaptation Workbook, developed by the Northern Institute of Applied Climate Science and published by the USDA Forest Service, and the U.S. Forest Service Transportation Resiliency Guidebook to aid land managers when assessing the vulnerability of recreation sites and infrastructure based on exposure, sensitivity, and adaptive capacity. This framework can be applied to recreation and infrastructure projects and plans at a variety of spatial scales. We tested this framework on the Mark Twain National Forest's Red Bluff recreation site in a collaborative workshop with recreation, hydrology, and other resource specialists. The participants rated the recreation site as having a moderate to high vulnerability based on its high risk of future flood damage and soil erosion. This framework can help managers in identifying site- and asset-specific climate-related risks and potential climate vulnerability, a critical component of climate adaptation planning.

KEYWORDS: climate change, vulnerability, adaptive capacity, infrastructure, extreme weather, flooding, camping, canoeing, expert elicitation

Cover Photo

Sheltered picnic area at the Red Bluff Recreation Area on the Mark Twain National Forest. USDA Forest Service photo.

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Contents

Executive Summary

This assessment evaluates how changes in climate, hydrology, and ecosystems influence the overall vulnerability of the Mark Twain National Forest's recreation opportunities and related infrastructure under a range of modeled projected future climates. The assessment summarizes current conditions for the national forest and key stressors that could be exacerbated by climatic change and identifies past and projected trends in climate. These projections, combined with resource specialists' local knowledge and expertise, can be used to identify the factors that contribute to the vulnerability of forest ecosystems, local recreation sites, and infrastructure to climate impacts. A vulnerability framework developed to help address these impacts was applied to the national forest's Red Bluff recreation site in a collaborative workshop with recreation, hydrology, and other resource specialists. This framework can help managers identify climate-related risks and potential vulnerability for sites and recreation assets in support of recreation management and climate adaptation planning.

Chapter 1: Current Conditions and Observed Climate Trends

This chapter describes current conditions for the Mark Twain National Forest personnel, including climate, land cover and use, physiology, hydrologic and disturbance events, and trends in recreation activities. The information establishes a baseline for comparison with the projected changes discussed in Chapter 2.

Main Points

- Of the 1.5 million acres (608,000 ha) administered by the Mark Twain National Forest, approximately 79 percent is forested, 14 percent is agricultural, 3 percent is developed, and 2 percent is covered by water.
- Annually 880,000 people visit the Mark Twain National Forest, primarily from distances within 50 miles (80 km).
- Recreational amenities on the Mark Twain National Forest include the following.
    - 750 miles (1,200 km) of trails for hiking, horseback riding, mountain biking, and motorized use
    - 350 miles (560 km) of perennial streams for floating, canoeing, kayaking, and fishing
    - 166 sites for recreation
    - 79 locations for recreation opportunities
    - 35 campgrounds and picnic areas

- The following trends were observed across Missouri from 1960 through 2019.
  - Mean annual temperatures increased at a rate of 0.3 to 0.4 °F (0.16 to 0.22 °C) per decade.
  - Annual precipitation increased by 0.4 to 1.3 inches (1.0 to 3.3 cm) per decade.
  - Indices of drought-impacted conditions showed a trend toward less frequent and less severe droughts.
- Floods are inherently large on the Mark Twain National Forest, with observed data also indicating increasing magnitudes and greater event frequency that are likely due to climate change.

Chapter 2: Projected Changes in Climate

Climate projections representing four scenarios (MRI RCP 4.5, MRI RCP 8.5, IPSL RCP 4.5, IPSL RCP 8.5) provide a range of plausible conditions that could impact forest ecosystems, infrastructure, and recreation activities on the Mark Twain National Forest. The information provides the basis for impacts presented in Chapter 3.

Main Points

Climate projections through the end of the 21st century indicate the following.

- Mean annual temperatures could increase by 2.5 to 10.6 °F (1.4 to 5.9 °C).
- Annual precipitation could decrease by up to 7 inches (18 cm) per year or increase by 4.3 inches (11 cm) as compared with the 1980 through 2009 average.
- More heavy rain events are expected, leading to more frequent and increased severity of flooding events.

Chapter 3: Impacts to Ecosystems, Infrastructure, and Recreation Opportunities

This chapter summarizes how projected climate change could impact ecosystems, infrastructure, and recreation on the Mark Twain National Forest. It includes impacts to tree species, invasive species, insects and pathogens, wildfires, wildlife, infrastructure, and public health and safety.

Main Points

- Habitat suitability is projected to decline for some oak and hickory species and increase for shortleaf pine, black hickory, blackgum, and blackjack oak.
- White-tailed deer and wild turkey could be vulnerable to projected climate change.
- Damage from flooding, erosion, wind, and extreme temperatures is likely to impact infrastructure.
- Warmer temperatures could extend the period of seasonal recreation activities; water-based activities are likely to be in greater demand.
- The impacts of extreme weather can lead to temporary closures when roads, trails, and recreation sites are damaged, inaccessible, or under water.

Chapter 4: Recreation and Infrastructure Vulnerability Assessment Framework

This chapter presents a framework for assessing the vulnerability of recreation sites and infrastructure based on exposure, sensitivity, and adaptive capacity. The framework can be adapted to specific sites and consideration of additional hazards. An example application of the framework is provided for the Red Bluff recreation site on the Mark Twain National Forest.

Main Points

- We developed a framework for assessing vulnerability and risk to recreation sites. The framework builds on the Adaptation Workbook, which was developed by the Northern Institute of Applied Climate Science and published by the USDA Forest Service, and the U.S. Forest Service Transportation Resiliency Guidebook.
- We provide worksheets and a process for using the framework.
- This framework was tested on the Red Bluff day-use site and campground on the Mark Twain National Forest.
- In this case study, several site characteristics influenced the exposure and sensitivity and therefore vulnerability evaluation. For example, the projected increased flood frequency and severity are likely to affect the recreation site due to its position in a floodplain. Regional models project warmer temperatures and more low flow days in the summer, which may impact visitor demand on the site, water quality, and river access. Managers of this site rated the site as having moderate to high vulnerability to climate change and a reduced capacity to cope with or adapt to changes without intervention.

Chapter 5: Implications for Recreation and Infrastructure Management

This chapter discusses the broader climate impacts that could affect recreation and infrastructure management on the Mark Twain National Forest. Topics include staffing, site use and maintenance, health risks, and project planning.

Main Points

- Climate change is very likely to have important impacts on the management of the Mark Twain National Forest's recreation assets and programs, now and in the future.
- More flexibility and new resources may be needed to meet the challenges of changing visitor use patterns, increased damage to infrastructure and vegetation, and human health and safety concerns.
- Using vulnerability assessments and developing targeted adaptation strategies can help identify and prepare for these risks.
- Resources are already available to assist managers in adapting recreation programs to climate change.

Chapter 1: Current Conditions and Observed Climate Trends

The Mark Twain National Forest ("the national forest") covers approximately 1.5 million acres (608,000 ha) across 29 counties in Missouri (Fig. 1) and provides many recreation opportunities to visitors. There are over 750 miles (1,200 km) of trails for hiking, horseback riding, mountain biking, and motorized use. Popular activities are floating, canoeing, and kayaking on its 350 miles (560 km) of perennial streams. There are more than 35 campgrounds and picnic areas situated near scenic areas. Semi-primitive and wilderness camping opportunities are also provided throughout the national forest. Recognizing the importance of recreation in connecting current and future generations to national forests, the U.S. Department of Agriculture (USDA) Forest Service issued the "Framework for Sustainable Recreation" in 2010 (USDA Forest Service 2010). In this report, sustainable recreation is defined as "the set of recreation settings and opportunities on the National Forest System that is ecologically, economically, and socially sustainable for present and future generations" (2012 Planning Rule; USDA Forest Service n.d.a). One key aspect of ensuring the sustainability of recreation into the future is understanding the current and potential future risks from a changing climate. This chapter examines the current trends in climate that may already be affecting recreation opportunities on the Mark Twain National Forest.

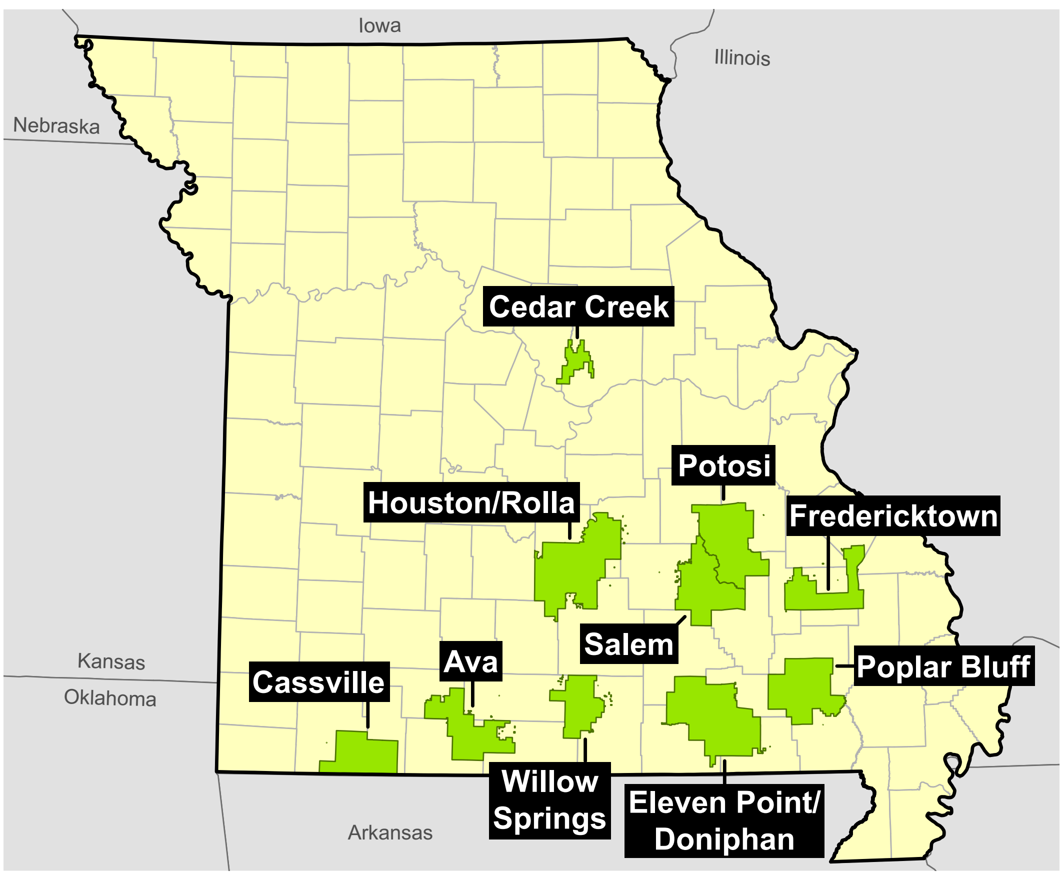

Figure 1.—Map of the State of Missouri and the boundaries of the 12 units of the Mark Twain National Forest (green polygons), labeled in bold. Adapted from U.S. Department of Agriculture Forest Service, Mark Twain National Forest (2005).

Current Conditions

Physiographic Region

The Mark Twain National Forest is situated in the Ozark Plateau, an unglaciated area of southern Missouri with rolling hills and unique geologic features. Karst features such as springs, losing streams, sinkholes, and caves are common. Elevation ranges from 590 to 1,399 feet (180 to 426 m) on the national forest, with a mean elevation of 956 feet (291 m). Topographic aspect obtained from a 10-meter (33-foot) U.S. Geological Survey (USGS) digital elevation model is mostly evenly distributed across the Mark Twain National Forest, with 48 percent northerly and 50 percent southerly facing slopes. Limestone and dolomite glades can be found on hilltops throughout the national forest and consist of rocky, desert-like landscapes.

Land Cover and Use

Based on the 2019 National Land Cover Database (Wickham et al. 2021), the Mark Twain National Forest is composed of approximately 79 percent forested land, 14 percent pastureland, 3 percent developed open space, and 2 percent water. These percentages differ by ranger district, influencing the recreation opportunities offered at each location. Between the 2006 and 2011 database updates, 99 percent of Missouri experienced no change in land cover or use, but slight increases occurred in the developed and agricultural classes. Between the 2011 and 2016 classifications, 80 percent of the state remained unchanged, with increases in the agricultural (9 percent), developed (2 percent), forest (7 percent), and wetland (1 percent) classes. Between the 2016 and 2019 classifications, 95 percent of Missouri remained unchanged, with about a 2 percent increase in developed and deciduous forest land.

Recreation Uses

The Mark Twain National Forest serves nearly 880,000 visitors each year (USDA Forest Service 2019). Most visitors (68 percent) are from areas within 50 miles (80 km) of the national forest, and this area is primarily rural. The nearest larger population centers include St. Louis, Springfield, and Columbia, as well as the smaller town of Branson, a popular destination. The primary recreation activities enjoyed by visitors to the Mark Twain National Forest include wildlife and natural feature viewing, hiking, fishing, motorized and nonmotorized water recreation, picnicking, bicycling, and camping. Minor components of recreation use include hunting, horseback riding, and off-highway vehicle use. Winter sports are not reported on the Mark Twain National Forest due to low snow cover. Floating (i.e., floating down a river in a canoe, raft, kayak, or tube) is a unique recreation activity on the national forest and a contributor to the surrounding area's recreation economy (Fig. 2). An estimated 54 percent of Missouri residents participate in outdoor recreation each year, resulting in an average spending of $14.9 billion annually (Missouri Department of Natural Resources 2020, Outdoor Industry Association 2017). An estimated $20.6 million is spent annually by visitors to the Mark Twain National Forest (Ecosystem Management and Coordination – Economics Group 2018).

Many rivers and lakes throughout Missouri are classified for recreation use. Nearly 110,000 miles (176,000 km) of rivers and streams and nearly 320,000 acres (133,000 ha) of lakes can be used for various recreation activities, such as swimming, fishing, floating, kayaking, and paddling (Missouri Department of Natural Resources 2020). Clear, cold, clean water is a recreation and economic asset to the Mark Twain National Forest. With hundreds of miles of rivers and streams, the Mark Twain National Forest also contains 44 miles (70 km) of designated Wild and Scenic River. Fishing is an economic engine for Missouri, bringing in an estimated $685 million of revenue in 2011 from anglers spending on various fishing activities (Missouri Department of Natural Resources 2020); for instance, fishing license sales alone totaled $12.85 million in 2017 (Missouri Department of Natural Resources 2020). Recreational fishing includes angling for black bass, catfish, rock bass, suckers, sunfish, white bass, crappie, walleye, and trout (Missouri Department of Natural Resources 2020). Although trout were introduced to the area by settlers, their populations today are managed and maintained by the State of Missouri (Missouri Department of Conservation 2024).

Figure 2.—Canoe-based recreation on the Eleven Point Wild and Scenic River, on the Mark Twain National Forest. USDA Forest Service photo by Steven Yochum.

Recreation Assets

Mark Twain National Forest personnel manage a wide array of infrastructure that helps support access and opportunities for recreation. Within the administrative boundaries of the Mark Twain National Forest there are 2 bridges; 409 Federally owned or leased buildings; 79 locations for recreation opportunities; 166 sites for recreation; 6,041 surveyed aquatic organism passage (AOP) crossings; 8,642 roads and 11,946 miles (19,114 km) of roads; and 292 trails and 958 miles (1,533 km) of trails (Table 1, Fig. 3). Across the Mark Twain National Forest, the dataset indicates many assets are within the expected 100-year flood zone (Q_{100}) of the adjacent stream or within 1/8 mile (0.2 km) of a stream or both. A few of the assets are found within an established U.S. Department of Homeland Security, Federal Emergency Management Agency (FEMA) regulatory flood zone (intended to be used as the basis for official actions required by the National Flood Insurance Program; FEMA 2017). It is important to note that FEMA flood zone mapping is not available for all counties, and thus there may be additional assets at risk to flooding in areas that have not been mapped.

Table 1.—Assets on the Mark Twain National Forest and their relationship to current flood zones (100 year and 500 year). Note that Federal Emergency Management Agency flood maps were not available for all locations within the national forest.

Assets	Number of assets analyzed	Number of assets within 100-year flood zone	Number of assets within 500-year flood zone
Bridges	2	0	2
Missouri Department of Transportation bridges	337	3	186
Dams	32	1	4
Buildings	409	5	123
Recreation opportunities	79	1	33
Recreation sites	166	1	55

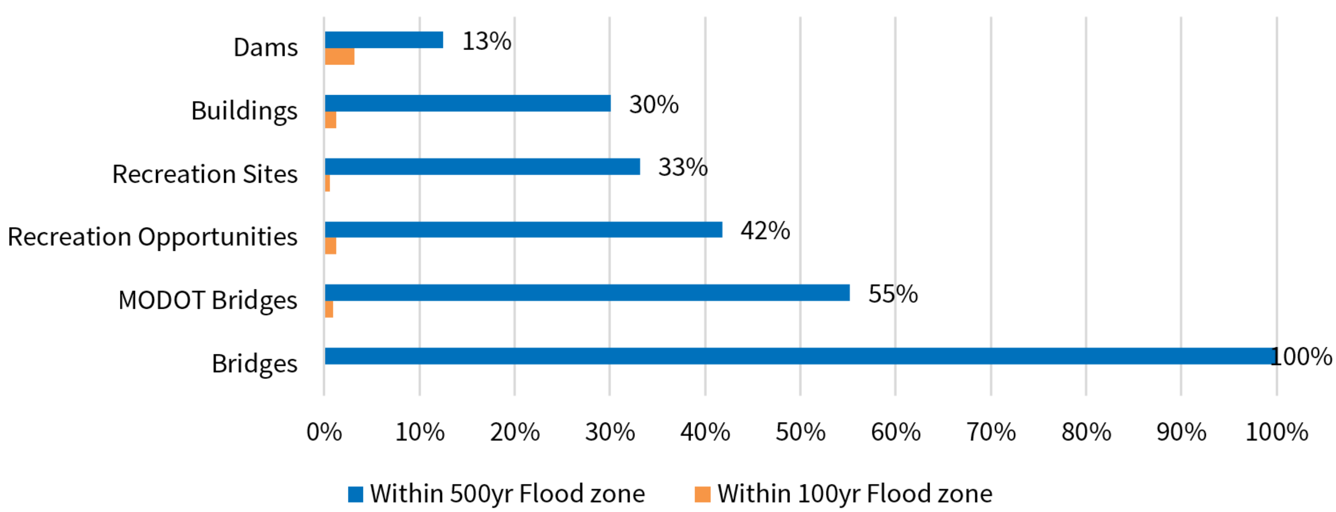

Figure 3.—Percentage of assets on the Mark Twain National Forest in current flood zones (100 year and 500 year). MODOT: Missouri Department of Transportation.

Current Climate

Missouri has a continental climate, with cold, often dry, winters and hot summers marked by intense storms and periods of drought. Precipitation varies greatly across the state, from an average of 48 inches (1220 mm) in the southeast Bootheel region to 39 inches (990 mm) in the Northwest Prairie region, with other areas falling in between. Summer is the wettest season in both the Northeast and Northwest Prairie Regions and West Central Plains regions, whereas precipitation is highest in the spring and fall in the Ozarks and Bootheel regions. Consistent temperature records for the state are available from 1960 to present (Table 2; see Figure 4 for climatic regions map). Annual and seasonal temperature and precipitation are highest in the Bootheel region and lowest in the Northwest Prairie region.

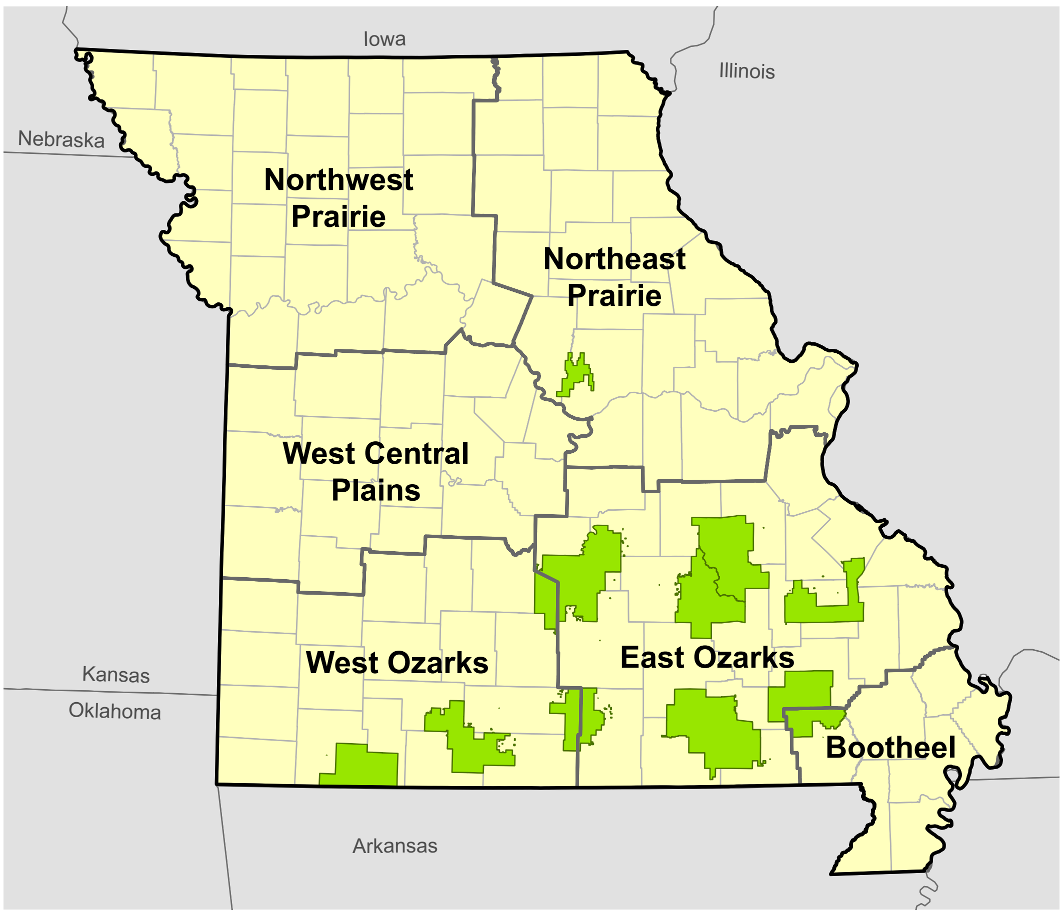

Figure 4.—Map of Missouri climatic regions, labeled in bold, and the boundaries of the Mark Twain National Forest units (green polygons).

Table 2.—Sixty-year mean daily mean, maximum, and minimum temperature and total precipitation for each climatic zone in Missouri from 1960 through 2019. Winter: December–February; spring: March–May; summer: June–August; fall: September–November. Source: National Oceanic and Atmospheric Administration, National Centers for Environmental Information (2020).

Mean daily temperature in °F (°C)

Missouri climatic zone	Annual	Winter	Spring	Summer	Fall
Northwest Prairie	52.9 (11.6)	29.6 (-1.3)	52.8 (11.6)	74.8 (23.8)	54.4 (12.4)
Northeast Prairie	53.6 (12.0)	31.0 (-0.6)	53.4 (11.9)	74.9 (23.8)	55.2 (12.9)
West Central Plains	55.5 (13.1)	33.7 (0.9)	55.1 (12.8)	76.3 (24.6)	56.9 (14.1)
West Ozarks	56.1 (13.4)	35.7 (2.1)	55.7 (13.2)	75.8 (24.3)	57.4 (14.1)
East Ozarks	55.6 (13.1)	34.9 (1.6)	55.4 (13.0)	75.3 (24.1)	56.7 (13.7)
Bootheel	58.5 (14.7)	37.9 (3.3)	58.4 (14.7)	78.2 (25.7)	59.6 (15.3)

Mean daily maximum temperature in °F (°C)

Missouri climatic zone	Annual	Winter	Spring	Summer	Fall
Northwest Prairie	63.3 (17.4)	38.7 (3.7)	63.7 (17.6)	85.4 (29.7)	65.2 (18.4)
Northeast Prairie	64.0 (17.8)	40.1 (4.5)	64.4 (18.0)	85.7 (29.8)	66.1 (18.9)
West Central Plains	66.2 (19.0)	43.5 (6.4)	66.4 (19.1)	87.1 (30.6)	68.1 (20.1)
West Ozarks	67.4 (19.7)	46.2 (7.9)	67.4 (19.7)	87.0 (30.6)	69.0 (20.6)
East Ozarks	67.2 (19.6)	45.3 (7.4)	67.6 (19.8)	87.0 (30.6)	68.8 (20.4)
Bootheel	69.0 (20.6)	46.8 (8.2)	69.8 (21.0)	89.0 (31.7)	70.8 (21.6)

Mean daily minimum temperature in °F (°C)

Missouri climatic zone	Annual	Winter	Spring	Summer	Fall
Northwest Prairie	42.5 (5.8)	20.3 (-6.5)	41.9 (5.5)	64.2 (17.9)	43.5 (6.4)
Northeast Prairie	43.2 (6.2)	21.9 (-5.6)	42.4 (5.8)	64.2 (17.9)	44.4 (6.9)
West Central Plains	44.7 (7.1)	23.8 (-4.6)	43.9 (6.6)	63.4 (17.4)	45.7 (7.6)
West Ozarks	44.9 (7.2)	25.3 (-3.7)	44.1 (6.7)	64.5 (18.1)	45.8 (7.7)
East Ozarks	44.0 (6.7)	24.4 (-4.2)	43.2 (6.2)	63.5 (17.5)	44.7 (7.1)
Bootheel	48.1 (8.9)	29.1 (-1.6)	47.5 (8.6)	67.4 (19.7)	48.4 (9.1)

Total precipitation in inches (mm)

Missouri climatic zone	Annual	Winter	Spring	Summer	Fall
Northwest Prairie	38.6 (980)	4.3 (108)	11.1 (283)	13.6 (346)	9.5 (242)
Northeast Prairie	40.7 (1034)	6.2 (157)	11.7 (297)	12.4 (316)	10.4 (264)
West Central Plains	42.8 (1087)	6.0 (152)	12.5 (318)	13.1 (332)	11.1 (283)
West Ozarks	44.7 (1135)	7.7 (196)	13.1 (332)	11.7 (298)	12.1 (308)
East Ozarks	45.6 (1158)	9.0 (229)	13.3 (337)	11.3 (286)	12.1 (306)
Bootheel	48.2 (1224)	11.6 (295)	13.8 (351)	10.7 (271)	11.9 (303)

Observed Changing Climate Variables

Recent changes in climate can be informative for understanding current trends and helping to anticipate changes. Trends in temperature and precipitation for each climatic region in Missouri from 1960 (when consistent data collection began) through 2019 were compiled using the National Oceanic and Atmospheric Administration (NOAA) Climate at a Glance tool (Table 3).

Table 3.—Change in temperature and precipitation from 1960 through 2019 for each climatic zone in Missouri. Source: National Oceanic and Atmospheric Administration, National Centers for Environmental Information (2020).

Change in mean temperature in °F (°C) per decade

Missouri climatic zone	Annual	Winter	Spring	Summer	Fall
Northwest Prairie	0.3 (0.16)	0.6 (0.33)	0.3	0.2 (0.11)	0.1 (0.055)
Northeast Prairie	0.3	0.6	0.4 (0.22)	0.2	0.1
West Central Plains	0.3	0.6	0.3	0.2	0.1
West Ozarks	0.3	0.6	0.2	0.2	0.1
East Ozarks	0.4	0.7 (0.38)	0.4	0.3	0.2
Bootheel	0.4	0.7	0.3	0.3	0.2

Change in maximum temperature in °F (°C) per decade

Missouri climatic zone	Annual	Winter	Spring	Summer	Fall
Northwest Prairie	0.3	0.6	0.3	0.1	0.1
Northeast Prairie	0.3	0.6	0.4	0.1	0.1
West Central Plains	0.2	0.5 (0.27)	0.2	0.0	0.0
West Ozarks	0.3	0.5	0.2	0.1	0.1
East Ozarks	0.2	0.5	0.2	0.0	0.1
Bootheel	0.2	0.5	0.2	0.0	0.1

Change in minimum temperature in °F per decade

Missouri climatic zone	Annual	Winter	Spring	Summer	Fall
Northwest Prairie	0.4	0.6	0.3	0.4	0.1
Northeast Prairie	0.4	0.6	0.4	0.4	0.1
West Central Plains	0.4	0.7	0.4	0.3	0.2
West Ozarks	0.4	0.7	0.4	0.4	0.1
East Ozarks	0.6	0.8	0.5	0.5	0.3
Bootheel	0.6	0.8	0.5	0.6	0.3

Change in precipitation in inches (mm) per decade

Missouri climatic zone	Annual	Winter	Spring	Summer	Fall
Northwest Prairie	0.42 (10.7)	0.11 (2.8)	0.25 (6.4)	0.34 (8.6)	-0.28 (-7.1)
Northeast Prairie	0.96 (24.4)	0.26 (6.6)	0.32 (8.1)	0.44 (11.2)	-0.05 (-1.3)
West Central Plains	0.72 (18.3)	0.23 (5.8)	0.32 (8.1)	0.40 (10.2)	-0.21 (-5.3)
West Ozarks	1.34 (34.0)	0.35 (8.9)	0.67 (17.0)	0.36 (9.1)	-0.03 (-0.8)
East Ozarks	1.38 (35.1)	0.27 (6.9)	0.57 (14.5)	0.38 (9.7)	0.15 (3.8)
Bootheel	0.74 (18.8)	0.33 (8.4)	0.22 (5.6)	0.1 (25.4)	0.14 (3.6)

Temperature

Mean annual temperatures increased across Missouri, including the Mark Twain National Forest, at a rate of 0.3 to 0.4 °F (0.0 to 0.055 °C) per decade over the 60-year period. Winter low temperatures increased the most, at a rate of 0.6 to 0.8 °F (0.33 to 0.44 °C) per decade. Summer and fall high temperatures changed the least (0.0 to 0.1 °F per decade).

Despite an overall increase in average temperatures, the number of extremely hot days (over 100 °F [37.8 °C]) has been lower than what was experienced earlier in the 20th century, particularly during the 1930s dust bowl and early 1950s (Frankson et al. 2017). In more recent decades, the period from 1980 to 1984 had the most extremely hot days. However, the number of extremely warm summer nights (above 75 °F [23.9 °C]) is increasing. The number of extremely cold nights (below 0 °F [-17.8 °C]) has decreased in recent years, with the most extremely cold nights during the 60-year period occurring in the 1970s and 1980s.

Precipitation

Annual precipitation increased across the state since 1960, with the greatest increases in both the West and East Ozarks of 1.3 to 1.4 inches (33.0 to 35.6 mm) per decade. Changes in precipitation vary seasonally and by climatic region. In both Ozark regions, about half the precipitation increase occurred in the spring, with the other half about evenly distributed between summer and winter. Increases in the Bootheel have been primarily during winter. The other regions have experienced decreases in fall and increases in other months.

Precipitation Extremes

Droughts have become less frequent and severe over the past 60 years (Table 4). The Palmer Drought Severity Index (PDSI), Hydrological Drought Index, Modified Drought Index, and Z Index all indicate an increasing trend toward less droughty conditions, as indicated by positive values. The PDSI attempts to measure the duration and intensity of long-term drought-inducing circulation patterns. The Palmer Hydrological Drought Index measures hydrologic impacts of drought (e.g., reservoir levels, groundwater levels), which take longer to develop and longer to recover from, and thus it does not change as rapidly as PDSI. The Palmer Modified Drought Index has the same value as the PDSI during established dry or wet spells but can be different during transition periods based on probability values. The Palmer Z Index measures short-term drought on a monthly scale.

From 1985 to 2014 (the most recent period available), Missouri experienced an above-average number of extreme precipitation events, with the highest number occurring between 2005 and 2009 (Frankson et al. 2017). Two to three such events are experienced each year on average, and the coupling of these events with snowmelt originating in the Northern Rockies can make the area extremely vulnerable to spring flooding.

Precipitation events of at least 4.5 inches (114 mm) of rain in a 24-hour period occur approximately once every 2 years in southwestern Missouri. Precipitation events of at least 5.5, 6, 7, 8, and 9 inches (140, 152, 178, 203, and 228 mm) of rain occur on average every 5, 10, 25, 50, and 100 years, respectively. Probabilities decline to the north and east, away from southwestern Missouri (Decker 2022).

Table 4.—Decadal change trend in drought indices for the each climatic zone in Missouri from 1960 through 2019. Positive values indicate a trend toward less drought-stressed conditions. Source: National Oceanic and Atmospheric Administration, National Centers for Environmental Information (2020).

Missouri climatic zone	Palmer Drought Severity Index	Palmer Hydrological Drought Index	Palmer Modified Drought index	Palmer Z Index
Northwest Prairie	0.12	0.08	0.08	0.03
Northeast Prairie	0.22	0.24	0.23	0.08
West Central Plains	0.09	0.15	0.12	0.05
West Ozarks	0.20	0.21	0.17	0.09
East Ozarks	0.25	0.28	0.24	0.10
Bootheel	0.06	0.08	0.05	0.02

Winter Conditions

Winters in Missouri are getting warmer, with less snow on average. One study found the date of last spring frost (less than or equal to 28 °F [-6.4 °C]) occurred between 0.5 and 1.5 days earlier per decade between 1901 and 2007 in areas including the Missouri Ozarks (Marino et al. 2011). A study using satellite data of forest leaf emergence found a trend toward a later end of the growing season between 1989 and 2008 across much of the eastern United States, including the Missouri Ozarks (Dragoni and Rahman 2012). Missouri averages about 10 inches (254 mm; in the southeast) to 20 inches (508 mm; in the northwest) of snow per year, and that snow usually does not stay on the ground more than a week or two. Long-term records reveal a general decrease in snowfall in Missouri since the 1930s (Kunkel et al. 2009). The ratio of snow to total precipitation during the winter decreased in the area between 1949 and 2005 due to both a decrease in snowfall and an increase in rain during that time (Feng and Hu 2007). Although average winter temperatures are relatively mild and getting milder, extreme cold temperatures resulted in 631 cold-related deaths between 1979 and 2017 (National Oceanic and Atmospheric Administration, National Weather Service 2017).

Winter Storms

Snowstorms occur about once per year on average in the region and have decreased over the last century in Missouri (Changnon et al. 2006). In a study examining winter storms from 1949 to 2003, there appeared to be neither a negative nor a positive trend in the number of winter storms in the central United States. However, there was a trend toward an increasing amount of damage from those storms due to both an increase in infrastructure and an increase in storm intensity; this trend was interpreted as being consistent with increased warming (Changnon 2007). The region has on average 3 to 4 days of freezing-rain events per year, which can occur between November and April, with a peak in January (Changnon 2003). A study examining changes in freezing rain over the United States from 1949 to 1999 showed no significant change in the number of freezing-rain events for much of the region (Changnon and Bigley 2005).

Extreme Wind Events

The central United States has the highest frequency of tornadoes in the world (Bates 1962). About 30 tornadoes occur per year across the state (Decker 2022). Tornadoes typically occur April through June, with a second peak in the fall. Five of the 25 deadliest tornadoes ever recorded in the United States occurred in Missouri, where 3 of these events rank among the top 10. The 2011 Joplin tornado was the deadliest in Missouri history, killing 158 people (with an additional 8 indirect deaths), injuring some 1,150 others, and causing damages amounting to a total of $2.8 billion. Although the total number of tornadoes detected in the region increased over the 20th century, this is likely due to greater detection of low-severity tornadoes rather than an actual increase in events (Kunkel et al. 2013).

Derechos, which are large swaths of destructive straight-line winds, are less well known than tornadoes but just as powerful. A "super derecho" on May 8, 2009, stretched from Kansas to Kentucky and was one of the most intense and unusual derechos ever observed. It produced winds up to 90 miles per hour and caused flash flooding in parts of Missouri.

Observed Hydrologic Status and Change

Watershed Context

Missouri can be divided into nine drainage basins or subregional units. The Mark Twain National Forest is spread across multiple watersheds. The larger watersheds include several major drainage basins (classified at the USGS 4-digit hydrologic unit code level): Gasconade-Osage, Upper White, Upper Mississippi-Kaskaskia-Meramec, and Lower Mississippi-St. Francis. Many smaller hydrologic units are described at the USGS 8-digit hydrologic unit code level.

Streamflow and Runoff Trends

Soil moisture, surface water, groundwater quality, and water quantity can vary based on climate, geology, and land use characteristics. Annual streamflow can influence geomorphologic processes, aquatic species composition, and riparian and floodplain ecosystem processes. Streamflow in rivers and streams can also negatively affect the built environment during flood events.

The Missouri Water Resources Plan (Missouri Department of Natural Resources 2020) outlines several key characteristics of Missouri watersheds. A typical water year in Missouri can be described in terms of seasonal streamflow timing: snowmelt and rain events inducing runoff and higher streamflow in early spring (March), followed by streamflow peaks driven by rainfall through late spring and early summer (April to June), a decline in streamflow into early fall (September), and a slight increase again as the soil recharges and then plateaus as soils freeze (October to January). This seasonal description of streamflow timing is a description of broad trends across Missouri and is not meant to be a precise explanation for all areas of the state, as water availability and climate conditions are not uniform, and variations do exist. Between 53 and 62 percent of precipitation is lost to evaporation and transpiration. The rest contributes to streamflow or recharges Missouri aquifers. On average across the state, about 12 inches (303 mm) per year or just under one-third of precipitation becomes streamflow. Streamflow that is generated from precipitation falling in each subregion ranges from 8 inches (203 mm) per year in the Lower Mississippi-St. Francis drainage basin to 18 inches (457 mm) per year in the Upper White drainage basin. Broadly, streamflow varies across the state in relation to precipitation, with the lowest streamflow in the northwest and the most in the southeast. Streamflow in the Upper White drainage basin is considered abundant and relatively consistent even in drought periods due to springs and outlets in the Salem Plateau that provide consistent baseflow to streams (Missouri Department of Natural Resources 2020).

The 2020 Missouri Water Resources Plan includes an analysis of mean daily streamflow from 1950 to 2017 for 52 streamgaging stations (Missouri Department of Natural Resources 2020: Appendix H). Results of this evaluation indicate streamflow is generally increasing across the state, with significantly increasing trends in annual mean daily streamflow for 41 streamgaging stations. According to this assessment, 46 of the 52 streamgages indicate a significantly increasing trend for annual minimum daily flows and a significantly increasing trend for both annual and seasonal mean daily streamflow. Streamflow increases were strongly correlated with increasing precipitation trends across the state, and in some watersheds, an increase in streamflow was driven by increases in both precipitation and land development (Missouri Department of Natural Resources 2020: Appendix H). Few USGS streamgaging stations used in the analysis are located on or immediately adjacent to the Mark Twain National Forest, but all streamgages in the vicinity describe increasing mean daily streamflow trends (0.5 to 1 percent per year; Fig. 5).

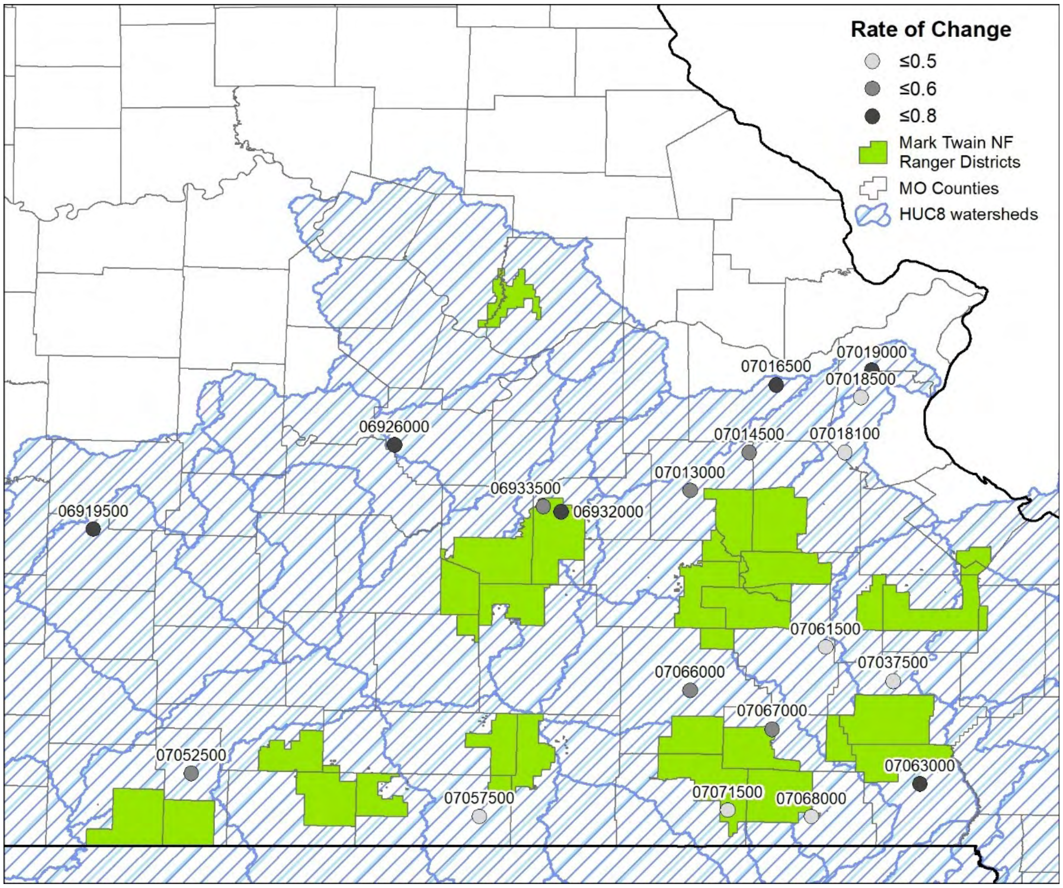

Figure 5.—Map of selected U.S. Geological Survey streamgaging stations near the Mark Twain National Forest, with the change in mean daily discharge (1950 to 2017). The rate of change (percent per year) is described in three categories. Data source: Missouri Department of Natural Resources (2020: Appendix H).

Flood Variability

Floods vary significantly across the Interior Highlands region, which includes Missouri, Arkansas, and Oklahoma (the Ozarks) and nearby areas. Flood variability experienced in a place is dependent on a variety of climatological and hydrologic mechanisms including rainfall duration, intensity, storm size, snowmelt, and rain-on-snow processes. Local characteristics and conditions within the watershed can also drive flood responses affecting the magnitude and severity of flooding. These local factors include soils, vegetative and litter cover, land uses, underlying geology, watershed shape and storage, the ability of the watershed to attenuate flood flows (floodplain access, wetlands, depressional storage areas), and the orientation of the watershed relative to storm tracks. Flood variability and the rate of runoff also depend on the ability of the watershed to infiltrate incoming water during the rain event, the moisture held in the watershed before the event (antecedent soil moisture levels), and the intensity and duration of the storm event. Despite this complexity, the area can be grouped into zones with similar flood characteristics following methods developed by Yochum et al. (2019) (Fig. 6). This categorization may be useful when evaluating hydrologic patterns and a change in flooding over time.

Past flood magnitudes are not uniform across the Mark Twain National Forest ranger districts. When these data are evaluated as a flood potential index (Yochum 2021, Yochum and Arabi 2024), the flood magnitudes experienced in the southern ranger districts are on average larger in this zone than all but 4 percent of zones across the country (96th percentile of all zones in the United States). The magnitude of flooding decreases from south to north such that floods in the northern ranger districts are 29 percent smaller than in the southern ranger districts. The magnitudes of floods across the national forest vary by seasonality.

Flood timing in the south, zone 59S (Fig. 7), occurs in two peak seasons with the largest 5 percent of floods occurring in spring (peaking in April) and early winter (peaking in December). Historical datasets indicate that 26 percent of all large floods have occurred in April, and 17 percent of large floods have occurred in December. However, throughout the record it is evident that large floods have occurred in every month. In the northern Ozarks (zone 59N), large floods also occur in every month. They are most frequent during the early winter with December (17 percent of the events), April (14 percent), and May (13 percent), with a third seasonality peak in August (12 percent). In zone 61, the peak seasonality is in July (22 percent), with April a less distinct peak (16 percent). Floods on the Mark Twain National Forest are inherently large, especially in the southern ranger districts, with these areas experiencing some of the largest floods in the United States. The largest floods are also substantially larger than more-common floods occurring in the area. Additional information and analysis are provided in Appendix 2.

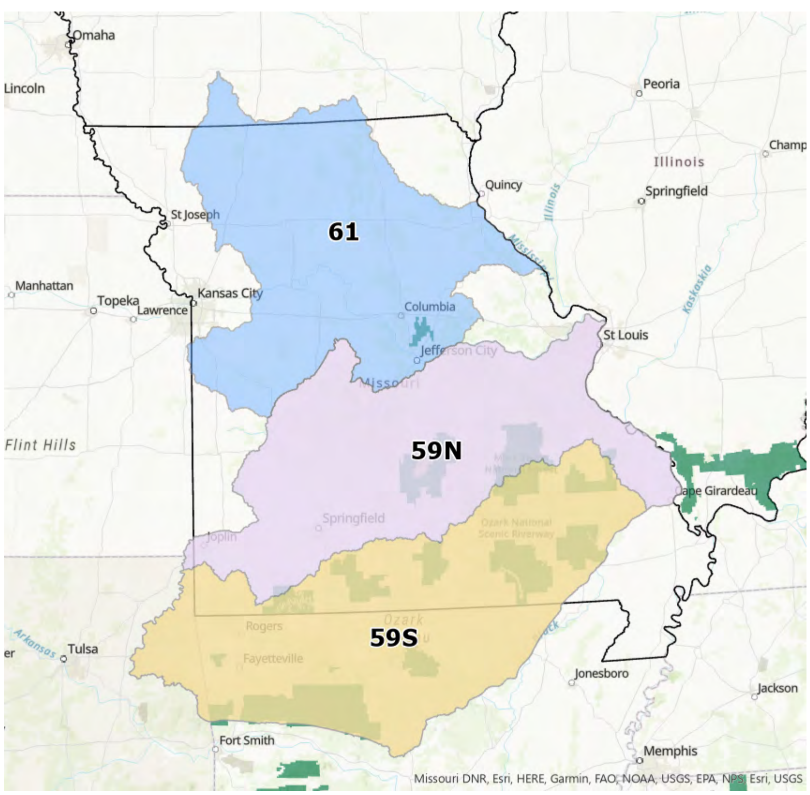

Figure 6.—Boundaries for flood potential zones (61, 59N, and 59S) overlaid on Mark Twain National Forest units.

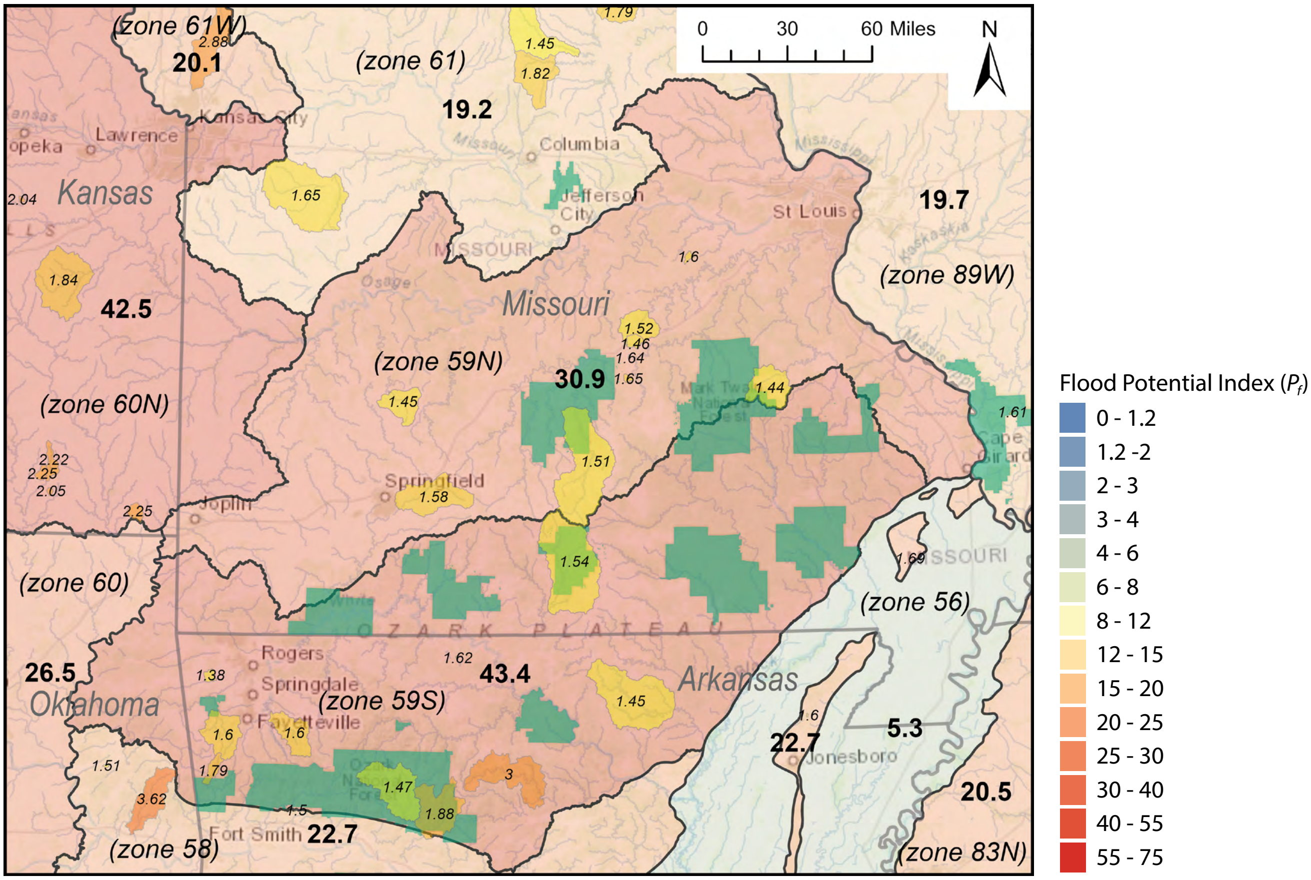

Figure 7.—Variability of flooding across the Mark Twain National Forest (green polygons) and adjacent areas, within labeled flood potential zones. Large bold labels are flood potential index values. Watersheds that have experienced extreme floods are shown in deeper shades of orange, indicating more extreme events. Source: Yochum and Arabi (2024).

Flood Trends

Not only are floods inherently large on the Mark Twain National Forest, they are also becoming more severe in a number of ways. Evaluating the magnitudes, frequency, and flashiness of floods can inform understanding of the broader risk of current and future flood occurrences.

Between 1960 and 2019, trends in the Ozarks indicate very little change in the magnitude of the largest 5 percent of annual peak discharges across the region, yet the trends indicate an increase in the largest flood events that occur least often; the overall rate of change is about 6 percent or greater (Yochum and Arabi 2024). For the largest quarter of annual peak discharges, the central ranger districts of the Mark Twain National Forest, in the northern Ozarks, are experiencing the greatest increases in large flood magnitude (Yochum and Arabi 2024). An increase in magnitude of moderate-scale floods and more frequently occurring bankfull-scale floods can impact the national forest in many ways, such as contributing to geomorphic adjustments (erosion) of stream channels and surrounding flood-prone areas. Within the record, an increasing trend in the smallest floods indicates that annual peak flows during dry years are also becoming larger.

The frequency of flood events is increasing across the Mark Twain National Forest with the highest rate of occurrence in the central and northern ranger districts within the central and northern flood potential zones. Flood flashiness has not changed and is not increasing across the national forest. Flashiness is decreasing in the northern section of the national forest. Additional information and analysis are provided in Appendix 2.

Large and Extreme Floods

As described in previous sections, the magnitude, frequency, and flashiness of floods vary across the region, with floods having inherently larger magnitudes in the southern ranger districts of the Mark Twain National Forest (Fig. 7). The primary driver of major floods, heavy precipitation events, has been observed to be increasing across Missouri (see the "Precipitation Extremes" section in this chapter), which can lead to increases in runoff and flooding (see the preceding section). However, antecedent soil moisture and other hydrologic mechanisms are also important in the production of large floods, which complicates interpretations.

Large flood events have occurred consistently throughout the streamgage record, from 1897 to present within the Mark Twain National Forest and neighboring lands. Within zone 59S, 10 major floods have occurred from 1904 to 2017; and within zone 59N, 11 major floods have occurred from 1897 to 2017. More information on specific events is available for floods occurring in 1982 (Parrett et al. 1993, Sauer and Fulford 1983), December 2015 to January 2016 (Holmes et al. 2016), and April to May 2017 (Heimann et al. 2018). Additional information and analysis are provided in Appendix 2.

Highlight: 2017 Storms

In April 2017, rainfall of up to 15 inches (381 mm) fell in parts of southern Missouri, inducing large floods and record peak discharges in numerous rivers. The Current River, which flows through the Eleven Point unit, had peak floodwaters of 40 feet (12 m). The North Fork River in the Willow Springs unit rose 4 to 5 feet (1.2 to 1.5 m) per hour, peaking nearly 14 feet (4.3 m) above the previous record high-water mark set in 1985 (with 72 years of record). The flooding that ensued on the North Fork was extreme, as systematically defined by the flood potential method, though not extreme for the Current River. Extreme or not, these large floods had catastrophic consequences for communities and infrastructure (Fig. 8). Illustrating the volatile and regularly repeating nature of storms in this area, a second round of severe thunderstorms brought straight-line winds, large hail, more flooding, and tornadoes to the same area at the end of May, damaging infrastructure that had recently been repaired after the April floodwaters subsided.

Figure 8.—Flood damage on the Mark Twain National Forest, 2017. USDA Forest Service photos by Melissa Steward.

These storms caused significant damage to the Mark Twain National Forest's infrastructure and recreation sites. Roughly half of the national forest's roads were damaged (Operational Maintenance Levels 3 and 4). At least 86 percent of trails on the national forest were damaged, and one-third of recreation sites on the Salem and Potosi/Fredericktown units were damaged or closed. On the Current River, 40 percent of sites were inaccessible. The storms led to 41 temporary recreation site closures, but robust staffing and coordination ensured public access was restored to all but 7 major recreation sites several weeks later (summarized from Eastern Area Incident Management Team [2017], with flood potential results added for context).

Other Key Disturbances and Hazards

Wildfire

Fire plays an important role in shaping the structure and composition of Missouri forests. The historical role of fire in the development and maintenance of oak forests has been well-established across much of the eastern deciduous biome (Abrams 1992, Brose et al. 1999, Lorimer 1985). Both natural and human-caused fire have been components of ecosystems in the Midwest for thousands of years (Abrams 1992, Heikens and Robertson 1995, Ruffner and Abrams 2003).

Today, both wildfire and prescribed fire are common on the Missouri landscape. The fire season for Missouri is currently from February through April and September through October. When conditions are dry during these periods, wildfires tend to increase, and prescribed burning tends to decrease (Godwin 2013). Prescribed fire has been increasingly used as a tool for ecosystem management in Missouri, and there appears to be an overall upward trend in the number of acres burned annually on public land (MoGreenStats 2016). Wildland fires (i.e., unintentional burns) are more variable from year to year and related to climate conditions during the burn season. These fires are usually human caused and often intentional (Brosofske et al. 2007).

Wildfire can pose a risk to both residents and visitors near the Mark Twain National Forest. Akinola and Adegoke (2019) created an assessment of forest fire vulnerability and found that the portion of the Ozarks located in Missouri was the most at-risk for wildfire based on factors such as vegetation type, housing density, and elevation. This vulnerability map lined up well with where fires had occurred in the historical record. A second paper by the same group showed that social vulnerability to wildfire in the state is elevated among people who have education less than a college degree, have low income, and rent (rather than own) their homes (Akinola et al. 2019).

Forest Pests and Pathogens

Insect pests and pathogens can influence the condition of Missouri forests, affecting recreation opportunities through loss of aesthetics and increased hazards from dying trees. Oak decline, caused by a complex set of biological and physical factors, has had a major negative influence on the health of species in the red oak group (Dwyer et al. 1995, Fan et al. 2006, Haavik et al. 2015, Jenkins and Pallardy 1995, Wang et al. 2008). Droughts in the late 1990s appear to have at least in part contributed to oak decline (Haavik et al. 2011, 2015). Other current pests and diseases in the state include emerald ash borer, anthracnose of sycamore, oak wilt, and rapid white oak mortality (Missouri Department of Conservation 2020a). Missouri is also monitoring for potential new pests and diseases, most notably thousand cankers disease, laurel wilt of sassafras, and spongy moth (Krist and Romero 2015).

Human Health Hazards

Risks to human health for recreationists on the Mark Twain National Forest include insect-borne illness, reactions to plants, and weather-related illness. Insect-borne illnesses common in Missouri include those from ticks, such as the Rocky Mountain spotted fever, ehrlichiosis, tularemia, Heartland virus, Bourbon virus, and Lyme disease. The most common mosquito-borne illness is West Nile virus. Poison ivy is found throughout the national forest and can lead to severe rashes in some people. Heat-related illness is also a risk on the national forest in the summer months and is one of the leading weather-related causes of death in the United States. Illnesses such as heat stroke and heat exhaustion are more common in hot, humid conditions.

Chapter Summary

Mark Twain National Forest personnel manage a wide variety of infrastructure that helps support access and recreation opportunities for the approximately 880,000 visitors to the national forest each year. A summary of changes in climatic conditions and hydrologic and disturbance events reported for Missouri over several decades can help recreation managers understand current trends and inform management planning. During a 60-year record for the state, mean annual temperatures increased by 0.3 to 0.4 °F per decade, and annual precipitation increased by 0.4 to 1.3 inches per decade. Indices of drought-impacted conditions showed a trend toward less frequent and less severe droughts across Missouri over this timeframe. Winters have been becoming warmer, and annual snowfall has been decreasing on average across the state. Past flood magnitudes vary by national forest unit and season, but floods are inherently large across the units. The 30-year record for the area indicates increasing flood magnitudes and greater event frequency that are likely due to climate change. Wildfire and prescribed fire are common on the Missouri landscape, and prescribed burns for ecosystem management are being implemented more often. Forest managers are also monitoring for insect pests and pathogens, both those currently present and potential new arrivals. Information from multidecadal observations of conditions defines the baseline for comparison with projected future changes in climate and hydrology, discussed in Chapter 2.

Chapter 2: Projected Changes in Climate

Changes in temperature and precipitation may have potentially profound effects on the Mark Twain National Forest's recreation infrastructure and opportunities. This chapter summarizes projected changes in temperature and precipitation over the rest of the 21st century and how these changes could potentially influence the hydrology of the Mark Twain National Forest.

Future Temperature and Precipitation

Projections of future climate are made by using global climate models. Dozens of climate models are available, each with its own nuances in how the Earth-atmosphere system is represented. Consequently, some models may represent an area as warmer or drier than other models. To help reduce the amount of noise among them, models can be averaged or a subset of models can be selected that represent the extremes of the spectrum. This assessment examines the risk of floods, which are driven by extreme events; accordingly, we chose models that represent the far ends of the spectrum.

Future climate projections from the MRI-CGCM3 (Yukimoto et al. 2012) and IPSL-CM5A-MR (Dufresne et al. 2013) models (hereafter referred to as MRI and IPSL) under the representative concentration pathway (RCP) 4.5 and RCP 8.5 (Moss et al. 2008) were used to provide a range of potential conditions (Table 5). RCP scenarios describe different pathways of greenhouse gas emissions and atmospheric concentrations as well as air pollutant emissions and land use (Intergovernmental Panel on Climate Change 2021). The RCP 4.5 scenario represents an intermediate scenario in which atmospheric carbon dioxide (CO_2) levels remain below 550 ppm, whereas the RCP 8.5 scenario includes continued increases in greenhouse gas emissions and is considered the "high end" scenario (high emissions, high greenhouse gas concentrations, and usually a large temperature increase on a global scale). Projections were downscaled using the Multivariate Adapted Constructed Analogs (MACA) approach described by Abatzoglou and Brown (2012) and obtained and processed within Google Earth Engine (Alphabet Inc., Mountain View, CA). Three 30-year periods (2010 through 2039; mid-century, 2040 through 2069; and end of century, 2070 through 2099) were processed to examine the trends and rates of potential change among various climatic indices and metrics. We sorted projections from five downscaled climate models and two RCPs from wettest to driest and greatest to least temperature change for the Mark Twain National Forest and selected a set of four combinations that bracketed the greatest spread of temperature and precipitation change (Table 5; Appendix 3, Fig. 19).

Table 5.—Summary of climate models and scenarios used to examine temperature and precipitation trends

Model and RCP pathway	Description
MRI, RCP 4.5	Least warming, slight decrease in mean annual precipitation
MRI, RCP 8.5	Moderate warming, increase in mean annual precipitation
IPSL, RCP 4.5	Moderate warming, increase in mean annual precipitation
IPSL, RCP 8.5	Higher warming, greatest decrease in mean annual precipitation

Temperature

All models project an increase in temperature across all seasons (Fig. 9). By the end of the century, mean annual temperatures are projected to increase by between 2.5 and 10.6 °F (1.4 and 5.9 °C) compared with past averages (1980 through 2009). However, the amount of warming varies by season and by scenario. Summers are projected to warm by between 3 and 14 °F (1.7 and 7.8 °C), and winter temperatures are projected to increase by 1.8 to 10.2 °F (1.0 and 5.7 °C). Projected changes in mean temperatures for each Mark Twain National Forest unit are presented in Appendix 3.

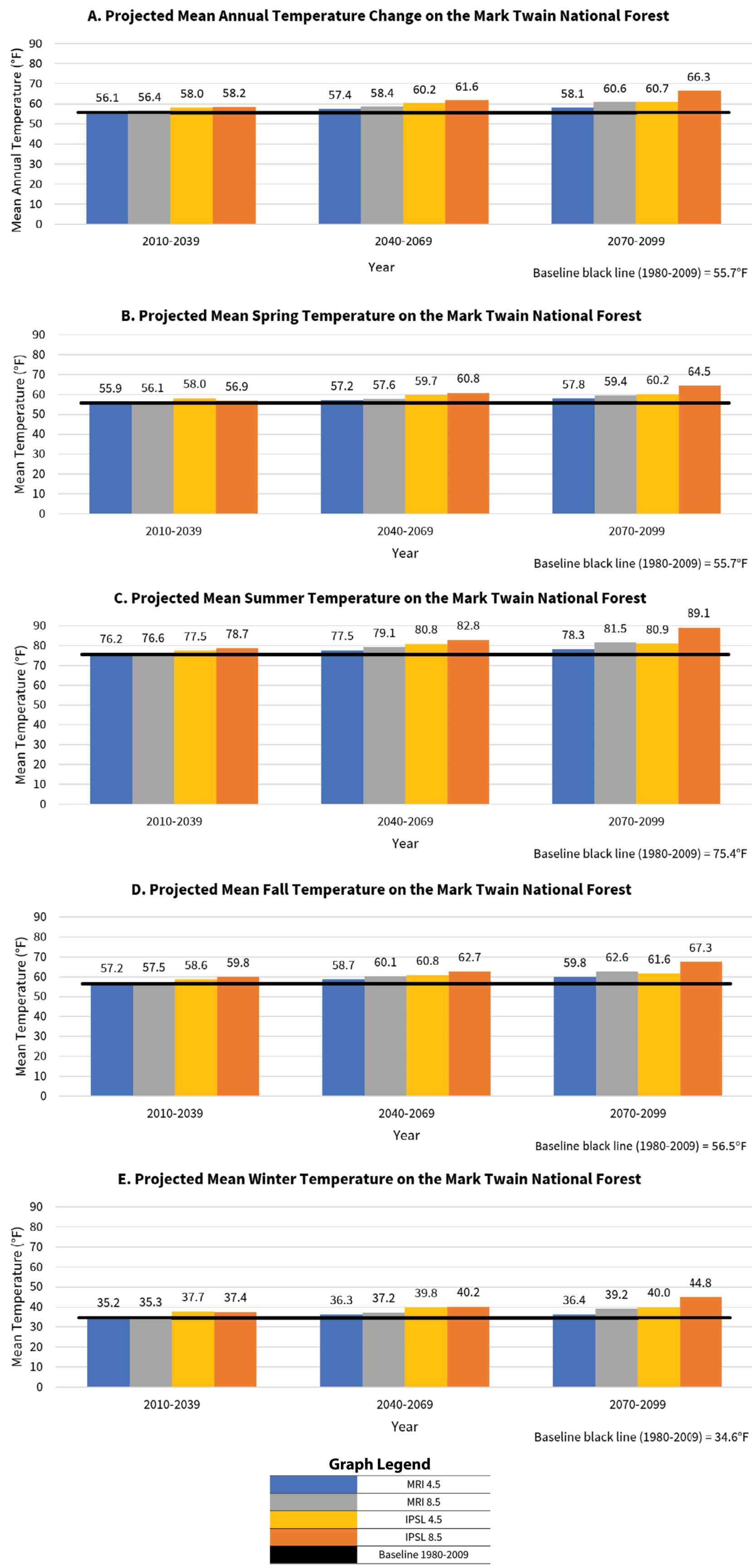

Figure 9.—Projected change in annual (A) and seasonal (B-E) mean temperatures under the four scenario combinations for three 30-year periods compared with the baseline period of 1980 through 2009 for the Mark Twain National Forest.

Precipitation

Models are not consistent in their projections of precipitation, with some projecting an increase and others a decrease (Fig. 10). By the end of the century, annual precipitation could decrease by 7 inches (178 mm) under the IPSL 8.5 scenario or increase by 4.3 inches (117 mm) under the MRI 8.5 scenario compared with the 1980 through 2009 average. The IPSL 8.5 scenario projects decreases in annual and seasonal precipitation for each 30-year period, except for spring 2010 through 2039. Across all seasons, the scenario combinations that project the greatest precipitation increases are MRI 8.5 and IPSL 4.5. The MRI 4.5 scenario represents a future closest to current conditions, and the IPSL 8.5 scenario represents a drier future. All annual projections are within a few inches of the baseline, however, indicating that total precipitation may not change dramatically, which is consistent with findings in the Fourth National Climate Assessment (U.S. Global Change Research Program [USGCRP] 2018). Annual precipitation results are presented by Mark Twain National Forest unit in Appendix 3.

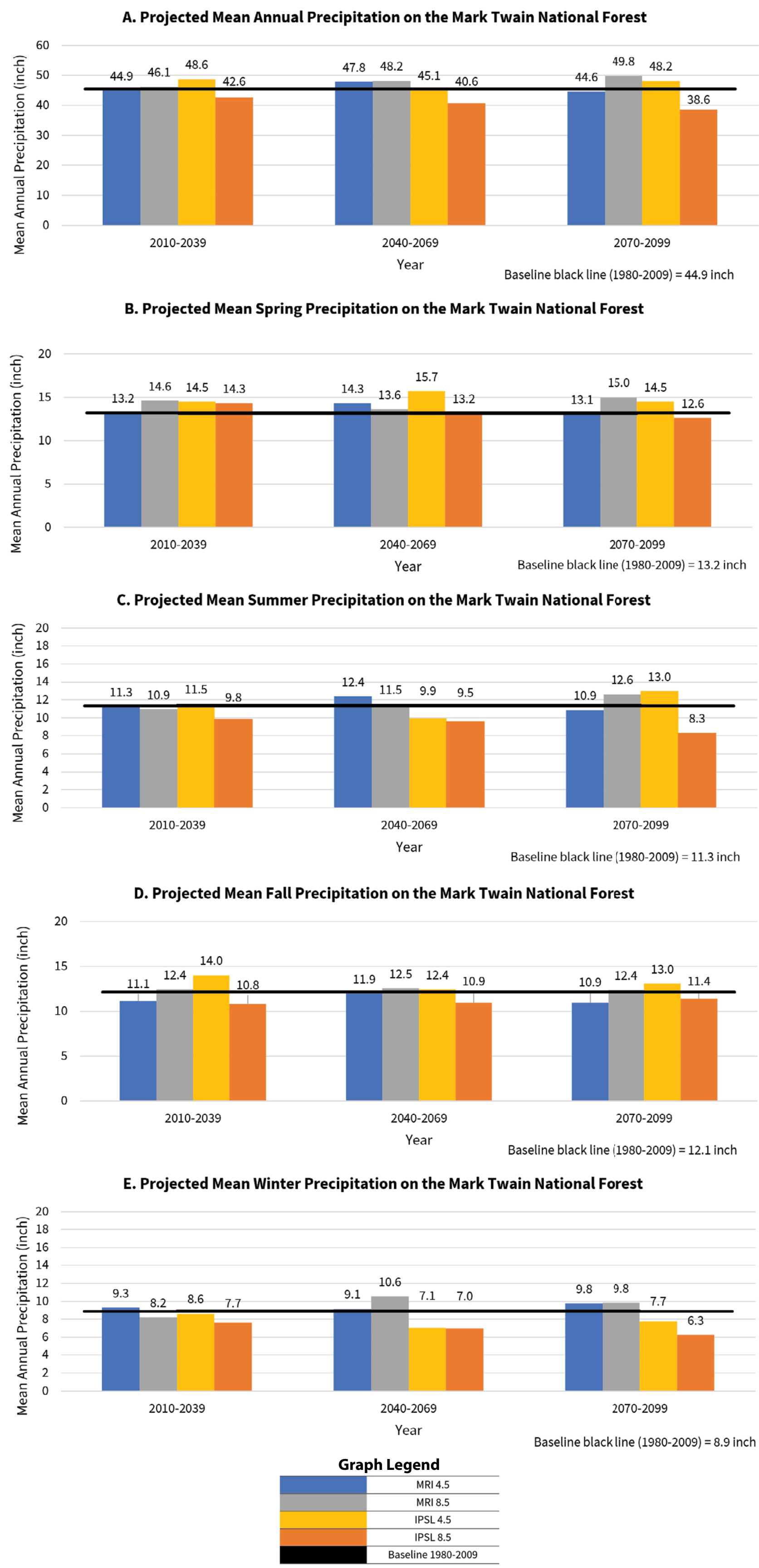

Figure 10.—Projected change in annual (A) and seasonal (B–E) precipitation under the four scenario combinations for three 30-year periods compared with the baseline period of 1980 through 2009 for the Mark Twain National Forest.

Winter Conditions

Winters are projected to be warmer and drier on average. Studies project that the Midwest will experience between 25 and 38 fewer days below freezing by the end of the 21st century (Ford et al. 2021, Sinha and Cherkauer 2010, U.S. Global Change Research Program 2017). Snowfall in Missouri is projected to decrease by 7 to 28 inches (178 to 711 mm) by the end of the century, depending on scenario (Notaro et al. 2014). Warming temperatures may lead to a decrease in the overall frequency of ice storms and snowstorms due to a reduction in the number of days that are cold enough for those events to occur. However, these events may still occur in certain microclimates, and there is also some evidence to suggest that these events could be more intense when they do happen. Wang and Zhang (2008) examined changes in risk of extreme precipitation during the winter months under a high greenhouse gas emissions scenario (similar to RCP 8.5) using statistically downscaled climate projections. They found an increased risk for extreme winter events at the end of the century for the central United States, which includes the Mark Twain National Forest area. However, other research suggests this may be an overestimate. Kawazoe and Gutowski (2013) compared future climate projections with observations for winter precipitation within the Upper Mississippi watershed and found the model simulations by Wang and Zhang (2008) overestimated the frequency and intensity of events that occurred between 1980 and 1999. They suggest that the driver for intense winter storms is warmer sea surface temperatures in the Gulf of Mexico. Whether these events occur as rain, snow, or ice will depend on the exact timing of these events and their interaction with projected changes in temperature.

Extremes: Disturbance Frequency and Intensity

Extreme Temperature

Extreme high and low temperatures are expected to increase. Future climate projections indicate that the number of days with minimum temperatures at or below 4.2 °F (-15.6 °C; derived as the first percentile of climate values over the baseline period) could decrease over the century (Fig. 11). Generally, across both the greatest warming scenarios (RCP 8.5), fewer extremely cold days are projected to occur in the last 30 years of the century as compared with the lower warming scenarios (RCP 4.5). The number of days at or above the 99th percentile for maximum temperatures (96 °F; 36 °C) is projected to increase in the greatest warming scenario (RCP 8.5) by 4 to 12 times as many days by the end of the century (Fig. 11). This is consistent with studies from across the Midwest that indicate there could be more days per year that are warmer than 95 °F (35 °C) and a greater frequency of multiday heat waves over the 21st century (Kunkel et al. 2013, Winkler et al. 2012).

Figure 11.—Projected change in the number of days per year below the current 1st (A) and 5th (B) percentile for annual minimum temperatures and projected change in the number of days per year above the current 95th (C) and 99th (D) percentile for annual maximum temperatures under the four scenario combinations for three 30-year periods compared with the baseline period of 1980 through 2009.

Precipitation Extremes and Flooding

Consistent with recent trends, the frequency and intensity of extreme rainfall events is expected to increase in the coming decades. Two ways to define extreme precipitation events are to consider events at or above some volume or to use a percentile of observed volumes to determine what are normally occurring values. In the recent 30-year period (1980 to 2009), most precipitation events were less than 2 inches (51 mm), and 2-inch events occurred on average 1.4 days per year. Most scenarios projected increases in extreme rain events in the 95th and 99th percentiles. The IPSL 8.5 scenario projects 2 to 3 fewer days per year, while the remaining scenarios project increases of 1 to 4 days per year, with precipitation at or above the 95th percentile (0.7 inch [18 mm] or greater, Fig. 12). All scenarios project increased precipitation up to an average of 2 days per year at or above the 99th percentile (1.5 inches [38 mm]), and increases in 2-, 3- (76-mm), and 4-inch (102-mm) events. Although single events with large volumes of precipitation can lead to flooding, consecutive events with lower volumes can also produce flooding due to saturated landscapes that cannot accommodate additional water inputs.

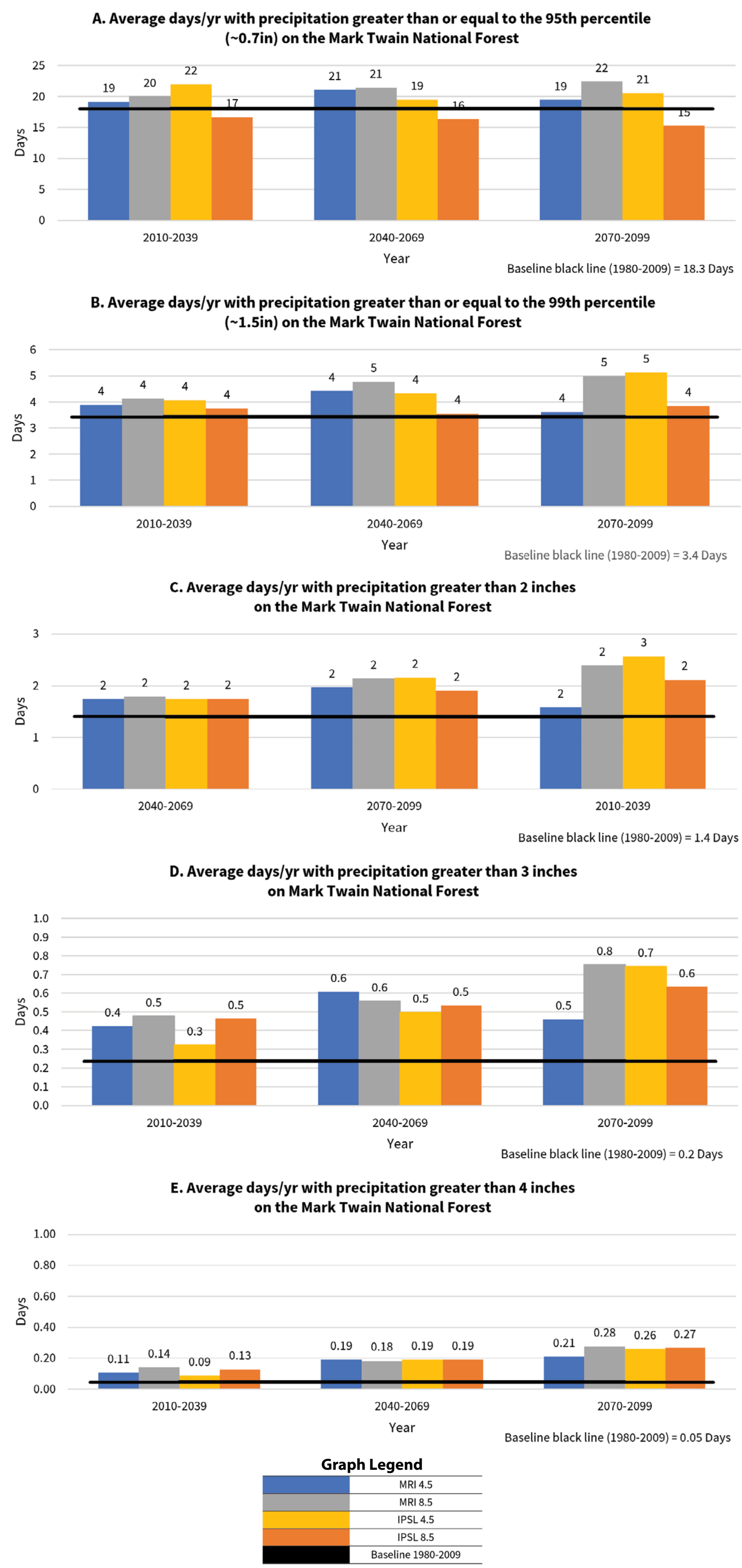

Figure 12.—Projected change in the average number of days per year experiencing precipitation events above the 95th percentile (A), the 99th percentile (B), 2 inches (C), 3 inches (D), and 4 inches (E) under the four scenario combinations for three 30-year periods compared with the baseline period of 1980 through 2009.

Future Hydrologic Changes

Warmer temperatures often increase the intensity and magnitude of precipitation events (USGCRP 2018). As a result, higher water levels, earlier spring flows, more flashy (episodic) streamflows, and greater streamflow and flooding are expected to occur across the Mark Twain National Forest watersheds by the end of the century (USGCRP 2018). This projection is consistent with streamgage observations that large floods are occurring more frequently. Soil moisture regimes may be altered by warmer and longer growing seasons, evaporation, and an increased vapor pressure deficit, thereby reducing low flows during the growing season by the end of the century (USGCRP 2018).

The timing, form, and spatial distribution of precipitation is changing with climate, and this change can have cascading effects on forest hydrologic cycles affecting water yield and water quality. Although extreme precipitation events and drier soils may become more common, ultimately the local land cover, slope, geology, and land use characteristics of a particular site determine the vulnerability of a site to these long-term changes. Alterations to the hydrologic cycle can affect recreation timing, usage, and public health and safety (such as drowning, injury, motor vehicle accidents, water contamination, loss of recreational benefits and opportunities). Summaries of extreme streamflows are provided in the following sections, and detailed tables by Mark Twain National Forest unit are included in Appendix 5.

Hydrologic Flows

Projected streamflow modeling across the contiguous United States using the Variable Infiltration Capacity (VIC) macroscale hydrologic model was performed by specialists at the USDA Forest Service Office of Sustainability and Climate (2022) using an ensemble of five CMIP5 global climate models used by the 2020 Forest Service RPA Assessment (Joyce and Coulson 2020) under RCP 8.5 for mid-century and end of century. These data were summarized in comparison with baseline conditions (1977 through 2006) for the Mark Twain National Forest units. Hydrologic changes as compared with baseline conditions for streams flowing through the national forest are described in map form in Appendix 4. The following is a summary of key findings.

- **Annual flow (mean)** is projected to decrease by 10 to 25 percent as compared to baseline by mid-century (2031 through 2059) across most ranger districts except for the Cedar Creek and Rolla units, which are projected to be at baseline to slightly above baseline conditions (increase of 0 to 10 percent). This trend is projected to continue through the end of the century (2070 through 2099) for most units. Notable decreases in mean annual flows as compared to baseline (25 through 50 percent) are projected for the Ava, the Cassville, and parts of the Houston and Rolla units.

- **The percent change in the 1.5-year flood (bankfull)** is projected to moderately increase (0 to 10 percent) across most ranger districts, with greater increases (10 to 25 percent) projected for the Cedar Creek, Poplar Bluff, Potosi, and Salem units, and parts of the Fredericktown unit by mid-century (2031 through 2059). This trend is projected to continue into the end of the century, with some units (noted previously) projected to experience 10 to 25 percent more 1.5-year flood events and others projected to experience the same or slightly less frequent 1.5-year flood events as compared to baseline (a decrease of 0 to 10 percent).
- **The percent change in the 10-year flood** is projected to increase (10 to 25 percent) as compared to baseline across most ranger districts except for portions of the Ava, Houston, and Willow Springs units, which are projected to experience fewer 10-year flood events (0 to 10 percent, and in some areas localized reductions up to 25 percent as compared to baseline). The greatest increases (25 to 50 percent) are projected for the Fredericktown, Poplar Bluff, Potosi, and Salem units, and easterly areas of the Eleven Point and Doniphan units by mid-century. Trends continue through the modeled end of the century for most ranger districts. However, a slight decreasing trend is noted for some units as compared with mid-century projections, particularly for the Eleven Point, Potosi, and Rolla units.

Extreme Streamflows

A commonly used variable to describe extreme streamflows in a river or stream is the 1 percent annual exceedance probability (AEP), which is also known as the 100-year flood. An AEP conveys the statistical probability (or percent chance) of a flood event. The 1 percent AEP is a variable that describes flood peaks with a 1 percent chance of being equaled or exceeded in any given year (USGS 2018). It is important to emphasize that AEP does not dictate a length of time between rare events, when an event might occur, or the chances of another rare event occurring within a short period of time (USGS 2018). Understanding how potential future changes in the hydrologic cycle and precipitation may affect inland flooding and flood surges is critical to planning and is particularly important when evaluating risks to infrastructure, facilities, and recreation management.

Here we provide a summary of peer-reviewed regional projections in flood areas that include the Mark Twain National Forest (Demaria et al. 2016, Mills et al. 2018, Wobus et al. 2017). Map results found in Mills et al. (2018) were summarized for each ranger district on the national forest to assist local managers (see Appendix 5). Local project site investigations may require additional localized modeling and ground truthing to estimate on-the-ground risks at an asset level.

Frequency of Large Floods

The direction of change in future flood flows for the Mark Twain National Forest could vary by county and ranger district. Future flood flows are projected to increase in frequency across all ranger districts using an ensemble of models under both warming scenarios (RCP 4.5 and 8.5) when values are compared with the baseline (2001 through 2020). The greatest increases in 1 percent AEP events are projected in the greatest warming scenario (RCP 8.5) (Mills et al. 2018). Such increasing frequency trends are already being observed by the streamgaging network in this area; these projections are confirmed through trend tests of streamgage data for periods ending in 2020.

- **Mid-century** (2040 through 2059). Under the lower warming scenario (RCP 4.5), 1 percent AEP flood flows are projected to be the same or slightly more frequent than baseline (2001 through 2020); however, in the greatest warming scenario (RCP 8.5), flows are projected to be **2 to 3 times** more frequent in all ranger districts.
- **End of century** (2080 through 2099). One percent AEP flows are projected to be slightly more frequent in the lower warming scenario (RCP 4.5) as compared with baseline (2001 through 2020) conditions. One percent AEP flows are projected to be greatest in the Poplar Bluff unit as compared with other units. In the greatest warming scenario (RCP 8.5), flood flows are projected to be **2 to 3 times** more frequent in all ranger districts. Notably, in the greatest warming scenario, eastern districts (the Fredericktown, Poplar Bluff, Potosi, and Salem units) are projected to experience the largest increases in the frequency of floods as compared with other districts, with **3 to 4 times** more frequent 1 percent AEP flood flow events projected in the easternmost units and **4 to 6 times** more projected in the northwestern section of the Potosi unit.

Magnitude of Large Floods

The magnitude of future flood flows is projected to increase across all ranger districts on the Mark Twain National Forest but could vary by county. Generally, the magnitude of future 1 percent AEP flows as compared with the 2001 through 2020 baseline is projected to increase under both RCP 4.5 and 8.5. The largest increases in flood flow magnitude are projected in the greatest warming scenario (Mills et al. 2018). Projections of increasing flood magnitudes are not consistent with observations of streamgage records; trends tests for periods ending in 2020 indicate that there are no existing trends in flood magnitudes on the Mark Twain National Forest.

- **Mid-century** (2040 through 2059). In the lower warming scenario (RCP 4.5), the magnitude of 1 percent AEP flood flows is projected to be slightly smaller or the same as baseline conditions; however, in the greatest warming scenario (RCP 8.5), the magnitude of flood flows is projected to be **10 to 20 percent** larger.
- **End of century** (2080 through 2099). The magnitude of 1 percent AEP flood flows is projected to be about the same or slightly larger in the lower warming scenario (RCP 4.5); however, in the high emissions scenario, the magnitude of flows is projected to be **10 to 20 percent** larger. Notably, in the high emissions scenario, eastern ranger districts (the Fredericktown, Poplar Bluff, Potosi, and Salem units) are projected to experience flows of **20 to 30 percent** greater magnitude.

Low Flows

Demaria et al. (2016) used a climate model ensemble average and the VIC hydrologic model (Liang et al. 1994) to evaluate the magnitude of mean baseflow, peak flows, and low flows across the Midwest and Northeast regions for two 55-year periods: a historical period (1951 through 2005) and a projected future "mid-century" (2028 through 2082) period. Their results indicate that the magnitude of low flows is projected to decline by the end of the century, leading to decreased low flows in a 7-day period and lower mean baseflows across much of Missouri's central and southern tiers by the end of the century in the greatest warming scenario (RCP 8.5). Generally, the magnitude of 7-day low flows as compared with the historical baseline is projected to be reduced under both warming scenarios by 0 to 20 percent. This decreasing low flow trend aligns with the additional interpretations and analysis summarized from Walker and Luce (2021) and LaFontaine et al. (2019), provided in the following sections (Appendix 5 contains additional information).

To examine changes at a more local level, minimum hydrologic variables for the Mark Twain National Forest ranger districts were also evaluated using the Walker and Luce (2021) and LaFontaine et al. (2019) datasets. The annual minimum flow (baseflow) is generally projected to decrease or remain similar to observed historical conditions across all districts on the Mark Twain National Forest across both datasets and under both scenarios and models (MRI and IPSL) for the LaFontaine et al. (2019) dataset (Appendix 6 contains additional information). The slight decreasing trend is consistent across most ranger districts, models, and scenarios. The greatest decreases in baseflow are projected for most districts in the greatest warming scenario and range from 52 to 74 percent. By the end of the century (2070 through 2099), the Walker and Luce (2021) dataset projects baseflows to slightly increase across all ranger districts, with the largest increases in the Cassville, Ava, Potosi, and Salem units.

The date of minimum weekly flow (absolute change) is projected to remain the same or shift slightly earlier (by 0 to 10 days earlier) for most ranger districts (Walker and Luce 2021). However, portions of most units are projected to experience minimum weekly flows much earlier (25 to 50 days earlier). End-of-century (2070 through 2099) projections indicate minimum weekly flows may occur earlier in the Fredericktown, Houston, Poplar Bluff, and Rolla units, and portions of the Doniphan and Eleven Point units. Extreme 10-year minimum weekly flows are projected to occur at normal to slightly decreased percentages (0 to 10 percent), as compared with baseline conditions, through the end of the century (Walker and Luce 2021) (Appendix 6 contains additional information).

Seasonal Changes

Spring Streamflow

Demaria et al. (2016) used an ensemble average of 10 climate models and the VIC hydrologic model to evaluate changes in snow cover and the magnitude and timing of spring maximum streamflow across the Midwest and Northeast. Results of this study suggest that because of warmer temperatures, the projected snowpack volume and duration in Missouri are expected to be greatly reduced, possibly resulting in a snow-free February by the end of the century, under both emissions scenarios. By the second half of the century, spring streamflow (March through May) is projected to occur 10 to 20 days earlier across the Mark Twain National Forest under both warming scenarios, a statistically significant trend of change. Additionally, spring peak flow magnitudes are projected to increase.

Walker and Luce (2021) evaluated the center of flow mass date, finding the timing of spring streamflows may increase slightly by 0 to 10 days through the end of the century (2070 through 2099). The percent change in average spring flow across most ranger districts is projected to be near normal (baseline) to slightly increasing (0 to 10 percent). The Cedar Creek and eastern Fredericktown units are projected to experience 10 to 25 percent greater spring streamflow. The Ava and Cassville units are projected to experience slight to extreme decreases in spring streamflows (decreases of 10 to 25 percent) by the end of the century.

Summer Minimum Streamflow

Summer (July through September) seasonal minimum streamflows were evaluated for each ranger district (Appendix 6: Table 18). Summer minimum streamflow is projected to decrease or be similar to observed historical conditions for most districts, with notable increasing summer seasonal 3-day and 7-day streamflows projected for the Cedar Creek and Fredericktown units under the high emissions scenario for both IPSL and NorESM models.

Walker and Luce (2021) evaluated the percent change in average summer flow. By mid-century (2031 through 2059), some districts are projected to experience summer streamflow near baseline conditions (the Ava, Cassville, Potosi-Salem, and Willow Springs units, and portions of the Houston, Rolla, and Eleven Point units) or experience moderate declines (10 to 25 percent). Severe decreases to summer streamflows are projected through the end of the century (2070 through 2099) for all ranger districts (25 to 50 percent), with the Ava and Cassville units projected to experience the least amount of change (decreases of 0 to 10 percent).

Chapter Summary

Projections of future climate from downscaled climate models under two scenarios for the Mark Twain National Forest were sorted by change in precipitation (wettest to driest) and change in temperature (greatest to least) through the end of the 21st century. The four general circulation model–scenario combinations selected represent a range of plausible climate futures and were used to project mean annual and seasonal temperature and precipitation across the national forest for three 30-year periods: 2010 through 2039, 2040 through 2069 (mid-century), and 2070 through 2099 (end of century). The projections were compared with averages of data recorded over the previous 30 years (baseline conditions). All models project an increase in mean annual and seasonal temperatures as compared to the baseline. By the end of the century, an increase of 2.5 to 10.6 °F is projected for mean annual temperatures, and the national forest may be subject to 4 to 12 times as many extremely hot days as during the baseline period. Models differ in their outlook for end-of-century precipitation. Annual precipitation could potentially decrease by 7 inches or increase by 4.3 inches, depending on the model. Models agree that the frequency and intensity of heavy rainfall events are expected to increase over the remainder of the century. These projections underpinned an analysis of potential effects of climatic changes on hydrologic flows and cycles in the region. By mid-century, mean annual flow is projected to decrease by 10 to 25 percent as compared with a baseline of 1977 through 2006 for streams across much of the national forest, and the trend is projected to continue, with a few exceptions, through the end of the century. Projections for summer streamflows vary by location and model at mid-century, but sharp decreases to summer streamflows are projected across the national forest by the end of the century. Chapter 3 examines how these projected changes in climatic and hydrologic variables could affect the forest ecosystems, seasonal recreation opportunities, facilities, and infrastructure on the Mark Twain National Forest.

Chapter 3: Impacts to Ecosystems, Infrastructure, and Recreation Opportunities

The effects of a changing climate on ecosystems can also influence opportunities for recreation. Increased tree mortality can lead to hazards and a greater need for trail maintenance. Timing of fall color viewing, migratory bird watching, and fruiting of foraged food may also be altered. Over the long term, alterations to the forest landscape through shifting species composition may also affect the way the public interacts with the forest. This chapter summarizes key impacts to forest ecosystems and implications for seasonal recreation opportunities, facilities, and infrastructure. The Central Hardwoods Ecosystem Vulnerability Assessment and Synthesis contains more information on climate change impacts on regional ecosystems (Brandt et al. 2014).

Effects of Climate Change on Forests and Ecosystems

Although many tree species are projected to retain or even gain suitable habitat under future climate projections, declines in suitable habitat for some common trees could create increased hazards for recreation. Scientists have modeled the current and future suitable habitat for 125 tree species in the eastern United States; here we present a summarized result for the Mark Twain National Forest (Iverson et al. 2019, Peters et al. 2020). White oak is the most common tree species in the Missouri Ozarks. Although suitable habitat for white oak is projected to decline in the next 80 years, its current high abundance and adaptive capacity could allow it to persist as a dominant feature on the landscape (Table 6). Black oak is currently the second most common species, and its lower adaptive capacity may lead to more decline of suitable habitat than for white oak. Scarlet oak, also common in the Missouri Ozarks, is expected to experience dramatic declines due to its lower adaptive capacity and projected declines in habitat suitability in this region. Other common tree species expected to decline in suitable habitat include shagbark hickory, pignut hickory, sassafras, shingle oak, and bur oak. Declines in suitable habitat for these species could lead to more direct and indirect mortality, leading to a buildup of fuels and hazard trees. However, it is unclear when climatic conditions are beyond the threshold of a species' tolerance and would result in mortality. It is more likely that many compounding factors (Franklin et al. 1987), some exacerbated by climate change, lead to mortality.

Table 6.—Projected changes in habitat suitability for trees on the Mark Twain National Forest under a lower climate change scenario (RCP 4.5) and a higher climate change scenario (RCP 8.5) by the end of the century (2070 through 2099). Source: Peters et al. (2020).

Species with poor capability to cope with or persist under one or both scenarios, given climate changes in this region

Tree species	Adaptability score	Habitat change under RCP 4.5	Capability rating under RCP 4.5	Habitat change under RCP 8.5	Capability rating under RCP 8.5
American basswood	Medium	Decrease	Poor	Decrease	Poor
Black maple	High	Decrease	Poor	Decrease	Poor
Blue ash	Low	Decrease	Poor	Decrease	Poor
Bur oak	High	Decrease	Poor	Decrease	Poor
Eastern cottonwood	Medium	Decrease	Poor	Decrease	Poor
Ohio buckeye	Medium	Decrease	Poor	Decrease	Poor
Overcup oak	Low	No change	Poor	No change	Poor
Pawpaw	Medium	Decrease	Poor	Decrease	Poor
Pignut hickory	Medium	Decrease	Poor	Decrease	Poor
Pin oak	Low	No change	Poor	No change	Poor
Sassafras	Medium	Decrease	Poor	Decrease	Poor
Scarlet oak	Medium	Decrease	Poor	Decrease	Poor
Serviceberry	Medium	Decrease	Poor	Decrease	Poor
Shagbark hickory	Medium	Decrease	Poor	Decrease	Poor
Shingle oak	Medium	Decrease	Poor	Decrease	Poor
Swamp chestnut oak	Medium	Decrease	Poor	Decrease	Poor
Swamp white oak	Medium	Decrease	Poor	Decrease	Poor
Water tupelo	Low	Decrease	Poor	Decrease	Poor

Key definitions and table legend

Adaptability: Life-history factors, such as the ability to respond favorably to disturbance, that are not included in the Tree Atlas model and may make a species more or less able to adapt to future stressors. Adapt scores derived from a literature review of 12 disturbance and 9 biological characteristics, or modification factors.
High: Species may perform better than modeled
Medium: Species may perform similarly to modeled
Low: Species may perform worse than modeled

Habitat Change: Projected change in suitable habitat between current (2001 through 2016) and potential future conditions (2070 through 2099), across three general circulation models (GCMs) under RCP 4.5 or RCP 8.5 (Peters et al. 2020).
Increase: projected increase of more than 20 percent by 2100
No change: projected change of less than 20 percent by 2100
Decrease: projected decrease of more than 20 percent by 2100
New habitat: new habitat projected for species not currently present

Capability: An overall rating that describes a species' ability to cope or persist with climate change based on suitable habitat change class (statistical modeling), adaptability (literature review and expert opinion), and abundance within this region, using three GCMs at lower emissions scenario RCP 4.5 or higher emissions scenario RCP 8.5.
Good: increasing suitable habitat, medium or high adaptability, and common or abundant
Fair: mixed combinations, such as a rare species with increasing suitable habitat and medium adaptability
Poor: decreasing suitable habitat, medium or low adaptability, and uncommon or rare
N/A: not applicable

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Table 6 (continued).—Projected changes in habitat suitability for trees on the Mark Twain National Forest under two climate change scenarios by the end of the century. Source: Peters et al. (2020).

Species with fair capability to cope with or persist under one or both scenarios, given climate changes in this region

Tree species	Adaptability score	Habitat change under RCP 4.5	Capability rating under RCP 4.5	Habitat change under RCP 8.5	Capability rating under RCP 8.5
Black oak	Medium	No change	Good	Decrease	Fair
Black willow	Low	Increase	Poor	Increase	Fair
Boxelder	High	No change	Fair	No change	Fair
Cherrybark oak; swamp red oak	Medium	No change	Poor	Increase	Fair
Chinkapin oak	Medium	No change	Fair	No change	Fair
Flowering dogwood	Medium	No change	Fair	No change	Fair
Red mulberry	Medium	No change	Poor	Increase	Fair
River birch	Medium	No change	Poor	Increase	Fair
Silver maple	High	No change	Fair	No change	Fair
Willow oak	Medium	Increase	Fair	No change	Fair

(For key definitions and table legend, please see page 39)

Species with good capability to cope with or persist under one or both scenarios, given climate changes in this region

Tree species	Adaptability score	Habitat change under RCP 4.5	Capability rating under RCP 4.5	Habitat change under RCP 8.5	Capability rating under RCP 8.5
American elm	Medium	Increase	Good	Increase	Good
American hornbeam (musclewood)	Medium	No change	Poor	Increase	Good
Bitternut hickory	High	Increase	Good	Increase	Good
Black cherry	Low	Increase	Fair	Increase	Good
Black hickory	Medium	Increase	Good	Increase	Good
Black locust	Medium	Increase	Good	Increase	Good
Black walnut	Medium	Increase	Good	Increase	Good
Blackgum	High	Increase	Good	Increase	Good
Blackjack oak	High	Increase	Good	Increase	Good
Cittamwood (gum bumelia)	High	Increase	Good	Increase	Good
Common persimmon	High	Increase	Good	Increase	Good
Eastern hophornbeam (ironwood)	High	Increase	Good	Increase	Good
Eastern redbud	Medium	Increase	Good	Increase	Good
Eastern redcedar	Medium	Increase	Good	Increase	Good
Green ash	Medium	Increase	Good	Increase	Good
Hackberry	High	Increase	Good	Increase	Good
Honeylocust	High	Increase	Good	Increase	Good
Mockernut hickory	High	Increase	Good	Increase	Good
Northern red oak	High	Increase	Good	No change	Good
Osage-orange	High	Increase	Good	Increase	Good
Post oak	High	Increase	Good	Increase	Good
Red maple	High	Increase	Good	Increase	Good
Shortleaf pine	Medium	Increase	Good	Increase	Good
Shumard oak	High	No change	Fair	Increase	Good
Slippery elm	Medium	Increase	Good	Increase	Good

(continued on next page)

Table 6 (continued)

Species with good capability to cope with or persist under one or both scenarios, given climate changes in this region (continued)

Tree species	Adaptability score	Habitat change under RCP 4.5	Capability rating under RCP 4.5	Habitat change under RCP 8.5	Capability rating under RCP 8.5
Southern red oak	High	Increase	Good	Increase	Good
Sugar maple	High	No change	Good	No change	Good
Sugarberry	Medium	Increase	Good	Increase	Good
Sweetgum	Medium	Increase	Good	Increase	Good
Sycamore	Medium	Increase	Good	Increase	Good
White ash	Low	Increase	Good	Increase	Good
White oak	High	Decrease	Good	Decrease	Good
Winged elm	Medium	Increase	Good	Increase	Good

(For key definitions and table legend, please see page 39)

Species that may have new habitat given climate changes in this region

Tree species	Adaptability score	Habitat change under RCP 4.5	Capability rating under RCP 4.5	Habitat change under RCP 8.5	Capability rating umder RCP 8.5
American beech	Medium	New habitat	N/A	New habitat	N/A
American holly	Medium	Unknown	N/A	New habitat	N/A
Ashe juniper	Medium	New habitat	N/A	New habitat	N/A
Black ash	Low	New habitat	N/A	New habitat	N/A
Cedar elm	Low	New habitat	N/A	New habitat	N/A
Chestnut oak	High	New habitat	N/A	New habitat	N/A
Florida maple	High	New habitat	N/A	New habitat	N/A
Live oak	Medium	New habitat	N/A	New habitat	N/A
Loblolly pine	Medium	New habitat	N/A	New habitat	N/A
Longleaf pine	Medium	New habitat	N/A	New habitat	N/A
Pecan	Low	New habitat	N/A	New habitat	N/A
Shellbark hickory	Medium	Unknown	N/A	New habitat	N/A
Sourwood	High	New habitat	N/A	New habitat	N/A
Virginia pine	Medium	New habitat	N/A	New habitat	N/A
Water oak	Medium	New habitat	N/A	New habitat	N/A
Yellow-poplar	High	New habitat	N/A	New habitat	N/A

(For key definitions and table legend, please see page 39)

Intensified Stressors to Ecosystems

Wildfire

Wildfires can be part of natural disturbance regimes that support regeneration of certain species, such as shortleaf pine and some oak species, and retention of ecosystems such as glades, prairies, and savannas. However, higher severity wildfires can create direct risks to human health and safety as well as damage infrastructure and natural areas used for recreation. Because most wildfires are human caused on the Mark Twain National Forest (Brosofske et al. 2007), suppression efforts can reduce risks in some areas. Many of the human-caused wildfires in Missouri are small and occur in spring and fall. Between 2005 and 2015, 54 percent of events were attributed to human causes, resulting in 0.26 to 4 acres (0.11 to 1.6 ha) of burned area (Short 2017). Risk of higher severity wildfire on the Mark Twain National Forest may increase both from direct changes in climate and from changes in fuel loads, particularly in remote areas with easy access (Brosofske et al. 2007). At a global scale, the scientific consensus is that wildfire risk may increase by 10 to 30 percent over the next century because of higher summer temperatures (Intergovernmental Panel on Climate Change 2021). In the central United States, risks could increase particularly in the summer and fall due to warmer and potentially drier conditions (Liu et al. 2013, Stambaugh et al. 2018). A study across the United States conducted model simulations of vegetation types under both suppressed and unsuppressed wildfire using two emissions scenarios to examine the relationship among climate change, potential vegetation cover, and wildfire (Lenihan et al. 2008). When future wildfires were not suppressed, the Central Hardwoods region was projected to convert from a temperate deciduous forest type to a woodland or savanna type. When fire was suppressed, on the other hand, the temperate deciduous forest type was projected to remain stable.

Invasive Plant Species

Invasive plant species can have a serious adverse effect on biological, economic, social, and aesthetic values in the region. Invasive plant species can be introduced into native ecosystems through transportation of seed on vehicles, equipment, or the soles of shoes; in manure from domestic or wild animals; or via wind and water. Changes in climate may increase habitat suitability for some invasive species (Fig. 13). Some drought- and fire-tolerant invasive plants, such as sericea lespedeza, may also benefit from projected climatic changes. Sericea lespedeza is a common invasive species in much of Missouri. Model projections suggest habitat suitability for this species may remain stable and potentially expand to northern parts of the state (Fig. 13). In addition, a warming climate may make conditions more favorable for invasive species that are currently invading from south of the area, such as kudzu and princesstree. Japanese stiltgrass and princesstree, both currently found in the southeastern part of the state, have the potential to gain additional suitable habitat throughout Missouri (Fig. 13). Other invasive plants may experience reduced habitat suitability, such as autumn olive (Fig. 13).

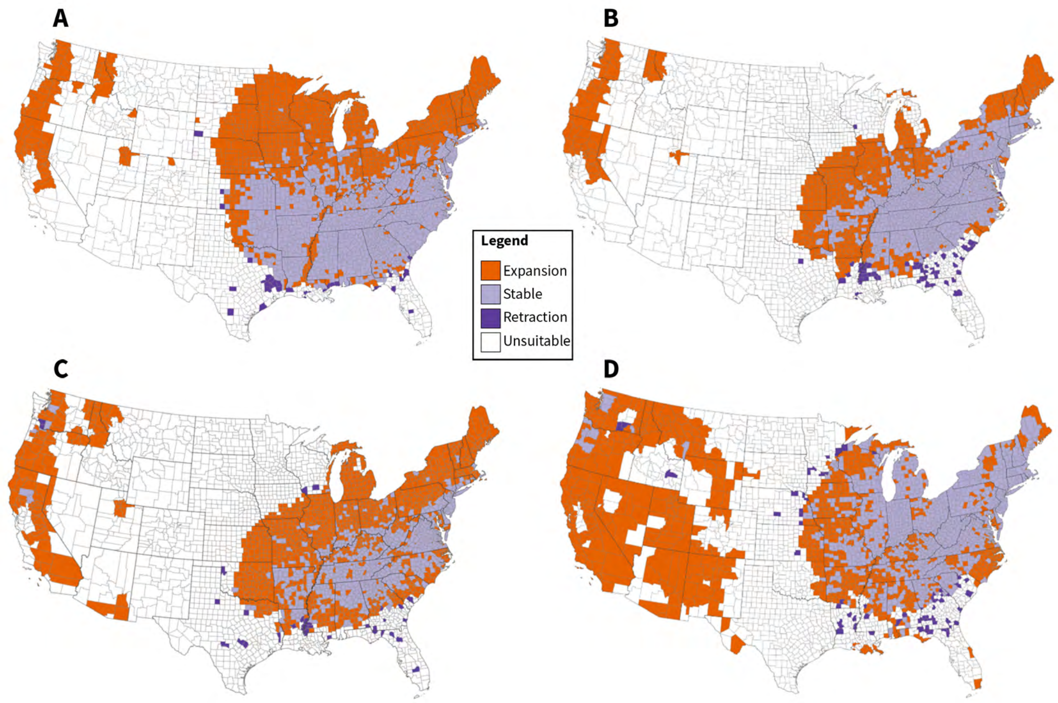

Figure 13.—Projected future range of invasive species (2040–2060): sericea lespedeza (A), Japanese stiltgrass (B), princesstree (C), and autumn olive (D). Source: University of Georgia - Center for Invasive Species and Ecosystem Health (n.d.).

Pests and Pathogens

Warmer temperatures and stressed trees may increase the abundance of pests and pathogens that are currently present. Many insects and their associated pathogens are exacerbated by drought, including forest tent caterpillar, hickory bark beetle and its associated canker pathogen, bacterial leaf scorch, and Diplodia shoot blight (Babin-Fenske and Anand 2011, Park et al. 2013, Sinclair and Lyon 2005). Wetter springs with increased precipitation have been associated with severe outbreaks of bur oak blight in Iowa (Harrington et al. 2012). Another important stressor that could be exacerbated by climate change is oak decline, which is in part driven by drought conditions that predispose species to insect pest and pathogen attack (Haavik et al. 2015). If droughts become longer and more widespread, stressors like oak wilt could become more common across the Mark Twain National Forest.

Other pests and diseases that affect Central Hardwoods forests and could affect the Mark Twain National Forest in the coming decades include spongy moth, thousand cankers disease, sudden oak death, and southern pine beetle. Model projections, for example, suggest that climate conditions for southern pine beetle may be favorable throughout much of the Northeast by mid-century (Lesk et al. 2017). Extreme low and high temperatures are expected to be major factors determining the beetle's success such that extremely hot conditions (above 90 °F [32 °C]) can also lead to reductions in population growth (Friedenberg et al. 2008). As high temperatures above 90 °F are projected to be more common by the end of the century, there could be first an increase and then a decline in southern pine beetle in the region over the next 80 years.

Wildlife

Wildlife viewing, hunting, and fishing are beloved recreation activities on the Mark Twain National Forest. Hunted species include white-tailed deer, wild turkey, rabbit, squirrel, woodcock, mourning dove, ducks, raccoon, bobcat, fox, and coyote. White-tailed deer are a major big game species and are vulnerable to increases in hemorrhagic disease during hot, dry summers (Inkley et al. 2013). As these conditions are projected to be more frequent in the future, hemorrhagic disease may become a more frequent problem for white-tailed deer, reducing hunting opportunities. Wild turkey is another important game species for Missouri, and populations are already declining. Among the factors for this decline are habitat loss and shifting weather patterns, particularly more severe spring rainstorms that can influence hatchling survival (Missouri Department of Conservation 2020b; NPR, St. Louis 2021). More research could provide information on how changes in food, habitat, climate, and other factors may affect various wildlife populations.

Impacts to Infrastructure and Recreation Opportunities

Flooding

Increases in the frequency of heavy rain events, especially events greater than 1.5 inches, are projected to occur under all four scenario combinations used in this assessment (Figure 12 in Chapter 2), even under the driest scenarios. These increases are expected to induce flooding in low-lying areas, with projections from Mills et al. (2018) indicating an increase in both the frequency and magnitude of floods across the Mark Twain National Forest (Chapter 2). However, analysis of streamgage data indicates that large floods are becoming more frequent but are not yet increasing in magnitude (Yochum 2021). Flooding can lead to temporary closures while roads, trails, and recreation sites are under water. Once the water has receded, damage to infrastructure from water, debris, and sediment can lead to longer-term closures while repairs are made (Keller and Ketcheson 2015). The Mark Twain National Forest has already experienced major damage and flooding following heavy rains, as recently as 2017, and these events are becoming more frequent.

Wind Damage

Projections for changes in wind events are not clear, but some evidence suggests a shift in peak tornado season to earlier in the year (Long and Stoy 2014). Recent data also show that tornadoes are increasing in the central United States, including Missouri (Gensini and Brooks 2018). Although there is high confidence that the Mark Twain National Forest is very likely to experience more heavy rain events, there is less certainty regarding thunderstorms and associated damaging winds (Allen 2018). If extreme events do occur, they can down trees, damaging property and leading to temporary road and trail closures. Buildings and electric wires may also be vulnerable to damage from wind, threatening human health and safety.

Erosion

Increased runoff and flooding linked to projected heavy rain events can lead to floods that induce fluvial geomorphic adjustment, including stream channel and floodplain scouring and deposition (Yochum and Scott 2017). Increased soil erosion from steep slopes is also possible, especially after other disturbances. The Mark Twain National Forest includes Missouri Ozarks topography and weathered soils that are more susceptible to erosion than those in other parts of the country. Although efforts to stabilize soils through best management practices have been effective in the past, it is unclear whether these efforts will be sufficient under more extreme rains. A study by Segura et al. (2014) found that the East Ozarks may be the most vulnerable to erosion and mass wasting events compared with the rest of the state. Hence, such flooding and geomorphic adjustment is expected to impact trails and roads.

Drought and Low Flows

Some models and scenarios, especially the IPSL 8.5 scenario, suggest that summers may be considerably hotter and drier by the end of the century. Streamflow could potentially be reduced during these periods, reducing water levels and impacting both access to boat launches for recreational floating and passage through shallow river channels for aquatic species. Summer opportunities for recreation on some water bodies may be reduced in the future, which could limit activities on some water bodies and cause recreationists to travel farther to seek opportunities.

Temperature Effects

Temperature extremes in both directions (cold or hot) can cause damage to infrastructure. Fewer freeze-thaw cycles toward the end of the century could reduce some damage to paved roads. However, extreme summer heat could also lead to additional damage to roads and other structures. Temperatures can also affect recreation opportunities and types of opportunities chosen. Warmer conditions in the fall, winter, and spring may increase the frequency and number of visitors to the Mark Twain National Forest during those periods. Shifting temperatures could potentially affect hunting opportunities for migratory waterfowl as birds shift their arrival and departure migratory timing based on temperature cues and food availability. Hotter summers could increase demand for water-based recreation and reduce demand for hiking or other physically strenuous activities at mid-day.

Public Health and Safety

Warmer conditions and changing precipitation patterns can affect human health and safety (Ebi et al. 2018). Vector-borne diseases from ticks and mosquitoes may become more prevalent as conditions become hotter (Ogden and Lindsay 2016). Air quality can also be affected by higher temperatures, with dust during extreme drought and smoke from large western wildfires leading to respiratory and cardiovascular effects (Nolte et al. 2018). Poison ivy may also benefit from increased CO_2 levels through enhanced growth and increased production of urushiol, the oily compound that causes allergenic reactions (Ziska et al. 2009). Increased extremely hot days in summer also pose a major threat to human health by increasing risk of heat-related illnesses (Ebi et al. 2018). Storms and flash floods are another major threat to safety. Floods can increase the susceptibility to drowning and water-borne illness, while storm events can lead to falling trees and damaged infrastructure.

Chapter Summary

Projected climate change could affect habitat suitability for many tree species on the Mark Twain National Forest. By the end of the century, habitat suitability is projected to decline for some oaks and hickories and increase for shortleaf pine, black hickory, blackgum, and blackjack oak. Under the projected hotter and drier conditions, the risk of wildfire could increase. Habitat suitability for some invasive plant species could also increase under projected climatic changes. Pests and pathogens currently present on the national forest could increase in abundance and new threats, such as southern pine beetle, could emerge. Shifts in species composition could also occur for fauna, including popular game species such as white-tailed deer and wild turkey. Projected warmer and potentially drier conditions may increase wildfire risk. Increased flooding, erosion, wind, and temperature shifts may damage infrastructure and lead to temporary closures on roads, trails, and recreation sites. Projected warmer temperatures could extend the period of seasonal recreation activities and increase demand for water-based activities. Projected warmer conditions, changing precipitation patterns, and elevated carbon dioxide levels could exacerbate the threat of vector-borne illness, poison ivy, and extreme heat. To help managers address these and other climate impacts, a vulnerability assessment framework for recreation has been developed. The framework is discussed and used in an example application in Chapter 4.

Chapter 4: Recreation and Infrastructure Vulnerability Assessment Framework

This chapter provides a framework for assessing the vulnerability of recreation assets to climate change, based on both the Adaptation Workbook, which was developed by the Northern Institute of Applied Climate Science and published by the USDA Forest Service (Swanston et al. 2016), and the U.S. Forest Service Transportation Guidebook (Rasmussen et al. 2018). Information in this chapter may be useful to local staff and specialists evaluating site-specific vulnerability to climate change as it relies on site-specific knowledge of recreation assets on the national forest. Climate change vulnerability is a function of the impacts on a system and the system's adaptive capacity to cope with those changes. The impacts of climate change on a system are defined in terms of its exposure and sensitivity to hazard (Fig. 14). Adaptive capacity is defined as the system's ability to adjust with potential impacts from a climate stressor. The general definitions and example factors for assessing vulnerability described in section 2.7 of Rasmussen et al. (2018) were expanded and modified in this chapter to put them in the context of recreation aspects and include specific factors of interest to the Mark Twain National Forest. A risk matrix is included as a mechanism to analyze the direct impacts of climate change on the asset. Although this framework can be applied at a larger geographic scale, it is best used when evaluating assets at the local level.

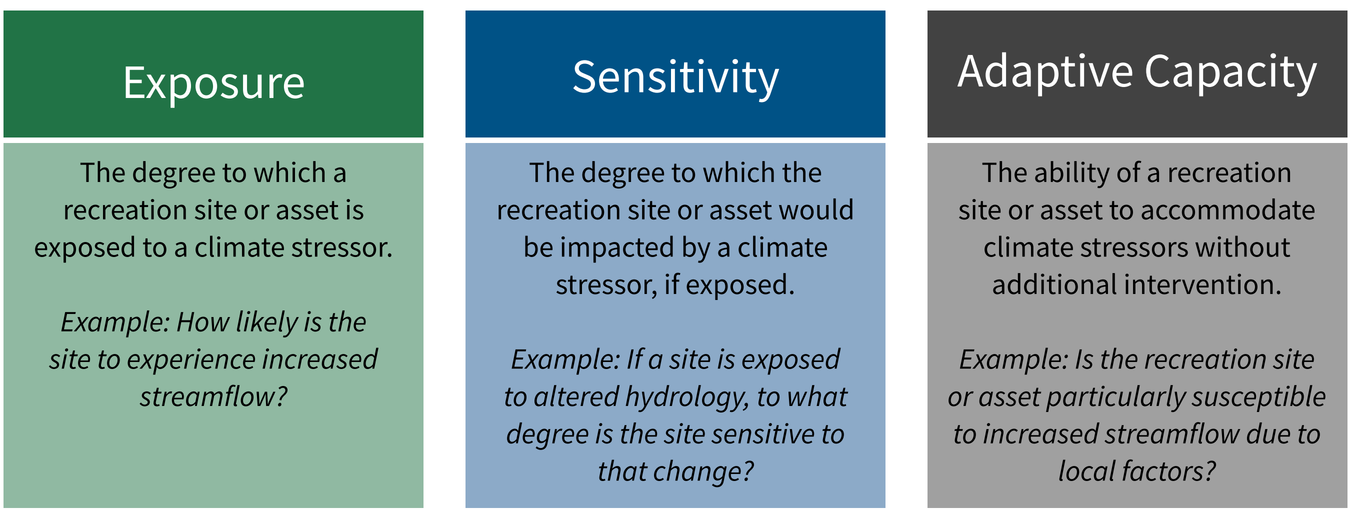

Figure 14.—Components of vulnerability for recreation sites or assets. Vulnerability is defined in terms of exposure, sensitivity, and adaptive capacity. These depend on the specific type of asset, location, and the climate impacts of greatest concern for the area.

Climate Impacts and Adaptive Capacity of Recreation Assets

Exposure of Recreation Sites or Assets

Exposure is the evaluation of the degree to which a recreation site or asset is exposed to a significant variation and change in climate. Exposure factors are typically related to past or projected changes in climate averages and extremes within the area of the asset (Halofsky et al. 2018: Box 11.4). A thorough examination of the potential exposure of a given system, site, or asset to various climate stressors can help refine a list of climate stressors of greatest concern. In the context of recreation sites or assets on the Mark Twain National Forest, exposure factors may include the following.

- **Number of hot days:** More hot days may shift recreation uses to more demand for water-based recreation in summer.
- **Number of cold days:** Fewer cold days may change the timing of recreation use, type of use, and visitor concentration of use in the winter months.
- **Frequency and severity of heavy rain events:** Extreme events may contribute to flash floods that potentially endanger visitors, erode steep hillsides, overtop infrastructure, and plug culverts with debris.
- **Increased streamflow and flooding:** More flooding and higher water levels may increase safety concerns for recreational boaters and float trips due to faster in-stream flows, more streambank erosion, increased channel deposition, and more abundant woody debris. Additionally, some recreation sites may become inaccessible.
- **More low-streamflow days in late summer/fall:** More frequent lower streamflow days may result in fewer float trip opportunities and a greater concentration of visitors around segments of streams that still contain water or flowing water features.
- **Higher severity wildfire:** More frequent higher severity wildfire events may cause damage to infrastructure, alter recreation experiences (affecting the scenery and ecology), and reduce recreation accessibility across the national forest due to erosion of streambanks and hillslope failure.
- **Longer fall and spring recreation season:** A longer growing season may increase recreation demand on the national forest outside of the traditional season, resulting in more recreation use earlier in spring and later in fall.
- **Tree mortality:** Tree mortality may occur due to declining forest health and habitat suitability challenges that may increase hazards on trails and along roads, as well as reduce shade opportunities for visitors. Loss of riparian canopy shade may also contribute to streambank erosion and increased stream water temperatures.

Sensitivity of Recreation Sites or Assets

Sensitivity is the degree to which the recreation site or asset would be impacted by a climate stressor, if exposed. These factors are related to climate-driven changes that may affect site-level characteristics such as surrounding topography, soils and vegetation, the type of site or asset, and the specific characteristics and condition (Keller and Ketcheson 2015). The sensitivity of a system to changing climate stressors can clarify specific thresholds, dependencies, and specialized characteristics of a site or asset that may be negatively affected by changing conditions. For the Mark Twain National Forest, sensitivity factors may include the following.

- **Site or asset position compared with the current 100-year (Q_{100}) flood level:** Recreation sites or assets located within the currently described "100-year floodplain" may be more susceptible and sensitive to changes in hydrology than other sites. These are characterized as "high" (susceptible to flooding) or "low" (not susceptible to flooding) based on the asset location at the current observed 100-year flood level.
- **Site or asset position compared with the expected flood potential (Q_{efp}) flood level:** Recreation sites or assets located in expected flood potential zones (as indicated in the USDA Forest Service's Flood Potential Portal) may be more susceptible and sensitive to changes in hydrology than other sites in the future. Position in the expected flood level zone is characterized by the user as "high" or "low" relative to surrounding watersheds.
- **Site or asset proximity to flood zones:** Recreation sites or assets that are located close to a known flood zone may experience more days with reduced access to sites. These are characterized as high, moderate, or low based on proximity.
- **Susceptibility to erosion (percent slope and parent material):** Recreation sites or assets located on steep angled slopes may become sensitive to changes in hydrology that increase susceptibility to erosion, streambank loss, and hillslope failure. These are characterized as "high," "moderate," or "low" relative to the slope angle (or percentage) and erodibility of the parent material.
- **Type of activities and duration of visit at site or asset:** Recreation sites or assets where visitors remain in the same location for long periods of time may be more at risk. This is especially true for camping areas, where people sleep at the site and would be unable to evacuate if conditions changed quickly. Activities that occur in or near water may be more at risk than dryland activities. Sensitivity of activities is characterized by duration of use as "high" for assets that experience longer duration visitation such as camping, water-based activities, and parking areas; "moderate" for assets that experience moderate duration visitation such as picnic areas, trail heads and trails, visitor centers, and toilets; and "low" for assets that experience low duration visitation such as scenic overlooks.
- **History of damage at site or asset:** Recreation sites or assets with a history of flooding, wildfires, or other damages may be more sensitive to future disturbances and extreme events. These are characterized as "high" for assets with a history of severe or repeated damages, "moderate" for assets that have a history of few damages over time, and "low" for assets with no history of damage.

- **Site or asset condition, relative age to designed lifespan, and composition:** Recreation sites or assets that are older, in poor condition, or designed using outdated standards may be more sensitive to damages. These are characterized as "high," "moderate," and "low" according to a site or asset's current condition, age relative to lifespan, and composition.
- **Electricity and plumbing:** Recreation sites or assets containing electricity and plumbing may become susceptible to damages brought about by extreme changes in temperature and precipitation. These are characterized as "high," "moderate," and "low" according to risk of potential damage, essential priority to operations, and current safeguards on-site.
- **Visitor use:** Recreation sites or assets that experience higher visitor use may become more sensitive to increased crowding, which may result in added damages, especially during wet weather or on saturated soils. These are characterized as "high" for frequent visitation levels, "moderate" for moderate visitation levels, and "low" for infrequent or rare visitation levels.

Adaptive Capacity of Recreation Assets

Adaptive capacity is the ability of a recreation site or asset to accommodate climate stressors without additional intervention. These factors relate to flexibility in the use of the site during an event and could include the following.

- **Access:** Sites or assets that have a single access point or are very remote may have lower adaptive capacity than those that have multiple access points and are near major roads and hospitals. These are characterized as "high" or "low" based on known access points and proximity to other infrastructure.
- **Redundancy of sites, assets, or opportunities:** Areas where all recreation sites or assets are concentrated in a small area may have lower adaptive capacity and less flexibility to cope with and adjust to an impact from a climate stressor than sites or assets that are more dispersed. These are characterized as "high" or "low" based on the alternative recreation opportunities or assets in the vicinity.
- **Flexibility of type and timing of use of site or asset:** Recreation sites or assets that are tied to a specific type of seasonal activity may have lower adaptive capacity than those that can be used year-round for multiple activities. These are characterized as "high" or "low" based on the uses of the site or asset throughout the year.
- **Buffer space:** Buffer space around the recreation site or asset could help protect it from disturbances. Additional space may increase the adaptive capacity of the site or asset to accommodate and adjust to a climate impact or stressor. Examples include a wetland between a waterbody and a campsite or a defensible space around structures that can reduce the likelihood of wildfire damage. These are characterized as "high" or "low" based on the amount of space surrounding the site or asset that can buffer the asset from disturbance and reduce damages.
- **Cost and time to rebuild:** Recreation sites or assets that may be less expensive to repair, replace, or rebuild may have higher adaptive capacity to cope with climate stressors over time. These are characterized as "high" or "low" based on expenses needed to repair, replace, or rebuild.

Vulnerability Matrix and Worksheets

We created a series of tables that can be used by recreation managers to develop a site-level assessment of vulnerability for a recreation site or asset. The tables are presented to help managers document considerations when evaluating and rating exposure (Table 7), sensitivity (Table 8), adaptive capacity (Table 9), vulnerability (Table 10), and risk (Table 11). The rating framework was modified from the basic scoring system described in section 2.8 of Rasmussen et al. (2018) to include definitions specific to recreation and each vulnerability component.

Exposure Ratings

Exposure factors are related to climate stressors. For example, an exposure factor for heavy precipitation may be the "average number of days per year with heavy precipitation" ("heavy precipitation" is regionally defined).

Table 7.—Worksheet table and rating definitions to define exposure of the site. Rate each individual exposure factor (see first section of Chapter 4, this volume); then rate the overall exposure of the site or asset to climate change.

Site or Asset Exposure Factors Based on Regional Climate Projections	Description of Consequences of Exposure Factor on Site/Asset	Exposure Rating
Hot days		
Cold days/nights		
Heavy rain events		
Increased streamflow and flooding		
More low-flow days in late summer/fall		
Higher severity wildfire		
Longer fall/spring rec season		
More tree mortality		
Other:		
Other:		
OVERALL SITE OR ASSET EXPOSURE TO CLIMATE CHANGE (SEE BELOW):		

Exposure Rating Definitions

- **High:** The site or asset is very likely to be affected by this factor
- **Moderate:** The site or asset is somewhat likely to be affected by this factor
- **Low:** The site or asset is unlikely to be affected by this factor

Sensitivity Ratings

Sensitivity factors include site or asset history of damage, bridge elevation, culvert volume or flow data, or other factors affecting the extent to which a climate stressor would damage an asset or its services.

Table 8.—Worksheet table and rating definitions to define sensitivity at the asset site. Rate each individual sensitivity factor (see first section of Chapter 4, this volume); then rate the overall sensitivity of the site or asset to climate change.

Site Sensitivity Factors	Description of Consequences of Sensitivity Factors on Site/Asset	Sensitivity Factor Level (Use Levels Noted in First Column)
Site or asset position compared with the current 100-year (Q_{100}) flood level • High: Site or asset is located within current 100-year flood level. • Low: Site or asset is located outside of current 100-year flood level.		
Site or asset position compared with the expected flood potential (Q_{efp}) flood level • High: Site or asset is located within expected flood level. • Low: Site or asset is located outside of expected flood level.		
Site or asset proximity to flood zones • High: Site or asset is located within a known flood zone. • Moderate: Site or asset is located in proximity to a known flood zone. • Low: Site or asset is not located in proximity to a known flood zone.		
Susceptibility to erosion (% slope and parent material) • High: Site or asset is susceptible to erosion based on slope and parent material. • Moderate: Site or asset is moderately susceptible to erosion based on slope and parent material. • Low: Site or asset is not susceptible to erosion based on slope and parent material.		
Type of activities and duration of visit at site or asset • High: Site or asset experiences longer duration visitation such as camping, water-based activities, parking areas. • Moderate: Site or asset experiences moderate duration visitation such as at picnic areas, trail heads and trails, visitor centers, and toilets. • Low: Site or asset experiences infrequent or short duration visitation such as at scenic overlooks.		
History of damages at site or asset • High: Site or asset has a history of severe or repeated damages. • Moderate: Site or asset has experienced few damages over time. • Low: Site or asset has no history of damage.		

(continued on next page)

Table 8 (continued).—Worksheet table and rating definitions to define sensitivity at the asset site. Rate each individual sensitivity factor (see first section of Chapter 4, this volume); then rate the overall sensitivity of the site or asset to climate change.

Site Sensitivity Factors	Description of Consequences of Sensitivity Factors on Site/Asset	Sensitivity Factor Level (Use Levels Noted in First Column)
Site or asset current condition • High: Site or asset is in poor to fair condition. • Moderate: Site or asset is in fair to good condition. • Low: Site or asset is in excellent condition.		
Site or asset age relative to designed lifespan • High: Site or asset is at or is considered older than projected lifespan. • Moderate: Site or asset is in the middle of lifespan. • Low: Site or asset is new or recently repaired.		
Site or asset composition and materials • High: Site or asset is made of low-quality materials or easily damages. • Low: Site or asset is made of high-quality materials designed to withstand projected disturbances.		
Electricity and plumbing at site or asset • High: Site or asset has electricity and/or plumbing that is essential to operations and is at risk for potential damages. • Moderate: Site or asset has electricity and/or plumbing is present but not essential for operations or is safeguarded from potential damage. • Low: Site or asset has no electricity or plumbing.		
Visitor use at site or asset • High: Site or asset is used frequently. • Moderate: Site or asset is moderate used. • Low: Site or asset is used infrequently or rarely.		
Other factor:		
OVERALL SENSITIVITY OF SITE OR ASSET (SEE BELOW):		

Site Sensitivity Rating Definitions

- **High:** Site or asset is highly sensitive and more likely to be damaged if exposed
- **Moderate:** Site or asset is moderately sensitive, could experience some damage if exposed
- **Low:** Site or asset is not sensitive, unlikely to be severely damaged if exposed

Adaptive Capacity Ratings

Adaptive capacity factors may include the projected costs of site or asset repairs, average daily traffic, or the presence of alternate routes. These factors help analyze the ability of the transportation system to adjust to climate change, moderate potential damages, or cope with the consequences.

Table 9.—Worksheet table and rating definitions to define adaptative capacity at the asset site. Rate each individual adaptive capacity factor; then rate the overall adaptive capacity of the site or asset to climate change.

Adaptive Capacity Factor for a Site or Asset	Description	Adaptive Capacity Level
Access to and from recreation site or asset • High: Site or asset has more than one access point and/or is near major road or hospital. • Low: Site or asset is remote with only one access point.		
Redundancy of sites/assets or opportunities in proximity • High: Site or asset has many alternative opportunities nearby. • Low: Site or asset is the only opportunity in the area.		
Flexibility of recreation use, type, and timing of use at site or asset • High: Site or asset can be used for multiple purposes across a wide range of seasons. • Low: Site or asset is limited to one type of use and only in specific seasons.		
Buffer space around site or asset or recreation site • High: Site or asset has buffer space around the asset. • Low: Site or asset has no buffer space.		
Cost, and time to repair, replace, or rebuild site or asset • High: Site or asset is inexpensive and easy to rebuild. • Low: Site or asset is expensive and difficult to rebuild or replace.		
OVERALL ADAPTIVE CAPACITY OF SITE OR ASSET (SEE BELOW):		

Adaptive Capacity Rating Definitions

- **High:** Site or asset is able to cope with or adjust to climate impacts
- **Moderate:** Site or asset is moderately able to cope with or adjust to climate impacts
- **Low:** Site or asset is unable to cope with or adjust to climate impacts without significant investment

Vulnerability Matrix

The vulnerability of a system can be assessed by integrating the exposure, sensitivity, and adaptive capacity based on ratings as defined in a vulnerabiity matrix (Table 10). The vulnerability of the site or asset can be determined in both the near term (current to 30 years) and long term (30 to 50 years).

Table 10.—Worksheet table and rating definitions to define overall vulnerability at the project site or asset. From previous tables, use the defined "overall site or asset exposure to climate change," "overall sensitivity of site or asset," and "overall adaptive capacity of site or asset" to identify the overall vulnerability in the following matrix. Consider one or multiple points in time.

Adaptive Capacity Rating	High Exposure, High Sensitivity	High Exposure, Moderate Sensitivity or Moderate Exposure, High Sensitivity	High Exposure, Low Sensitivity or Low Exposure, High Sensitivity	Moderate Exposure, Moderate Sensitivity	Low Exposure, Moderate Sensitivity or Moderate Exposure, Low Sensitivity	Low Exposure, Low Sensitivity
Low	High Vulnerability	High Vulnerability	Moderate-High Vulnerability	Moderate Vulnerability	Moderate Vulnerability	Low-Moderate Vulnerability
Moderate	High Vulnerability	Moderate-High Vulnerability	Moderate Vulnerability	Moderate Vulnerability	Low-Moderate Vulnerability	Low Vulnerability
High	Moderate-High Vulnerability	Moderate Vulnerability	Moderate Vulnerability	Low-Moderate Vulnerability	Low Vulnerability	Low Vulnerability

Vulnerability Determination of Site or Asset

Determine the vulnerability of site or asset by time period:

- Near-term (current to 30 years)
- Long-term (30 to 50+ years)

Risk Matrix

With an understanding of the recreation site or asset potential vulnerability to climate change (derived in Table 10 in the previous section) and site-specific knowledge, a practitioner can evaluate the potential risk of damage or loss due to the consequences of a changing climate over time. A risk matrix is a tool to evaluate the direct effects of climate change by rating the expected magnitude of consequences brought about by climate impacts relative to the recreation site or asset's known characteristics and probability of damage or loss. The risk matrix is adapted from Rasmussen et al. (2018) and can be a useful decision-support tool when strategically prioritizing recreation sites or assets for adaptation efforts.

Table 11.—Worksheet table and rating definitions to define risk at the recreation site or asset (from Rasmussen et al. 2018)

Probability of Damage or Loss	Major Consequences	Moderate Consequences	Minor Consequences
Very likely	Very High Risk	Very High Risk	Low Risk
Likely	Very High Risk	High Risk	Low Risk
Possible	High Risk	Intermediate Risk	Low Risk
Unlikely	Intermediate Risk	Low Risk	Very Low Risk

Probability of Damage or Loss Rating of Site Definitions

Note: Probability definitions are derived from the U.S. Forest Service Transportation Resiliency Guidebook.

- **Very likely:** Nearly certain (90 percent chance) to happen in the lifespan of the site or asset.
- **Likely:** Greater than 50 percent of happening in the lifespan of the site or asset.
- **Possible:** 10 to 50 percent chance of happening in the lifespan of the site or asset.
- **Unlikely:** Less than 10 percent chance of happening in the lifespan of the site or asset.

Magnitude of Consequence Rating Definitions

- **Major:** Loss of life or injury, major and/or irreversible damage to infrastructure or natural resources (or both).
- **Moderate:** Possible injury, moderate-long-term, but temporary damage to infrastructure or natural resources (or both).
- **Minor:** Minimal, short-term damage to infrastructure or natural resources or short-term loss of use (or both).
- **Unlikely:** Less than 10 percent chance of damage happening.

Risk Assessment and Level of Intervention Definitions

- **Very high:** Site or asset is very likely to need significant adaptation interventions.
- **High:** Site or asset is likely to need significant adaptation interventions.
- **Intermediate:** Site or asset may require some adaptation interventions.
- **Low:** Monitor for future risks. Site or asset may not need adaptation interventions at this time.
- **Very low:** Monitor for future risks. Site or asset unlikely to need adaptation interventions.

Red Bluff Recreation Area: Day-use Area and Campground (Potosi/Fredericktown Ranger District)

Potential climate-related vulnerability was evaluated for the Red Bluff day-use area and campground by staff members of the Potosi/Fredericktown Ranger District and Mark Twain National Forest at a virtual workshop in April 2021. The workshop process was informed by the Adaptation Workbook, and the U.S. Forest Service Transportation Resiliency Guidebook was modified to create the worksheets provided in this document. Workshop exercises helped the team evaluate exposure and sensitivity of the area and infrastructure to various climate stressors and then weigh the adaptive capacity of the system to cope with changes. These evaluations were combined into vulnerability and risk ratings for the recreation area through group discussion and voting. A summary of this work is available on the Climate Change Response Framework website: Mark Twain National Forest: Red Bluff Recreation Area.

The Red Bluff day-use area and campground are located in the Huzzah Creek watershed within the Potosi/Fredericktown Ranger District on the Mark Twain National Forest (approximately Lat. 37.82, Long. -91.17). The day-use facilities and lower campground are located within the floodplain. Facilities on-site include vault toilets (4), pavilion (1), group shelter (1), storage shed (1), picnic areas (7), and several campsites (41), some of which are electrical sites (5). The day-use area and campground provide multiple uses such as access to recreation opportunities on Huzzah Creek (fishing, canoeing, tubing, wading, water play), camping, historic quality, and visual aesthetic value that draw many visitors to the recreation area each season. Huzzah Creek is a forested headwater stream. Groundwater springs help to maintain a consistent flow; however, low water levels are typically observed in late summer. Water levels are highest in winter and spring, the wetter seasons of the year, when prolonged precipitation and flash flood events resulting from localized rain events are a common occurrences. The following sections provide summaries of site-specific considerations for this recreation area.

Summary of Exposure Ratings

The recreation area's exposure to climate impacts was evaluated and rated using the process described earlier in this chapter. The climate change information presented here is described in more detail in Chapter 2 of this report. Climate change impacts and related factors of greatest concern to the Red Bluff site are as follows.

- **More days with extreme heat, such as 20 to 80 more days per year above 92 °F by the end of the century.** Following are exposure considerations. Warmer temperatures may draw more people to the Red Bluff day-use area and campground as people seek water to cool off. As visitation to the national forest increases, this site is likely to draw more recreation users for swimming, boating, and fishing. Much warmer temperatures may also increase the demand for electric sites as tent camping becomes unbearable during the summer. Day-use activities and interest in picnic sites (particularly where there is shade) may increase and expand as temperatures increase, producing warmer shoulder seasons.
- **Increased frequency of larger streamflow events (1 percent AEP) leading to increased frequency of flood events; and more frequent heavy precipitation events—up to 1.5 more 2-inch, 0.6 more 3-inch, and 0.2 more 4-inch rain events per year.** Exposure considerations include the following. More frequent heavy precipitation events may increase water levels in the river, resulting in more frequent flooding. Of concern is the impact this might have in areas not historically flooded in the past. More frequent larger streamflow may create flood hazards and reduce access to attractions near water (particularly if river channel morphology adjusts to larger, more frequent streamflow, resulting in altered streambank shape and erosion). Wetter conditions may increase temporary closures; however, there is no gate on-site to limit access during flood days, so ensuring safety during hazardous conditions is a concern. Prolonged flooding may occur at the site, particularly in the lower campsites and day-use area due to capacity of downstream infrastructure to convey higher water levels, resulting in "backed up" water at the day-use area.
- **Shorter winters, less snow, and more variable ice conditions on land and water. The site is likely to be snow-free in February by the end of the century; average winter temperatures could increase by up to 10 °F, leading to earlier spring thaws and earlier spring streamflows.** Exposure considerations include the following. Warmer winters with more variable conditions (freeze-thaw cycles) may increase damage to gravel roads, resulting in closures to sections of roads to limit vehicle use.
- **Longer frost-free season. The frost-free season is projected to increase by several weeks (resulting in a longer fall and spring recreation season).** Following are exposure considerations. A longer frost-free season is likely to extend the recreation season. Increased demand may strain staff capacity during traditionally lower-staffed seasons and may require additional site management (particularly to facilities). A longer growing season may require additional invasive species control.

Summary of Sensitivity Ratings

The recreation area's sensitivity to climate impacts was evaluated and rated using categories defining how sensitive the area is to damage if exposed to changing conditions. The more sensitive components of the recreation area (ranked as highly sensitive and more likely to incur damage due to climate change) are as follows.

- **Upper and lower campground loops** (five electric sites, host site, day-use area). The day-use area and campground were constructed within the 100-year floodplain of Huzzah Creek and are at risk of severe damage due to projected increasing frequency and magnitude of precipitation and flooding. The recreation area has a history of damage from past flash flood and prolonged precipitation events that have resulted in flood debris throughout the campground loops, loss of campsites, lost sections of road asphalt, and damaged restroom facilities.
- **Visitors using the recreation area.** This area is considered an attraction that is used frequently, with heavy use throughout the summer season which typically runs Memorial Day to Labor Day, and heaviest use on the weekends. More people visiting the area may create additional safety issues if the area is experiencing extreme heat spells and flash flood events.
- **Camping activities** (particularly overnight uses) and water-based uses may be affected by extreme heat and flash flood events.

The least sensitive parts of this recreation area (ranked as low sensitivity to climate change) are as follows.

- **Location in high slope erodible area.** Currently the recreation area does not experience slumping or sliding of soils and materials; however, increased visitor demand along the river could increase pressures on the streambank and associated vegetation, resulting in destabilization and increased erosion.
- **Facilities and infrastructure at this recreation area are composed of materials that are not likely to easily break down or become damaged** (concrete, metal, lumber). However, several items within the campground are mobile and are considered highly sensitive if not removed (fire rings, shepherd hooks for lanterns, electric covers).
- **Many facilities are new or were recently repaired after the 2017 flood event;** therefore, the age and possible degradation of assets are not a current concern.

Summary of Adaptive Capacity

The recreation area's adaptive capacity to easily cope with or adjust to climate impacts was evaluated and rated using the categories "high," "medium," and "low." Features that were rated to have low adaptive capacity (unable to cope with or adjust to climate impacts) are as follows.

- **A remote recreation area with limited access.** Located in a remote area with one access point to a state highway, the recreation area contains one 2-lane road through the campground. Limited access to the recreation area presents safety concerns and reduces flexibility to adjust to weather disturbances.
- **A unique recreation area, with few other options nearby.** This recreation area may be the only opportunity for the public to access the river and to camp in the immediate vicinity. There are few access points to the river available to the public when fishing and boating other than at this site. Similarly, there are few public alternatives to camp in this region, with the nearest public campground about 50 miles away. Limited alternative locations may magnify the interest and visitation of this recreation area by the local public.

Features of the recreation area that were ranked to have a high adaptive capacity (easily able to cope with climate impacts) are as follows.

- **Flexibility of type and timing of recreation uses.** This recreation area can be used across a wide range of seasons for multiple purposes, such as camping, picnicking, and canoeing. The camping opportunities include diverse amenities (day-use and overnight camping with electrical and nonelectrical sites).

Sitewide Vulnerability Rating for the Red Bluff Recreation Area

The vulnerability of the recreation area to climate change impacts was determined based on the exposure, sensitivity, and adaptive capacity evaluations by a team of Mark Twain National Forest staff with expertise in recreation, hydrology, engineering, and climate change. Each participant provided their own expert opinion on the overall exposure, sensitivity, and adaptive capacity of the recreation area (Fig. 15). The team was generally in agreement that exposure and sensitivity are both high at this recreation area but had less agreement on the adaptive capacity of the area to cope with climate stressors over time. Using a vulnerability matrix (defined earlier in this chapter), national forest staff members rated the recreation area's vulnerability to climate change as "moderate to high" in both the near term (10 to 30 years) and long term (more than 50 years) (Fig. 16).

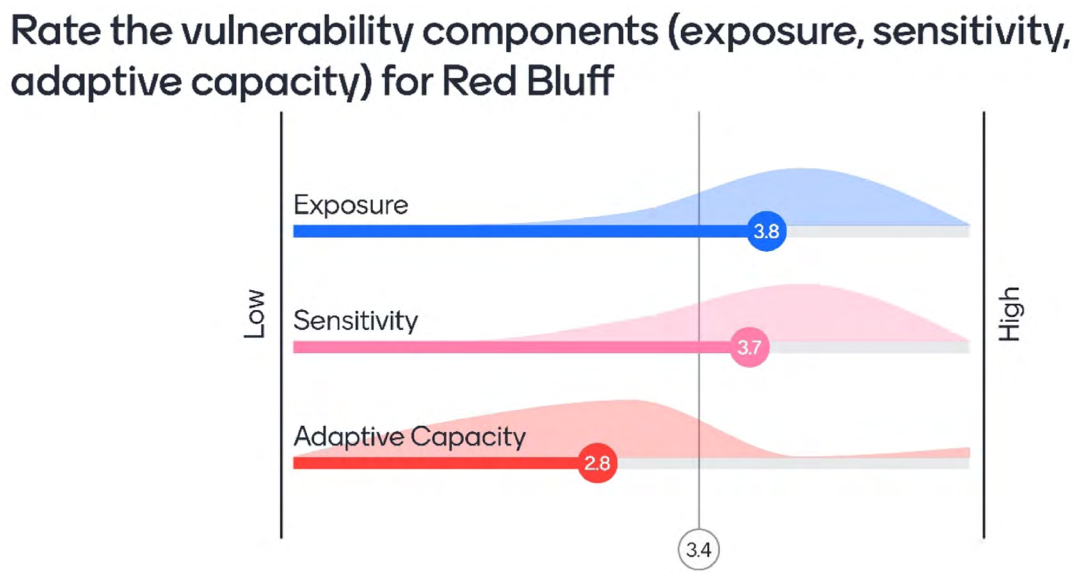

Figure 15.—Ranking of vulnerability components (exposure, sensitivity, adaptive capacity) from Red Bluff vulnerability workshop (11 individuals participated in the ranking).

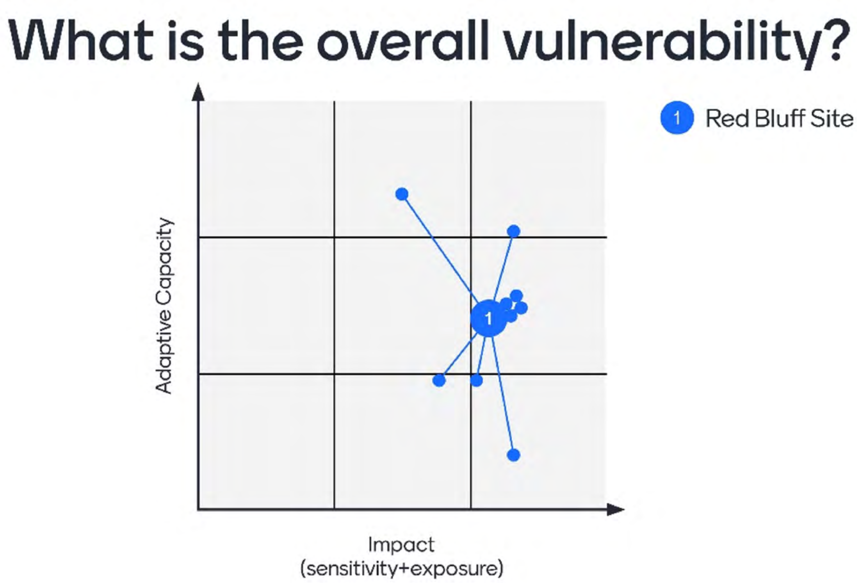

Figure 16.—Vulnerability determination activity outcome from Red Bluff vulnerability workshop (nine individuals participated in the ranking).

Risk Rating for the Red Bluff Recreation Area

Using the risk matrix (defined earlier in this chapter), the expected risk of damage or losses brought about by climate change impacts to this recreation site was assessed by national forest staff members. The team evaluated risk by weighting the probability of damage or loss of the recreation site in relation to the consequences of change due to climate impacts (flooding, wildlife, low flows, human health effects, tree mortality, erosion and slope failure) (Fig. 17). Of the potential climate change impacts evaluated, flooding was determined to pose the greatest risk to the recreation area, whereas wildfire is expected to pose the lowest risk. Other factors were considered to be of moderate to intermediate risk. Across the recreation area, risk was determined to be "high" in the day-use area if upcoming planned changes are not implemented and a rating of "intermediate" if planned changes occur. This risk assessment activity helped inform prioritization of adaptation planning activities and helped the team prioritize climate impacts of greatest concern in relation to risk of damage and loss.

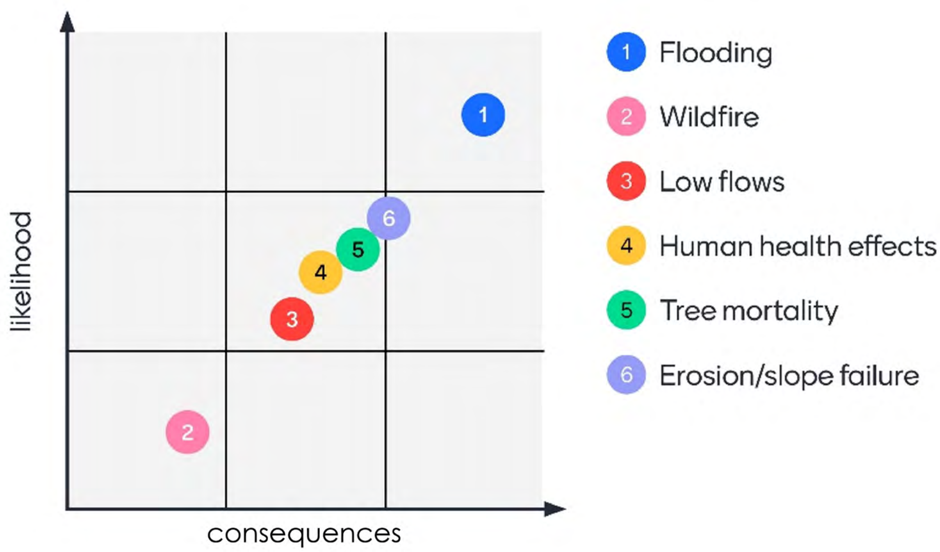

Figure 17.—Risk activity outcome from Red Bluff vulnerability workshop (10 individuals participated in the ranking).

Chapter Summary

We developed a framework that builds on the Adaptation Workbook and the U.S. Forest Service Transportation Resiliency Guidebook to aid land managers in evaluating vulnerability of recreation and infrastructure assets. This framework can be applied to recreation and infrastructure projects and plans at a variety of spatial scales. We tested this framework for the Mark Twain National Forest's Red Bluff recreation site through a collaborative workshop with recreation, hydrology, and other resource specialists. Major factors affecting exposure and sensitivity of the site were a projected risk of increased flood frequency and severity and the site's position in a floodplain. Warmer temperatures and more low flow days in the summer also posed risks to visitor demand, water quality, and river access. The participants rated the site as having a moderate to high vulnerability based on its high risk of future flood damage and soil erosion. This framework can help managers identify their top risks and sources of vulnerability for adaptation planning. A variety of strategies and resources to assist recreation managers in adaptation planning is provided in Chapter 5.

Chapter 5: Implications for Recreation and Infrastructure Management

Temperatures and precipitation patterns have changed and are likely to continue to do so in the coming decades. These changes may have impacts on recreation resources and visitation both directly and indirectly. This chapter summarizes the implications of these changes for recreation management on the Mark Twain National Forest. Strategies to adapt recreation management to these changing conditions are summarized from O'Toole et al. (2019). Adaptation strategies for recreation can span from protecting at-risk sites, to adjusting to changing visitor use patterns, to aligning recreation opportunities with future conditions. Adaptation strategies depend on the goals and objectives for a particular site and the specific climate risks at that location (Ontl et al. 2018, Swanston et al. 2016). Additional resources provided in this chapter are meant to help managers explore these topics in greater depth and begin developing potential management strategies.

Changing Visitation and Use

The Mark Twain National Forest may experience shifts in visitation due to shifts in seasonal temperatures and precipitation (Askew and Bowker 2018, Fisichelli et al. 2015). One study suggests the overall demand for recreation on public lands in Missouri may decrease, especially during summer months (Wilkins et al. 2021). For example, fewer people may visit for float trips during dry conditions if there is insufficient streamflow or conditions are too hot in exposed areas. Conversely, more people may engage in water-based recreation to cool off during hot summers if there is adequate streamflow, shade, and boat access. Heavy rain events can affect immediate visitation if conditions are incompatible with recreation activities. If these rain events result in sufficient flooding or damage, some recreation sites may become inaccessible.

Mark Twain National Forest personnel may consider ways to accommodate or prepare for these changes. For example, parking, restroom facilities, and access points could be added or improved to meet increased demand in certain areas, or new sites could be established to accommodate increased visitation.

Additional Resources

- Protected Area Tourism in a Changing Climate: Will Visitation at US National Parks Warm Up or Overheat? (Fisichelli et al. 2015) https://doi.org/10.1371/journal.pone.0128226
- Outdoor Recreation Participation in the United States - Projections to 2060: a Technical Document Supporting the Forest Service 2010 RPA Assessment (Bowker et al. 2012) https://doi.org/10.2737/SRS-GTR-160

Impacts on Staff Capacity and Infrastructure Maintenance

In addition to affecting visitation, changes in climate may strain the capacity or ability to manage recreation sites on the national forest. More frequent weather extremes may increase maintenance needs and decrease the lifespan of assets (Neumann et al. 2015), necessitating increased outlays and staff time to repair or replace recreation infrastructure. Repair and maintenance timelines may not always align with organizational priorities and available resources. Higher expenses and mismatched timelines present an added challenge to the Mark Twain National Forest, as the State and county share responsibilities for various components of the recreation and infrastructure system. Additionally, visitation may increase earlier in the spring and later in the fall when seasonal staffing may not be available.

Alternative staffing mechanisms or changes to visitor management could be used during shoulder seasons and visitation surges during peak times of the year. Options could include the use of volunteer programs or external contractors. Efforts to repair, improve, or even relocate assets may be expensive and rely on additional funding sources such as external competitive grants and funding specifically designated for building infrastructure resilience.

Additional Resources

- The Legacy Restoration Fund through the Great American Outdoors Act provides funding to support recreation infrastructure. https://www.fs.usda.gov/managing-land/gaoa
- The Emergency Relief for Federally Owned Roads (ERFO) program assists Federal agencies with the repair of roads that have suffered serious damage from a natural disaster over a wide area or by a catastrophic failure. https://highways.dot.gov/federal-lands/programs/erfo
- The Infrastructure Investment and Jobs Act provides funding to increase the resilience of infrastructure to climate change and other threats. https://www.congress.gov/117/plaws/publ58/PLAW-117publ58.pdf

Interaction Between Changing Ecosystem and Recreation

Changes in forest composition and ecosystem structure can present additional challenges to the maintenance and viability of some recreation assets and may alter future recreation opportunities. For example, some studies suggest that certain forest types or structures may make the area more susceptible to wildfire (Lenihan et al. 2008). Loss of tree species in floodplains may increase flood risk without the buffering provided by the floodplain forest (Brandt et al. 2014). Loss of forest canopy cover due to species mortality may affect user experience, especially in areas that act as shade refuges from the summer heat, notably in campgrounds, waterways, and trails. Standing dead trees from climate-induced mortality, while providing benefits for wildlife habitat, can also pose a direct hazard to life and property when near campsites, trails, and other recreation use areas.

Coordination between recreation and vegetation managers can help ensure vegetation in recreation sites is able to withstand current and future climatic changes. Managers can work together to manage for species that have low vulnerability to climate change and also provide recreation benefits (such as shade or habitat for recreationally important wildlife) while helping to reduce risks from invasive species. Climate-adapted vegetation could also be strategically planted in recreation sites to reduce the risk of erosion or flooding during heavy rain events. In fire-prone landscapes, preemptive measures can be taken to reduce fuel loads around recreation infrastructure. Prompt removal of hazard trees in recreation sites can reduce risks to staff and visitors while also opening up opportunities for climate-adapted tree planting.

Additional Resources

- The Central Hardwoods Ecosystem Vulnerability Assessment and Synthesis: a Report from the Central Hardwoods Climate Change Response Framework Project (Brandt et al. 2014) https://doi.org/10.2737/NRS-GTR-124
- Climate change projections for individual trees in the Central Hardwoods region https://forestadaptation.org/tree-species-projections-central-hardwoods

Human Health Risks

Climate change poses a risk to human health (Sarofim et al. 2016). Higher temperatures may place people at risk for heat stroke or exhaustion when working or recreating during hot summer months (Luber and McGeehin 2008). Climate change may also create conditions that are more favorable to vector-borne diseases, such as tick-borne and mosquito-borne illnesses (Ogden and Lindsay 2016). Poison ivy may also become more prolific and more potent under warmer conditions and higher CO_2 levels (Mohan et al. 2006). In addition, air quality could be affected by more wildfires across the United States, higher temperatures, and more allergens (Poole et al. 2019). Warmer waters, storm events, and changes in streamflow may affect water quality (Xia et al. 2015). These impacts can create risks for both recreation staff and visitors.

Preventive action can help protect the health and safety of visitors and staff from these and other impacts. The public may benefit from additional information and warnings regarding these risks at trailheads and on the web and via social media. The timing of interpretive events may be adjusted to avoid extreme heat, such as hosting events in the early mornings or late evenings and moving events to earlier or later in the season. Additional training and protective equipment may increase staff awareness of and protection from ticks, mosquitoes, and poison ivy. Staff schedules may be altered in response to changes, such as shifting schedules to avoid the hottest parts of the day or when air quality reaches dangerous levels.

Additional Resources

- The Centers for Disease Control and Prevention (CDC) Climate Effects on Health website https://www.cdc.gov/climateandhealth/effects/default.htm
- The American Public Health Association Climate Change topic page https://www.apha.org/topics-and-issues/climate-change

Landscape-scale Impacts

Landscape-scale impacts from a changing climate may lead to downstream impacts on the Mark Twain National Forest's recreation sites. For example, changes in snowmelt near the headwaters of the Missouri River watershed can have cascading impacts on flooding and streamflow (Wise et al. 2018). Fires in the western United States and Canada driven in part by hot, dry weather can affect air quality thousands of miles from the source (Burke et al. 2021). Local storms that lead to road or bridge closures can affect access and traffic on the national forest as well. In turn, effects of extreme events on roads, bridges, and other infrastructure can also affect the hydrologic and transportation systems surrounding the national forest.

Tracking global, national, and regional patterns can help staff anticipate local impacts before they occur. National, regional, and state climatology offices can provide outlooks to help managers anticipate such events. Communication and coordination with local, regional, and national partners can help ensure safe and functioning recreation infrastructure during an emergency. Limiting access to sites or providing early warning systems to visitors can help reduce the risk to local recreationists before an event.

Additional Resources

- The National Weather Service Storm Prediction Center provides multiday outlooks for severe weather across the United States. https://www.spc.noaa.gov
- The Midwest Regional Climate Center provides summaries of regional climate and weather trends. https://mrcc.purdue.edu
- The Missouri Climate Center provides statewide summaries of climate trends. http://climate.missouri.edu

Planning Implications

Climate change has important implications for various planning processes on the Mark Twain National Forest. The 2012 Planning Rule (USDA Forest Service, n.d.a) requires that all Land Management Plans consider climate change impacts and potential adaptation actions. Effects on recreation use and infrastructure are likely to be important to considerations at the plan level. In addition, the effects of climate change may be important to consider in project-level National Environmental Policy Act (1969) and other planning efforts such as Comprehensive River Management Plans (CRMPs) and Watershed Restoration Action Plans (WRAPs; USDA Forest Service, n.d.b).

Integrating climate change into planning involves both intentional consideration of climate change trends and projections and thoughtful integration of climate change adaptation strategies into goals and activities. Vulnerability assessments, like this document, can be an important resource for informing projects and plans (Timberlake and Schultz 2019). Resources are also available to assist in selecting appropriate adaptation strategies to align with project or plan goals while addressing vulnerabilities (Swanston et al. 2016). Resources have also been developed that focus specifically on adaptation strategies for infrastructure and recreation (O'Toole et al. 2019, Rasmussen et al. 2018).

Additional Resources

- The Adaptation Workbook decision-support framework provides a flexible process for developing adaptation strategies that accommodates a wide variety of geographic locations, scales, ecosystems, land uses, management goals, and ownership types. https://forestadaptation.org/adapt/adaptation-workbook
- U.S. Forest Service Transportation Resiliency Guidebook: Addressing Climate Change Impacts on U.S. Forest Service Transportation Assets (Rasmussen et al. 2018) is a resource to help managers identify climate change vulnerabilities within the USDA Forest Service transportation network and reduce transportation vulnerability to climate change. https://rosap.ntl.bts.gov/view/dot/38737
- The adaptation menu in Climate Change Adaptation Strategies and Approaches for Outdoor Recreation provides stepping stones to enable natural resource and recreation managers to translate broad concepts into targeted and prescriptive actions for implementing adaptation in recreation, https://doi.org/10.3390/su11247030. Learn more about this resource and find real-world project examples at: https://forestadaptation.org/recreation.

Chapter Summary

Climate change is very likely to have important impacts on the way the Mark Twain National Forest staff manages its recreation assets and programs, now and in the future. More flexibility and new resources may be needed to meet the challenges of changing visitor use patterns, increased damage to infrastructure and vegetation, and human health and safety concerns. Utilizing vulnerability assessments and developing targeted adaptation strategies can help identify and prepare for these risks. Resources are already available to assist managers in adapting recreation programs to climate change.

Glossary

adaptive capacity
the general ability of institutions, systems, and individuals to moderate the risks of climate change, or to realize benefits, through changes in their characteristics or behavior. Adaptive capacity can be an inherent property, or it could have been developed as a result of previous policy, planning, or design decisions.

annual exceedance probability (AEP)
conveys the statistical probability (or percent chance) of a flood event. The 1 percent AEP is a variable that describes flood peaks with a 1 percent chance of being equaled or exceeded in any given year. To learn more, see USGS (2018).

annual flow (mean)
the mean annual flow calculated as the mean of the yearly discharge values. Units: cubic feet per second.

bankfull (discharge or stage)
the elevation at which a stream first begins to overflow its natural banks onto the active flood plain, associated with approximately the 1.5-year recurrence interval on the annual series.

baseflow
that part of the stream discharge that is not attributable to direct runoff from precipitation or melting snow; it is usually sustained by groundwater discharge.

center of flow mass date

the winter/spring center of streamflow volume, which is when half of the spring volume of river flow has occurred. Climate change may influence rivers' flow patterns from snowmelt to rain dominated systems. These changes can be measured by the timing of the center of mass of annual flow metric.

climate change
a change in the state of the climate that can be identified (for example, by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external factors, or to persistent anthropogenic changes in the composition of the atmosphere or in land use.

climate model
see general circulation model.

disturbance
stresses and destructive agents such as invasive species, diseases, and fire; changes in climate and severe weather events such as hurricanes and ice storms; pollution of the air, water, and soil; real estate development of forest lands; and timber harvest. Some of these are caused by humans, in part or entirely; others are not.

driver
any natural or human-induced factor that directly or indirectly causes a change in an ecosystem.

ecosystem
a volumetric unit of the Earth's surface that includes air (climate), land (landform, soil, water), and biota. Ecosystems are defined by land area and contain all the interactions between living organisms and their physical environment.

emissions scenario
a plausible representation of the future development of emissions of greenhouse gases and aerosols that are potentially radiatively active, based on demographic, technological, or environmental developments.

exposure
the nature and degree to which a system is exposed to significant climate variations.

flashiness
the speed at which water rises.

forest type
a classification of forest vegetation based on the dominant species present, as well as associate species commonly occurring with the dominant species.

general circulation model (GCM)
numerical representation of the climate system based on the physical, chemical, and biological properties of its components, their interactions, and their feedback processes, and accounting for all or some of its known properties (also called climate model).

growing season
the period in each year when the temperature is favorable for plant growth.

impact
the direct and indirect consequences of climate change on systems, particularly those that would occur without adaptation.

invasive species
any species that is nonnative (or alien) to the ecosystem under consideration and whose introduction causes or is likely to cause damage, injury, or disruption to ecosystem processes or other species within that ecosystem.

peak flow
the maximum instantaneous discharge of a stream or river at a given location.

percent change in the 1.5-year flood (bankfull)
1.5-year flood—Calculated by first finding the greatest daily flow from each year; the 33rd percentile of the annual maximum series defines the flow that occurs every 1.5 years, on average. Units: cubic feet per second. See "bankfull".

percent change in the 10-year flood
10-year flood—Calculated by first finding the greatest daily flow from each year; the 90th percentile of the annual maximum series defines the flow that occurs every 10 years, on average. Units: cubic feet per second.

percentile
a value on a scale of 0 to 100 that indicates the percent of a distribution that is equal to or below it. The 50^{th} percentile is the median value.

precipitation
the process by which water vapor condenses in the atmosphere to form water droplets that fall to the Earth as rain, sleet, snow, hail, etc.

projection
a potential future evolution of a quantity or set of quantities, often computed with the aid of a model. Projections are distinguished from predictions in order to emphasize that projections involve assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realized, and are therefore subject to substantial uncertainty.

runoff
that part of the precipitation that appears in surface streams. It is the same as streamflow unaffected by artificial diversions or storage.

scenario
a plausible and often simplified description of how the future may develop, based on a coherent and internally consistent set of assumptions about driving forces and key relationships. Scenarios may be derived from projections but are often based on additional information from other sources, sometimes combined with a narrative storyline (see also emissions scenario).

sensitivity
the degree to which a system is affected, either adversely or beneficially, by climate-related stimuli.

severity
the proportion of aboveground vegetation killed and the degree of forest floor and soil disruption.

shoulder season
the time between the peak travel season and the off-season for a destination, during which visitation is lower than at the peaks but conditions are still good for travel.

significant trend
a statistical term describing the least-squares regression p-values of observed climate trends. In this report, trends are significant when $p < 0.10$. For trends where $p > 0.10$, observed trends have a higher probability of being due to chance alone.

snowpack
layers of accumulated snow that usually melts during warmer months.

streamflow
discharge that occurs in a natural surface stream course whether or not it is diverted or regulated.

stressor
an agent, condition, change in condition, or other stimulus that causes stress to an organism.

suitable habitat
in the Forest Ecosystem Atlas model, the area-weighted importance value, or the product of tree species abundance and the number of cells with projected occupancy.

uncertainty
an expression of the degree to which a value (such as the future state of the climate system) is unknown. Uncertainty can result from lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from quantifiable errors in the data to ambiguously defined concepts or terminology, or uncertain projections of human behavior. Uncertainty can be described using quantitative measures or by qualitative statements.

vulnerability
the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the impacts and adaptive capacity of a system. For this assessment, a system may be considered to be vulnerable if it is at risk of a composition change leading to a new identity, or if the system is anticipated to suffer substantial declines in health or productivity.

weather
the state of the atmosphere at a given time and place, with respect to variables such as temperature, moisture, wind velocity, and barometric pressure.

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Appendix 1: Common and Scientific Names of Species Mentioned in this Report

Flora

Common name	Scientific name
American basswood	*Tilia americana*
American beech	*Fagus grandifolia*
American elm	*Ulmus americana*
American holly	*Ilex opaca*
American hornbeam (musclewood)	*Carpinus caroliniana*
Ashe juniper	*Juniperus ashei*
autumn olive	*Elaeagnus umbellata*
bitternut hickory	*Carya cordiformis*
black ash	*Fraxinus nigra*
black cherry	*Prunus serotina*
black hickory	*Carya texana*
black locust	*Robinia pseudoacacia*
black maple	*Acer nigrum*
black oak	*Quercus velutina*
black walnut	*Juglans nigra*
black willow	*Salix nigra*
blackgum	*Nyssa sylvatica*
blackjack oak	*Quercus marilandica*
blue ash	*Fraxinus quadrangulata*
boxelder	*Acer negundo*
bur oak	*Quercus macrocarpa*
cedar elm	*Ulmus crassifolia*
cherrybark oak	*Quercus pagoda*
chestnut oak	*Quercus prinus*
chinkapin oak	*Quercus muehlenbergii*
cittamwood (gum bumelia)	*Sideroxylon lanuginosum*
common persimmon	*Diospyros virginiana*
eastern cottonwood	*Populus deltoides*
eastern hophornbeam (ironwood)	*Ostrya virginiana*
eastern redbud	*Cercis canadensis*
eastern redcedar	*Juniperus virginiana*
Florida maple	*Acer floridanum*
flowering dogwood	*Cornus florida*
green ash	*Fraxinus pennsylvanica*
hackberry	*Celtis occidentalis*
honeylocust	*Gleditsia triacanthos*
Japanese stiltgrass	*Microstegium vimineum*

(continued on next page)

Flora (continued)

Common name	Scientific name
kudzu	*Pueraria montana*
live oak	*Quercus virginiana*
loblolly pine	*Pinus taeda*
longleaf pine	*Pinus palustris*
mockernut hickory	*Carya alba*
northern red oak	*Quercus rubra*
Ohio buckeye	*Aesculus glabra*
Osage-orange	*Maclura pomifera*
overcup oak	*Quercus lyrata*
pawpaw	*Asimina triloba*
pecan	*Carya illinoinensis*
pignut hickory	*Carya glabra*
pin oak	*Quercus palustris*
poison ivy	*Toxicodendron radicans*
post oak	*Quercus stellata*
princesstree	*Paulownia tomentosa*
red maple	*Acer rubrum*
red mulberry	*Morus rubra*
river birch	*Betula nigra*
sassafras	*Sassafras albidum*
scarlet oak	*Quercus coccinea*
sericea lespedeza	*Lespedeza cuneata*
shagbark hickory	*Carya ovata*
shellbark hickory	*Carya laciniosa*
shingle oak	*Quercus imbricaria*
shortleaf pine	*Pinus echinata*
Shumard oak	*Quercus shumardii*
silver maple	*Acer saccharinum*
slippery elm	*Ulmus rubra*
sourwood	*Oxydendrum arboreum*
southern red oak	*Quercus falcata*
sugar maple	*Acer saccharum*
sugarberry	*Celtis laevigata*
swamp chestnut oak	*Quercus michauxii*
swamp red oak	*Quercus falcata*
swamp white oak	*Quercus bicolor*
sycamore	*Platanus occidentalis*
Virginia pine	*Pinus virginiana*
water oak	*Quercus nigra*
water tupelo	*Nyssa aquatica*
white ash	*Fraxinus americana*
white oak	*Quercus alba*
willow oak	*Quercus phellos*
winged elm	*Ulmus alata*
yellow-poplar	*Liriodendron tulipifera*

Fauna

Common name	Scientific name
black bass	Genus *Micropterus*
bobcat	*Lynx rufus*
catfish	Order Siluriformes
coyote	*Canis latrans*
crappie	*Pomoxis annularis*
ducks	*Anas* spp.
emerald ash borer	*Agrilus planipennis*
forest tent caterpillar	*Malacosoma disstria*
fox	
gray fox	*Urocyon cinereoargenteus*
red fox	*Vulpes vulpes*
hickory bark beetle	*Scolytus quadrispinosus*
mosquito	Family Culicidae
mourning dove	*Zenaida macroura*
rabbit	*Sylvilagus* spp.
raccoon	*Procyon lotor*
rock bass	*Ambloplites rupestris*
southern pine beetle	*Dendroctonus frontalis*
spongy moth	*Lymantria dispar dispar*
squirrel	Family Sciuridae
sucker	Family Catostomidae
sunfish	Family Centrarchidae
walnut twig beetle (thousand cankers disease)	*Pityophthorus juglandis*
tick	Order Parasitiformes, subclass Acari
trout	*Salvelinus* spp.
walleye	*Sander vitreus*
white bass	*Morone chrysops*
white-tailed deer	*Odocoileus virginianus*
wild turkey	*Meleagris gallopavo*
woodcock	*Scolopax minor*

Bacterial and Fungal Pathogen Species

Common name	Scientific name
anthracnose of sycamore	*Gnomonia leptostyla*
bur oak blight	*Tubakia iowensis*
Diplodia shoot blight	*Diplodia pinea*
laurel wilt of sassafras	*Raffaelea lauricola*
oak wilt	*Ceratocystis fagacearum*
sudden oak death	*Phytophthora ramorum*
thousand cankers disease	*Geosmithia morbida*

Appendix 2: Observed Flood Potential Data

The status of floods in the Mark Twain National Forest and surrounding areas as observed by the streamgaging network is described in this section and includes synthesized data from the flood potential framework and mapping tool (Yochum 2021, Yochum and Arabi 2024, Yochum et al. 2019).

The Flood Potential Portal is a map-based decision support system for enhancing the understanding and quantification of riverine flood hazards in the United States through use of the observational (streamgage) record. More information can be found at: https://floodpotential.erams.com.

Flood History

The Mark Twain National Forest and neighboring lands in and adjacent to the Ozarks have an extensive flooding history. Large flood events have occurred consistently throughout the streamgage record, from 1897 to present. Within flood potential zone 59S (see Figure 6 in Chapter 1 for locations of flood potential zones), major floods have occurred in 1904 (March), 1915 (August), 1949 (January), 1960 (May), 1961 (August), 1982 (December), 2008 (March and April), 2011 (April), and 2017 (April). Within zone 59N, major floods have occurred in 1897 (January), 1915 (August), 1945 (June), 1958 (July), 1982 (August), 1993 (September and November), 2008 (September), 2015 (December), and 2017 (late April and early May). The largest flood recorded (in watersheds of less than 3,860 square miles [1 million ha]) in the vicinity of the national forest occurred on the Spring River on December 3, 1982 (peak discharge = 244,000 cubic feet per second [24.9 million cubic meters per hour]). More information on specific events is available for the floods of 1982 (Parrett et al. 1993, Sauer and Fulford 1983), December 2015 through January 2016 (Holmes et al. 2016), and April and May 2017 (Heimann et al. 2018).

Extreme floods, as recorded by streamgages with at least 10 years of record and systematically defined using the flood potential method (Yochum 2021, Yochum and Arabi 2024, Yochum et al. 2019), have occurred in 10 watersheds on and near the national forest (see Chapter 1, Figure 7: highlighted watershed polygons, labeled with flood extreme index, E_f). These floods occurred in 1909, 1945, 1958, 1968, 1979, 1982, 1993, 2014, and 2017, in watersheds ranging in size from 0.36 to 562 square miles (100 to 15,000 ha). During the 2017 event, extreme flood magnitudes were experienced on the North Fork and Big Piney Rivers. Floods recorded on or near the Mark Twain National Forest have been less extreme than floods in other parts of the United States; however, floods on the national forest are generally large and occur regularly.

Flood Variability

The Mark Twain National Forest experiences a variety of floods, with larger flood magnitudes in the south and smaller magnitudes in the north (Fig. 7). The flood potential index (P_f) quantifies variability in the status of flooding (Yochum 2021, Yochum and Arabi 2024, Yochum et al. 2019). The Mark Twain National Forest southern units are in zone 59S (southern Ozarks) with a P_f = 43.4. This zone is in the 96th percentile of the 207 flood potential zones across the contiguous United States; that is, flood magnitudes, on average, are larger in this zone than in all but 4 percent of the zones. Floods also tend to have a moderate level of bimodality in zone 59S, with a bimodality index (B_i) of 6.9 (58th percentile). This means that the largest floods are 6.9 times larger than common (median) annual peak discharges, on average. Units in the middle portion of the Mark Twain National Forest are predominantly in zone 59N (northern Ozarks), which has a lower flood potential (P_f = 30.9; 90th percentile). Flood magnitudes in zone 59N, on average, are only 71 percent of the magnitude of zone 59S (30.9/43.4 × 100%); floods are 29 percent smaller in the northern Ozarks compared to the southern Ozarks. Bimodality (B_i = 5.0; 41st percentile) is less in zone 59N than 59S, on average. The northernmost unit, north of Jefferson City, is in zone 61 and has a P_f = 19.2 (73rd percentile). Floods in zone 61 are less than half the magnitude, on average, of those in the southern Ozarks (19.2/43.4 × 100% = 44%). The bimodality is also lower (B_i = 3.9; 27th percentile), with the largest floods being much more similar to typical annual peak discharges.

Flood Trends

Not only are floods inherently large on the Mark Twain National Forest, they are also becoming more severe in a number of ways. Eight tests for trends in the magnitudes, frequency, and flashiness of floods were evaluated as a part of the flood potential portal; the results are summarized in the following paragraphs (Yochum 2021, Yochum and Arabi 2024).

In the Ozarks, trends are not significantly (p-value ≤ 0.05) or possibly (0.05 < p-value ≤ 0.15) changing for the largest 5 percent of annual peak discharges (Fig. 18A), but trends are significantly increasing for the largest quarter (Q4; greater than 4-year return interval) of annual peak discharges (Fig. 18B) at a rate of change of 5.8, 9.3, and 7.6 percent from south to north, in zones 59S, 59N, and 61, respectively. (Percent increases in flood magnitudes are computed by comparing the most recent 30 years of data with the entire record of each zone.) For the largest quarter of annual peak discharges, the central units of the Mark Twain National Forest, in the northern Ozarks, are experiencing the most substantial increases in large flood magnitudes.

More frequently occurring floods are also showing significantly increasing trends, with moderate-scale floods (Q3; 2- to 4-year return interval) (Fig. 18C) increasing by 7.7, 9.2, and 8.5 percent from south to north, bankfull-scale floods (Q2; 1.33- to 2-year return interval) (Fig. 18D) increasing by 7.1, 17.5, and 14.2 percent, and the smallest floods (Q1; less than 1.33-year return interval; Fig. 18E) increasing by 8.9, 10.3, and 14.4 percent from south to north, respectively. The increases in the smallest floods indicate that annual peak flows during dry years are also becoming larger.

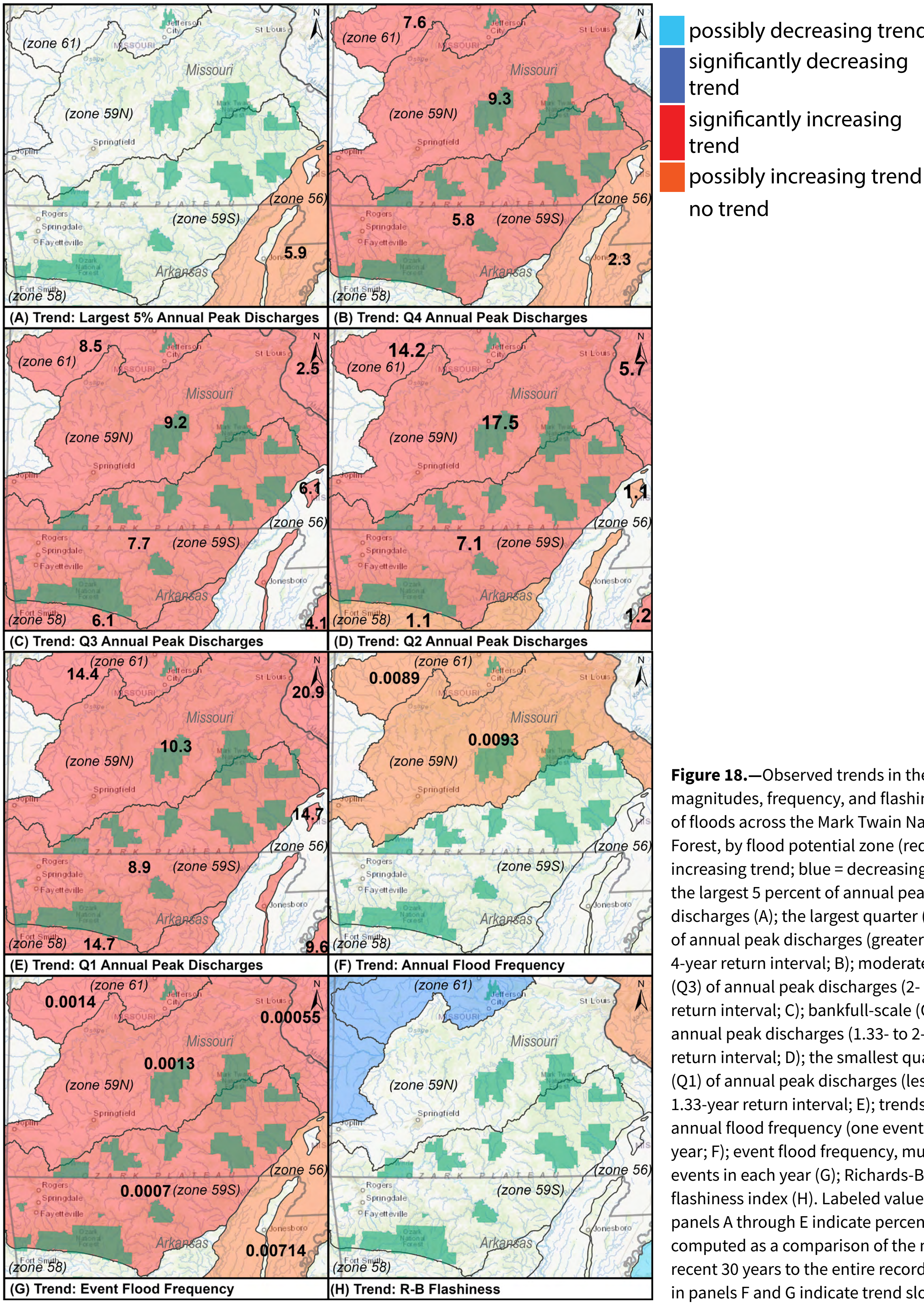

Figure 18.—Observed trends in the magnitudes, frequency, and flashiness of floods across the Mark Twain National Forest, by flood potential zone (red = increasing trend; blue = decreasing trend): the largest 5 percent of annual peak discharges (A); the largest quarter (Q4) of annual peak discharges (greater than 4-year return interval; B); moderate quarter (Q3) of annual peak discharges (2- to 4-year return interval; C); bankfull-scale (Q2) annual peak discharges (1.33- to 2-year return interval; D); the smallest quarter (Q1) of annual peak discharges (less than 1.33-year return interval; E); trends in annual flood frequency (one event per year; F); event flood frequency, multiple events in each year (G); Richards-Baker flashiness index (H). Labeled values for panels A through E indicate percent change computed as a comparison of the most recent 30 years to the entire record; labels in panels F and G indicate trend slope.

The frequency of flood events is also increasing on the Mark Twain National Forest, with annual flood frequency possibly increasing in zones 59N and 61 (Fig. 18F), and event flood frequency (which takes into account multiple flood peaks in each year) significantly increasing across all three zones (Fig. 18G). Frequency is increasing at the highest rate in zone 59N (annual) and zone 61 (event).

Flood flashiness (as tested using the Richards-Baker index) is not increasing across the Mark Twain National Forest (Fig. 18H), with a significantly decreasing trend in zone 61.

Other indices can be used to further explore the status of flooding, such as the watershed scale ratio, Beard and Richards-Baker flashiness indices, the flood variability index, and the flood hazard index.

The Watershed Analysis and Streamgage Analysis modules of the Flood Potential Portal provide tools for quantifying flood magnitudes.

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Yochum, S.E.; Scott, J.A.; Levinson, D.H. 2019. **Methods for assessing expected flood potential and variability: Southern Rocky Mountains region.** Water Resources Research. 55(8): 6392–6416. https://doi.org/10.1029/2018wr024604.

Appendix 3: Climate Change Data

Downscaled climate projections used in the Resource Planning Act (RPA) 2020 assessment (Joyce and Coulson 2020) were summarized for Missouri to present potential future conditions that were warmer to hotter and drier to wetter compared with a 30-year baseline period of 1981 through 2010. Five general circulation models (GCMs) and two representative concentration pathways (RCPs) were evaluated to determine how future climate conditions could change across Missouri (Fig. 19). The GCMs were CNRM-CM5, IPSL-CM5A-MR, HadGEM2-ES365, MRI-CGCM3, and NorESM1-M, and the RCPs were 4.5 and 8.5 to represent the bookends of potential global greenhouse gas emissions by the end of the century. Figure 19 shows the potential change in mean annual temperature and total precipitation for each GCM and RCP scenario from the observed 30-year mean. The MRI-CGCM3 model (MRI) under RCP 4.5 represents a slightly warmer and drier future compared to baseline. The IPSL-CM5A-MR model (IPSL) under RCP 8.5 projects the lowest annual precipitation and was the second warmest scenario of those evaluated. Both IPSL 4.5 and MRI 8.5 project a mid-range of warming and the greatest increase in precipitation. To avoid mixing projections from different models and to reduce the number of scenarios that managers and planners would have to evaluate, we chose the MRI and IPSL models to represent a range of future warming and precipitation regimes for the Mark Twain National Forest (Tables 12–15).

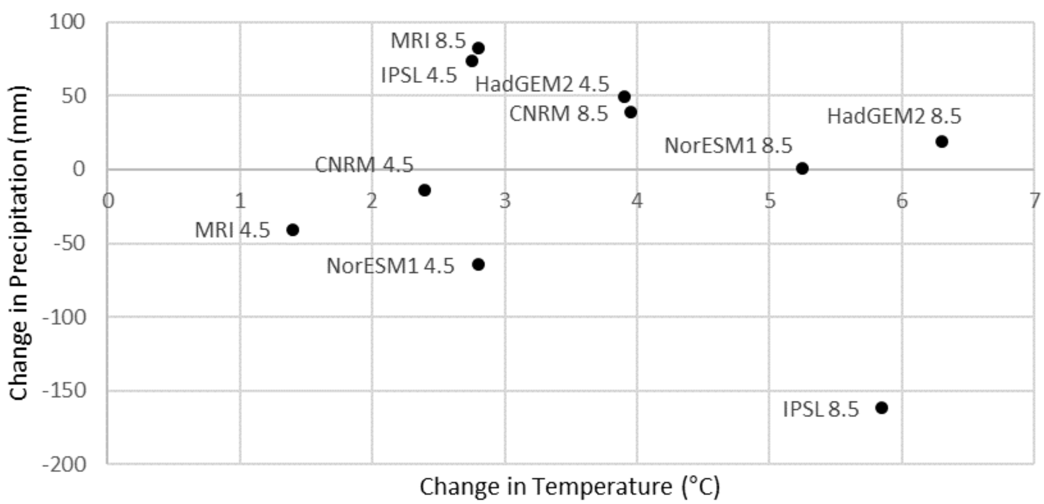

Figure 19.—Projected change in mean annual temperature and annual precipitation from a 30-year baseline period (1981 through 2010) to end of century (2070 through 2099) averaged across Missouri, described by five models (MRI, CNRM, HadGEM, NorESM, IPSL) under two scenarios (RCP 4.5, RCP 8.5).

Table 12.—Annual mean temperature in degrees Fahrenheit (degrees Celsius) for a baseline period (1980 through 2009) and projected annual mean temperature for three time periods using model MRI-CGCM3 for a lower climate change scenario (RCP 4.5) and a higher climate change scenario (RCP 8.5), by Mark Twain National Forest ranger district

Ranger district	Observed (1980–2009)	RCP 4.5 (2010–2039)	RCP 4.5 (2040–2069)	RCP 4.5 (2070–2099)	RCP 8.5 (2010–2039)	RCP 8.5 (2040–2069)	RCP 8.5 (2070–2099)
Houston/Rolla/Cedar Creek	55.3 (12.9)	55.8 (13.2)	57.1 (13.9)	57.8 (14.3)	56.0 (13.3)	58.1 (14.5)	60.3 (15.7)
Houston/Rolla/Cedar Creek - Northern	54.5 (12.5)	55.0 (12.8)	56.4 (13.6)	57.1 (13.9)	55.3 (12.9)	57.4 (14.1)	59.7 (15.4)
Poplar Bluff	56.7 (13.7)	57.2 (14.0)	58.5 (14.7)	59.1 (15.1)	57.4 (14.1)	59.5 (15.3)	61.6 (16.4)
Potosi/Fredericktown - Eastern	55.0 (12.8)	55.5 (13.1)	56.8 (13.8)	57.5 (14.2)	55.7 (13.2)	57.8 (14.3)	60.0 (15.6)
Potosi/Fredericktown - Western	54.9 (12.7)	55.4 (13.0)	56.7 (13.7)	57.4 (14.1)	55.6 (13.1)	57.7 (14.3)	59.9 (15.5)
Salem	55.3 (12.9)	55.7 (13.2)	57.0 (13.9)	57.7 (14.3)	56.0 (13.3)	58.0 (14.4)	60.2 (15.7)
Ava/Cassville/Willow Springs - Central	56.2 (13.4)	56.6 (13.7)	57.9 (14.4)	58.5 (14.7)	56.9 (13.8)	58.8 (14.9)	61.1 (16.2)
Ava/Cassville/Willow Springs - Eastern	56.1 (13.4)	56.6 (13.7)	57.9 (14.4)	58.5 (14.7)	56.8 (13.8)	58.8 (14.9)	61.0 (16.1)
Ava/Cassville/Willow Springs - Western	56.4 (13.6)	56.9 (13.8)	58.1 (14.5)	58.8 (14.9)	57.1 (13.9)	59.1 (15.1)	61.4 (16.3)
Doniphan/Eleven Point	56.4 (13.6)	56.9 (13.8)	58.2 (14.6)	58.8 (14.9)	57.1 (13.9)	59.1 (15.1)	61.3 (16.3)
Average	**55.7 (13.2)**	**56.1 (13.2)**	**57.4 (14.1)**	**58.1 (14.5)**	**56.4 (13.6)**	**58.4 (14.7)**	**60.6 (15.9)**

Table 13.—Annual mean temperature in degrees Fahrenheit (degrees Celsius) for a baseline period (1980 through 2009) and projected annual mean temperature for three time periods using model IPSL-CM5A-MR for a lower climate change scenario (RCP 4.5) and a higher climate change scenario (RCP 8.5), by Mark Twain National Forest ranger district

Ranger district	Observed (1980–2009)	RCP 4.5 (2010–2039)	RCP 4.5 (2040–2069)	RCP 4.5 (2070–2099)	RCP 8.5 (2010–2039)	RCP 8.5 (2040–2069)	RCP 8.5 (2070–2099)
Houston/Rolla/Cedar Creek	55.3 (12.9)	57.6 (14.2)	59.8 (15.4)	60.4 (15.8)	57.9 (14.4)	61.3 (16.3)	66.1 (18.9)
Houston/Rolla/Cedar Creek - Northern	54.5 (12.5)	56.8 (13.8)	59.0 (15.0)	59.5 (15.3)	57.1 (13.9)	60.6 (15.9)	65.1 (18.4)
Poplar Bluff	56.7 (13.7)	59.0 (15.0)	61.1 (16.2)	61.5 (16.4)	59.2 (15.1)	62.5 (16.9)	67.1 (19.5)
Potosi/Fredericktown - Eastern	55.0 (12.8)	57.3 (14.1)	59.4 (15.2)	59.9 (15.5)	57.6 (14.2)	60.9 (16.1)	65.5 (18.6)
Potosi/Fredericktown - Western	54.9 12.7)	57.2 (14.0)	59.4 (15.2)	59.9 (15.5)	57.5 (14.2)	60.9 (16.1)	65.5 (18.6)
Salem	55.3 (12.9)	57.6 (14.2)	59.8 (15.4)	60.2 (15.7)	57.8 (14.3)	61.2 (16.2)	65.9 (18.8)
Ava/Cassville/Willow Springs - Central	56.2 (13.4)	58.5 (14.7)	60.7 (15.9)	61.3 (16.3)	58.7 (14.8)	62.2 (16.8)	67.0 (19.4)
Ava/Cassville/Willow Springs - Eastern	56.1 (13.4)	58.4 (14.7)	60.5 (15.8)	61.1 (16.2)	58.6 (14.8)	61.9 (16.6)	66.7 (19.3)
Ava/Cassville/Willow Springs - Western	56.4 (13.6)	58.6 (14.8)	61.0 (16.1)	61.5 (16.4)	58.9 (14.9)	62.4 (16.9)	67.3 (19.6)
Doniphan/Eleven Point	56.4 (13.6)	58.7 (14.8)	60.8 (16.0)	61.3 (16.3)	58.9 (14.9)	62.2 (16.8)	66.9 (19.4)
Average	**55.7 (13.2)**	**58.0 (14.4)**	**60.2 (15.7)**	**60.7 (15.9)**	**58.2 (14.6)**	**61.6 (16.4)**	**66.3 (19.1)**

Table 14.—Annual mean precipitation in inches (mm) for a baseline period (1980 through 2009) and projected annual mean precipitation for three time periods using model MRI-CGCM3 for a lower climate change scenario (RCP 4.5) and a higher climate change scenario (RCP 8.5), by Mark Twain National Forest ranger district

Ranger district	Observed (1980–2009)	RCP 4.5 (2010–2039)	RCP 4.5 (2040–2069)	RCP 4.5 (2070–2099)	RCP 8.5 (2010–2039)	RCP 8.5 (2040–2069)	RCP 8.5 (2070–2099)
Houston/Rolla/Cedar Creek	44.7 (1135)	45.2 (1148)	48.1 (1222)	44.4 (11285)	45.8 (1163)	48.1 (1222)	50.3 (1278)
Houston/Rolla/Cedar Creek - Northern	42.2 (1072)	44.7 (1135)	47.0 (1194)	42.1 (1069)	44.2 (1123)	46.6 (1184)	49.1 (1247)
Poplar Bluff	47.5 (1207)	46.1 (1171)	48.3 (1227)	46.0 (1168)	47.8 (1214)	49.5 (1257)	50.8 (1290)
Potosi/Fredericktown - Eastern	47.0 (1194)	45.2 (1148)	48.5 (1232)	45.7 (1161)	47.7 (1212)	49.2 (1250)	50.6 (1285)
Potosi/Fredericktown - Western	45.5 (1156)	44.3 (1125)	47.1 (1196)	43.8 (1113)	45.8 (1163)	47.8 (1214)	49.1 (1247)
Salem	46.6 (1184)	45.4 (1153)	48.4 (1229)	45.3 (1151)	47.1 (1196)	49.2 (1250)	50.4 (1280)
Ava/Cassville/Willow Springs - Central	44.0 (1118)	43.5 (1105)	46.6 (1184)	43.7 (1110)	44.7 (1135)	46.6 (1184)	48.4 (1229)
Ava/Cassville/Willow Springs - Eastern	45.0 (1143)	43.9 (1115)	47.0 (1194)	44.1 (1120)	45.3 (1151)	47.4 (1204)	48.9 (1242)
Ava/Cassville/Willow Springs - Western	45.0 (1143)	45.0 (1143)	48.1 (1222)	44.5 (1130)	45.3 (1151)	47.6 (1209)	49.5 (1257)
Doniphan/Eleven Point	47.7 (1212)	45.8 (1163)	48.4 (1229)	46.5 (1181)	47.6 (1209)	50.0 (1270)	50.8 (1290)
Average	**45.5 (1156)**	**44.9 (1141)**	**47.8 (1214)**	**44.6 (1133)**	**46.1 (1171)**	**48.2 (1224)**	**49.8 (1265)**

Table 15.—Annual mean precipitation in inches (mm) for a baseline period (1980 through 2009) and projected annual mean precipitation for three time periods using model IPSL-CM5A-MR for a lower climate change scenario (RCP 4.5) and a higher climate change scenario (RCP 8.5), by Mark Twain National Forest ranger district

Ranger district	Observed (1980–2009)	RCP 4.5 (2010–2039)	RCP 4.5 (2040–2069)	RCP 4.5 (2070–2099)	RCP 8.5 (2010–2039)	RCP 8.5 (2040–2069)	RCP 8.5 (2070–2099)
Houston/Rolla/Cedar Creek	44.7 (1135)	48.3 (1227)	44.1 (1120)	47.7(1212)	41.2 (1046)	39.7 (1008)	37.2 (945)
Houston/Rolla/Cedar Creek -Northern	42.2 (1072)	47.0 (1194)	42.3 (1074)	45.9 (1166)	38.8 (986)	38.7 (983)	36.5 (927)
Poplar Bluff	47.5 (1207)	50.0 (1270)	47.9 (1217)	50.2 (1275)	45.5 (1156)	43.2 (1097)	41.4 (1052)
Potosi/Fredericktown - Eastern	47.0 (1194)	50.1 (1273)	47.9 (1217)	51.0 (1295)	45.2 (1148)	43.2 (1097)	42.2 (1072)
Potosi/Fredericktown - Western	45.5 (1156)	48.8 (1240)	45.6 (1158)	49.2 (1250)	43.0 (1029)	41.0 (1041)	39.6 (1006)
Salem	46.6 (1184)	50.1 (1273)	46.7 (1186)	50.3 (1278)	44.1 (1120)	42.2 (1072)	40.5 (1029)
Ava/Cassville/Willow Springs - Central	44.0 (1118)	46.5 (1181)	42.5 (1080)	45.4 (1153)	40.5 (1029)	38.0 (965)	35.5 (902)
Ava/Cassville/Willow Springs - Eastern	45.0 (1143)	47.8 (1214)	44.1 (1120)	46.6 (1184)	41.9 (1064)	39.1 (993)	36.6 (930)
Ava/Cassville/Willow Springs - Western	45.0 (1143)	47.3 (1201)	42.6 (1082)	45.8 (1163)	40.8 (1036)	38.7 (983)	35.7 (907)
Doniphan/Eleven Point	47.7 (1212)	50.5 (1283)	47.6 (1209)	50.0 (1270)	44.9 (1141)	42.3 (1074)	40.5 (1029)
Average	**45.5 (1156)**	**48.6 (1234)**	**45.1 (1146)**	**48.2 (1224)**	**42.6 (1082)**	**40.6 (1031)**	**38.6 (980)**

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Appendix 4: Comparison of Hydrologic Flow Projections with Baseline Conditions

Projections of streamflow across Mark Twain National Forest ranger districts at mid-century and end of century are compared with baseline conditions (1977 through 2006) in the following maps. Streamflow was modeled using the Variable Infiltration Capacity hydrologic model and an ensemble of five CMIP5 global climate models under a higher climate change scenario, representative concentration pathway (RCP) 8.5. The difference between projected and baseline streamflow magnitudes is expressed as a percent change for mean annual flow (Figs. 20, 21), the 1.5-year flood (bankfull; Figs. 22, 23), and the 10-year flood (Figs. 24, 25).

Mean Annual Flow by Mid-Century

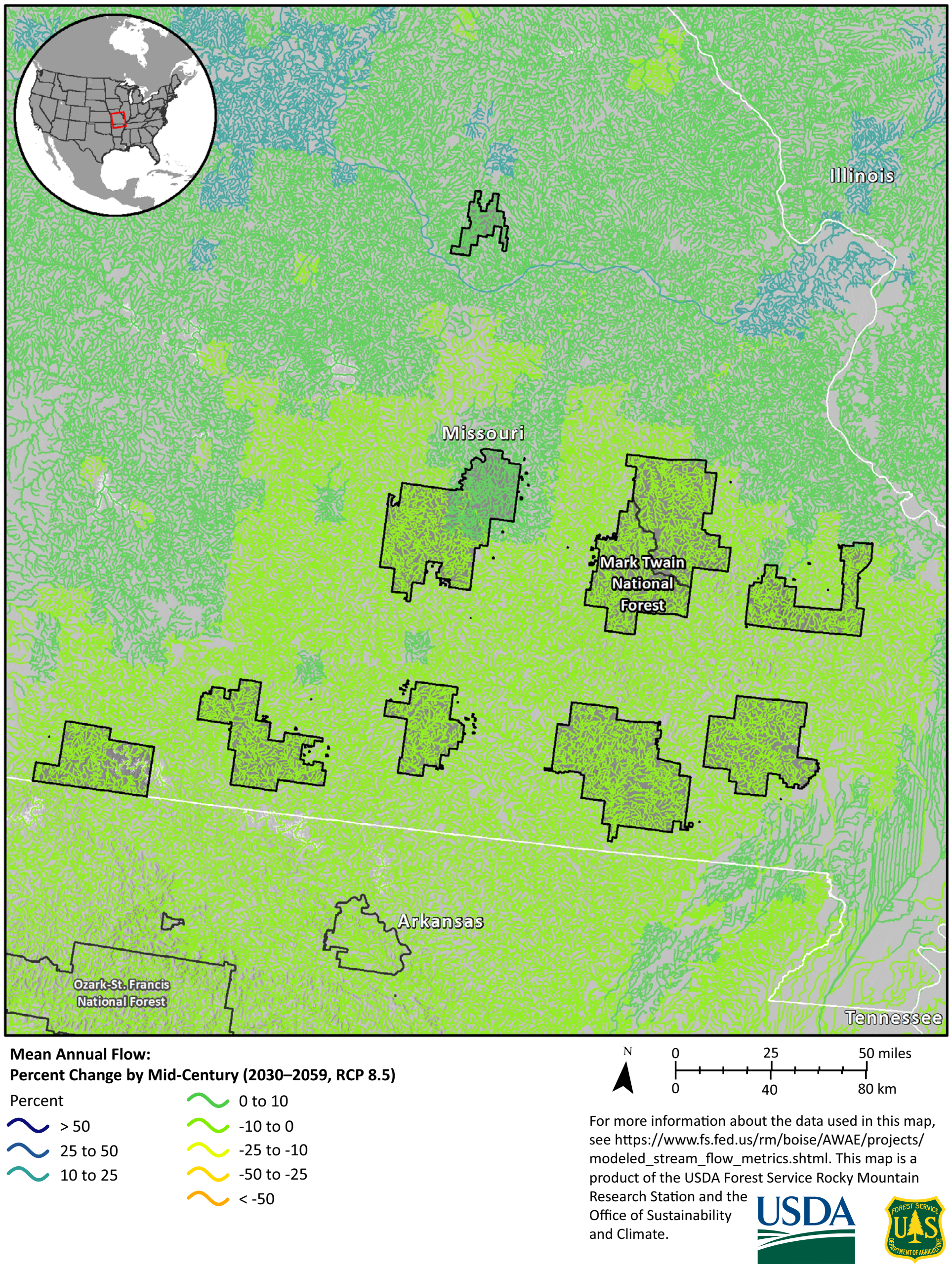

Figure 20.—Projected percent change in mean annual flow by mid-century (2030 through 2059) under RCP 8.5, as compared with baseline conditions (1977 through 2006), on the Mark Twain National Forest (green polygons). Inset map shows location of Missouri within the contiguous United States. Image reproduced from U.S. Department of Agriculture Forest Service, Office of Sustainability and Climate (2022).

Mean Annual Flow by End of Century

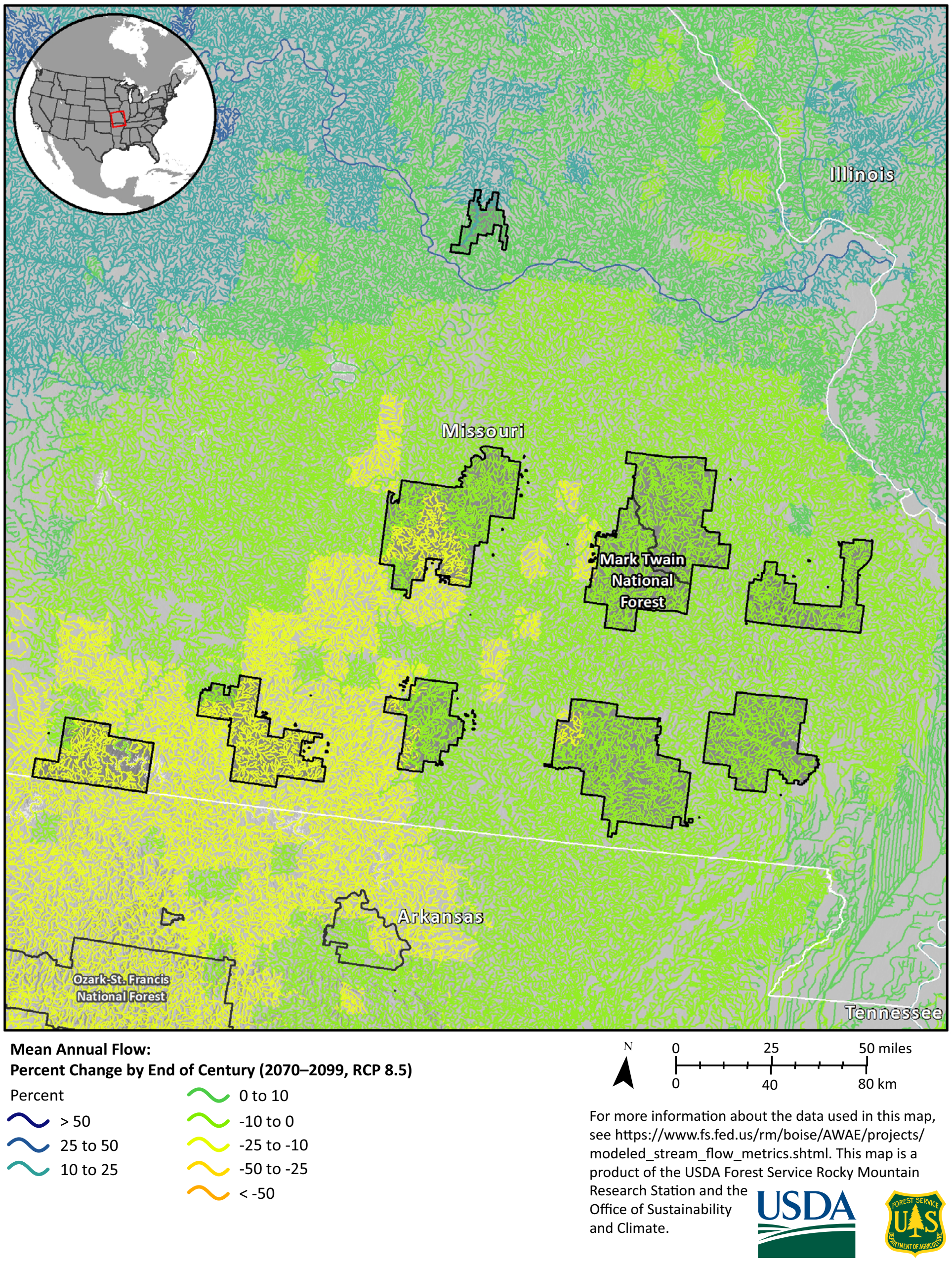

Figure 21.—Projected percent change in mean annual flow by the end of the century (2070 through 2099) under RCP 8.5, as compared with baseline conditions (1977 through 2006), on the Mark Twain National Forest (green polygons). Inset map shows location of Missouri within the contiguous United States. Image reproduced from U.S. Department of Agriculture Forest Service, Office of Sustainability and Climate (2022).

1.5-Year Flood (Bankfull) by Mid-Century

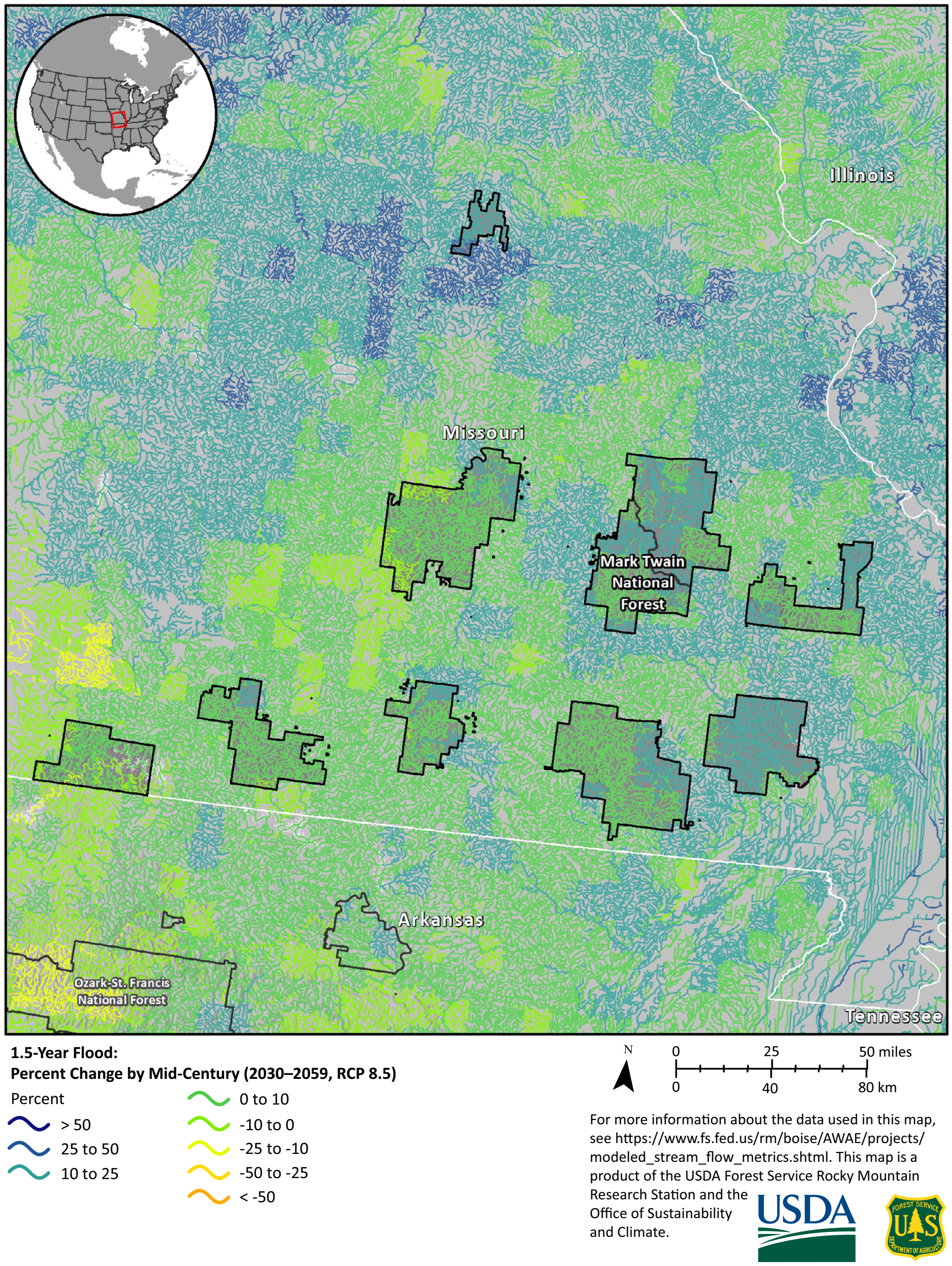

Figure 22.—Projected percent change in the 1.5-year flood magnitude by mid-century (2030 through 2059) under RCP 8.5, as compared with baseline conditions (1977 through 2006), on the Mark Twain National Forest (green polygons). Inset map shows location of Missouri within the contiguous United States. Image reproduced from U.S. Department of Agriculture Forest Service, Office of Sustainability and Climate (2022).

1.5-Year Flood (Bankfull) by End of Century

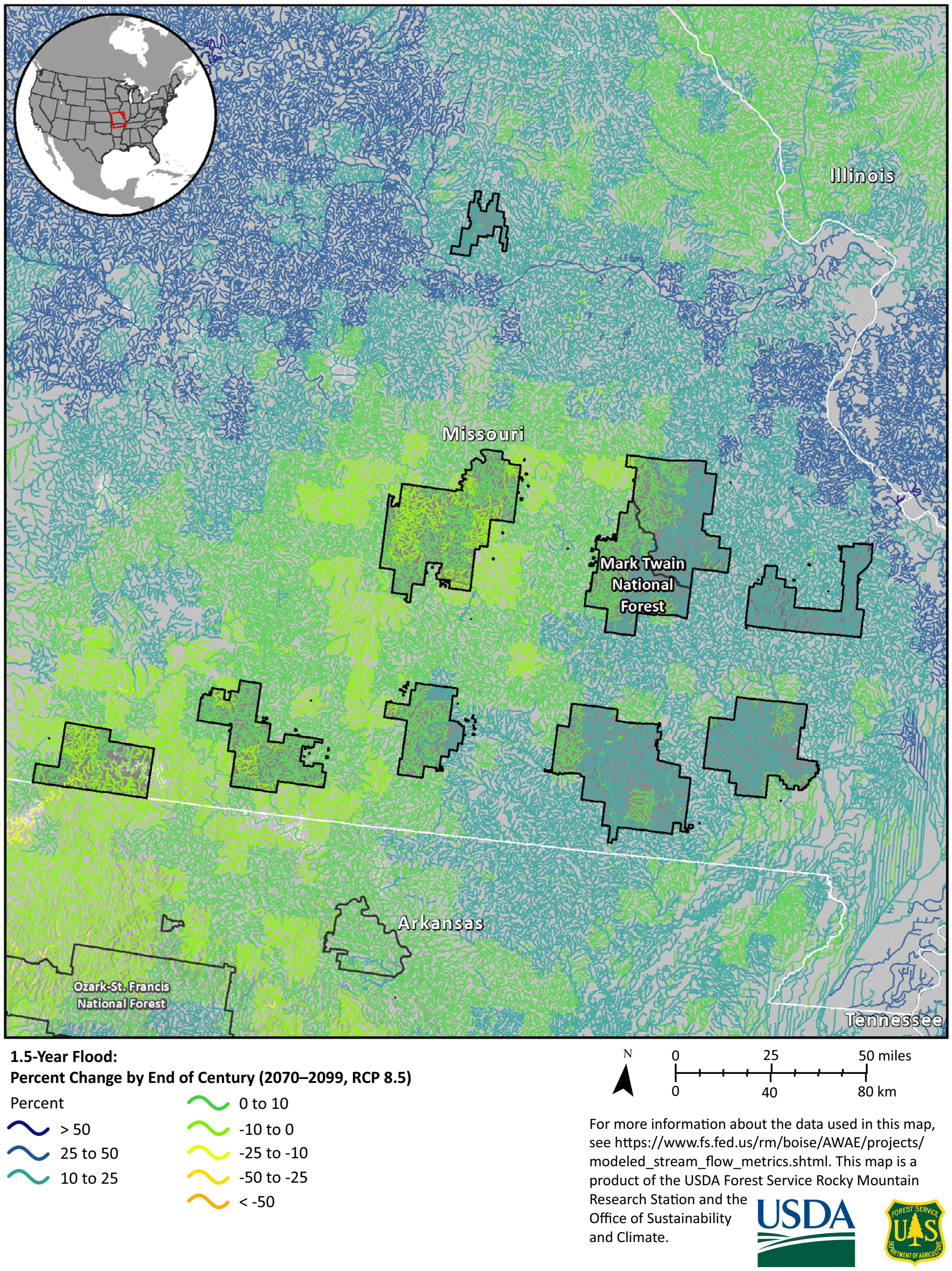

Figure 23.—Projected percent change in the 1.5-year flood magnitude by the end of the century (2070 through 2099) under RCP 8.5, as compared with baseline conditions (1977 through 2006), on the Mark Twain National Forest (green polygons). Inset map shows location of Missouri within the contiguous United States. Image reproduced from U.S. Department of Agriculture Forest Service, Office of Sustainability and Climate (2022).

10-Year Flood by Mid-Century

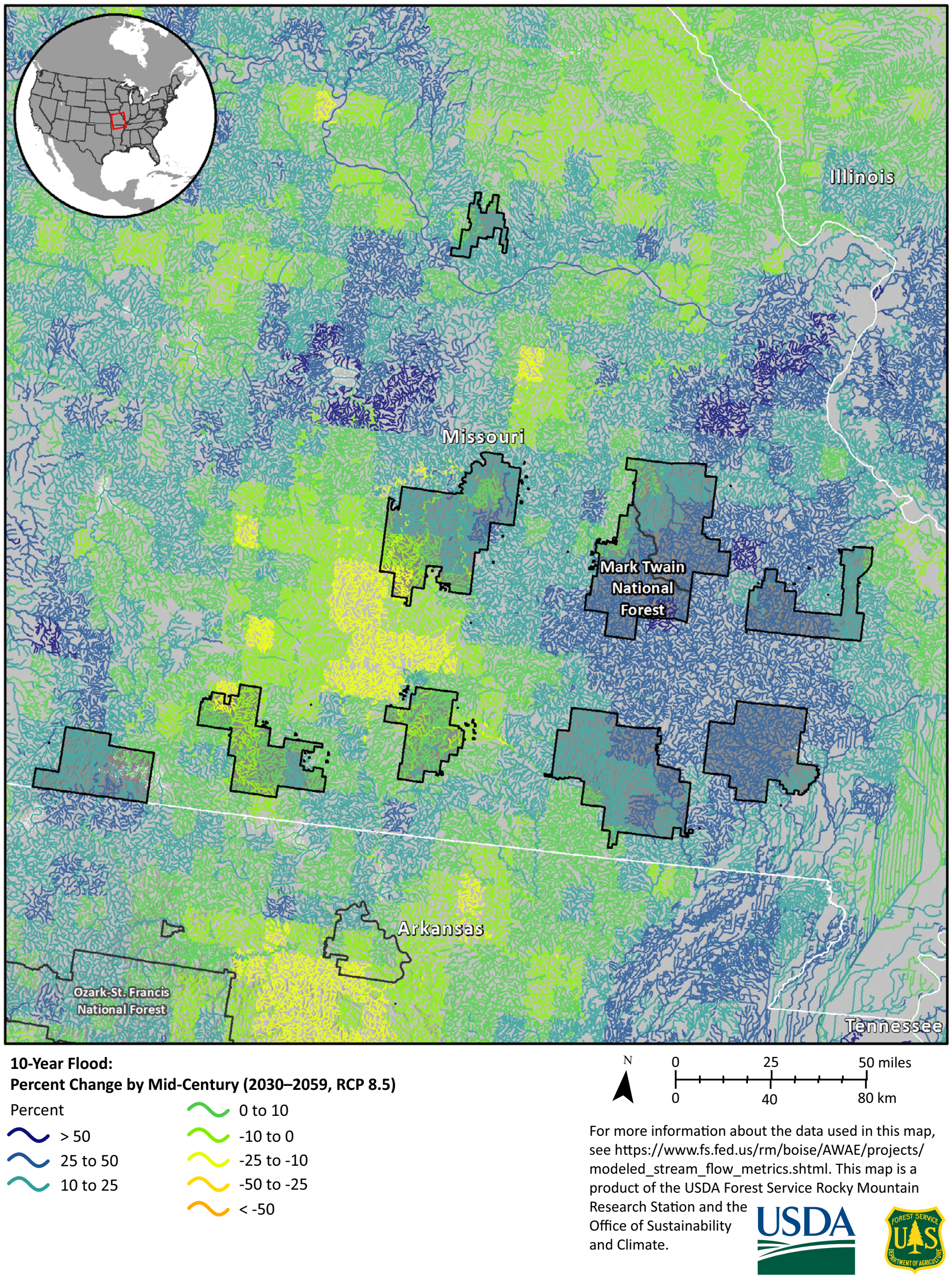

Figure 24.—Projected percent change in the 10-year flood magnitude by mid-century (2030 through 2059) under RCP 8.5, as compared with baseline conditions (1977 through 2006), on the Mark Twain National Forest (green polygons). Inset map shows location of Missouri within the contiguous United States. Image reproduced from U.S. Department of Agriculture Forest Service, Office of Sustainability and Climate (2022).

10-Year Flood by End of Century

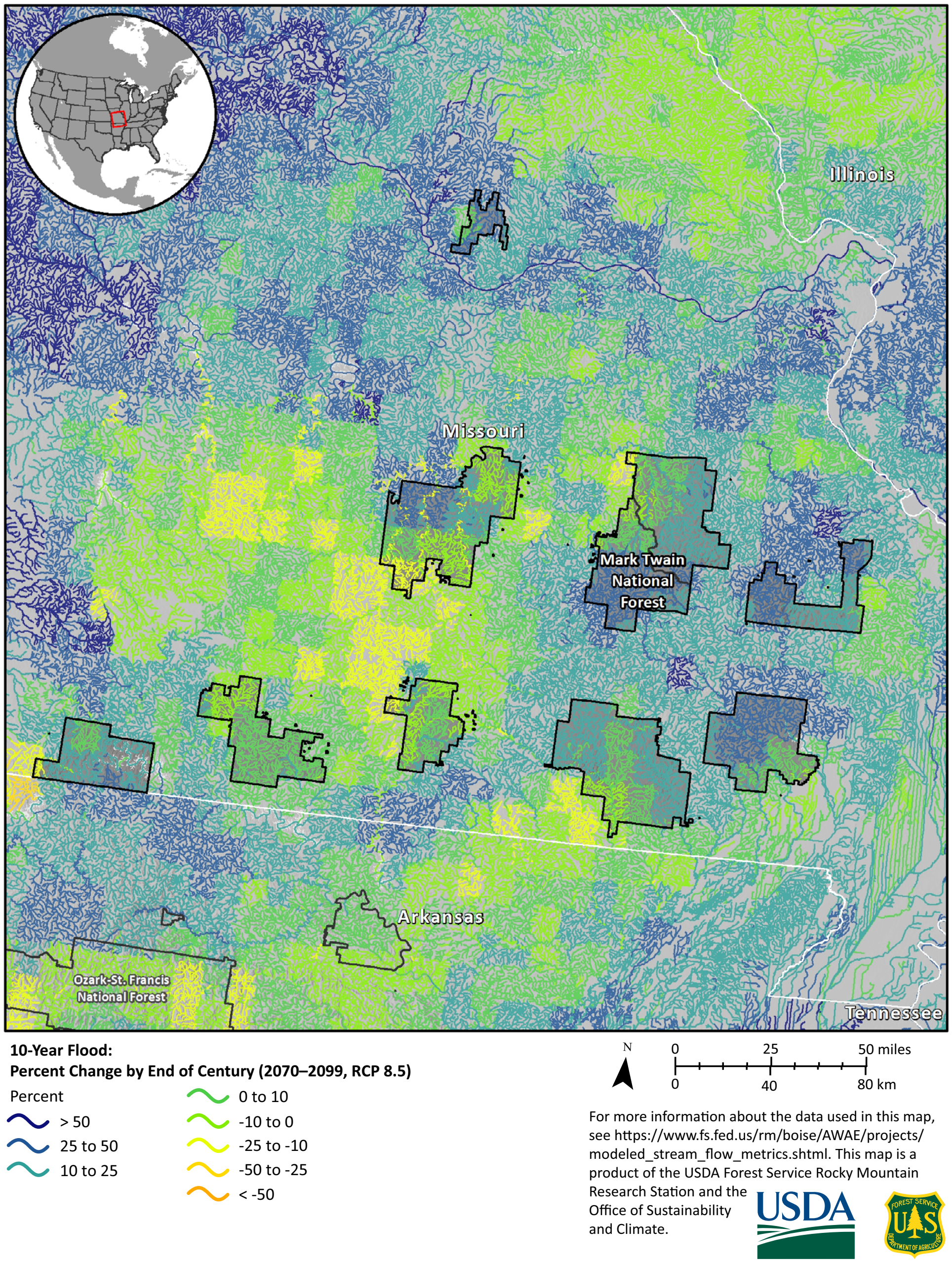

Figure 25.—Projected percent change in the 10-year flood magnitude by the end of the century (2070 through 2099) under RCP 8.5, as compared with baseline conditions (1977 through 2006), on the Mark Twain National Forest (green polygons). Inset map shows location of Missouri within the contiguous United States. Image reproduced from U.S. Department of Agriculture Forest Service, Office of Sustainability and Climate (2022).

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Appendix 5: Flood Frequency and Flow Magnitude Tables

Background on Derived Datasets

This report synthesized information for the Mark Twain National Forest using projected future 1 percent annual exceedance probability (AEP) data from studies that also extrapolated future flood frequency and flood magnitude across the conterminous United States (Mills et al. 2018, Wobus et al. 2017). The 1 percent AEP conveys the statistical probability (or percent chance) of a flood event. The 1 percent AEP is a common variable to evaluate extreme flooding, and by proxy, it helps to delineate the Special Flood Hazard Areas in Federal flood insurance maps (Federal Emergency Management Agency 2017, Mills et al. 2018). The projected future 1 percent AEP dataset was derived using climate projections from 29 general circulation models (GCMs) under 2 warming or representative concentration pathways (RCP) scenarios (RCP 4.5, RCP 8.5) in the Variable Infiltration Capacity (VIC) hydrologic model (Liang et al. 1994) to simulate watershed hydrology and mapped to hydrologic response units and U.S. Geological Survey Geospatial Fabric (Mills et al. 2018, Wobus et al. 2017).

For each stream segment, the authors extracted modeled time series for annual maximum flows for the entire 21st century (2001 to 2099) from each of the 29 GCMs and 2 warming scenarios (RCP 4.5, RCP 8.5) and then created ensemble averages and divided the time series into three 20-year intervals: a modeled baseline (2001 to 2020), mid-century (2040 to 2059), and end of century (2080 to 2099). The dataset was analyzed for flood frequency within a county by calculating a count of average future change in the recurrence interval compared with baseline 1 percent AEP observations. Similarly, when evaluating changes in flood magnitude, future 1 percent AEP flow was compared with the flow for the baseline 1 percent AEP flood for each river segment at the county level. More information on the generalized extreme value distribution method, statistical Monte Carlo methodology, and uncertainty can be found in Wobus et al. (2017).

Future Frequency of Baseline 1 Percent AEP Flood Events by Unit

The information in this section is drawn from Mills et al. (2018) and describes the projected future frequency of baseline 100-year floods (modeled 2001 to 2020) by mid-century and end of century under the lower warming (RCP 4.5) and greatest warming (RCP 8.5) scenarios on the Mark Twain National Forest. County-level results found in Mills et al. (2018) were used to analyze projected 1 percent AEP event trends for the national forest (Table 16).

By **mid-century**, 1 percent AEP flows across the national forest are projected to be **2 to 3 times** more frequent under the greatest warming scenario as compared to baseline observations. Future 1 percent AEP flows are projected to stay at the same frequency or become slightly more frequent under the lower warming.

By the **end of the century**, 1 percent AEP flows across the national forest are projected to be **2 to 4 times** more frequent under the greatest warming scenario as compared to baseline observations. Future 1 percent AEP flows are projected to be slightly more frequent under the lower warming, with the greatest increases under the low emissions scenario on the Poplar Bluff unit (up to 2 times more frequent). Notably, under the high emissions scenario, eastern units (Potosi, Salem, Fredericktown, Poplar Bluff) are projected to experience the largest increases in the frequency of flows at 3 to 4 times more, with 4 to 6 times more in the northwestern section of the Potosi unit.

Table 16.—Projected change in frequency of baseline (2000 to 2019) 100-year floods for Mark Twain National Forest units for mid-century (2040 to 2059) and end of century (2080 to 2099) under a lower climate change scenario (RCP 4.5) and a higher climate change scenario (RCP 8.5; "greatest warming scenario"). Projected increases in frequency for the baseline flood are described as values greater than 1, while decreases in frequency are presented as values less than 1. Source: Mills et al. (2018).

Unit	Mid-century, RCP 4.5	Mid-century, RCP 8.5	End of century, RCP 4.5	End of century, RCP 8.5	Trend summary
Cedar Creek	1.2–1.3	1.3–2.0	1.2–1.3	1.3–2.0	• By mid-century flows are slightly more frequent compared to baseline in the lower scenario and up to 2 times more frequent in the greatest warming scenario. • By end of century flows are slightly more frequent compared to baseline in the lower scenario and up to 2 times more frequent in the greatest warming scenario.
Houston-Rolla	1.2–1.3 (western), 0.8–1.0 (eastern), 1.0–1.2 (southern)	2.0–2.8, 1.3–2.0 (southwestern)	0.8–1.0, 0.7–0.8 (northwestern)	2.0–2.8 (eastern) 1.3–2.0 (western)	• By mid-century flows are slightly more frequent compared to baseline in the lower scenario and 2 times more frequent in the greatest warming scenario. • By end of century flows are slightly less frequent compared to baseline in the lower scenario and 2 to 3 times more frequent in the greatest warming scenario.
Potosi	0.8–1.0, 1.0–1.2 (northeastern)	2.0–2.8, 2.9–4.0 (northeastern)	1.0–1.2, 1.2–1.3 (S)	2.9–4.0, 4.0–6.6 (northwestern)	• By mid-century flows are slightly less than or about the same compared to baseline in the lower scenario and 4 times more frequent in the greatest warming scenario. • By end of century flows are slightly more frequent compared to baseline in the lower scenario and 3 to 6 times more frequent in the greatest warming scenario, particularly in the northwestern portion of the unit (6 times more frequent).
Salem	0.8–1.0	2.0–2.8	1.2–1.0 (western), 1.2–1.3 (eastern)	2.9–4.0	• By mid-century flows are slightly less than or about the same compared to baseline in the lower scenario and 2 to 3 times more frequent in the greatest warming scenario. • By end of century flows are slightly more frequent compared to baseline in the lower scenario and 3 to 4 times more frequent in the greatest warming scenario.

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Table 16 (continued).—Projected change in frequency of baseline (2000 to 2019) 100-year floods for Mark Twain National Forest units for mid-century (2040 to 2059) and end of century (2080 to 2099) under a lower climate change scenario (RCP 4.5) and a higher climate change scenario (RCP 8.5; "greatest warming scenario"). Projected increases in frequency for the baseline flood are described as values greater than 1, while decreases in frequency are presented as values less than 1. Source: Mills et al. (2018).

Unit	Mid-century, RCP 4.5	Mid-century, RCP 8.5	End of century, RCP 4.5	End of century, RCP 8.5	Trend summary
Fredericktown	0.7–0.8 (western), 0.8–1.0 (eastern)	2.0–2.8	1.2–1.3 (western), 1.0–1.2 (eastern)	2.9–4.0	• By mid-century flows are slightly less frequent compared to baseline in the lower scenario and 2 to 3 times more frequent in the greatest warming scenario. • By end of century flows are slightly more frequent compared to baseline in the lower scenario and 3 to 4 times more frequent in the greatest warming scenario.
Poplar Bluff	0.8–1.0 (northern), 1.0–1.2 (southern)	2.0–2.8	1.3–2.0 (northern), 1.2–1.3 (southern)	2.9–4.0 (northern), 2.0–2.8 (southern)	• By mid-century flows are slightly less than or about the same compared to baseline in the lower scenario and 2 to 3 times more frequent in the greatest warming scenario. • By end of century flows are slightly more frequent compared to baseline in the lower scenario and 2 to 4 times more frequent in the greatest warming scenario.
Eleven Point	0.8–1.0 (northern), 1.0–1.2 (southern)	2.0–2.8, 1.3–2.0 (southwestern)	1.1–1.2 (northwestern, southeastern), 1.2–1.3 (northeastern, southwestern)	2.0–2.8	• By mid-century flows are slightly less to slightly more frequent compared to baseline in the lower scenario; flows are up to 2 to 3 times more frequent in the greatest warming scenario and slightly less so in the southwestern corner of the unit. • By end of century flows are slightly more frequent compared to baseline in the lower scenario and 2 to 3 times more frequent in the greatest warming scenario.
Willow Springs	0.8–1.0	2.0–2.8 (western), 1.3–2.0 (eastern)	0.8–1.0 (western), 1.0–1.2 (eastern)	2.0–2.8 (western), 1.3–2.0 (eastern)	• By mid-century flows are slightly less than or about the same compared to baseline in the lower scenario and 2 to 3 times more frequent in the greatest warming scenario. • By end of century flows are the same or slightly more frequent compared to baseline in the lower scenario and 2 to 3 times more frequent in the western half of the unit under the greatest warming scenario, and less so in the eastern half of the unit.
Ava	0.8–1.0	2.0–2.8, 1.3–2.0 (southeastern corner)	0.8–1.0, 1.0–1.2 (southwestern corner)	2.0–2.8	• By mid-century flows are slightly less than or about the same compared to baseline in the lower scenario and 2 to 3 times more frequent in the greatest warming scenario. • By end of century flows are the same or slightly more frequent compared to baseline in the lower scenario and 2 to 3 times more frequent in the greatest warming scenario.
Cassville	0.8–1.0	2.0–2.8	1.2–1.3 (western), 1.0–1.2 (eastern)	2.0–2.8	• By mid-century flows are slightly less than or about the same compared to baseline in the lower scenario and 2 to 3 times more frequent in the greatest warming scenario. • By end of century flows are slightly more frequent compared to baseline in the lower scenario and 2 to 3 times more frequent in the greatest warming scenario.

Flood Magnitude Trends by Unit

By mid-century flood flows across the Mark Twain National Forest are projected to be similar to or slightly smaller than baseline under the lower emissions scenario and approximately 0 to 20 percent larger under the greatest warming scenario. County-level results from Mills et al. (2018) were used to analyze trends in projected future flood magnitude for Mark Twain National Forest units (Table 17).

By the end of the century, flows are projected to be similar to or slightly smaller than baseline under the lower emissions scenario and approximately 11 to 30 percent larger under the greatest warming scenario. Notably, the eastern units (Potosi, Salem, Fredericktown, Cassville) are projected to experience 20 to 30 percent greater magnitude flows under the greatest warming scenario.

Table 17.—Projected percent change in flood magnitude compared to baseline (2001 to 2019) for Mark Twain National Forest units for mid-century (2040 to 2059) and end of century (2080 to 2099) under a lower climate change scenario (RCP 4.5) and a higher climate change scenario (RCP 8.5; "greatest warming scenario"). Percentages greater than 1 indicate a projected increase. Source: Mills et al. (2018).

Unit	Mid-century, RCP 4.5	Mid-century, RCP 8.5	End of century, RCP 4.5	End of century, RCP 8.5	Trend summary
Cedar Creek	1–10%	1–10%	1–10%	1–10%	• At mid-century flows are the same size to 10% larger in both the lower and greatest warming scenarios. • By end of century flows are the same size to 10% larger in both the lower and greatest warming scenarios.
Houston-Rolla	-9–0% (eastern), 1–10% (western)	11–20% (eastern), 1–10% (western)	-9– 0%	11–20% (eastern), 1– 10% (western)	• At mid-century flows are the same size or smaller in the lower scenario and 10 to 20% larger in the greatest warming scenario. • By end of century flows are the same size or smaller in the low scenario and up to 20% larger in the greatest warming scenarios.
Potosi	-9–0% (western), 1–10% (eastern)	11–20% (western), 21–30% (eastern)	1–10%	21–30%	• At mid-century flows are slightly less to the same size in the lower scenario and 11 to 30% larger in the greatest warming scenario. • By end of century flows are slightly less than baseline conditions to up to 10% larger in the lower scenario and 21 to 30% greater in the greatest warming scenario.
Salem	-9–0%	11–20%	1–10%	21–30%	• At mid-century flows are slightly less to the same size in the lower scenario and 11 to 20% larger in the greatest warming scenario. • By end of century flows are slightly less than baseline conditions to up to 10% larger in the lower scenario and 21 to 30% greater in the greatest warming scenario.
Fredericktown	-9–0%, 1–10% (northeastern corner)	11–20%	1–10%	21–30%	• At mid-century flows are slightly less to the same size in the lower scenario and 11 to 20% larger in the greatest warming scenario. • By end of century flows are slightly less than baseline conditions to up to 10% larger in the lower scenario and 21 to 30% greater in the greatest warming scenarios.

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Table 17 (continued).—Projected percent change in flood magnitude compared to baseline (2001 to 2019) for Mark Twain National Forest units for mid-century (2040 to 2059) and end of century (2080 to 2099) under a lower climate change scenario (RCP 4.5) and a higher climate change scenario (RCP 8.5; "greatest warming scenario"). Percentages greater than 1 indicate a projected increase. Source: Mills et al. (2018).

Unit	Mid-century, RCP 4.5	Mid-century, RCP 8.5	End of century, RCP 4.5	End of century, RCP 8.5	Trend summary
Poplar Bluff	-9–0%, 11–20% (southern)	11–20%	1–10%	11–20%	• At mid-century flows are slightly less to the same size predominantly with 11 to 20% increases in the southern half of the unit in the lower scenario and 11 to 20% larger in the greatest warming scenario. • By end of century flows are the same size to up to 10% larger in the lower scenario and 11 to 20% greater in the greatest warming scenarios.
Eleven Point	-9–0% (northern), 1–10% (southern)	11–20% (northern), 1–10% (southern)	1–10%	11–20%	• At mid-century flows are slightly less to the same size in the lower scenario and up to 20% larger in the greatest warming scenario in the northern half of the unit. • By end of century flows are the same size to up to 10% larger in the lower scenario and 11–20% greater in the greatest warming scenarios.
Willow Springs	-9–0%	11–20%	-9–0%	11–20%	• At mid-century flows are the same size or smaller in the lower scenario and 11 to 20% larger in the greatest warming scenario. • By end of century flows are slightly less than baseline conditions to up to 10% larger in the lower scenario and 11 to 20% greater in the greatest warming scenarios.
Ava	-9–0%	11–20%	-9–0% (northern), 1–10% (southern)	11–20%	• At mid-century flows are the same size or smaller in the lower scenario and 11 to 20% larger in the greatest warming scenario. • By end of century flows are slightly less than baseline conditions to up to 10% larger in the lower scenario and 11 to 20% greater in the greatest warming scenarios.
Cassville	-9–0%	11–20%	1–10%	21–30% (western), 11–20% (eastern)	• At mid-century flows are the same size or smaller in the lower scenario and 10 to 20% larger in the greatest warming scenario. • By end of century flows are the same size to up to 10% larger in the lower scenario, and predominantly 21 to 30% greater flows in the western half of the unit and 11 to 20% greater flows in the eastern half, in the greatest warming scenarios.

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Wobus, C.; Gutmann, E.; Jones, R.; Rissing, M.; Mizukami, N.; Lorie, M.; Mahoney, H.; Wood, A.W.; Mills, D.; Martinich, J. 2017. **Climate change impacts on flood risk and asset damages within mapped 100-year floodplains of the contiguous United States.** Natural Hazards and Earth System Sciences. 17(12): 2199. https://doi.org/10.5194/nhess-17-2199-2017.

Appendix 6: Streamflow Projections

Regional future projections of hydrologic variables were compared with historical conditions on the Mark Twain National Forest to provide an indication of projected changes by national forest unit at mid- and end of century. This comparison is based on data in LaFontaine et al. (2019), who simulated water availability and streamflow dynamics across the southeastern United States for a historical and projected future climate. The hydrologic model was developed using the U.S. Geological Survey Precipitation-Runoff Modeling system and calibrated using several models and datasets. The models incorporate 16 models under both representative concentration pathway (RCP) 4.5 and 8.5 scenarios, over an observed historical baseline period of record and a mid-century period (2046 to 2075). Although the LaFontaine et al. (2019) include a longer historical period in their dataset documentation, we used the most recent 30-year period (1976 to 2005) for our analysis because it provides a better comparison with most recent events. All data are summarized by hydrologic response units (HRUs). ArcGIS spatial tools were used to identify HRUs within each national forest unit boundary; then data from those HRUs were averaged to generate a value for each flow variable by national forest unit. To align with Chapter 2, this analysis describes the results of the MRI, NorESM, and IPSL models under RCP 4.5 and RCP 8.5 scenarios by average HRUs for each of the national forest units.

Note that LaFontaine et al. assessed the quality of the models included in their broader study and found that MRI model insufficiently reproduced at least 75 percent of the historical distribution of observation-based simulations. The MRI data were subsequently excluded from the list of reliable models in the study (LaFontaine et al. 2019). The authors of this report included MRI results (Table 5) to be consistent with other elements in this report; however, due to the problematic issues noted in LaFontaine et al. (2019), the MRI hydrologic results have a higher level of uncertainty and are excluded from the narrative analysis. The CMIP5 NorESM model was chosen as a replacement for MRI results and provides a reasonable comparison to the IPSL model results.

Following is a list of statistics computed using runoff (HRU-based) time series described in previous chapters. The hydrologic variables were simulated for each calendar year and then summarized for each period using a mean or median of the yearly values based on the type (LaFontaine et al. 2019). The difference between projected future HRU values and model simulated historical HRU observations is described as a percent change (Table 18).

- Annual minimum daily flow (ft^3/s)—Magnitude of minimum annual flow at a daily timestep (DL3) (LaFontaine et al. 2019, Olden and Poff 2003). Computed as the minimum 1-day average flow for each year. DL3 is the median of these values (cubic feet per second – temporal).
- Annual maximum daily flow—Magnitude of maximum annual flow at a daily timestep (DH1). Computed as the maximum of a 1-day moving average flow for each year. DH1 is the median of these values (cubic feet per second – temporal).
- Summer (July–September) minimum of 3-day moving average flow (ft^3/s)—Computed as the minimum of a 3-day moving average flow for each year. SUM_DUR3 is the median of these values (cubic feet per second – temporal).
- Summer (July–September) minimum of 7-day moving average flow (ft^3/s)—Computed as the minimum of a 7-day moving average flow for each year. SUM_DUR7 is the median of these values (cubic feet per second – temporal).

Maximum daily flow may increase or decrease depending on model and location (Table 18). The annual maximum flow is generally projected to slightly decrease or be similar to observed historical conditions across all Mark Twain National Forest units under both IPSL and NorESM models and warming scenarios (RCP 4.5, 8.5). The greatest decreases in maximum daily flow are projected under the IPSL 8.5 scenario on the Fredericktown (-21 percent), Cassville (-22 percent), and Cedar Creek (-25 percent) units. Notably, some increases in maximum daily flow are projected under the IPSL 4.5 scenario on the Poplar Bluff (11 percent), Potosi (11 percent), Eleven Point (16 percent), and Salem units (18 percent) (La Fontaine et al. 2019).

The percent change in the 25-year flood is projected to increase more sharply in some units and decrease substantially in others by mid-century (2031 to 2059) (Walker and Luce 2021). Notable increases (25 to 50 percent and greater) are concentrated in the Potosi and Salem units and portions of the Eleven Point unit and western corner of the Cassville unit. Decreasing trends (-50 to -10 percent) are concentrated in the Houston and Willow Springs units and portions of the Ava, Eleven Point, and Cedar Creek units. Trends continue through the end of the century (2070 to 2099) for most units, with slight decreases in number of 25-year flood events projected. A significant portion of the Salem Ranger District is projected to have increases greater than 50 percent in the 25-year flood event by the end of the century.

Table 18.—Projected percent change in maximum, minimum, and summer (July to September) flows across the Mark Twain National Forest during a mid-century period (2046 to 2075) as compared with a recent 30-year period (1976 to 2005). Values by unit are compared with simulated historical observations and then presented as a percent change. Source: LaFontaine et al. (2019).

Unit	Climate model	Maximum daily flow, RCP 4.5	Maximum daily flow, RCP 8.5	Annual minimum of 7-day moving average flow, RCP 4.5	Annual minimum of 7-day moving average flow, RCP 8.5	Summer minimum of 3-day moving average flow, RCP 4.5	Summer minimum of 3-day moving average flow, RCP 8.5	Summer minimum of 7-day moving average flow, RCP 4.5	Summer minimum of 7-day moving average flow, RCP 8.5
Ava	MRI	8%	13%	-12%	0%	20%	3%	19%	2%
Ava	NorESM	-21%	-12%	-38%	-23%	-1%	17%	-8%	17%
Ava	IPSL	-6%	-30%	-9%	-56%	-98%	16%	-100%	1%
Willow Springs	MRI	4%	10%	9%	19%	21%	15%	18%	12%
Willow Springs	NorESM	-10%	-5%	-23%	-14%	21%	5%	20%	2%
Willow Springs	IPSL	9%	-16%	-20%	-54%	-18%	12%	-29%	9%
Cassville	MRI	13%	15%	-1%	9%	9%	-23%	9%	-26%
Cassville	NorESM	-14%	-3%	-41%	-18%	-10%	-12%	-8%	-11%
Cassville	IPSL	0%	-22%	-16%	-70%	-85%	-30%	-88%	-53%
Doniphan/ Eleven Point	MRI	12%	23%	-2%	6%	21%	16%	21%	15%
Doniphan/ Eleven Point	NorESM	-10%	2%	-31%	-14%	-34%	7%	-42%	10%
Doniphan/ Eleven Point	IPSL	16%	-16%	-20%	-62%	-90%	41%	-92%	38%
Houston-Rolla	MRI	-1%	-10%	4%	-6%	2%	-5%	3%	-9%
Houston-Rolla	NorESM	-15%	-6%	-32%	-19%	46%	32%	58%	43%
Houston-Rolla	IPSL	6%	-14%	-25%	-61%	-30%	7%	-45%	-10%
Cedar Creek	MRI	-4%	1%	-8%	3%	-25%	-14%	-15%	-15%
Cedar Creek	NorESM	-28%	-6%	-24%	-9%	151%	56%	177%	60%
Cedar Creek	IPSL	-10%	-25%	-21%	-35%	1%	42%	-9%	31%
Poplar Bluff	MRI	7%	17%	0%	-4%	27%	15%	24%	8%
Poplar Bluff	NorESM	-9%	3%	-45%	-20%	-8%	-5%	-2%	13%
Poplar Bluff	IPSL	11%	-17%	-25%	-74%	-22%	4%	-29%	-12%
Fredericktown	MRI	0%	8%	-2%	-7%	26%	16%	32%	14%
Fredericktown	NorESM	-20%	-11%	-18%	-1%	67%	26%	97%	48%
Fredericktown	IPSL	-7%	-21%	-15%	-49%	-55%	39%	-74%	25%

(continued on next page)

Table 18 (continued).—Projected percent change in maximum, minimum, and summer (July to September) flows across the Mark Twain National Forest during a mid-century period (2046 to 2075) as compared with a recent 30-year period (1976 to 2005). Values by unit are compared with simulated historical observations and then presented as a percent change. Source: LaFontaine et al. (2019).

Unit	Climate model	Maximum daily flow, RCP 4.5	Maximum daily flow, RCP 8.5	Annual minimum of 7-day moving average flow, RCP 4.5	Annual minimum of 7-day moving average flow, RCP 8.5	Summer minimum of 3-day moving average flow, RCP 4.5	Summer minimum of 3-day moving average flow, RCP 8.5	Summer minimum of 7-day moving average flow, RCP 4.5	Summer minimum of 7-day moving average flow, RCP 8.5
Potosi	MRI	-3%	-4%	4%	-6%	-6%	-10%	-1%	-11%
Potosi	NorESM	-13%	0%	-29%	-15%	36%	-4%	44%	-4%
Potosi	IPSL	11%	-17%	-12%	-53%	-67%	-23%	-77%	-42%
Salem	MRI	7%	12%	-1%	1%	3%	-27%	3%	-34%
Salem	NorESM	-11%	2%	-32%	-14%	3%	10%	7%	15%
Salem	IPSL	18%	-6%	-4%	-52%	-23%	-13%	-34%	-25%

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