Chapter 4

Water Resources of the Front Range National Forests

D. Max Smith

Introduction

The Colorado Front Range is the meeting of the Rocky Mountains and the Great Plains, a nexus of great topographic, geologic, and atmospheric forces. As water collects in the mountains and moves to the deserts and plains, it fosters unique ecosystems, some of which support rare and sensitive species. This water also creates opportunities and challenges for a growing metro area, fuels the recreational activities of residents and visitors, and supports an expansive agricultural industry. A complex system of ditches, pipelines, reservoirs, and transbasin diversions has been constructed to meet these myriad uses. The management challenges of the Front Range national forests are exacerbated by a warming climate and associated changes in hydrological patterns (Brown et al. 2019). In particular, the water resources provided by the Rocky Mountains in Colorado are vulnerable to the interacting effects of rising temperatures and increasing demands (Imerzeel et al. 2019). A detailed understanding of this vulnerability is necessary to plan management activities that will benefit natural and human communities through the end of the 21st century.

For this chapter, I reviewed the literature to describe the underlying components of Front Range water resources. This information was then incorporated into an assessment of the vulnerability of key water resources under four climate change scenarios. This was completed by selecting resources for analysis and discussing exposure, sensitivity, and adaptive capacity to the four scenarios. Finally, I provided a ranking of uncertainty based on the volume of empirical evidence supporting similar effects and responses. Datasets used in this assessment are listed in the appendix.

Environmental Setting

The natural hydrology of the Front Range was shaped by geological events and long-term climatic changes. The dynamics of surface water and groundwater are also influenced by the modern climate, plant and animal communities, and the activities of an expanding human population.

Geography

The region now known as the Front Range is located on the traditional territories and homelands of the Arapaho, Apache, Cheyenne, Comanche, Ute, and many other Indigenous nations (https://native-land.ca/). Front Range lands are now managed by a number of entities including the U.S. Department of Agriculture, Forest Service. For the purposes of this report, I focus on the resources provided by the Arapaho-Roosevelt National Forests (AR) and the Pike-San Isabel National Forests (PSI). In the AR National Forests, streams flow east and west of the Continental Divide, feeding into three river basins. Streams drain into the South Platte and North Platte Basins east of the divide, and into the Upper Colorado Basin west of the divide (fig. 1). Greater than 50 percent of the stream miles of the AR National Forests are in the South Platte Basin. In the PSI National Forests, streams drain east of the Continental Divide into the Arkansas and South Platte Basins. Greater than 50 percent of PSI National Forests stream miles are in the Arkansas Basin.

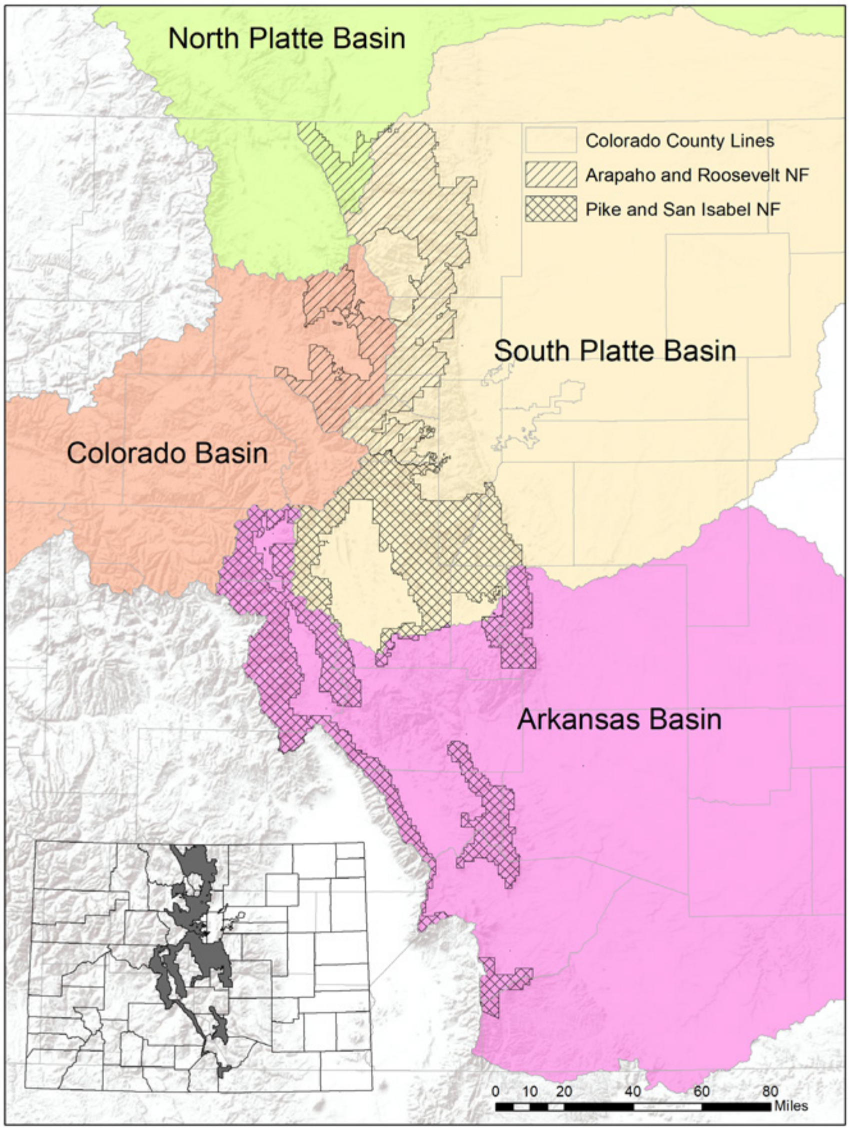

Figure 1—Location of the Front Range National Forests and major river basins.

The South Platte Basin contains 85 percent of Colorado's human population and the State's greatest concentration of irrigated cropland. Population centers in the Arkansas Basin include the cities of Colorado Springs and Pueblo. Ranching and livestock production are the dominant land uses in the portions of the North Platte and Upper Colorado Basins that are near the Front Range national forests (CWCB 2019).

For analysis purposes, the river basins are subdivided into 8-digit Hydrologic Unit Code (HUC8) watersheds that overlap the AR and PSI National Forests (Jones et al. 2022). Seven of these watersheds are in the South Platte Basin, six are in the Arkansas Basin, and there is one each in the North Platte and Upper Colorado Basins (table 1, fig. 2).

Table 1—Physical and administrative characteristics of 8-digit Hydrologic Unit Code (HUC8) watersheds overlapping the Arapaho and Roosevelt (AR) and Pike and San Isabel (PSI) National Forests. Data fields are described in the appendix.

Basin	HUC8 watershed	National Forest	Acres	Elevation range (ft)	Percent of HUC8 within Front Range NF Boundaries (%)	Private land (%)	Decreed instream flow miles
North Platte	Upper Laramie	AR	1,453,543	7,550–12,954*	65*	22*	92*
South Platte	Cache La Poudre	AR	1,209,013	4,593–13,574*	32*	52*	395*
	Big Thompson	AR	532,352	4,670–14,258	23	52	58
	St. Vrain	AR	626,865	4,736–14,257	26	51	341
	Clear	AR	364,755	5,101–14,270	38	48	127
	South Platte Headwaters	AR, PSI	1,025,992	7,217–14,287	39	44	318
	Upper South Platte	PSI	1,182,910	5,169–14,253	48	43	370
Upper Colorado	Colorado Headwaters	AR	1,856,423	5,716–13,547	22	25	822
Arkansas	Fountain	PSI	593,708	4,634–14,114	18	61	53
	Arkansas Headwaters	PSI	1,960,346	5,359–14,421	42	36	662
	Upper Arkansas	PSI	1,474,119	4,515–14,113	11	67	182
	Huerfano	PSI	1,189,513	4,440–14,330	12	79	53
	Apishapa	PSI	688,494	4,261–13,582	1	84	0
	Purgatoire	PSI	2,206,211	3,860–14,045	1	76	21

An asterisk (*) indicates that these data only apply to the portion of these watersheds within the State of Colorado.

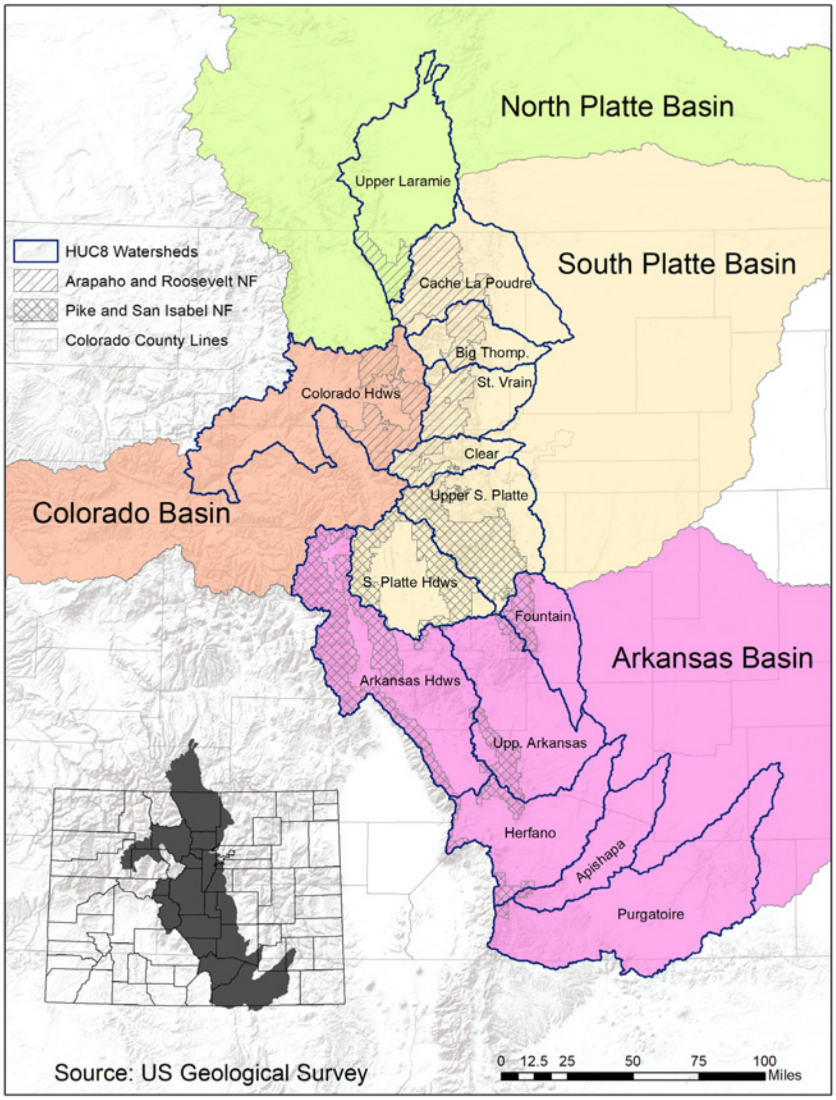

Figure 2—HUC 8 watersheds of the Front Range National Forests.

Physical Features

The AR and PSI National Forests were established on several mountain ranges that generally trend north to south. These ranges include the Medicine Bow Mountains and Front Range in northern Colorado, the Sawatch and Mosquito Ranges in the central portion of the State, and the Sangre de Cristo Mountains, Wet Mountains, and Spanish Peaks in the south. The cores and high peaks of these ranges are primarily composed of Precambrian intrusive igneous rocks and metamorphic rocks. These crystalline core complexes are flanked or overlaid by younger sedimentary rocks, including limestones, sandstones, and shales (Fields and Dethier 2019; Livers and Wohl 2015).

The upper elevations (approximately 8,000 ft and above) of the ranges were shaped by Pleistocene glaciers, which created mountain lakes, cirques, and broad valley bottoms (Caine 1995; Livers and Wohl 2015). Rock glaciers continue to influence the form and hydrology of mountains in some locations (Giardino et al. 1984; Jones et al. 2019). The lower elevations are dissected by stream-carved canyons, many of which are narrowly confined by crystalline bedrock (Clarey et al. 1999).

Climate

Snowfall typically occurs as a result of northwesterly airmass flow in the fall, winter, and early spring (Lukas et al. 2014). Storms from the south and east deliver moisture from the Gulf of Mexico to the Front Range via thunderstorms in late spring and summer. Precipitation ranges from less than 10 inches in lowland areas to greater than 40 inches in the highest mountains (Abbott 1985). Sixty percent of runoff in the Arkansas Basin occurs from April to July (Elgaali and Garcia 2007). Intense thunderstorms and multi-day precipitation events can occur from spring to fall. These storms are responsible for the largest floods on record on the eastern slope of the Front Range (Lukas et al. 2014).

Aquatic Ecosystems

Within the AR and PSI National Forests, aquatic ecosystems occur in natural settings, such as streams, ponds, and mountain lakes. Aquatic ecosystems also occur in anthropogenic features such as reservoirs, stock ponds, and irrigation ditches. After leaving the forests, surface flows sustain aquatic ecosystems in streams and reservoirs. Aquatic ecosystems contain plant and animal species that spend their entire lives in water, as well as animals that spend only certain stages of their life cycles in water. Specialized aquatic communities include amphibian larvae and benthic macroinvertebrates such as insects, snails, worms, and crayfish (Rice et al. 2018). Coldwater fish communities include the federally threatened greenback cutthroat trout (*Oncorhynchus clarkii stomias*) and the State-listed Colorado River cutthroat trout (*Oncorhynchus clarkii pleuriticus*; box 1). Introduced sportfish such as brook trout (*Salvelinus fontinalis*), rainbow trout (*Oncorhynchus mykiss*), and brown trout (*Salmo trutta*) are abundant in streams throughout the forests (Bestgen et al. 2019a; Naesser and Smith 1995; Richer et al. 2019). Lake trout (*Salvelinus namaycush*), kokanee salmon (*Oncorhynchus nerka*), and other nonnative sportfish are managed in lakes and reservoirs to provide recreational opportunities (Nesler 1981; Walch 1980). Downstream of the forests, surface flows support habitat for warm water fishes, including the Colorado pikeminnow (*Ptychocheilus lucius*), humpback chub (*Gila cypha*), and razorback sucker (*Xyrauchen texanus*), all of which are federally endangered (ARP 1997).

Box 1

Status of Cutthroat Trout Populations

South Platte Basin

The greenback cutthroat trout is a federally threatened salmonid native only to the South Platte Basin. The only known, genetically confirmed, strain was recently discovered in the Bear Creek drainage of the Arkansas Basin, where they were stocked in the late 1800s (Bestgen et al. 2019a). Since 2014, this strain has been reintroduced to stream segments in the South Platte Basin that are protected by barriers to invasion by nonnative salmonids. Populations in these segments are heavily managed and protected.

Arkansas Basin

There are currently no subspecies of cutthroat trout in Arkansas Basin that are considered native. However, at least one subspecies naturally occurred in the basin prior to Euro-American settlement and there are several extant populations representing unique genetic lineages (Janelle Valladares, USDA Forest Service, personal communication). The yellowfin cutthroat trout was a large subspecies that was extirpated from its range in the Twin Lakes area. The Bear Creek population of greenback cutthroat trout originated with fish stocked from the South Platte Basin in the late 1800s. Recent molecular analyses suggest that populations of the green lineage of Colorado River cutthroat are present east of the Continental Divide and may be native to the Arkansas Basin (Bestgen et al. 2019a). Another population, genetically similar to the yellowfin but classified as the Colorado River subspecies, has been found in Hayden Creek and is being reintroduced into suitable streams. Federal status of cutthroat trout in Arkansas Basin will likely be reexamined to incorporate results from recent molecular analyses (Rogers 2012).

Upper Colorado Basin

Populations of green lineage Colorado River cutthroat trout are native to streams in the basin, including a section of the AR that lies west of the Continental Divide. This subspecies is listed as a sensitive species by the Forest Service and the State of Colorado. A multi-state conservation agreement is in place to protect this subspecies (CRCT Coordination Team 2006).

Riparian Areas, Wetlands, and Groundwater-Dependent Ecosystems

In addition to aquatic habitats, Front Range water sustains riparian areas, wetlands, and groundwater-dependent ecosystems (box 2). Riparian ecosystems that occur along streams are influenced by geological setting, watershed hydrology, and biotic communities (Castro and Thorne 2019). Low-gradient, unconfined valley bottoms contain extensive riparian ecosystems, which can develop into mosaics of vegetation in various seral stages and growth forms (Livers and Wohl 2015). Confined stream reaches, often found in bedrock canyons, support smaller riparian areas, which may be difficult to distinguish from adjacent uplands (Polvi et al. 2011). Partially confined reaches contain features of both canyons and low-gradient, unconfined valley bottoms. Groundwater-dependent ecosystems (GDEs) occur where groundwater discharges to the surface or near the surface, supporting unique communities of plants and animals. GDEs in the AR and PSI National Forests include springbrooks, spring pools, fens, and other wetlands.

Box 2

Definitions of Riparian and Wetland Ecosystems

Authors use various criteria to describe riparian ecosystems, but their definitions typically contain at least one of these components: (1) an interface of terrestrial and aquatic communities at a body of water; (2) landforms and organisms that are influenced by surface water and groundwater; and/or (3) plant communities near water that differ in composition and/or structure from those in adjacent upland ecosystems (Dall et al. 1997; Gregory et al. 1991).

The Federal regulatory definition of wetlands is "ecosystems that are inundated or saturated by surface or groundwater at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions." This and other definitions of wetlands allows for some overlap with riparian ecosystems.

Groundwater-dependent ecosystems are defined by the Forest Service as "communities of plants, animals, and other organisms whose extent and life processes are dependent on access to or discharge of groundwater." Springs, fens, and certain riparian areas are examples of groundwater-dependent ecosystems. Springs are sites where groundwater is discharged or exposed at the soil surface. Unlike riparian ecosystems, spring ecosystems are entirely supported by groundwater. There are several types of springs in the Front Range forests, each of which can support unique flora and fauna (Springer and Stevens 2009; Stevens and Meretsky 2008).

Fens are groundwater-dependent wetlands with saturated organic soils that have accumulated a minimum of 30 to 40 cm of peat. These conditions support unique plant communities that include many species typically associated with higher latitudes (Bedford and Godwin 2003; Chadde et al. 1998; USDA FS 2007; 2012).

Water Uses and Infrastructure

Humans have long shaped the hydrology of the Front Range watersheds, with influences accelerating following Euro-American settlement and culminating in today's complex system of reservoirs, wells, ditches, and pipelines. It is often stated that most of Colorado's population lives east of the Rocky Mountains, yet most of the State's water flows west of the Continental Divide (Jones and Cech 2009). This distribution of people and water has resulted in the alteration of the hydrology of streams and lakes throughout the AR and PSI National Forests. The Cache La Poudre River, Big Thompson River, and other streams in the South Platte Basin are augmented by transbasin diversions, but these streams are heavily depleted by agricultural and municipal uses before reaching their confluences (Bestgen et al. 2019b). The Arkansas River is augmented by transbasin diversions as well, with surface flows heavily manipulated by dams and diversions (Abbott 1985).

Irrigation canals have been used to divert water from streams to farms since the 1850s or earlier (Abbott 1985). Average-year surface flows were fully appropriated on the eastern slope of the Front Range prior to surface flows on the western slope being fully appropriated, creating the need and opportunity for transbasin diversions from the west to the east. These include the Colorado–Big Thompson Project, the Frying Pan–

Arkansas Project, The Twin Lakes Project, and several smaller tunnels and ditches that cross the Continental Divide. These projects provide water for municipal, agricultural, and other consumptive uses on the eastern slope, as well as water for energy generation and recreational activities (Naesser and Smith 1995; Nessler 1981; Walch 1980). As a result of water releases timed to meet these needs, the natural flow regime (timing and volume) of many streams has been altered. In general, west side water is stored in reservoirs, transported to the east side through tunnels, stored in east side reservoirs, and transported through natural stream channels, augmenting native flows in the process.

Water Resource Components

Based on the above literature review (conducted in 2020) and feedback from managers at the November 2019 vulnerability workshop, I selected seven water resource components for further analysis. These components are described below, along with climate change implications specific to the Front Range national forests (table 2).

Table 2—Climate change implications for water resource components, obtained from literature review.

Water Resource Component	Implication
1. Streamflow	• Atmospheric warming decreases the contribution of snowmelt to surface flows (Ficklin et al. 2013; Johnson et al. 2015; Kampf and Lefsky 2016; Perry et al. 2019; Rasmussen et al. 2014; Zhang et al. 2018). • In the snow/rain transition zones, peak flows result from rain instead of snowmelt (Kampf and Lefsky 2016; Zhang et al. 2018). • Increasing temperatures and decreasing winter precipitation lead to earlier peak runoff in snowmelt-dominated streams (Clow 2010). • Atmospheric warming decreases the amount of water leaving the forests in streamflows as a result of increased rates of evapotranspiration (Ficklin et al. 2013; Foster et al. 2016; Rasmussen et al. 2014). • Combined effects of drought, bark beetles, and dust on snow result in earlier snowmelt and peak discharge in mountain streams (Deems et al. 2013; Livneh et al. 2015).
2. Snowpack	• Change in precipitation type at middle elevations (6,500–8,000 feet) will shift the transition zone upwards causing the lower elevation of the snowpack zone to shift upwards (Kampf and Lefsky 2016; Rasmussen et al. 2011, 2014; Zhang et al. 2018). • Change in vegetation cover following drought, bark beetles, and fire influences snowpack characteristics and infiltration rates below canopies (Harpold et al. 2015; Livneh et al. 2015).

Table 2 continued.

Water Resource Component	Implication
	• Change in lowland vegetation cover following drought increases atmospheric dust, which influences snowpack behavior (Deems et al. 2013). • Dust on snow interacts with climatic warming to decrease the ability for snowpack to act as water storage throughout the growing season (Painter et al. 2018). • Decreasing winter precipitation and increasing temperatures result in a trend of decreasing snow water equivalent (SWE) in Colorado (Clow 2010).
3. Groundwater	• Change from snow to rain at upper elevations likely decreases groundwater recharge, altering transit times and chemistry of water discharged at springs (Earman and Dettinger 2011; Fields and Dethier 2019). • Growing demand for groundwater may decrease its availability for aquatic, riparian, and wetland ecosystems (Kundzewicz and Doll 2009).
4. Drought	• Higher temperatures increase the likelihood and severity of drought (Breshears et al. 2005; Udall and Overpeck 2017). • Periods of drought result in water shortages in Front Range basins. Future long-term drought may tax storage and diversion infrastructure (Kenney et al. 2004; Salas et al. 2005).
5. Extreme Rainfall Events	• Atmospheric moisture increases with atmospheric warming, but there is uncertainty about projected changes in frequency and intensity of rain events (Mahoney et al. 2013). • Post-wildfire sites are prone to erosion, heavy flooding, and debris flows during extreme rainfall events (Lukas et al. 2014).
6. Water Quality	• Atmospheric warming results in increased stream temperatures, with consequences for aquatic ecosystems (Isaak et al. 2015; Roberts et al. 2017a). • Drought decreases the dilution of pollutants in streams, lakes, reservoirs, and groundwater (Johnson et al. 2015; Saunders and Lewis 2003; Sprague et al. 2005). • Atmospheric warming increases the risk of wildfire, which reduces vegetation cover, increasing the risk of debris flows and sedimentation (Rice et al. 2018).
7. Water Use Infrastructure	• Evaporative losses from reservoirs reduce the availability of surface flows and water uses (Naeser and Smith 1991). • Aging infrastructure is at risk of damage from floods and fires (Lukas et al. 2014). • Aging infrastructure is not capable of meeting challenges from increasing demands and a changing climate (Dettinger et al. 2015).

Streamflows

Surface water in streams is habitat for native fish and other aquatic organisms. The movement of this water influences streambed, streambank, and floodplain habitat features. Surface flows also contribute to groundwater and soil moisture, helping to sustain riparian and wetland ecosystems (Bestgen et al. 2019b). Aquatic and riparian organisms have traits that are adapted to the natural flow regimes of Front Range streams. Therefore, changes to the timing, magnitude, and frequency of high flows and low flows have the potential to alter ecosystem structure (Poff et al. 1997). Under typical conditions, surface flows originate as runoff from snowmelt, runoff from rain, or from groundwater discharge (Williams et al. 2015a). Runoff in large streams is usually snowmelt-dominated, with peak flows occurring in May or June (table 3; fig. 3) (Bartholow 2010; Lukas et al. 2014). Groundwater and rain have greater contributions to streamflows at lower elevations (Kampf and Lefsky 2016; Livers and Wohl 2015). Peak flows from rain-produced floods are typically more severe than those arising from snowmelt (fig. 3) (Jarrett and Costa 1988). Variation in magnitude and timing of peak flows is generally greater at lower elevations, as a result of these rainfall events (table 2). By decreasing interception and infiltration of precipitation, wildfire increases the amount of runoff from storms, magnifying peak flows for several years postburn (Moody and Martin 2001).

Low flows typically occur in late summer through winter and are sustained by persistent snowmelt, groundwater discharge, and in some areas by melting ice glaciers and rock glaciers (Williams et al. 2006). Because numerous factors determine the amount of precipitation that enters streams, year-to-year variation in streamflow is greater than that of precipitation (Lukas et al. 2014). Within and downstream of the AR and PSI National Forests, streamflows are diverted for a variety of anthropogenic uses, including municipal, agricultural, and industrial.

Table 3—Streamflow characteristics at select gages in 8-digit Hydrologic Unit Code (HUC8) watersheds of the Arapaho and Roosevelt (AR) and Pike and San Isabel (PSI) National Forests. Data fields are described in the appendix.

HUC8 watershed	Gage name	National Forest	Gage number	Elevation (ft)	Period examined	Mean discharge (cfs)	Max. discharge (cfs)	Mean peak date	Mean center of flow mass date	Peak discharge (cv)	Peak date (cv)	Center of flow mass date (cv)
Cache La Poudre	Joe Wright Creek above Joe Wright Reservoir	AR	06746095	9,990	1979 –2019	9.9	150	15-Jun	17-Jun	32.3	4.6	3.5
	Cache La Poudre at Ft Collins	AR	06752260	4,940	1976– 2019	175.8	7,150	6-Jun	8-Jun	75.6	15.9	7.2
Big Thompson	Big Thompson River below Moraine Park near Estes Park	AR	402114105 350101	8,005	2002–2019	53.7	761	17-Jun	15-Jun	43.0	10.0	2.9
	Big Thompson River at Loveland	AR	06741510	4,906	1980–2019	70.1	7,200	5-Jun	20-Jun	146.4	25.7	9.8
St. Vrain	Boulder Creek at North 75th	AR	06730200	5,106	1987–2019	95.6	4,770	20-Jun	12-Jun	97.6	10.7	7.9
Clear	Clear Creek near Lawson	AR	06716500	8,070	1995–2019	144.2	1440	14-Jun	16-Jun	38.1	4.2	3.5
	Clear Creek at Golden	AR	06719505	5,695	1975–2019	191.0	2,300	17-Jun	14-Jun	40.3	6.6	3.4
Upper South Platte	South Platte River Below Union Ave	AR, PSI	06710247	5,290	1997–2019	166.2	2,750	8-Jun	29-May	63.1	12.7	11.0
Colorado Headwaters	Colorado River below Baker Gulch near Grand Lake	AR	09010500	8,750	1954–2018	65.4	1,770	9-Jun	8-Jun	48.4	5.1	3.8
Fountain	Fountain Creek near Colorado Springs	PSI	07103700	6,110	1959–2019	16.4	813	2-Jul	6-May	126.9	14.5	17.3
Arkansas Headwaters	Arkansas River near Leadville	PSI	07081200	9,665	1991–2019	75.1	1,120	5-Jun	6-Jun	45.2	4.2	4.1
	Arkansas River at Canon City	PSI	07096000	5,342	1896–2017	717.8	9,480	14-Jun	6-Jun	40.8	8.9	8.0

Table 3 continued.

HUC8 watershed	Gage name	National Forest	Gage number	Elevation (ft)	Period examined	Mean discharge (cfs)	Max. discharge (cfs)	Mean peak date	Mean center of flow mass date	Peak discharge (cv)	Peak date (cv)	Center of flow mass date (cv)
Upper Arkansas	Arkansas River at Avondale	PSI	07109500	4,509	1966–2019	884.8	12,300	24-Jun	3-Jun	43.0	10.8	7.4
Huerfano	Huerfano River Near Boone	PSI	07116500	4,443	1980–2018	31.6	2,900	17-Jun	6-May	99.4	21.0	27.3
Apishapa	Apishapa River near Fowler	PSI	07119500	4,290	1940–2019	23.4	10,100	6-Jul	4-Jun	129.4	20.5	19.6
Purgatoire	Purgatoire River near Madrid	PSI	07124200	6,261	1973–2019	71.7	3,910	30-Jun	5-Jun	100.2	20.4	13.5

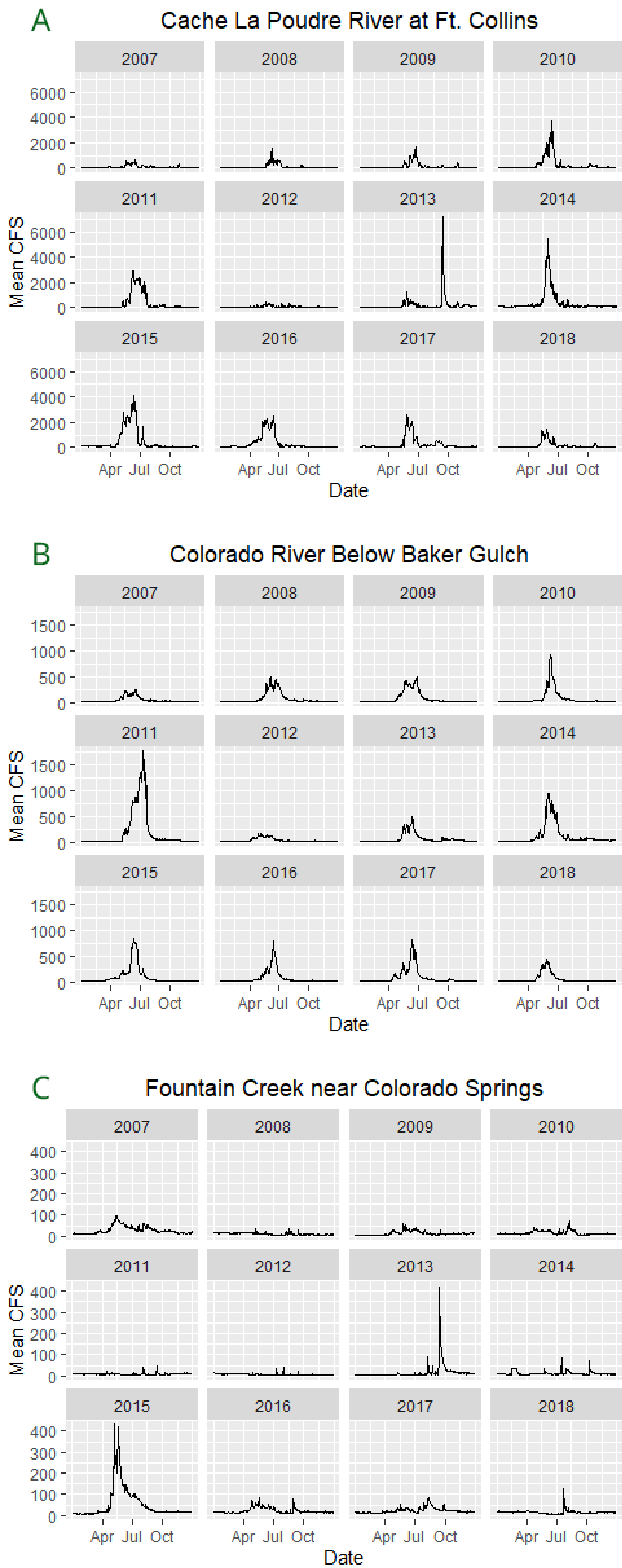

Figure 3—Hydrographs for three Front Range streams. Peak flows in the Cache la Poudre River are typically snowmelt-driven, with exceptions including the late summer rainstorm in 2013, which produced the largest discharge on record. Peak flows are snowmelt-driven in the Colorado River as well, with year-to-year variation in volume and timing of snowmelt runoff. In Fountain Creek, peak flows result from snowmelt runoff (as in 2007 and 2015), summer monsoon rains (2010, 2017, 2018), and the rainstorm of 2013.

Snowpack

Front Range streams with headwaters above 8,000 ft in elevation originate as melting snowpack (Lukas et al. 2014). Snowmelt is also the primary source of recharge for groundwater in upper elevations (Earman and Dettinger 2011; Fields and Dethier 2019). Movement of snow and snowmelt runoff influences sedimentation in streams and valley bottoms (Caine 1995). For these reasons, snowpack is important to a variety of aquatic, riparian, and anthropogenic resources.

Snowpack accumulates during the fall, winter, and spring months, with maximum snow water equivalent typically occurring in the spring (Lukas et al. 2014). Front Range snowmelt volume and runoff timing vary yearly and are influenced by numerous physical and biotic factors. Snow accumulation is influenced by complex interactions among topography, wind, temperature, and precipitation (Rasmussen et al. 2011). Snow accumulates at greater depths in open sites than under canopy (Harpold et al. 2015; Livneh et al. 2015). Winter temperatures determine the amount of energy required to melt snowpacks (Fyfe et al. 2017). Snowmelt rate is also influenced by snowpack depth, elevation, and solar radiation, factors that vary spatially and temporally (Caine 1995; Foster et al. 2016). Accumulation of dust and carbon on snow accelerates the warming and melting of the snowpack (Painter et al. 2018).

Groundwater

The Precambrian crystalline rock aquifers of the Front Range are recharged during large, infrequent precipitation or snowmelt events, with only a small fraction of precipitation and snowmelt becoming groundwater (Dwire et al. 2019). Recharge, storage, and transmission are low relative to sedimentary rocks and alluvial aquifers but remain critical components of the mountain hydrological cycle (Clarey et al. 1999; Williams et al. 2015a). The amount of recharge is dependent on the type of precipitation falling, snowpack depth, snow moisture content, rate of snowmelt, surface characteristics, and transpiration rate (Earman and Dettinger 2011; Fields and Dethier 2019). For the most part, wells drilled into crystalline bedrock can only accommodate domestic use and limited public water supply, whereas wells drilled into sedimentary aquifers can support agricultural, industrial, and municipal use (Topper et al. 2003).

Extreme Rainfall Events

Extreme rainfall events have produced damaging floods in many Front Range streams. Areas affected by extreme rainfall floods are typically below 7,500 feet in elevation. Above this elevation, most floods are caused by snowmelt and are not as destructive (Jarrett and Costa 1988). Extreme rainfall events arise from several atmospheric scenarios. In one, air masses arrive from the south or east and produce convective thunderstorms over mountain ranges. Such events occurred in 1976 and 1997, resulting in the Big Thompson and Fort Collins floods (Jarrett and Costa 2006; Weaver et al. 2000). In another scenario, persistent low-pressure systems keep low-intensity storms in place for several days, resulting in steady, widespread rainfall and flooding. Examples include the Front Range floods of 1938 and 2013 (Lukas et al. 2014).

Drought

It is difficult to define and evaluate droughts because of the complexities associated with measuring the temporal and spatial dynamics of the Colorado climate (Pielke et al. 2005). Factors contributing to droughts on the AR and PSI National Forests include sea surface temperature anomalies; antecedent conditions; above-average temperatures; precipitation-rainfall deficit; deficient atmospheric moisture; and absence of precipitation events such as winter frontal storms, spring low-pressure systems, and summer thunderstorms (Hoerling et al. 2014; Ryan et al. 2013).

Exceptionally dry years occurred in 2002 and 2012, providing lessons for drought effects on water resources. Increased rates of evapotranspiration reduce the amount of water that enters streams and aquifers (Udall and Overpeck 2017). During the 2002 drought, for example, streamflows at the mouth of the Poudre River Canyon were the lowest in recorded history (Salas et al. 2005). During the last 20 years, high temperatures have combined with dry conditions to shift modest droughts to extreme droughts (Udall and Overpeck 2017; Williams et al. 2020). As a result, Colorado has experienced some of its most severe plant die-offs and wildfire seasons in recent memory (Breshears et al. 2005; Pielke et al. 2005; Ryan et al. 2013). Water supplies were exhausted earlier than usual in the driest years, and water quality was affected (Pielke et al. 2005; Saunders and Lewis 2003; Sprague et al. 2005). A reduction in outdoor recreation also occurs during periods with low water levels and high fire danger (Ryan et al. 2013).

Water Quality

Changes in the chemical composition of streamflows have long-term potential to impact ecosystems and water uses on the Colorado Front Range (Caine 1995). Front Range water quality is particularly important to municipal users because 90 percent of Colorado's water supply comes from surface water in forested watersheds (Rhoades et al. 2011). Measures of water quality include stream and lake temperature, water chemistry, nitrification, dissolved oxygen, acidification, suspended sediment, and bacterial content. Several factors, directly and indirectly affected by climate, impact these variables.

Atmospheric warming has a direct influence on stream and lake temperature (Isaak et al. 2015; Roberts et al. 2017b). Higher temperatures contribute to lowered dissolved oxygen concentration of streams, with implications for aquatic communities (Sprague 2005). Heavy rainfall events elevate levels of suspended sediments and deliver various pollutants to streams and lakes (Caine 1995). Wildfire presents numerous challenges to maintaining water quality. Water temperatures immediately increase during fires, and stream temperatures remain high for several years because of increased exposure to solar radiation (Rhoades et al. 2011). Postfire increases in stream temperature add to the percentage of salmonid habitat lost by warming as a result of climate change (Rhoades et al. 2011). Smoke and ash deposits alter water chemistry, but conditions typically return to prefire levels several weeks postfire. Atmospherically deposited nitrogen is mobilized following wildfire and enters streams during runoff events (Riggan et al.

1994). Summer convective storms cause heavy runoff events in postfire watersheds, potentially raising nitrate loads above quality standards for drinking water. Suspended sediments increase during periods of runoff in postfire sites as well (Rhoades et al. 2011; Writer et al. 2012). Postfire sedimentation is thought to increase with the percentage of watershed that is burned with high severity (Mast et al. 2016). Elevated levels of nitrate, sedimentation, and other forms of pollution can persist for several years postfire and are recharged following heavy runoff events (Mast et al. 2016; Rhoades et al. 2011; Writer et al. 2012). These changes exacerbate preexisting water quality concerns in Front Range streams, especially following fires in the lower-elevation montane zones. Wildfire creates problems for municipal water supplies because nitrate levels can impact human health, while suspended sediment increases water treatment costs (Mast et al. 2016).

Additional water quality issues include livestock effects and legacy mining impacts. Most meadows along streams have been grazed by cattle during the last century, introducing pollutants that include nitrate, ammonia, bacteria, and sediment (Gary et al. 1983). High streamflows and lake levels protect ecosystem and human health by diluting these pollutants (Sprague 2005). In watersheds with a history of hard rock mining, abandoned tailings piles and polluted sediments remain in some floodplains. During periods of runoff, heavy metals and other pollutants are leached from these deposits into streams and lakes, with effects that cascade through aquatic and terrestrial ecosystems (Clements et al. 2010; Wohl 2001). Discharge from mine workings can also be a source of dissolved metals pollution, but this discharge is often only noticeable during periods of low flow (Steve Sanchez, PSI National Forests, personal communication).

Water Use Infrastructure

In addition to the naturally occurring streams, lakes, and groundwater systems, the AR and PSI National Forests contain diversions, ditches, pipelines, dams, reservoirs, stock tanks, catchment basins, and other engineered structures. This infrastructure currently influences the distribution, composition, and structure of aquatic, riparian, and wetland communities throughout the Forests (Decker et al. 2015). Reservoirs in the Front Range forests are critical to maintaining availability of water that is allocated for downstream uses (box 3). Reservoirs store water originating within their watersheds, as well as water delivered via transbasin diversions. Ditches and pipelines transport water to points of use both inside and outside of the Forests.

Box 3

Front Range Water Rights

Use of water on the AR and PSI National Forests and of water leaving the forests is governed by Colorado water laws, interstate compacts, and international treaties. Per the Colorado River Compact, water originating in the upper Colorado Basin can only be used within the basin after delivery quotas to the lower Colorado Basin are met (Udall and Overpeck 2017). This obligation also includes the amount of water allocated for use in Mexico.

The Forests own numerous water rights, which allow the storage of water, diversion of surface flows, or pumping of groundwater for beneficial use by the AR and PSI National Forests or leaseholders on the forests. Municipal and private interests own water rights on the Forests as well, allowing them to divert or store water from the forests for beneficial use. In the State of Colorado, water rights can be used to maintain instream flows for aquatic and riparian ecosystems, but such rights can only be held by the Colorado Water Conservation Board (Jones and Cech 2009). Decreed instream flow reaches are found throughout the Front Range national forests (fig. 4).

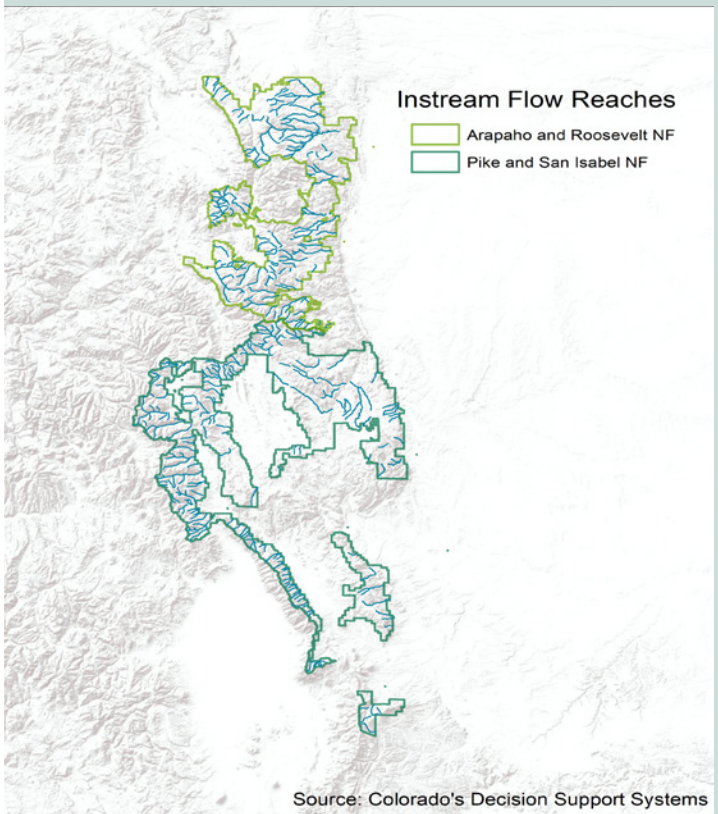

Figure 4—Location of stream segments with decreed instream flow protections in the Front Range National Forests.

Under Colorado's system of prior appropriation, water rights are adjudicated based on the date that water was first put to beneficial use. As a result, many Front Range water rights predate the establishment of the national forests (Hobbs 1997; Jones and Cech 2009). Junior water rights holders, including the AR and PSI National Forests, cannot divert water from a stream unless water will be available for decreed uses of downstream senior rights holders. Given the overallocation of streams in most watersheds, many junior water rights remain out of priority except during years with above-average surface flows. During periods of water scarcity, a call on water rights from downstream users will curtail the use of junior water rights on the national forests.

Vulnerability of Water Resources

In the Colorado Front Range, water creates resources that are valued for their ecological importance and for the services they provide to those that live near the forest, work in the forest, and visit the forests. In this section, I assess the vulnerability of cutthroat trout habitat; riparian areas, wetlands, and groundwater-dependent ecosystems; and anthropogenic water uses. I selected these key resources because (1) they are high management priorities for the AR and PSI National Forests and (2) they encompass many of the aquatic, riparian, and wetland ecosystems on the forests, along with numerous societal uses. Below are descriptions of each resource.

Cutthroat Trout Habitat

The AR and PSI National Forests contain aquatic habitats occupied by two known subspecies of native cutthroat trout (box 2). To prevent the extinction of these subspecies, managers must maintain water quality, habitat heterogeneity, and protection from nonnative fishes (fig. 4). Native cutthroat trout were once found in perennial streams throughout the Arkansas, South Platte, and Colorado Basins. Today, most of this habitat is occupied by nonnative salmonids (fig. 5; Wohl 2001). Front Range populations of cutthroat trout are now mostly limited to stream segments and lakes above 8,000 feet in elevation (Young 2009) According to data obtained from the inland cutthroat trout database in 2019, cutthroat trout populations are managed in nine of the 14 HUC8 watersheds that overlap the AR and PSI National Forests (table 4). The Colorado River Headwaters has the largest number, with 83 populations. The greatest numbers on the eastern slope are found in the Big Thompson, Upper Arkansas River, Cache La Poudre, and St. Vrain watersheds, with the remaining watersheds having fewer than 10 populations.

Water quality is a key aspect of cutthroat trout habitat. Maximum stream temperatures (hottest 7-day average) of less than 26 °C are required for survival. Mean monthly summer water temperatures between 9 °C and 18.0 °C provide ideal conditions for growth and recruitment but recruitment can occur at temperatures as low as 8.0 °C (Harig and Fausch 2002; Roberts et al. 2013). Declining growth occurs between 18.1 °C and 19.9 °C. Low to no growth occurs at temperatures 20 °C or greater. Suspended sediment reduces the amount of dissolved oxygen reaching eggs (Wohl 2001). Pollutants such as acids and heavy metals threaten the health of trout and aquatic food webs (Naeser and Smith 1995; Wohl 2001; Woodward et al. 1991).

Figure 5—Cutthroat trout were historically present across elevations in the Front Range National Forests, but, because of nonnative trout and other stressors, occupied streams are limited to high elevation stream reaches such as the one above. USDA Forest Service photo by Max Smith.

Instream features and riparian vegetation are important habitat components as well. Deep pools are needed for predation refugia and overwinter survival (Harig and Fausch 2002). Gravel beds provide incubation sites for eggs; logs and boulders provide protective cover for young (Wohl 2001). Annual high flows and periodic floods are necessary to create a substrate for spawning, induce spawning behavior, and scour pools used for overwintering habitat (Rathburn et al. 2009). Willows (*Salix* spp.), sedges (*Carex* spp.), and other native riparian plants stabilize soils to create overhanging banks, which are used for cover and thermal protection (Horan et al. 2000; Winward 2000). Willows, alders (*Alnus* spp.), cottonwoods (*Populus* spp.), and other woody plants provide shade that helps to maintain cool summer stream temperatures (Beschta 1997).

Table 4—Water resources mapped in 8-digit Hydrologic Unit Code (HUC8) watersheds.

Basin	HUC8 watershed	Cutthroat trout reaches	Perennial stream miles	Intermittent stream miles	Acres mapped wetlands (% of watershed)	Acres mapped fens	Mapped springs	Forest Service fishing and boating sites	Active ditches and pipelines	Active reservoirs	Active wells
North Platte	Upper Laramie	0	1,387	3,730	13,321 (5%)*	382*	10*	0*	73*	9*	8*
South Platte	Cache La Poudre	14	1,258	2,866	40,311 (4%)*	197*	81*	20*	377*	367*	2,240*
	Big Thompson	27	655	1,086	18,549 (3%)	0	44	2	217	251	699
	St Vrain	12	815	842	23,819 (4%)	7	36	7	564	535	1,894
	Clear	6	574	465	7,393 (2%)	549	50	0	184	171	1,209
	South Platte Headwaters	2	876	2,776	60,336 (6%)	3,430	62	3	191	209	1,936
	Upper South Platte	0	1,350	3,875	30,326 (3%)	646	66	1	581	470	4,783
Upper Colorado	Colorado Headwaters	83	2,751	3,506	82,694 (4%)	2,404	9	10	1,310	571	990
Arkansas	Fountain	0	502	1,987	9,454 (2%)	0	65	3	136	162	1,662
	Arkansas Headwaters	25	2,019	5,820	76,644(4%)	2,334	287	20	1,104	465	1,212
	Upper Arkansas	5	869	5,367	24,995 (2%)	0	113	3	335	234	1,728
	Huerfano	3	665	4,134	32,242 (3%)	0	164	2	368	198	802
	Apishapa	0	140	2,070	4,087 (1%)	0	81	0	38	22	517
	Purgatoire	0	790	6144	21,202 (1%)	0	276	0	221	133	3,026

*These data only apply to the portions of these watershed within the State of Colorado. See figures 10–13.

In addition to streams, mountain lakes provide important habitat for cutthroat trout and other native fishes (Young 2009). Though surface temperatures of lakes have increased as a result of atmospheric warming (Roberts et al. 2017b), lake-stream networks may increase watershed resistance to climate impacts because lakes and reservoirs have greater thermal stability than some streams and are less sensitive to disturbances such as fire, floods, debris flows, and ice (Roberts and Fausch 2015; Young 2009).

Cutthroat trout also require protection from nonnative salmonids, which threaten populations through hybridization, predation, displacement, and competition (McGrath and Lewis 2007; Young 2009). As a result of downstream habitat loss, Colorado River cutthroat trout are now limited to stream segments above 5,000 feet in elevation and greenback cutthroat trout are limited to segments above 8,000 feet (Roberts et al. 2013; Young 2009). At these elevations, stream temperatures act as a thermal barrier to rainbow trout and brown trout, which are less tolerant of cold stream temperatures. Brook trout, however, are tolerant of cold temperatures at higher elevations and must be excluded from cutthroat trout reaches via physical barriers (Roberts et al. 2017a).

Protection of stream reaches currently occupied by cutthroat trout is necessary to preserve the genetic diversity of greenback and Colorado River cutthroat trout populations (Bestgen et al. 2019a). Protecting potentially suitable stream reaches and expanding the range of greenback cutthroat trout is necessary to reduce extinction risk (Young and Harig 2001). Sportfishing for trout is a culturally and economically important form of recreation in the Colorado Rockies (Naeser and Smith 1995). Brook trout are found in many of the upper tributaries of Front Range streams, whereas rainbow trout and brown trout occupy streams in the lower portions of watersheds (Wohl 2001). Because there are many overlapping habitat requirements, actions that improve or harm habitat for native cutthroat trout will have similar impacts on nonnative, yet popular sport fisheries (Richer et al. 2019).

Riparian Areas, Wetlands, and Groundwater-Dependent Ecosystems

In the AR and PSI National Forests, valley bottom characteristics influence the structure and composition of many riparian and wetland ecosystems. Low-gradient streams meander through unconfined valley bottoms, creating extensive riparian and wetland habitats on floodplains and terraces (fig. 6) (Friedman et al. 1995). Low-gradient valley bottoms have been carved and filled by glaciers, incised by streams, and filled by beaver (*Castor canadensis*) pond sedimentation (Kramer et al. 2012). High-gradient streams in bedrock canyons typically have limited development of riparian vegetation (fig. 7) (O'Neil et al. 1997). Along partially confined streams, riparian ecosystems have characteristics of both unconfined valley bottoms and bedrock-restricted canyons. These settings contain a range of vegetation types that differ from one another in structure and composition. Depending on the setting, riparian ecosystems are dominated by coniferous trees, deciduous trees, willows, or herbaceous vegetation (Baker 1989).

Figure 6—Low-gradient riparian ecosystems contain riparian vegetation types dominated by deciduous trees, willows, and herbaceous plants. (USDA Forest Service photo by Max Smith.)

Figure 7—Riparian vegetation is limited in extent in the Big Thompson Canyon and other confined reaches. (USDA Forest Service photo by Max Smith.)

Within valley bottom types, the composition, structure, and arrangement of riparian communities are determined by the frequency and magnitude of floods, base flow levels, groundwater levels, groundwater discharge, and beaver activity (Polvi and Wohl 2011). Maintenance of diverse riparian vegetation types requires periodic floods of varying magnitudes along Front Range streams (Rathburn et al. 2009). Anthropogenic features such as dams, transbasin augmentation, diversion withdrawals, livestock, and roads influence riparian vegetation as well (Friedman et al. 1995; O'Neil et al. 1997; Rathburn et al. 2009).

Wetland types include wet meadows, emergent marshes, fens, and springs (Decker et al. 2015). Springs support components of aquatic and wetland ecosystems (Kreamer et al. 2015). Fens, which are unique, groundwater-dependent wetlands (fig. 8; box 2), tend to be dominated by sedges and other herbaceous plants, but shrubs and small trees may be present as well (Decker et al. 2015). Rare plants, including the threatened Penland's eutrema (*Eutrema penlandii*) and sensitive species such as livid sedge (*Carex livida*), Altai cottongrass (*Eriophorum altaicum*), and blueberry willow (*Salix myrtillifolia*) are found only in fens (ARP 1997; Wrigley et al. 2012). Environmental conditions, such as groundwater chemistry, drive plant composition, resulting in variable and rare communities among Front Range fens (Johnson and Steingraeber 2003).

Figure 8—The wetland vegetation in this montane fen is dominated by sedges, with buckbean (*Menyanthes trifolia*) and other forbs present as well. (USDA Forest Service photo by Max Smith.)

Riparian and wetland ecosystems provide a range of services, including sediment storage, carbon storage, and water quality maintenance (Beckman and Wohl 2014; Wohl et al. 2012). Some of the most ecologically important riparian ecosystems are dominated by cottonwood trees and willow shrubs (Hansen et al. 2002; Hansen 2009; Smith and Finch 2014). Riparian ecosystems are critical for habitat requirements of many wildlife species and serve as migration corridors and rare species habitat (Polvi et al. 2011). For example, the federally threatened Preble's meadow jumping mouse (*Zapus hudonius preblei*) is found in foothills riparian ecosystems that are heavily vegetated and near open, flowing water (Smith et al. 2004). Occupied sites are composed of dense herbaceous vegetation, such as grasses and sedges. Sites often contain an overstory of willows or other woody plants (Smith et al. 2004). These habitats are created by the expansion and contraction of beaver ponds (Frey and Malaney 2009). Amphibians, including tiger salamander (*Ambystoma mavortium*), boreal toad (*Anaxyrus boreas boreas*), northern leopard frog (*Rana pipiens*), and plains leopard frog (*Rana blairi*), use riparian areas, wetlands, and adjacent water bodies for foraging and reproduction (ARP 1997; Decker et al. 2015; Wrigley et al. 2012). Streamside riparian vegetation is also an important habitat component for cutthroat trout because it provides bank stability, stream shading, and instream wood (Dunaway et al. 1994; Hough-Snee et al. 2013; Wondzell et al. 2019).

Springs are found in a variety of settings, often at the contacts of permeable and nonpermeable bedrock layers (Kreamer and Springer 2008). Springs are mapped by the National Hydrography Dataset and the Spring Stewardship Institute (fig. 9). These datasets contain similar numbers of springs for the AR and PSI, but likely underestimate the actual abundance. Mapped springs are most abundant in the Upper Arkansas and Puragtoire watersheds (table 4). Fens have been delineated in some sections of the Front Range national forests, but a systematic mapping project has not been completed (Gabrielle Smith, Colorado Natural Heritage Program, personal communication). The area of wetlands, including fens, has been measured in the Upper Arkansas Basin, where 4,000 acres of seasonally flooded wetlands were classified as fens (Lemly et al. 2016). Large acreages of fens have also been mapped in the Colorado Headwaters and South Platte Headwaters (table 4). Fens are typically found above 7,000 ft, having formed where groundwater discharge supports perennially saturated soils (Decker et al. 2015).

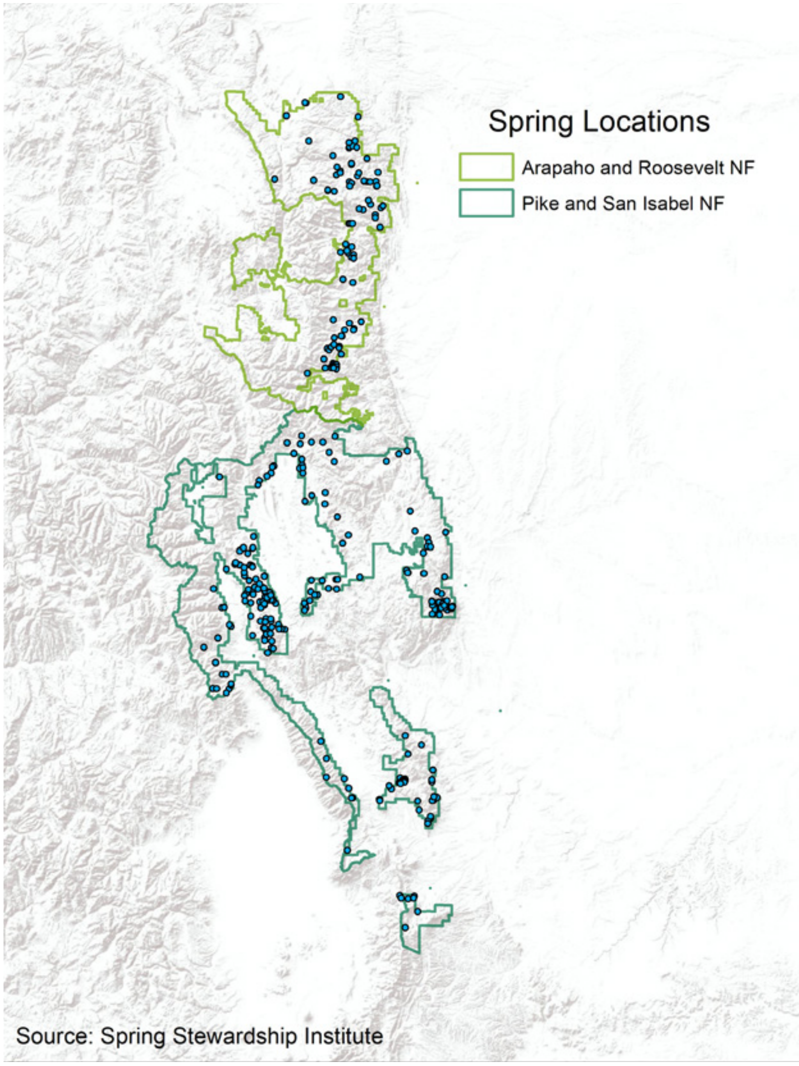

Figure 9—Location of springs mapped in the Front Range National Forests.

Anthropogenic Water Uses

There are numerous uses of surface and groundwater in the AR and PSI National Forests, both consumptive, and nonconsumptive, such as for recreation (figs. 10–15). Relatively small amounts of water are obtained from streams, springs, and wells for on-forest uses at administrative facilities, campgrounds, and grazing allotments (Jones and Cech 2009). Whitewater rafting and kayaking, both commercial and noncommercial, are economically important activities (Loomis and McTernan 2014; Naesser and Smith 1995). The Arkansas River, portions of which pass through the PSI National Forests, contains the most heavily used whitewater in the country. Upper portions of the Cache La Poudre River are designated as wild and scenic. On rivers, including the Arkansas and Cache La Poudre, fishing is popular prior to and after peak flows, whereas whitewater rafting is popular during the peak flow season (Daubert and Young 1981; Naesser and Smith 1995).

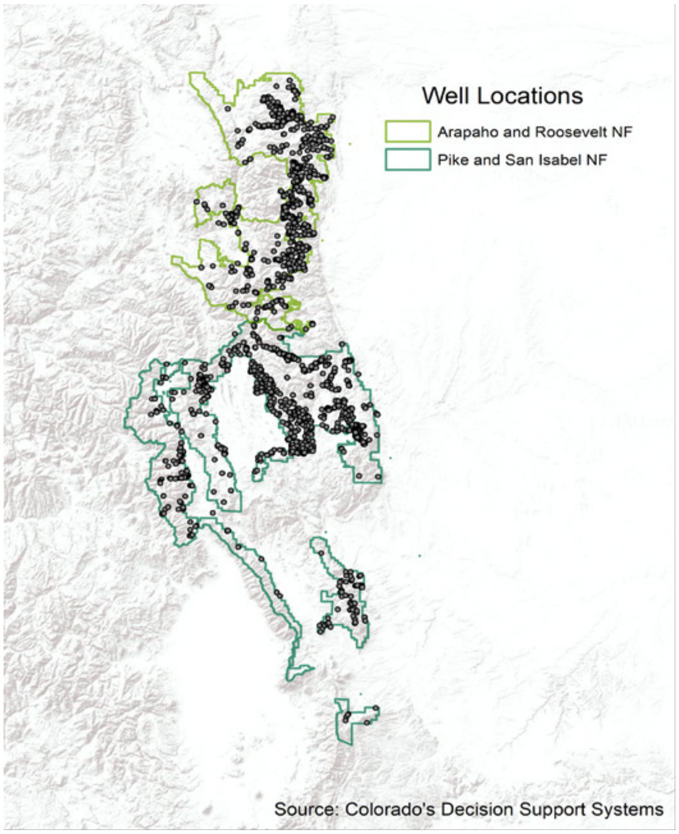

Figure 10—Location of active wells in the Front Range National Forests.

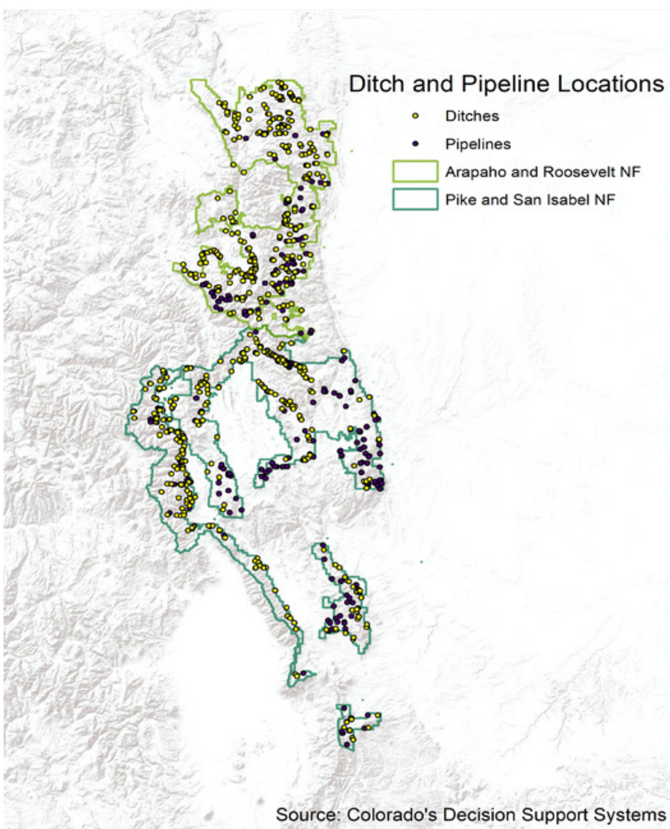

Figure 11—Location of active ditches and pipelines in the Front Range National Forests.

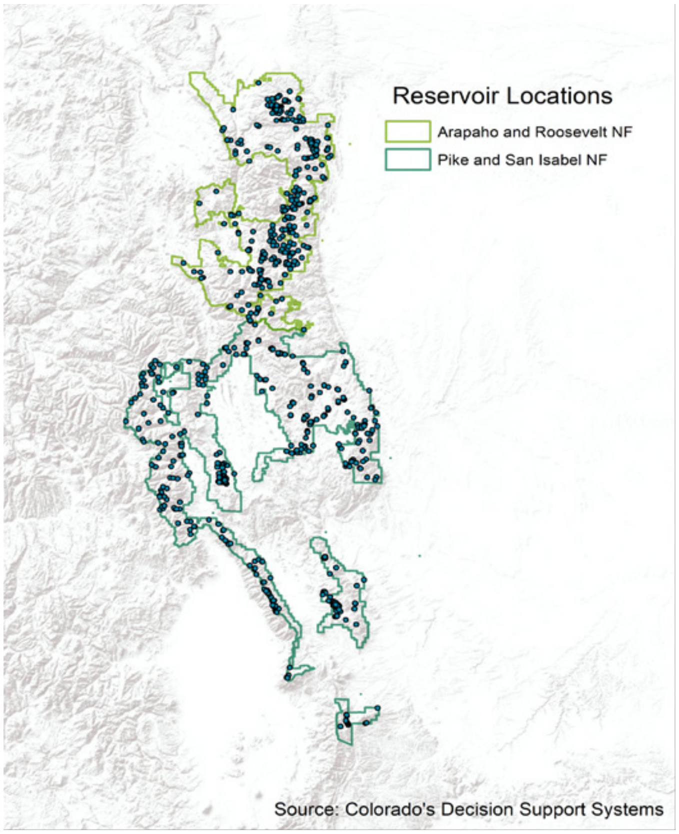

Figure 12—Location of reservoirs in the Front Range National Forests.

Figure 13—Corn and other crops are irrigated with water diverted from the South Platte River, whose water originates in the Front Range National Forests and is augmented by transbasin diversions. (USDA Forest Service photo by Max Smith.)

Figure 14—Water is diverted from the Cache La Poudre River for use by a growing municipal population. (USDA Forest Service photo by Max Smith.)

Figure 15—Twin Lakes, in the Arkansas Basin, is managed for many uses, including water storage, power generation, and a recreational fishery. (USDA Forest Service photo by Max Smith.)

Water originating in or passing through the AR and PSI National Forests is diverted for a variety of uses beyond the Forests' boundaries in Colorado and other States. The State of Colorado provides water to 18 downstream States in both the Colorado and Mississippi River drainages and is a party to nine interstate water compacts (Loomis 1997). Provision of clean water for downstream uses is one of the primary management goals of the AR and PSI National Forests (ARP 1997). Ditch and pipeline diversions are most abundant in the Arkansas headwaters, Cache La Poudre, Colorado headwaters, St. Vrain, and Upper South Platte watersheds. Active wells are widespread but are most abundant in the Cache La Poudre, Upper South Platte, and Purgatoire watersheds (table 4).

Agriculture has long been the primary use of water in the South Platte and Arkansas Basins (fig. 13; Abbott 1985; Watson and Davies 2011). Agricultural uses of water diverted from the Arkansas River include a variety of irrigated crops (CWCB 2019). The South Platte Basin, which includes irrigated crops and livestock production, is the highest-producing agricultural region in the state (CWCB 2019; Watson and Davies 2011). In the Colorado Basin, livestock production dominates agriculture in the upper reaches, with irrigated crops more prevalent near the western state line. As cities expand and the population grows, agriculture to urban water transfer is expected to increasingly occur, especially in the South Platte Basin (CWCB 2019; Howe and Geomans 2003).

The municipal and industrial sectors are second to agriculture as the primary users of water from the AR and PSI National Forests (CWCB 2019). The South Platte Basin is the most populous and rapidly growing basin in the State (Watson and Davies 2011). The population is projected to grow by 42 to 70 percent by 2050. This growth is dependent on water originating in or being transported through the Forests (fig. 14). Population growth is projected for the Arkansas Basin as well, by 45 to 61 percent by 2050 (CWCB 2019). The Upper Colorado Basin includes only 6 percent of the statewide population but is expected to grow by 48 to 88 percent by 2050. Water from several tributaries to the Colorado River is delivered to Front Range communities via transbasin diversions. Colorado water law allows for transbasin water to be fully consumed, thereby providing fewer ecological benefits than uses of native flows, which require the return of excess water to streams or aquifers (Jones and Cech 2009). Water from native flows and transbasin diversions is stored in a series of reservoirs in each basin (figs. 12 and 15). Primary sources of drinking water for Front Range cities include the South Platte River, the Roberts Tunnel transbasin diversion, the Colorado-Big Thompson Project transbasin diversion, the Homestake Project transbasin diversion, the Frying Pan–Arkansas Project transbasin diversion, the Pike's Peak watershed, and the Cache La Poudre River (Folk-Williams et al. 1985; Mast et al. 2016).

Climate Change Vulnerability

Exposure

I evaluated the projected climate change effects on water resources using the four climate change scenarios selected for this assessment. I conducted spatial analyses with Bureau of Reclamation's BCSD CMIP5 Climate and Hydrology Projection dataset. Using rasters covering the Front Range region, I evaluated magnitude of climatic changes among watersheds. I calculated spatial means for these variables, but it is important to note that I did not capture the small-scale variability within the watersheds caused by topographic and elevational differences. A finer-scale approach will be necessary to evaluate exposure for individual streams and sub-watersheds.

Results for each climate scenario are presented in table 5 and figures 16 to 20. Using these data, which were accessed in 2020, I evaluated exposure (magnitude and nature of hydrological change) of the study area. I used three exposure classes: 1 = positive or minimal negative effects; 2 = moderately negative effects or limited negative effects; and 3 = widespread, negative effects from multiple (>3) sources of climate exposure.

Table 5—Sources of water resource exposure under four climate change scenarios for the Colorado Front Range.

	Climate Scenario			
Exposure Source	**Very Hot and Wet**	**Hot**	**Warm and Wet**	**Very Hot and Dry**
Increases in maximum summer air temperature 2° C or greater are projected in all watersheds.	X	X	—	X
Spring snow water equivalent is projected to decrease in all watersheds.	X	X	X	X
Increases in spring runoff are projected in most watersheds.	X	X	X	—
Decreases in summer flows are projected in most watersheds.	X	X	X	X
Increases in annual runoff are projected in most watersheds.	X	—	—	—
Decreases in annual runoff are projected in most watersheds.	—	—	—	X
Increases in fire danger, drought severity, and/or extreme rainfall events are projected in the Front Range (Cook et al. 2022; Coop et al. 2022; Lukas et al. 2014; Mahoney et al. 2013).	X	X	X	X
Sum	6	5	4	5
Final Exposure Score	3	3	2	3

— indicates no data.

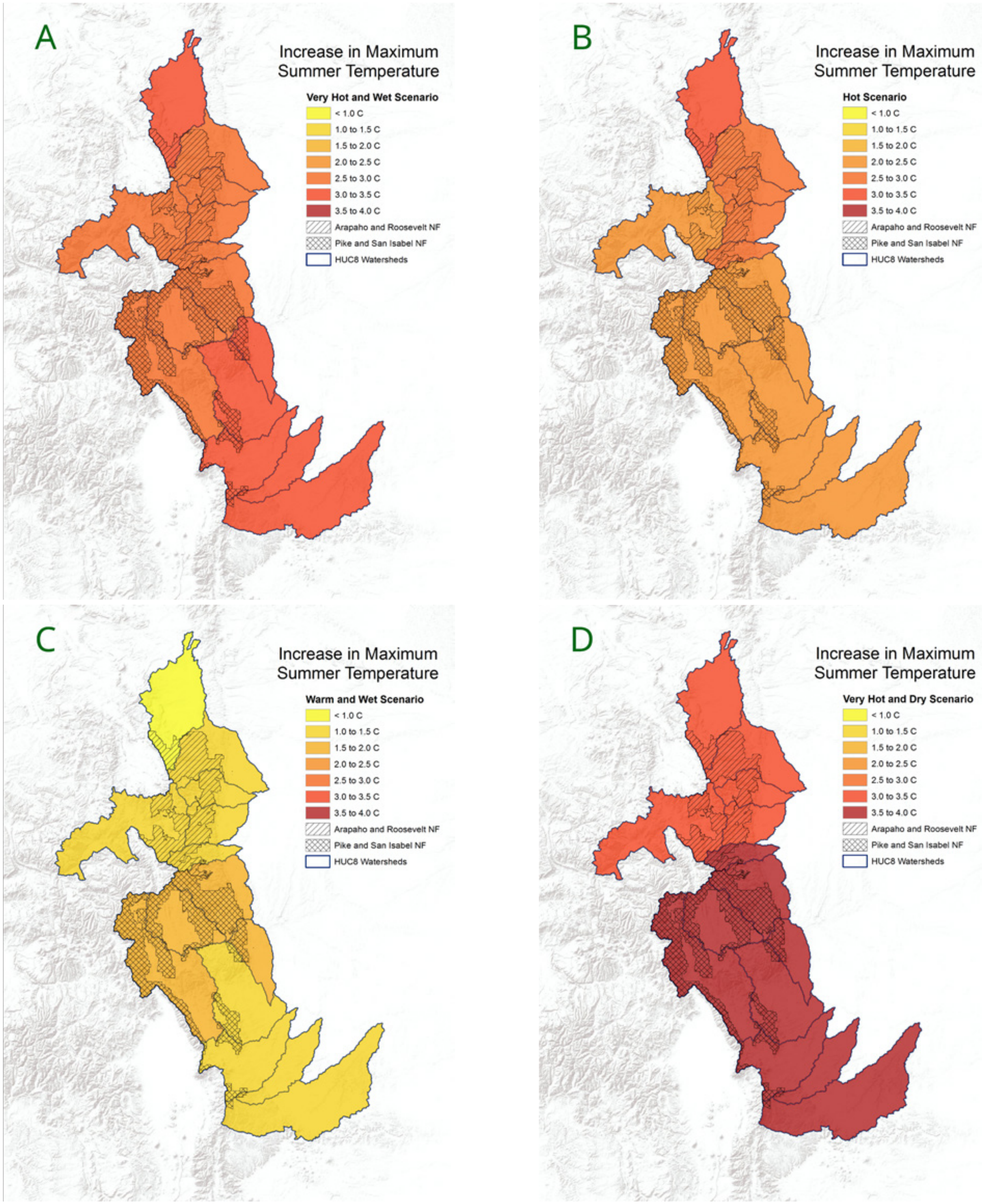

Figure 16a-d—Projected changes in maximum summer air temperatures under four climate scenarios. Values for watersheds depict change in conditions from 1985–2015 (historical) to 2035–2065 (future climate). Data were obtained from the Reclamation BCSD CMIP5 Climate and Hydrology Projection Project.

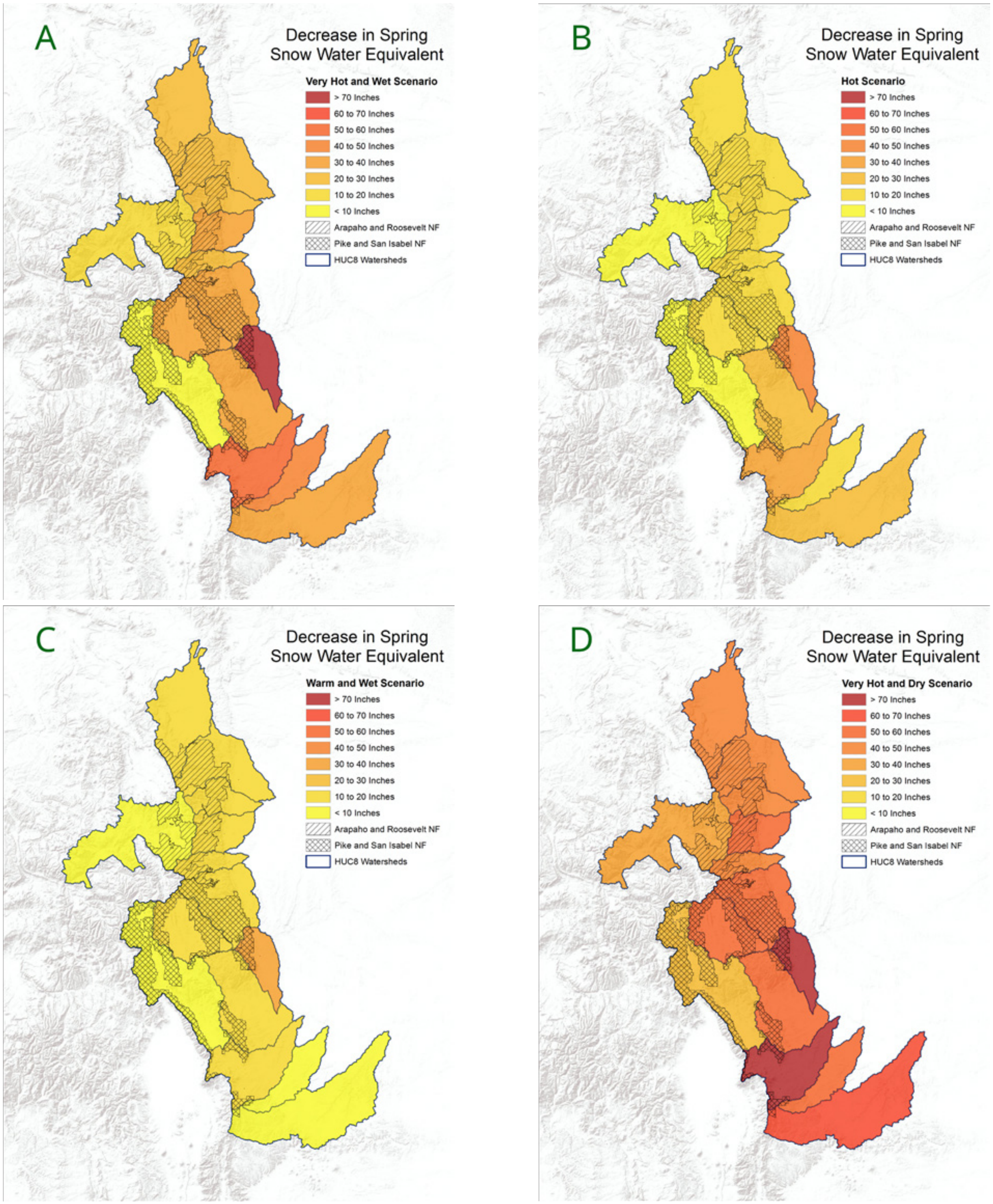

Figure 17a-d—Projected changes in spring snow water equivalent under four climate scenarios. Values for watersheds depict change in conditions from 1985–2015 (historical) to 2035–2065 (future climate). Data were obtained from the Reclamation BCSD CMIP5 Climate and Hydrology Projection Project.

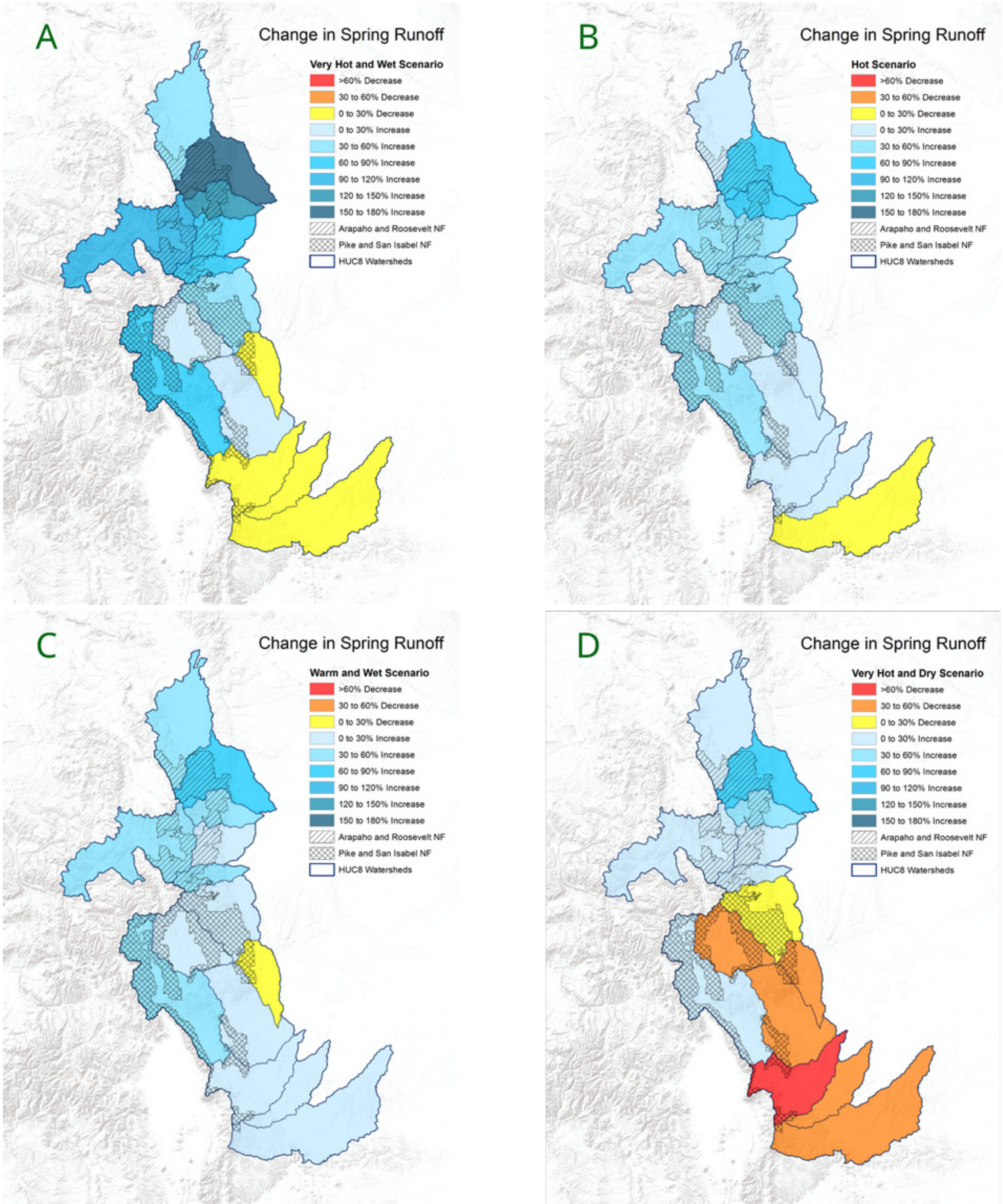

Figure 18a-d—Projected changes in spring runoff under four climate scenarios. Values for watersheds depict change in conditions from 1985–2015 (historical) to 2035–2065 (future climate). Data were obtained from the Reclamation BCSD CMIP5 Climate and Hydrology Projection Project.

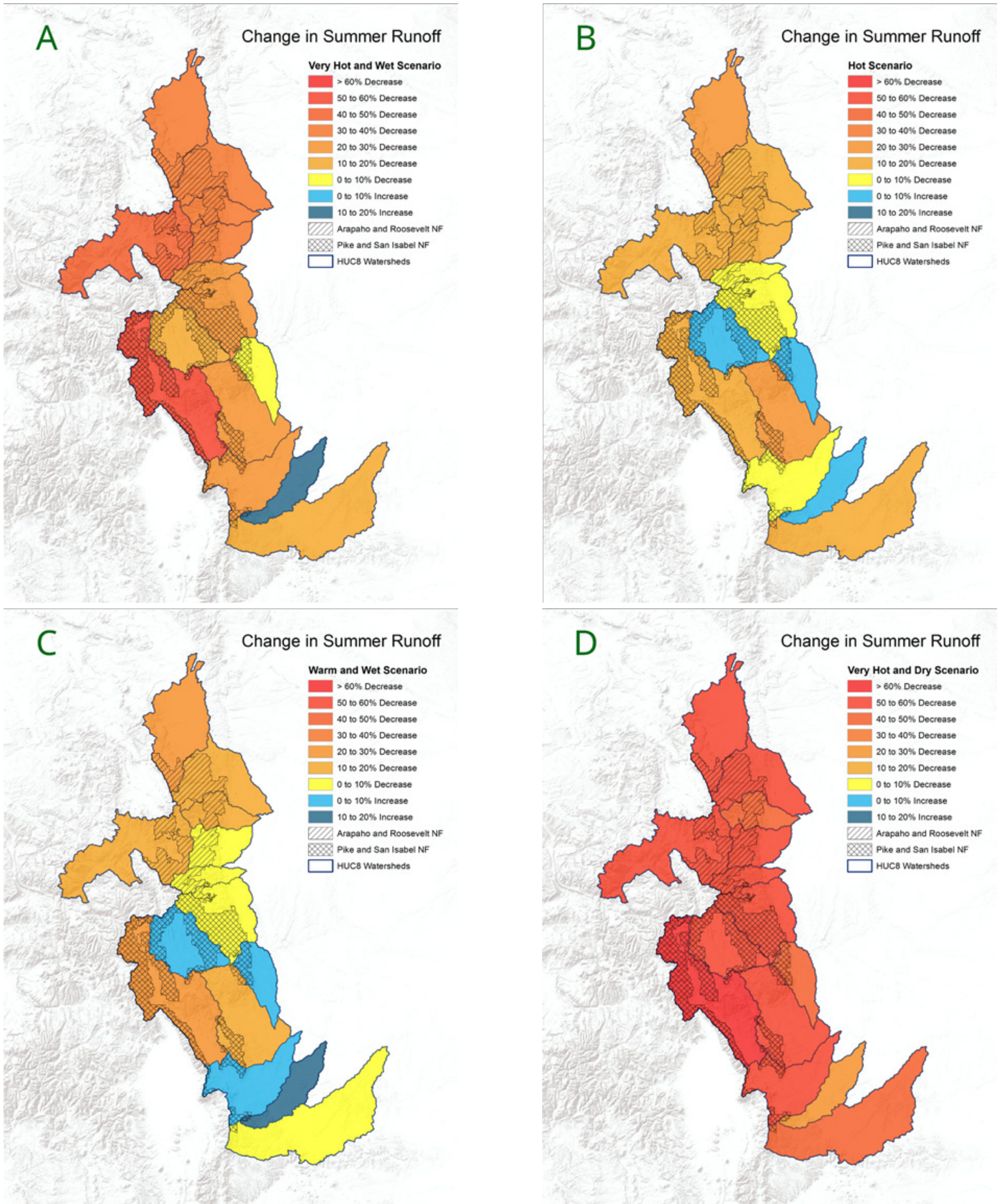

Figure 19a-d—Projected changes in summer runoff under four climate scenarios. Values for watersheds depict change in conditions from 1985–2015 (historical) to 2035–2065 (future climate). Data were obtained from the Reclamation BCSD CMIP5 Climate and Hydrology Projection Project.

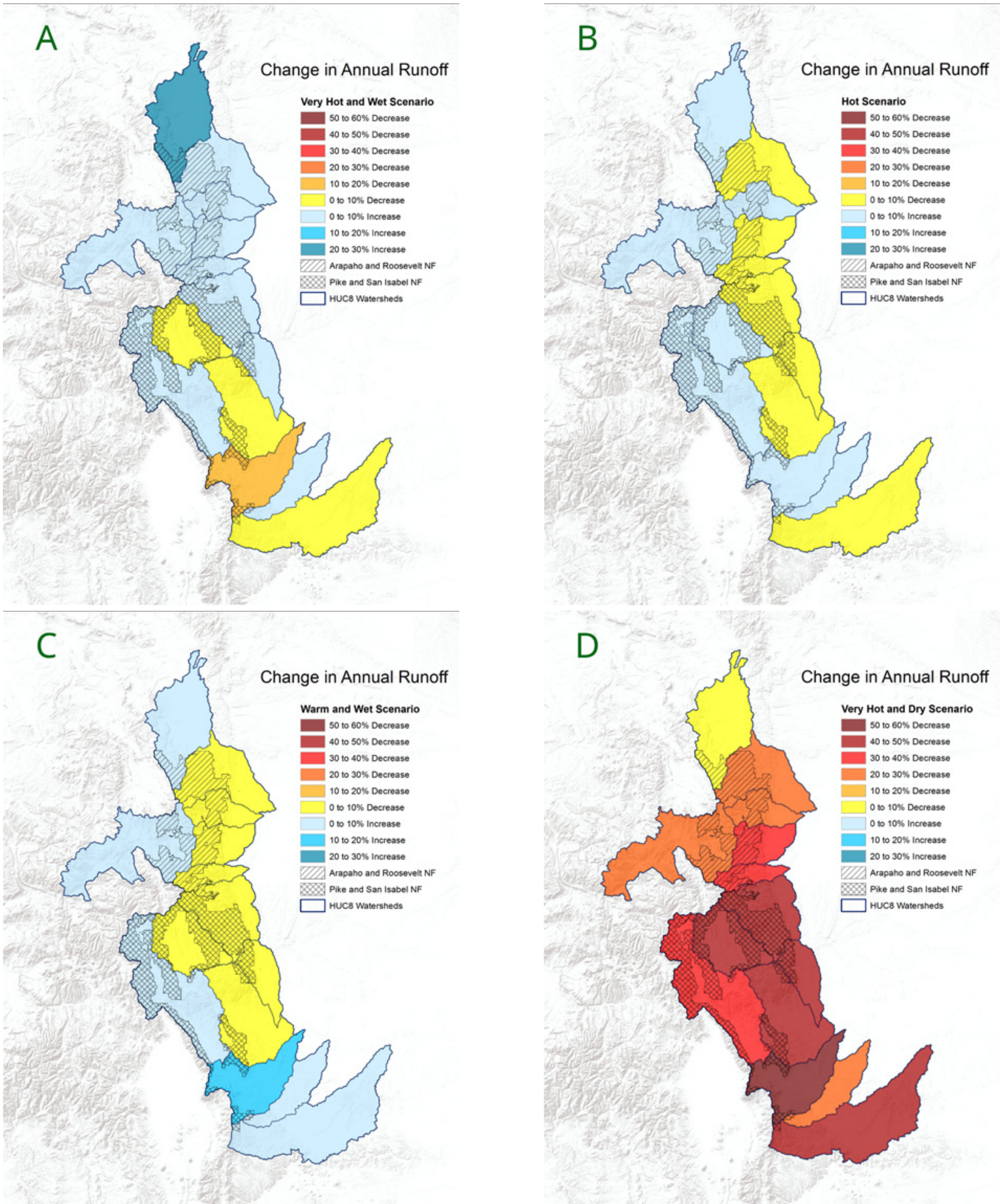

Figure 20a-d—Projected changes in annual runoff under four climate scenarios. Values for watersheds depict change in conditions from 1985–2015 (historical) to 2035–2065 (future climate). Data were obtained from the Reclamation BCSD CMIP5 Climate and Hydrology Projection Project.

On the AR, watersheds with the highest levels of exposure in the South Platte Basin are the Cache La Poudre (based on multiple models projecting increases in spring runoff), Big Thompson (based on multiple models projecting increases in spring runoff), and South Platte headwaters (based on multiple models projecting increases in summer runoff).

Two watersheds are partially within the AR. The Upper Laramie watershed has high levels of exposure based on multiple models projecting increases in maximum summer temperature, decreases in summer runoff, and increases in annual runoff. The Colorado headwaters watershed has high exposure based on multiple models projecting decreases in annual runoff (figs. 16 to 20).

On the PSI, the Arkansas Basin watersheds with the highest levels of exposure are the Fountain (based on multiple models projecting increases in maximum summer temperature, decreases in spring snow water equivalent, and decreases in annual runoff), Arkansas headwaters (based on multiple models projecting decreases in summer runoff), Upper Arkansas (based on multiple models projecting increases in maximum summer temperature and decreases in summer runoff), Huerfano (based on multiple models projecting increases in maximum summer temperature and increases in annual runoff), Apishapa (based on multiple models projecting increases in maximum summer temperature and increases in summer runoff), and Purgatoire (based on multiple models projecting increases in summer temperature and decreases in annual runoff).

Sensitivity

I used spatial data analysis, literature review, and comments from the November 2019 adaptation workshop to identify potential ways that species, ecosystems, and society will be affected under climate change scenarios. I ranked sensitivity as 1 = no or few negative responses; 2 = several negative responses; and 3 = numerous (>6) negative responses. Tables 6–8 show the results of the three resources under each scenario. Sensitivity of streams to climate change is relatively high in the Upper Laramie, Fountain, and Upper Arkansas watersheds (figs. 21 to 24). In the Upper Laramie watershed, projected decreases in summer stream volume and earlier center of flow mass timing are high. In the Fountain and Upper Arkansas watersheds, decreases in coldwater habitat and annual stream volume are relatively high.

Table 6—Sensitivity of cutthroat trout habitat to exposure under four climate change scenarios for the Colorado Front Range. For each row, an "X" indicates that there is potential for a negative response under a given scenario. A "+" indicates that there is potential for a positive response.

Sensitivity Source	Climate Scenario: Very Hot and Wet	Hot	Warm and Wet	Very Hot and Dry
Water temperatures increase, reducing the total miles of cold-water habitat in each watershed (fig. 22) (Decker et al. 2015; Isaak et al. 2015).	X	X	—	X
Water temperatures increase in lakes (Decker et al. 2015; Roberts et al. 2017a)	X	X	—	X
Increase in air temperatures results in decreases in summer streamflows in each watershed (fig. 23) (Decker et al. 2015; Lukas et al. 2014; Woodbury et al. 2012)	X	X	—	X
Springtime increases in streamflow volume benefit the growth and survival of young (2019 Workshop)	+	+	+	—
Barriers to migration and dispersal prevent natural adaptation (Decker et al. 2015; Young 2009).	X	X	X	X
Increasingly small, fragmented trout populations are at greater risk of stochastic disturbance events (Rieman and Isaak 2010; Rice et al. 2018; Roberts et al. 2013).	X	X	X	X
Native trout populations become more vulnerable to non-native species, livestock grazing, and pollution (Rice et al. 2018; Roberts et al. 2017b).	X	X	X	X
Water quality is affected by sedimentation, nutrient loading, increased runoff, and post-fire erosion (Decker et al. 2015; Rieman and Isaak 2010).	X	X	X	X
Groundwater recharge decreases at high elevations, which impacts instream flows (Earman and Dettinger 2011; Fields and Dethier 2019; Rice et al. 2018).	X	X	X	X
Sum Negative Responses	8	8	5	8
Sum Positive Responses	1	1	1	0
Final Sensitivity Score	3	3	2	3

Table 7—Sensitivity of riparian areas, wetlands, and groundwater-dependent ecosystems to exposure under four climate change scenarios for the Colorado Front Range. For each row, an "X" indicates that there is potential for a negative response under a given scenario. A "+" indicates that there is potential for a positive response.

Sensitivity Source	Climate Scenario			
	Very Hot and Wet	Hot	Warm and Wet	Very Hot and Dry
Changes in snowpack and precipitation result in larger, earlier peaks in runoff and decreased summer flows (figs. 23 and 24) (Decker et al. 2015; Ficklin et al. 2013; Rasmussen et al. 2014; Woodbury et al. 2012).	X	X	X	X
Decrease in snowpack and late-season flows causes stream intermittency or year-round drying (Decker et al. 2015).	—	—	—	X
Increasing temperatures lead to evaporative losses, increased atmospheric demand, and plant stress and mortality (Breshears et al. 2005).	X	X	—	X
Conifer encroachment is encouraged by a reduction in groundwater and soil moisture availability (Dwire et al. 2018).	X	X	—	X
Increases in wildfire and beetle kill occurrence results in long-term loss of floodplain carbon storage (Beckman and Wohl 2014).	X	X	—	X
Rates of erosion and sedimentation increase following loss of stabilizing vegetation and increasing severity of droughts, floods, and wildfires (Luce 2018).	X	X	X	X
Riparian and wetland ecosystems are at greater risk from non-native species, livestock grazing, and drainage via ditching (Rice et al. 2018).	X	X	X	X
Lower elevation systems are exposed to greater drought, flood, or fire disturbance, which degrades Preble's meadow jumping mouse habitat (2019 Workshop).	X	X	X	X
High spring flows or heavy precipitation events can sustain natural channel processes if stream channels are healthy, improving working relationships with engineering staff, while allowing riparian and aquatic animals to move among habitats (2019 workshop).	+	+	+	—
Decreases in groundwater recharge at high elevations impact downslope riparian communities (Luce 2018).	X	X	X	X
Peat soils and springbrook communities are affected by decreases in groundwater recharge (Dwire et al. 2018).	X	X	X	X
Sum Negative Responses	9	9	6	10
Sum Positive Responses	1	1	1	0
Final Sensitivity Score	3	3	2	3

Table 8—Sensitivity of anthropogenic water uses to exposure under four climate change scenarios for the Colorado Front Range. For each row, an "X" indicates that there is potential for a negative response under a given scenario. A "+" indicates that there is potential for a positive response.

	Climate Scenario			
Sensitivity Source	**Very Hot and Wet**	**Hot**	**Warm and Wet**	**Very Hot and Dry**
Reduction in stream flows reduces water available for junior water rights holders (fig. 24) (CWCB 2019).	X	X	X	X
Groundwater recharge decreases at high elevations, reducing water available from springs, streams, and wells (Earman and Dettinger 2011).	X	X	X	X
Reservoir storage capacity is reduced because of low surface flows, reduced rates of groundwater recharge, and high rates of evaporation (CWCB 2019; Lukas et al. 2014).	—	—	—	X
Population growth increases demand for a dwindling water supply, causing conflicts between storage and on-forest uses (CWCB 2019; Naeser and Smith 1995).	X	X	X	X
Commitments to interstate and international compacts further complicate water management in the forests (CWCB 2019).	X	X	X	X
Water quality is affected by heavy runoff and wildfires (Rhoades et al. 2011; Hohner et al. 2016).	X	X	X	X
High spring flows and runoff from heavy precipitation events threaten the function of outdated water storage and delivery infrastructure (Lukas et al. 2014).	X	X	X	X
Outdated infrastructure makes it difficult for agencies to meet future water demands (CWCB 2019).	X	X	X	X
Sum Negative Responses	7	7	7	8
Sum Positive Responses	0	0	0	0
Final Sensitivity Score	3	3	3	3

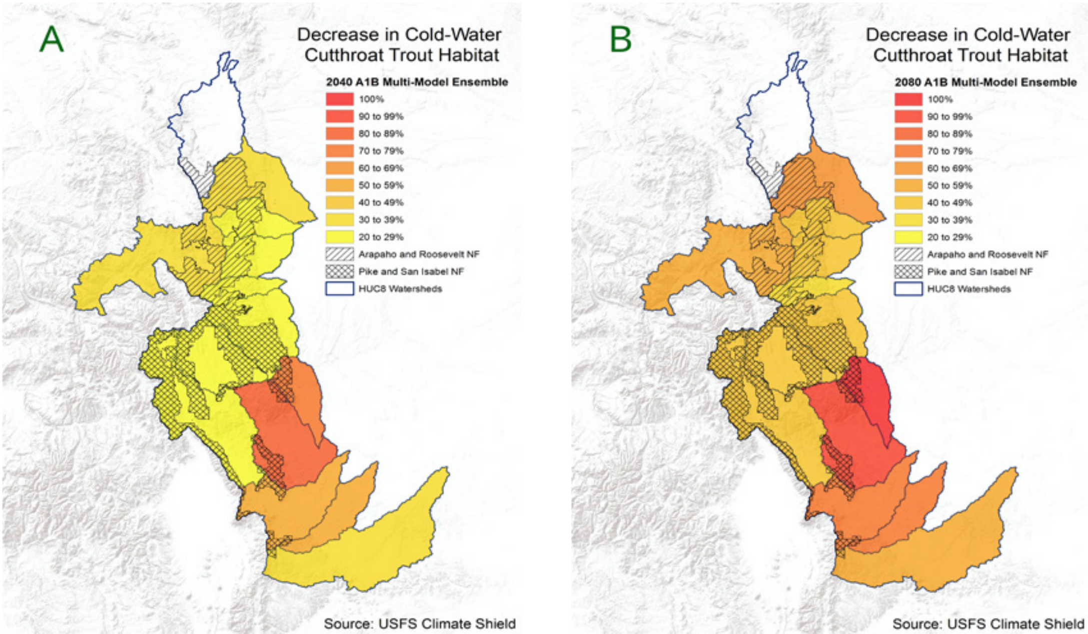

Figure 21a-b—Change in amount of cold-water cutthroat trout habitat based on stream temperatures ideal for reproduction. Projections were made under historical conditions and climate change scenarios. Projections for two future periods (1970–1999 and 2030–2059) were generated using the A1B emissions scenario applied to 10 global climate models. Percent change in miles of suitable stream habitat from the baseline period of 1970–1999 to the future period of 2030–2059 correspond to a moderate climate change scenario. Percent change from the baseline period to the period of 2070–2099 corresponds an extreme climate change scenario.

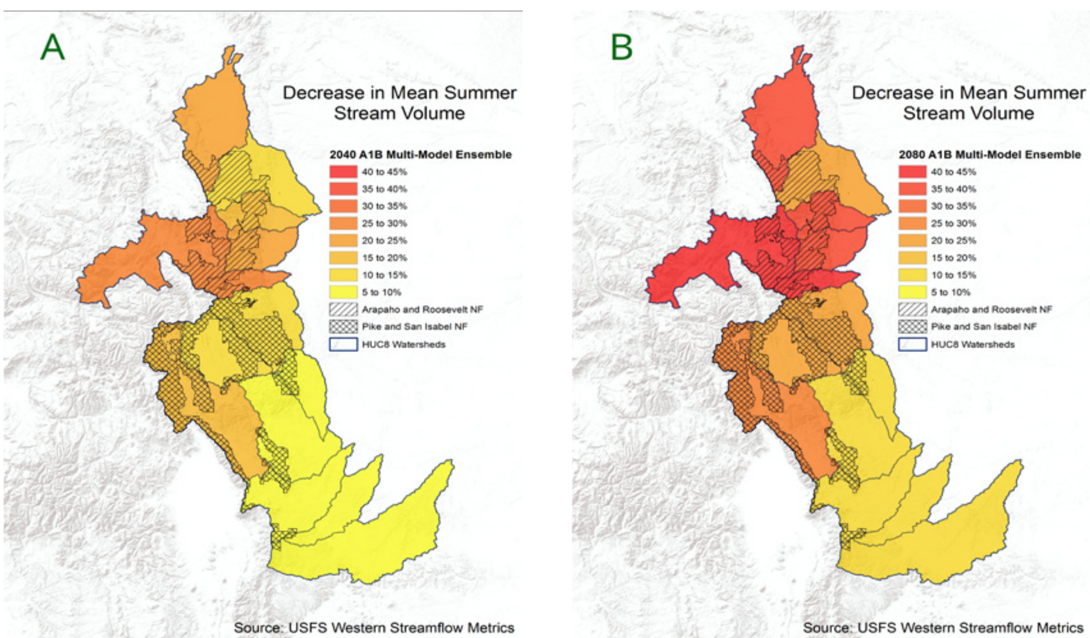

Figure 22a-b—Change in mean daily stream flow volume during the summer months. Streamflow projections were made under historical conditions and climate change scenarios. Projections for two future periods (2030–2059 and 2070–2099) were generated using the A1B emissions scenario applied to 10 global climate models. The VIC method was used to translate climate data into streamflow (USDA FS 2015). Percent change in mean summer stream volume from the baseline period of 1970–1999 to the future period of 2030–2059 corresponds to a moderate climate change scenario. Percent change from the baseline period to the period of 2070–2099 corresponds an extreme climate change scenario.

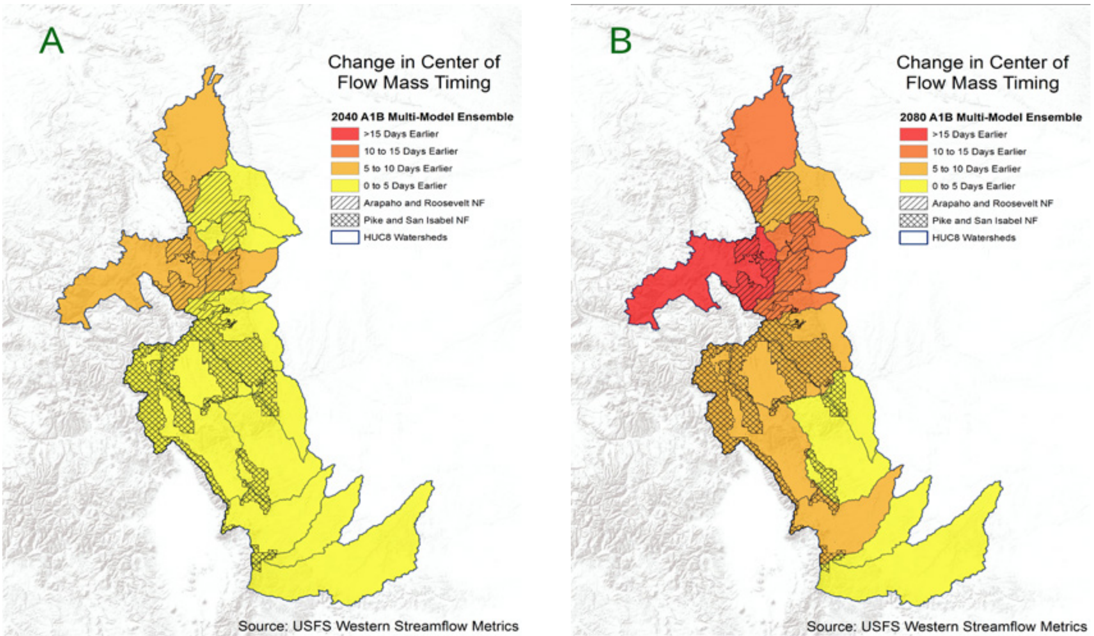

Figure 23a-b—Change, in number of days, of the center of flow mass timing, a measure of runoff timing. Streamflow projections were made under historical conditions and climate change scenarios. Projections for two future periods (2030–2059 and 2070–2099) were generated using the A1B emissions scenario applied to 10 global climate models. The VIC method was used to translate climate data into streamflow (USDA FS 2015). Change in flow mass timing from the baseline period of 197–1999 to the future period of 2030–2059 corresponds to a moderate climate change scenario. Change from the baseline period to the period of 2070–2099 corresponds to an extreme climate change scenario.

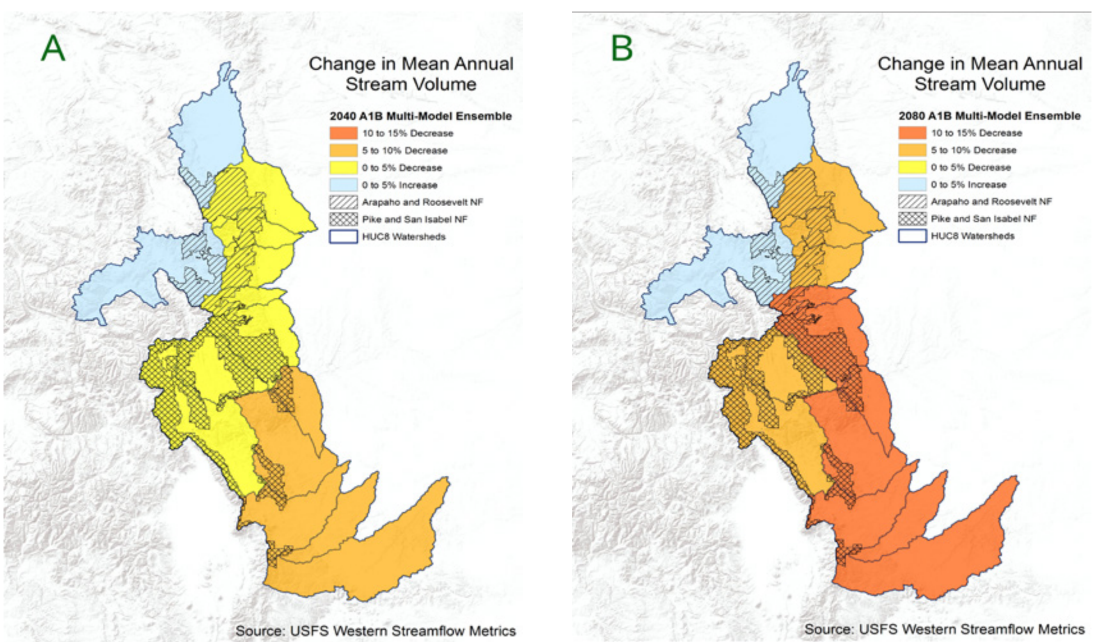

Figure 24a-b—Change in mean annual stream flow. Streamflow projections were made under historical conditions and climate change scenarios. Projections for two future periods (2030–2059 and 2070–2099) were generated using the A1B emissions scenario applied to 10 global climate models. The VIC method was used to translate climate data into streamflow (USDA FS 2015). Percent change in mean annual stream volume from the baseline period of 1970–1999 to the future period of 2030–2059 corresponds to a moderate climate change scenario. Percent change from the baseline period to the period of 2070–2099 corresponds to an extreme climate change scenario.

Adaptive Capacity

I used literature review and comments from the November 2019 workshop to identify the capacity of species, ecosystems, and society to cope with climate change scenarios with minimal disruption (Brandt et al. 2017). I ranked adaptive capacity as 1 = no or few opportunities to cope with changes; 2 = several opportunities to cope with changes (>2); and 3 = numerous opportunities to cope with changes. Results are presented in tables 9–11.

Table 9—Adaptive capacity of cutthroat trout habitat to climate impacts under four climate change scenarios for the Colorado Front Range. For each row, an X indicates that there is potential for adaption under a given climate scenario.

	Climate Scenario			
Adaptive Capacity Source	**Very Hot and Wet**	**Hot**	**Warm and Wet**	**Very Hot and Dry**
Reestablished beaver populations can create dams, canals, and ponds, which store water throughout valley bottoms, maintaining downstream perennial flows and providing cover in ponds (Grudzinski et al. 2020; Pollock et al. 2014).	X	X	X	X
Managers can move trout to cold stream segments and lakes as they become more thermally suitable in a warming climate (2019 workshop).	X	X	X	—
The AR, PSI, and other entities can change their water rights from consumptive uses to instream flows, which would sustain cold-water habitats during periods of drought (2019 workshop).	X	X	X	X
Sum Positive Responses	3	3	3	2
Final Adaptive Capacity Score	2	2	2	1

Table 10—Adaptive capacity of riparian areas, wetlands, and groundwater-dependent ecosystems to climate impacts under four climate change scenarios for the Colorado Front Range. For each row, an X indicates that there is potential for adaption under a given climate scenario.

	Climate Scenario			
Adaptive Capacity Source	**Very Hot and Wet**	**Hot**	**Warm and Wet**	**Very Hot and Dry**
Reestablished beaver populations can use dams, canals, and ponds to spread water throughout valley bottoms, protecting riparian and wetland ecosystems from drought and wildfire (Grudzinski et al. 2020; Fairfax and Whittle 2020).	X	X	X	X
Floodplains and vegetation adjust to reduction in streamflow volume, maintaining riparian habitats if surface flows and groundwater remain available (Stromberg et al. 2010).	X	X	X	—
If restored or kept in functioning condition, fens supported by large mountain aquifers may be resilient to droughts and warming (Drexler et al. 2013).	X	X	X	X
The AR, PSI, and other entities can change their water rights from consumptive uses to instream flows, which would maintain minimum flows and sustain riparian and wetland ecosystems during periods of drought (2019 workshop).	X	X	X	X
Reservoirs and transbasin diversion operations can be adjusted to maintain summer flows in large streams and peak flows could be timed to coincide with riparian plant seed release (Duan et al. 2023; Gill et al. 2018).	X	X	X	X
Sum Positive Responses	5	5	5	4
Final Adaptive Capacity Score	3	3	3	2

Table 11—Adaptive capacity of anthropogenic water uses to climate impacts under four climate change scenarios for the Colorado Front Range. For each row, an X indicate that there is potential for adaption under a given climate scenario.

	Climate Scenario			
Adaptive Capacity Source	**Very Hot and Wet**	**Hot**	**Warm and Wet**	**Very Hot and Dry**
Reestablished beaver populations can use dams, canals, and ponds to store water in valley bottoms, allowing for more on-forest and downstream uses (Grudzinski et al. 2020; Pollock et al. 2014).	X	X	X	X
Restoration of fens and other wetlands can increase water storage capacity in watersheds, allowing for more on-forest and downstream uses (Cooper et al. 1998; Hunt et al. 2018).	X	X	X	X
Infrastructure upgrades can improve efficiency of water transport and use (2019 workshop).	X	X	X	X
The AR, PSI, and other entities can change their water rights from consumptive uses to instream flows, which would sustain some water uses during periods of drought (2019 workshop).	X	X	X	X
Reservoirs and transbasin diversion operations can be adjusted to maximize storage of water from extreme precipitation events for drier seasons (Duan et al. 2023; 2019 workshop).	X	X	X	X
Sum Positive Responses	5	5	5	5
Final Adaptive Capacity Score	3	3	3	3

Vulnerability

Following the methods of Glick et al. (2011) and Brandt et al. (2017), I combined exposure and sensitivity scores into a single impact score, which represents direct and indirect consequences for resources. I compared this score with adaptive capacity in a vulnerability matrix (table 12) to rank vulnerability as low, moderate, high, or very high.

Table 12—Vulnerability matrix used to incorporate exposure, sensitivity, and adaptive capacity scores into a vulnerability ranking.

Adaptive capacity score	Impact score (exposure + sensitivity): 2	3	4	5	6
1	Low	Moderate	Moderate	High	Very High
2	Low	Low	Moderate	High	High
3	Very Low	Low	Moderate	Moderate	High

The final rankings of vulnerability differed between climate scenarios (table 13). The most vulnerable resource is cutthroat trout habitat under the Very Hot and Dry scenario. Riparian areas, wetlands, groundwater-dependent ecosystems, and water uses are also highly vulnerable under this scenario. All three resources were ranked as highly vulnerable under the Hot and the Very Hot and Wet scenarios. All three were ranked as moderately vulnerable under the Warm and Wet scenario.

Table 13—Final vulnerability rankings for water resources under four climate scenarios.

	Very Hot and Wet	Hot	Warm and Wet	Very Hot and Dry
Cutthroat trout habitat	High	High	Moderate	Very High
Riparian and wetland ecosystems	High	High	Moderate	High
Water uses	High	High	Moderate	High

Exposure to climate change is high in three of the four future scenarios. This exposure is driven by multiple indirect effects of increasing temperatures, which cancel out potential positive effects of increasing precipitation in the Very Hot and Wet scenario and the Hot scenario. Sensitivity of cutthroat trout is high in three of the four scenarios because of multiple threats to water quality and the confinement of populations to small stream segments. Drought, wildfire, extreme rainfall, and flood contribute to high sensitivity of each of the key resources (fig. 25). Changes in the timing of peak flows contribute to high sensitivity of riparian and wetland ecosystems. For water uses, water rights and use conflicts are major contributors to sensitivity. In summary, the results demonstrate substantial negative impacts of climate change for water resources under all but the Warm and Wet climate scenario.

Figure 25— Beaver dam complexes slow the movement of water through valley bottoms, providing adaptive capacity to cope with decreased summer flows and frequent droughts. (USDA Forest Service photo by Max Smith)

Riparian ecosystems, wetlands, and water uses have relatively high adaptive capacity because managers can use infrastructure for water storage and delivery to cope with droughts and periods of low flows. In addition, beaver dams can increase the adaptive capacity for each of the resources (fig. 26). Adaptive capacity is lowest for cutthroat trout because of current limitations on dispersal and assisted migration.

Figure 26—Post-wildfire floods and debris flows are an indirect effect of climate change on Front Range streams. These disturbances deliver large amounts of sediment to streams and floodplains. (USDA Forest Service photo by Max Smith)

Uncertainty

For each resource, I examined sources of uncertainty in the vulnerability determinations based on evidence for, and agreement with, the descriptions of exposure, sensitivity, and adaptive capacity (Brandt et al. 2017). I ranked uncertainty as low if there are multiple studies and assessments that report similar effects of climate change and resource responses in the region. If there are no studies or assessments reporting similar effects and responses, I ranked uncertainty as high. If there are few studies or assessments reporting similar effects and responses, I ranked uncertainty as moderate. Results are presented in tables 14a, 14b, and 14c.

Table 14a—Sources of low, moderate, and high uncertainty for cutthroat trout habitat vulnerability in this assessment of key water resources.

a. Low Uncertainty
    - The four climate scenarios agree on increasing temperatures, decreasing SWE, increasing spring runoff, decreasing summer runoff, and increases in extreme rainfall.
    - Multiple assessments project increases in stream temperatures, decreases in summer flows, and increases in spring flows of Front Range streams.
    - Multiple studies project increases in drought and wildfire effects.
    - Multiple assessments and studies report high vulnerability of cutthroat trout populations due to small habitat fragments, barriers to movement, and threats from non-native species.
    - Multiple assessments and studies report risks to water quality, including sedimentation, post-wildfire debris flows, and increased concentration of pollutants.
b. Moderate Uncertainty
    - Three of the four climate models agree on increases in drought severity and fire danger.
    - Assessments project decreases in groundwater discharge following a shift from rain to snow, but studies are needed to confirm this response.
c. High Uncertainty
    - Projected changes in precipitation totals and extreme precipitation effects vary among the four climate scenarios and models used in other Front Range assessments.
    - There are no studies reporting the effects of increased spring runoff on cutthroat trout reproduction.

Table 14b—Sources of low, moderate, and high uncertainty for riparian and wetland vulnerabilaity in this assessment of key water resources.

a. Low Uncertainty
    - The four climate scenarios agree on increasing temperatures, decreasing SWE, increasing spring runoff, decreasing summer runoff, and increases in extreme rainfall.
    - Multiple assessments project decreases in summer flows and earlier peak flows of Front Range streams.
    - Multiple studies show the response of riparian vegetation to changes in groundwater levels, peak flow timing, and soil moisture.
    - Several studies have examined the dynamics of carbon storage along Front Range streams.
    - Multiple studies show the contraction of riparian ecosystems, fens, and other wetlands in response to a reduction in groundwater and surface flows.
    - Multiple studies demonstrate that drought, fire, and extreme rainfall will increase rates of erosion and sedimentation.

b. Moderate Uncertainty

- Three of the four climate models agree on increases in drought severity and fire danger.
- Projected changes in precipitation totals and extreme precipitation effects vary among models used in Front Range assessments.
- Assessments project decreases in groundwater discharge following a shift from rain to snow, but studies are needed to confirm this response.
- Studies are needed to examine evaporative losses, increased atmospheric demand, plant stress, and mortality in Front Range riparian and wetland ecosystems.

c. High Uncertainty

- Little is known about climate impacts on Preble's meadow jumping mouse populations.
- Little is known about the resilience of Front Range fens and springs to drought and other disturbances.

Table 14c—Sources of low, moderate, and high uncertainty for water uses vulnerability in this assessment of key water resources.

a. Low Uncertainty

- The four climate scenarios agree on increasing temperatures, decreasing SWE, increasing spring runoff, decreasing summer runoff, and increases in extreme rainfall.
- Multiple assessments project decreases in streamflows and inflows into reservoirs.
- Multiple studies project increases in flood, drought, and wildfire effects on infrastructure.
- Multiple studies project increasing Front Range population growth and recreation use.
- Multiple assessments and studies report risks to water quality, including sedimentation, post-wildfire debris flows, and increased concentration of pollutants.
- Multiple studies project increasing water rights conflicts.

b. Moderate Uncertainty

- Three of the four climate models agree on increases in drought severity and fire danger.
- Projections of water availability and demand differ among models used in other assessments.

c. High Uncertainty

- The four climate models differ in projections of precipitation totals.

There is high certainty of future temperature increases and increasing risk of drought and wildfire effects. There is high uncertainty, however, on the effects of climate change on precipitation totals and the future frequency of extreme rainfall events in the region. There is also uncertainty concerning the response of cutthroat trout to increases in spring runoff and decreases in groundwater discharge. There is high certainty that prolonged decreases in streamflow and groundwater levels will cause the contraction of riparian and wetland ecosystems in the region. Still, additional information is needed to evaluate better the vulnerability of sensitive species associated with springs, fens, and low-gradient riparian ecosystems. Multiple studies report high vulnerability of water uses to climate change due to aging infrastructure, continued population growth, and decreasing stream flows.

Based on these results, key water resources are highly vulnerable to climate change. Uncertainty is low for cutthroat trout habitat, moderate for riparian and wetland ecosystems, and low for water uses.

Conclusions

Water resources of the AR and PSI National Forests are put to important beneficial ecological and societal uses, both inside and outside of the Forest boundaries. The demand for these resources will only increase in response to a warming climate and a growing human population. The specific climate scenario that will occur in the Front Range is unknown, but increasingly dry summer conditions are projected under all scenarios, necessitating adaptation measures (Cook et al. 2020). This chapter's vulnerability ranking system will give managers a starting point for creating adaptation strategies. Results from stream restoration projects have shown that managers can implement climate change adaptation by repairing habitat, updating water use policies, and allowing natural processes to enhance the resistance and resilience of water resources (Williams et al. 2015b).

For this chapter, key water resources were selected for analysis and discussion. Next, vulnerability to four climate change scenarios was assessed. Finally, a ranking of uncertainty was provided based on the available evidence for similar effects and responses. To summarize: The habitat for cutthroat trout, particularly greenback cutthroat trout, is likely the most vulnerable water resource, given the small size and fragmented nature of suitable stream segments. Without management to enhance climate adaptation, the establishment of self-sustaining populations will be increasingly unlikely under the drier climate scenarios. In areas with cutthroat trout habitat, restoration to reconstruct historical stream channels, enhance riparian cover, and reconnect mainstems and tributaries can decrease the sensitivity of water resources to the effects of climate change.

Forest Service managers can also maintain or enhance water resources by working with partners to establish priorities; for example, updating water storage infrastructure, developing conditional water storage rights, obtaining additional water rights, or changing the administration of existing rights (CWCB 2019). Well-designed and implemented plans to maintain or restore natural infrastructure such as beaver dams, aquifers, and fens can maintain surface flows and maximize groundwater recharge while storing and delivering water supplies to downstream users. The success of these efforts may depend on them being implemented at the watershed scale, involving multiple stakeholders from multiple professions, disciplines, and socioeconomic backgrounds (Lukas et al. 2014; Williams et al. 2015b). As detailed in this assessment, the prioritization of watersheds for restoration and protection should be based on the importance of their water resources, their levels of climate exposure and sensitivity, and their relevance to basin-wide management issues.

References

Abatzoglou, J. T. 2013. Development of gridded surface meteorological data for ecological applications and modelling. International Journal of Climatology. 33: 121–131. https://doi.org/10.1002/joc.3413

Abatzoglou J.T.; Brown T.J. 2012. A comparison of statistical downscaling methods suited for wildfire applications, International Journal of Climatology. 32: 772-780. https://doi.org/10.1002/joc.3413

Abatzoglou, J.T.; McEvoy, D.J.; Redmond, K.T. 2017. The west wide drought tracker: Drought monitoring at fine spatial scales. Bulletin of the American Meteorological Society. 98(9): 1815–1820. https://doi.org/10.1175/BAMS-D-16-0193.1

Arapaho and Roosevelt National Forests and Pawnee Grasslands (ARP). 1997. Revised Land and Resource Management Plan. 427 p. https://www.fs.usda.gov/detail/arp/landmanagement/planning/?cid=fsm91_058285

Clements, W.H.; Vieira, N.K.; Church, S.E. 2010. Quantifying restoration success and recovery in a metal-polluted stream: A 17-year assessment of physicochemical and biological responses. Journal of Applied Ecology. 47: 899–910. https://doi.org/10.1111/j.1365-2664.2010.01838.x

Clow, D.W. 2010. Changes in the timing of snowmelt and streamflow in Colorado: A response to recent warming. Journal of Climate. 23: 2293–2306. https://doi.org/10.1175/2009JCLI2951.1

Colorado Water Conservation Board [CWCB]. 2019. Analysis and technical update to the Colorado Water Plan. Denver: Colorado Water Conservation Board. https://www.colorado.gov/pacific/cowaterplan/analysis-and-technical-update

Cook, B.I.; Mankin; J.S.; Williams. A.P.; [et al.]. 2020. Twenty-first century drought projections in the CMIP6 forcing scenarios. Earth's Future. 8: p.e2019EF001461. https://doi.org/10.1029/2019EF001461

Cook, B.I.; Williams, A.P.; Marvel, K. 2022. Projected changes in early summer ridging and drought over the Central Plains. Environmental Research Letters. 17: 104020. https://doi.org/10.1088/1748-9326/ac8e1a

Coop, J.D.; Parks, S.A.; Stevens-Rumann, C.S.; [et al.]. Extreme fire spread events and area burned under recent and future climate in the Western USA. Global Ecology and Biogeography. 31: 1949–59. https://doi.org/10.1111/geb.13496

Colorado River Cutthroat Trout Coordination Team [CRCT Coordination Team]. 2006. Conservation strategy for Colorado River cutthroat trout (*Oncorhynchus clarkii pleuriticus*) in the States of Colorado, Utah, and Wyoming. Colorado Division of Wildlife, Fort Collins. 24 p. https://cpw.state.co.us/Documents/Research/Aquatic/pdf/CRCT_Conservation_Strategy_Jun06.pdf

Dall, D.; Elliott, C.; Peters, D. 1997. A system for mapping riparian areas in the western United States. Lakewood, CO: USDI Fish and Wildlife Service, National Wetlands Inventory. 43 p.

Daubert, J.T.; Young, R.A. 1981. Recreational demands for maintaining instream flows: A contingent valuation approach. American Journal of Agricultural Economics. 63: 666–676. https://doi.org/10.2307/1241209

Decker, K.; Grunau, L.; Handwerk, J.; [et al.], eds. 2015. Colorado Natural Heritage Program climate change vulnerability assessment for Colorado Bureau of Land Management. Fort Collins, CO: Colorado Natural Heritage Program, Colorado State University. 573 p.

Deems, J.S.; Painter, T.H.; Barsugli, J.J. 2013. Combined impacts of current and future dust deposition and regional warming on Colorado River Basin snow dynamics and hydrology. Hydrology and Earth System Sciences. 17: 4401–4413. https://doi.org/10.5194/hess-17-4401-2013

Dettinger, M.; Udall, B.; Georgakakos, A. 2015. Western water and climate change. Ecological Applications. 25: 2069–2093. https://doi.org/10.1890/15-0938.1

Drexler, J.Z.; Knifong, D.; Tuil, J.; [et al.]. 2013. Fens as whole-ecosystem gauges of groundwater recharge under climate change. Journal of Hydrology. 481: 22–34. https://doi.org/10.1016/j.jhydrol.2012.11.056

Duan, K.; Qu, S.; Liu, N.; [et al.]. 2023. Evolving efficiency of inter-basin water transfers in regional water stress alleviation. Resources, Conservation and Recycling. 191: 106878. https://doi.org/10.1016/j.resconrec.2023.106878

Dunaway, D.; Swanson, S.R.; Wendel, J.; [et al.]. 1994. The effect of herbaceous plant communities and soil textures on particle erosion of alluvial streambanks. Geomorphology. 9: 47–56. https://doi.org/10.1016/0169-555X(94)90030-2

Dwire, K.A.; Mellmann-Brown, S.; Gurrieri, J.T. 2018. Potential effects of climate change on riparian areas, wetlands, and groundwater-dependent ecosystems in the Blue Mountains, Oregon, USA. Climate Services. 10: 44–52. https://doi.org/10.1016/j.cliser.2017.10.002

Earman, S.; Dettinger, M. 2011. Potential impacts of climate change on groundwater resources—a global review. Journal of Water and Climate Change. 2: 213–229. https://doi.org/10.2166/wcc.2011.034

Elgaali, E.; Garcia, L.A. 2007. Using neural networks to model the impacts of climate change on water supplies. Journal of Water Resources Planning and Management. 133: 230–243. https://doi.org/10.1061/(ASCE)0733-9496(2007)133:3(230)

Ficklin, D.L.; Stewart, I.T.; Maurer, E.P. 2013. Climate change impacts on streamflow and subbasin-scale hydrology in the Upper Colorado River Basin. PLoS One. 8. https://doi.org/10.1371/journal.pone.0071297

Fields, J.F.; Dethier, D.P. 2019. From on high: Geochemistry of alpine springs, Niwot Ridge, Colorado Front Range, USA. Hydrological Processes. 33: 1756–1774. https://doi.org/10.1002/hyp.13436

Folk-Williams, J.A.; Fry, S.C.; Hilgendorf, L. 1985. Western water flows to the cities. Washington, DC: Island Press. 217 pp.

Foster, L.M.; Bearup, L.A.; Molotch, N.P.; [et al.]. 2016. Energy budget increases reduce mean streamflow more than snow–rain transitions: Using integrated modeling to isolate climate change impacts on Rocky Mountain hydrology. Environmental Research Letters. 11: 044015. https://doi.org/10.1088/1748-9326/11/4/044015

Frey, J.K.; Malaney, J.L. 2009. Decline of the meadow jumping mouse (*Zapus hudsonius luteus*) in two mountain ranges in New Mexico. The Southwestern Naturalist. 54: 31–44. https://www.jstor.org/stable/40263664

Friedman, J.M.; Scott, M.L.; Lewis, W.M. 1995. Restoration of riparian forest using irrigation, artificial disturbance, and natural seedfall. Environmental Management. 19: 547–557. https://doi.org/10.1007/BF02471966

Fyfe, J.C.; Derksen, C.; Mudryk, L.; [et al.]. 2017. Large near-term projected snowpack loss over the western United States. Nature Communications. 8: 14996. https://doi.org/10.1038/ncomms14996

Gary, H.L.; Johnson, S.R.; Ponce, S.L. 1983. Cattle grazing impact on surface water quality in a Colorado Front Range stream. Journal of Soil and Water Conservation. 38: 124–128. https://www.jswconline.org/content/38/2/124

Giardino, J.R.; Shroder Jr, J.F.; Lawson, M.P. 1984. Tree-ring analysis of movement of a rock-glacier complex on Mount Mestas, Colorado, USA. Arctic and Alpine Research. 16: 299–309. https://doi.org/10.2307/1550939

Gill, K.M.; Goater, L.A.; Braatne, J.H.; [et al.]. 2018. The irrigation effect: How river regulation can promote some riparian vegetation. Environmental Management. 61: 650–60. https://doi.org/10.1007/s00267-017-0991-4

Glick, P.; Stein, B.A.; Edelson, N.A. 2011. Scanning the conservation horizon: A guide to climate change vulnerability assessment. Washington, DC: National Wildlife Federation. Available: https://www.nwf.org/vulnerabilityguide

Gregory, S.V.; Swanson, F.J.; McKee, W.A.; [et al.]. 1991. An ecosystem perspective of riparian zones. BioScience. 41: 540–551. https://doi.org/10.2307/1311607

Grudzinski, B.P; Cummins, H.; Vang, T.K. 2020. Beaver canals and their environmental effects. Progress in Physical Geography: Earth and Environment. 44: 189–211. https://doi.org/10.1177/0309133319873116

Hansen, A.J. 2009. Species and habitats most at risk in Greater Yellowstone. Yellowstone Science. 17: 27–36. https://www.montana.edu/hansenlab/documents/bio515_13/Hansen12072009yellscience.pdf [Accessed 6 June 2024]

Hansen, A.J.; Rasker, R.; Maxwell, B.; [et al.]. 2002. Ecology and socioeconomics in the New West: A case study from Greater Yellowstone. BioScience. 52: 151–168. https://doi.org/10.1641/0006-3568(2002)052[0151:ECACOD]2.0.CO;2 [Accessed 6 June 2024]

Harig, A.L.; Fausch, K.D. 2002. Minimum habitat requirements for establishing translocated cutthroat trout populations. Ecological Applications. 12: 535–551. https://doi.org/10.1890/1051-0761(2002)012[0535:MHRFET]2.0.CO;2

Harpold, A.A.; Molotch, N.P.; Musselman, K.N.; [et al.]. 2015. Soil moisture response to snowmelt timing in mixed-conifer subalpine forests. Hydrological Processes. 29: 2782–2798. https://doi.org/10.1002/hyp.10400

Hobbs Jr., G.J. 1997. Colorado water law: An historical overview. University of Denver Water Law Review. 1: 1. https://www.judges.org/wp-content/uploads/2020/03/Colorado-Water-Law-An-Historical-Overview-through-8th-update.pdf [Accessed 6 June 2024]

Hoerling, M.; Eischeid, J.; Kumar, A.; [et al.]. 2014. Causes and predictability of the 2012 Great Plains drought. Bulletin of the American Meteorological Society. 95: 269–282. https://doi.org/10.1175/BAMS-D-13-00055.1

Hohner, A.K.; Cawley, K.; Oropeza, J.; [et al.]. 2016. Drinking water treatment response following a Colorado wildfire. Water Research. 105: 187–98. https://doi.org/10.1016/j.watres.2016.08.034

Horan, D.L.; Kershner, J.L.; Hawkins, C.P.; [et al.]. 2000. Effects of habitat area and complexity on Colorado River cutthroat trout density in Uinta Mountain streams. Transactions of the American Fisheries Society. 129: 1250–1263. https://doi.org/10.1577/1548-8659(2000)129<1250:EOHAAC>2.0.CO;2

Hough-Snee, N.; Roper, B.B.; Wheaton, J.M.; [et al.]. 2013. Riparian vegetation communities change rapidly following passive restoration at a northern Utah stream. Ecological Engineering. 58: 371–377. https://doi.org/10.1016/j.ecoleng.2013.07.042

Howe, C.W.; Goemans, C. 2003. Water transfers and their impacts: Lessons from three Colorado water markets 1. JAWRA, Journal of the American Water Resources Association. 39: 1055–1065. https://doi.org/10.1111/j.1752-1688.2003.tb03692.x

Hunt, L.J.H.; Fair, J.; Odland, M. 2018. Meadow restoration increases baseflow and groundwater storage in the Sierra Nevada Mountains of California. JAWRA, Journal of the American Water Resources Association. 54: 1127–1136. https://doi.org/10.1111/1752-1688.12675

Immerzeel, W.W.; Lutz, A.F.; Andrade, M.; [et al.]. 2019. Importance and vulnerability of the world's water towers. Nature. 577: 364–369. https://doi.org/10.1038/s41586-019-1822-y

Isaak, D.J.; Young, M.K.; Nagel, D.E.; [et al.]. 2015. The cold-water climate shield: Delineating refugia for preserving salmonid fishes through the 21st century. Global Change Biology. 21: 2540–2553. https://doi.org/10.1111/gcb.12879

Jarrett, R.D.; Costa, J.E. 1988. Evaluation of the flood hydrology in the Colorado Front Range using precipitation, streamflow, and paleoflood data for the Big Thompson River basin. Water Resources Investigations Report 87-4117. Denver, CO: Department of the Interior, U.S. Geological Survey. https://pubs.usgs.gov/wri/1987/4117/report.pdf [Accessed 6 June 2024]

Jarrett, R.D.; Costa, J.E. 2006. Big Thompson Flood, Colorado: Thirty years later. USGS Fact Sheet 2006-3095. Denver, CO: Department of the Interior, U.S. Geological Survey. 5 p. https://pubs.usgs.gov/fs/2006/3095/pdf/FS06-3095_508.pdf

Johnson, T.; Butcher, J.; Deb, D.; [et al.]. 2015. Modeling streamflow and water quality sensitivity to climate change and urban development in 20 U.S. watersheds. JAWRA, Journal of the American Water Resources Association. 51: 1321–1341. https://doi.org/10.1111/1752-1688.12308

Johnson, J.B.; Steingraeber, D.A. 2003. The vegetation and ecological gradients of calcareous mires in the South Park Valley, Colorado. Canadian Journal of Botany. 81: 201–219. https://doi.org/10.1139/b03-017

Jones, D.B.; Harrison, S.; Anderson, K; [et al.]. 2019. Rock glaciers and mountain hydrology: A review. Earth-Science Reviews. 193: 66–90. https://doi.org/10.1016/j.earscirev.2019.04.001

Jones, K.A.; Niknami, L.S.; Buto, S.G.; [et al.]. 2022. Federal standards and procedures for the national Watershed Boundary Dataset (WBD), 5th ed. U.S. Geological Survey Techniques and Methods 11-A3. Reston, VA: Department of the Interior, U.S. Geological Survey. 54 p. https://pubs.usgs.gov/tm/11/a3/

Jones, P.A.; Cech, T. 2009. Colorado water law for non-lawyers. Denver, CO: University Press of Colorado. 276 p.

Joyce, L.A.; Coulson, D. 2020. Climate scenarios and projections: A technical document supporting the USDA Forest Service 2020 RPA Assessment. Gen. Tech. Rep. RMRS-GTR-413. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 85 p. https://doi.org/10.2737/RMRS-GTR-413

Kampf, S.K.; Lefsky, M.A. 2016. Transition of dominant peak flow source from snowmelt to rainfall along the Colorado Front Range: Historical patterns, trends, and lessons from the 2013 Colorado Front Range floods. Water Resources Research. 52: 407–422. https://doi.org/10.1002/2015WR017784

Kenney, D.S.; Klein, R.A.; Clark, M.P. 2004. Use and effectiveness of municipal waters restrictions during drought in Colorado 1. JAWRA, Journal of the American Water Resources Association. 40: 77–87. https://doi.org/10.1111/j.1752-1688.2004.tb01011.x

Kramer, N.; Wohl, E.E.; Harry, D.L. 2012. Using ground penetrating radar to “unearth” buried beaver dams. Geology. 40: 43–46. https://doi.org/10.1130/G32682.1

Kreamer, D.K.; Springer, A.E. 2008. The hydrology of desert springs in North America. In: Stevens, LE: Meretsky, V.J., eds. 2008. Aridland springs in North America: Ecology and conservation. Tucson, AZ: University of Arizona Press. pp. 35-48.

Kreamer, D.K.; Stevens, L.E.; Ledbetter, J.D. 2015. Groundwater dependent ecosystems—Science, challenges, and policy directions. In: Groundwater. Adelana, S.M., ed. Hauppauge, NY: Nova Science Publishers, Inc. pp. 205-230.

Kundzewicz, Z.W.; Doll, P. 2009. Will groundwater ease freshwater stress under climate change? Hydrological Sciences Journal. 54: 665–675. https://doi.org/10.1623/hysj.54.4.665

Lemly, J. L.; Long, G.; Smith, G.; [et al.]. 2016. National wetland inventory mapping of the Arkansas headwaters subbasin. Fort Collins, CO: Colorado Natural Heritage Program, Colorado State University. 58 p. https://cnhp.colostate.edu/download/documents/2016/Arkansas_Headwaters_NWI_Mapping_Report_FINAL.pdf [Accessed 6 June 2024]

Livers, B.; Wohl, E. 2015. An evaluation of stream characteristics in glacial versus fluvial process domains in the Colorado Front Range. Geomorphology. 231: 72–82. https://doi.org/10.1016/j.geomorph.2014.12.003

Livneh, B.; Deems, J.S.; Buma, B.; [et al.]. 2015. Catchment response to bark beetle outbreak and dust-on-snow in the Colorado Rocky Mountains. Journal of Hydrology. 523: 196–210. https://doi.org/10.1016/j.jhydrol.2015.01.039

Loomis, J.; McTernan, J. 2014. Economic value of instream flow for non-commercial whitewater boating using recreation demand and contingent valuation methods. Environmental Management. 53: 510–519. https://doi.org/10.1007/s00267-014-0232-z

Luce, C.H. 2018. Effects of climate change on snowpack, glaciers, and water resources in the Northern Rockies region. In: Halofsky, J.E.; Peterson, D.L.; Dante-Wood, SK.; [et al.], eds. 2018. Climate change vulnerability and adaptation in the Northern Rocky Mountains. Gen. Tech. Rep. RMRS-GTR-374. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. Part 1: 1–273. https://www.fs.usda.gov/research/treesearch/55989

Lukas, J.; Barsugli, J.; Doesken, N.; [et al.]. K. 2014. Climate change in Colorado: A synthesis to support water resources management and adaptation. Boulder, CO: University of Colorado. https://www.cakex.org/sites/default/files/documents/Climate_Change_CO_Report_2014_FINAL_0.pdf [Accessed 6 June 2024]

Mahoney, K.; Alexander, M.; Scott, J.D; [et al.]. 2013. High-resolution downscaled simulations of warm-season extreme precipitation events in the Colorado Front Range under past and future climates. Journal of Climate. 26: 8671–8689. https://doi.org/10.1175/JCLI-D-12-00744.1

Mast, M.A.; Murphy, S.F.; Clow, D.W.; [et al.]. 2016. Water-quality response to a high-elevation wildfire in the Colorado Front Range. Hydrological Processes. 30: 1811–1823. https://doi.org/10.1002/hyp.10755

McGrath, C.C.; Lewis Jr., W.M. 2007. Competition and predation as mechanisms for displacement of greenback cutthroat trout by brook trout. Transactions of the American Fisheries Society. 136: 1381–1392. https://doi.org/10.1577/T07-017.1

Moody, J.A.; Martin, D.A. 2001. Initial hydrologic and geomorphic response following a wildfire in the Colorado Front Range. Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group. 26: 1049–1070. https://doi.org/10.1002/esp.253

Naeser, R.B.; Smith, M.G. 1995. Playing with borrowed water: Conflicts over instream flows on the Upper Arkansas river. Natural Resources Journal. 35 (1): 93-110). https://www.jstor.org/stable/24885635

Nesler, T.P. 1981. Studies of the limnology, fish populations, and fishery of Turquoise Lake, Colorado—1979–80. Report no. REC-ERC-82-5. Denver, CO: U.S. Department of Interior, Bureau of Reclamation. 31 p.

O'Neill, M.P.; Schmidt, J.C.; Dobrowolski, J.P.; [et al.]. 1997. Identifying sites for riparian wetland restoration: Application of a model to the Upper Arkansas River Basin. Restoration Ecology. 5: 85–102. https://doi.org/10.1111/j.1526-100X.1997.tb00208.x

Oyler, J.W.; Ballantyne A.; Jencso K.; Sweet M.; Running S.W. 2014. Creating a topoclimatic daily air temperature dataset for the conterminous United States using homogenized station data and remotely sensed land skin temperature. International Journal of Climatology. 35:2258-2279. http://dx.doi.org/10.1002/joc.4127. https://doi.org/10.1002/joc.4127

Painter, T.H.; Skiles, S.M.; Deems, J.S.; [et al.]. 2018. Variation in rising limb of Colorado River snowmelt runoff hydrograph controlled by dust radiative forcing in snow. Geophysical Research Letters. 45: 797–808. https://doi.org/10.1002/2017GL075826

Perry, L.G.; Shafroth, P.B.; Hay, L.E.; [et al.]. 2019. Projected warming disrupts the synchrony of riparian seed release and snowmelt streamflow. New Phytologist. 225: 693–712. https://doi.org/10.1111/nph.16191

Pielke, R.A.; Doesken, N.; Bliss, O.; [et al.]. 2005. Drought 2002 in Colorado: An unprecedented drought or a routine drought? Pure and Applied Geophysics. 162: 1455–1479. https://doi.org/10.1007/s00024-005-2679-6

Poff, N.L.; Allan, J.D.; Bain, M.B.; [et al.]. 1997. The natural flow regime. BioScience. 47: 769-784. https://doi.org/10.2307/1313099

Pollock, M.M.; Beechie, T.J.; Wheaton, J.M.; [et al.]. 2014. Using beaver dams to restore incised stream ecosystems. BioScience. 64: 279–90. https://doi.org/10.1093/biosci/biu036

Polvi, L.E.; Wohl, E.E.; Merritt, D.M. 2011. Geomorphic and process domain controls on riparian zones in the Colorado Front Range. Geomorphology. 125: 504–516. https://doi.org/10.1016/j.geomorph.2010.10.012

Rasmussen, R.; Ikeda, K.; Liu, C.; [et al.]. 2014. Climate change impacts on the water balance of the Colorado headwaters: High-resolution regional climate model simulations. Journal of Hydrometeorology. 15: 1091–1116. https://doi.org/10.1175/JHM-D-13-0118.1

Rasmussen, R.; Liu, C.; Ikeda, K.; [et al.]. 2011. High-resolution coupled climate runoff simulations of seasonal snowfall over Colorado: A process study of current and warmer climate. Journal of Climate. 24: 3015–3048. https://doi.org/10.1175/JHM-D-13-0118.1

Rathburn, S.L.; Merritt, D.M.; Wohl, E.E.; [et al.]. 2009. Characterizing environmental flows for maintenance of river ecosystems: North Fork Cache la Poudre River, Colorado. Management and restoration of fluvial systems with broad historical changes and human impacts. 451: 143. https://doi.org/10.1130/2009.2451(10)

Rhoades, C.C.; Entwistle, D.; Butler, D. 2011. The influence of wildfire extent and severity on streamwater chemistry, sediment, and temperature following the Hayman Fire, Colorado. International Journal of Wildland Fire. 20: 430–442. https://doi.org/10.1071/WF09086

Rice, J.R.; Winters, D.; Regan, C.; [et al.]. 2018. Aquatic, riparian, and wetland ecosystems in glaciated valleys: Vulnerability to nonclimate and climate stressors in the U.S. Forest Service Rocky Mountain Region. In: Rice, J.R.; Joyce, L.A.; Regan, C.; Winters, D.; Truex, R. Climate change vulnerability assessment of aquatic and terrestrial ecosystems in the U.S. Forest Service Rocky Mountain Region. Gen. Tech. Rep. RMRS-GTR-376. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 216 p. https://www.fs.usda.gov/research/treesearch/56392

Richer, E.E.; Gates, E.A.; Kondratieff, M.C.; [et al.]. 2019 Modelling changes in trout habitat following stream restoration. River Research and Applications. 35: 680–691. https://doi.org/10.1002/rra.3444

Rieman, B.E.; Isaak, D.J. 2010. Climate change, aquatic ecosystems, and fishes in the Rocky Mountain West: Implications and alternatives for management. Gen. Tech. Rep. RMRS-GTR-250. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 46 p. https://doi.org/10.2737/RMRS-GTR-250

Riggan, P.J.; Lockwood, R.N.; Jacks, P.M.; [et al.]. 1994. Effects of fire severity on nitrate mobilization in watersheds subject to chronic atmospheric deposition. Environmental Science & Technology. 28: 369–375. https://doi.org/10.1021/es00052a005

Roberts, J.J.; Fausch, K.; 2015. Consequences of climate change for mountain lakes and native cutthroat trout. Denver, CO: Colorado Parks and Wildlife. 29 p. https://cpw.state.co.us/Documents/Research/Aquatic/CutthroatTrout/Roberts2015FinalReport.pdf [Accessed 6 June 2024]

Roberts, J.J.; Fausch, K.D.; Peterson, D.P.; [et al.]. 2013. Fragmentation and thermal risks from climate change interact to affect persistence of native trout in the Colorado River basin. Global Change Biology. 19: 1383–1398. https://doi.org/10.1111/gcb.12136

Roberts, J.J.; Fausch, K.D.; Hooten, M.B.; [et al.]. 2017a. Non-native trout invasions combined with climate change threaten persistence of isolated cutthroat trout populations in the southern Rocky Mountains. North American Journal of Fisheries Management. 37: 314–325. https://doi.org/10.1080/02755947.2016.1264507

Roberts, J.J.; Fausch, K.D.; Schmidt, T.S.; [et al.]. 2017b. Thermal regimes of Rocky Mountain lakes warm with climate change. PLoS One. 12: p.e0179498. https://doi.org/10.1371/journal.pone.0179498

Rogers, K. 2012. Piecing together the past: Using DNA to resolve the heritage of our state fish. Colorado Outdoors. September/October: 28-32. https://cpw.state.co.us/Documents/Research/Aquatic/CutthroatTrout/Rogers2012CoOutdoors.pdf [Accessed 6 June 2024]

Rupp, D.E.; Abatzoglou, J.T.; Hegewisch, K.C. [et al.]. 2013. Evaluation of CMIP5 20th century climate simulations for the Pacific Northwest USA. Journal of Geophysical Research: Atmospheres. 118(19): 10–884. https://doi.org/10.1002/jgrd.50843

Ryan, W.; Doesken, N.; Center, C.C. 2013. Drought of 2012 in Colorado. Colorado Climate Center. 7 p. https://climate.colostate.edu/pdfs/drought_2012.pdf [Accessed 6 June 2024]

Salas, J.D.; Fu, C.; Cancelliere, A.; [et al.]. 2005. Characterizing the severity and risk of drought in the Poudre River, Colorado. Journal of Water Resources Planning and Management. 131: 383–393. https://doi.org/10.1061/(ASCE)0733-9496(2005)131:5(383)

Saunders III, J.F.; Lewis Jr., W.M. 2003. Implications of climatic variability for regulatory low flows in the South Platte River Basin, Colorado. JAWRA, Journal of the American Water Resources Association. 39: 33–45. https://doi.org/10.1111/j.1752-1688.2003.tb01559.x

Smith, H.; Beauvais, D.G.P.; Keinath, D.A. 2004. Species assessment for Preble's meadow jumping mouse (*Zapus hudsonius preblei*) in Wyoming. Laramie, WY: Wyoming Natural Diversity Database, University of Wyoming. https://www.uwyo.edu/wyndd/_files/docs/reports/speciesassessments/preblesmeadowjumpingmouse-oct2004.pdf [Accessed 6 June 2024]

Smith, D.M.; Finch, D.M. 2014. Use of native and non-native nest plants by riparian-nesting birds along two streams in New Mexico. River Research and Applications. 30: 1134–1145. https://doi.org/10.1002/rra.2713

Sprague, L.A. 2005. Drought effects on water quality in the South Platte River Basin, Colorado. JAWRA, Journal of the American Water Resources Association. 41: 11–24. https://doi.org/10.1111/j.1752-1688.2005.tb03713.x

Springer, A.E.; Stevens, L.E. 2009. Spheres of discharge of springs. Hydrogeology Journal. 17: 83–94. https://doi.org/10.1007/s10040-008-0341-y

Stevens L.E.; Meretsky, V.J., eds. 2008. Aridland springs in North America: Ecology and conservation. Tucson, AZ: University of Arizona Press.

Stromberg, J. C.; Lite, S.J.; Dixon, M.D. 2010. Effects of stream flow patterns on riparian vegetation of a semiarid river: Implications for a changing climate. River Research and Applications. 26: 712–29. https://doi.org/10.1002/rra.1272

Topper, R.; Spray, K.L.; Bellis, W.H.; [et al.]. 2003. SP-53 Ground water atlas of Colorado. Special Publications, SP-53. Denver, CO: Colorado Geological Survey, Division of Minerals and Geology, Department of Natural Resources.

Udall, B.; Overpeck, J. 2017. The 21st century Colorado River hot drought and implications for the future. Water Resources Research. 53: 2404–2418. https://doi.org/10.1002/2016WR019638

U.S. Department of the Interior, Bureau of Reclamation (Reclamation). 2014. Downscaled CMIP3 and CMIP5 climate and hydrology projections: Release of hydrology projections, comparison with preceding information, and summary of user needs. Denver, CO: U.S. Department of the Interior, Bureau of Reclamation, Technical Services Center. 110 pp. https://gdo-dcp.ucllnl.org/downscaled_cmip_projections/techmemo/BCSD5HydrologyMemo.pdf [Accessed 6 June 2024]

Vose, Russell S.; Applequist, S.; Squires, M.; Durre, I.; Menne, M. J.; Williams, C. N., Jr.; Fenimore, C.; Gleason, K.; Arndt, D. 2014. NOAA Monthly U.S. Climate Divisional Database (NClimDiv). NOAA National Climatic Data Center. https://doi.org/10.7289/V5M32STR

Walch, L.A. 1980. Movements of lake trout in Twin Lakes, Colorado, in relation to the Mt. Elbert pumped-storage powerplant. Applied Sciences Branch, Division of Research, Engineering and Research Center, U.S. Department of the Interior, Water and Resources Service. 82 p.

Watson, P.S.; Davies, S. 2011. Modeling the effects of population growth on water resources: A CGE analysis of the South Platte River Basin in Colorado. The Annals of Regional Science. 46: 331–348. https://doi.org/10.1007/s00168-009-0326-3

Weaver, J.F.; Gruntfest, E.; Levy, G.M. 2000. Two floods in Fort Collins, Colorado: Learning from a natural disaster. Bulletin of the American Meteorological Society. 81: 2359–2366. https://doi.org/10.1175/1520-0477(2000)081<2359:TFIFCC>2.3.CO;2

Williams, A.P.; Allen, C.D.; Macalady, A.K.; [et al.]. 2013. Temperature as a potent driver of regional forest drought stress and tree mortality. Nature Climate Change. 3(3): 292. https://doi.org/10.1038/nclimate1693

Williams, A.P.; Cook, E.R.; Smerdon, J.E.; [et al.]. 2020. Large contribution from anthropogenic warming to an emerging North American megadrought. Science. 368: 314–318. https://doi.org/10.1126/science.aaz9600

Williams, M.W.; Hood, E.; Molotch, N.P.; [et al.]. 2015a. The "Teflon basin" myth: Hydrology and hydrochemistry of a seasonally snow-covered catchment. Plant Ecology & Diversity. 8: 639–661. https://doi.org/10.1080/17550874.2015.1123318

Williams, M.W.; Knauf, M.; Caine, N.; [et al.]. 2006. Geochemistry and source waters of rock glacier outflow, Colorado Front Range. Permafrost and Periglacial Processes. 17: 13–33. https://doi.org/10.1002/ppp.535

Williams, J.E.; Neville, H.M.; Haak, A.L.; [et al.]. 2015b. Climate change adaptation and restoration of western trout streams: Opportunities and strategies. Fisheries. 40: 304–317. https://doi.org/10.1080/03632415.2015.1049692

Winward, A.H. 2000. Monitoring the vegetation resources in riparian areas. Gen. Tech. Rep. RMRS-GTR-47. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 49 p. https://doi.org/10.2737/RMRS-GTR-47

Wohl, E.E. 2001. Virtual rivers: Lessons from the mountain rivers of the Colorado Front Range. New Haven, CT: Yale University Press.

Wohl, E.; Dwire, K.; Sutfin, N.; [et al.]. 2012. Mechanisms of carbon storage in mountainous headwater rivers. Nature Communications. 3: 1263. https://doi.org/10.1038/ncomms2274

Wondzell, S.M.; Diabat, M.; Haggerty, R.. 2019. What matters most: Are future stream temperatures more sensitive to changing air temperatures, discharge, or riparian vegetation? JAWRA, Journal of the American Water Resources Association. 55: 116–132. https://doi.org/10.1111/1752-1688.12707

Woodbury, M.; Baldo, M.; Yates, D.; [et al.]. 2012. Joint Front Range climate change vulnerability study. Denver, CO: Water Research Foundation. 148 p. https://climatewise.org/images/stories/pdfs/Publications/ClimateWise/Joint_Front_Range_Climate_Vulnerability_Study.pdf [Accessed 6 June 2024]

Woodward, D.F.; Farag, A.M.; Little, E.E.; [et al.]. 1991. Sensitivity of greenback cutthroat trout to acidic pH and elevated aluminum. Transactions of the American Fisheries Society. 120: 34–42. https://doi.org/10.1577/1548-8659(1991)120<0034:SOGCTT>2.3.CO;2

Wrigley, M.J.; White, M.; Elliott, B.; [et al.]. 2012. Threatened, endangered, and Forest Service sensitive species on the Pike and San Isabel National Forests (updated June 2012). Unpublished Report on file with: U.S. Department of Agriculture, Forest Service, Pike and San Isabel National Forests and Comanche and Cimarron National Grasslands, Salida, Colorado. 115 p.

Writer, J.H.; McCleskey, R.B.; Murphy, S.F.; [et al.]. 2012. Effects of wildfire on source-water quality and aquatic ecosystems, Colorado Front Range. Wildfire and water quality: Processes, impacts and challenges. 354: 117–122. https://iahs.info/uploads/dms/16029.18-117-122-354-09-Writer-et-al-CORR.pdf [Accessed 6 June 2024]

Young, M.K. 2009. Greenback cutthroat trout (*Oncorhynchus clarkii stomias*): A technical conservation assessment. Golden, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Region. 100 p. https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb5206801.pdf [Accessed 6 June 2024]

Young, M.K.; Harig, A.L. 2001. A critique of the recovery of greenback cutthroat trout. Conservation Biology. 15: 1575–1584. https://www.jstor.org/stable/3061259

Zhang, Q.; Knowles, J.F.; Barnes, R.T.; [et al.]. 2018. Surface and subsurface water contributions to streamflow from a mesoscale watershed in complex mountain terrain. Hydrological Processes. 32: 954–967. https://doi.org/10.1002/hyp.11469

Appendix

Datasets used in water resources vulnerability analysis.

1. Watershed Elevation Range—Maximum and minimum elevation of HUC-8 watershed. Source: Colorado Natural Heritage Program (https://cnhp.colostate.edu)
2. Percent National Forest Land—Percentage of HUC8 watershed with AR or PSI National Forest land. Source: Colorado Natural Heritage Program (https://cnhp.colostate.edu)
3. Percent Private Land—Percentage of HUC8 watershed with privately owned land. Source: Colorado Natural Heritage Program (https://cnhp.colostate.edu)
4. Decreed Instream Flow Miles—Total length of stream miles with instream flow water rights managed by the Colorado Water Conservation Board. Source: Colorado's Decision Support System (https://dwr.state.co.us/Tools)
5. Mean Discharge—Mean daily discharge volume, in cubic feet per second, measured at stream gages across the period of record. Source: U.S. Geological Survey National Water Information System (https://waterdata.usgs.gov/nwis)
6. Max. Discharge—Maximum daily discharge volume, in cubic feet per second, measured at stream gages across the period of record. Source: U.S. Geological Survey National Water Information System (https://waterdata.usgs.gov/nwis)
7. Mean Peak Date—Mean calendar date, across years, when the annual peak daily discharge occurred at gage sites. Source: U.S. Geological Survey National Water Information System (https://waterdata.usgs.gov/nwis)
8. Mean Center of Flow Mass Date—Mean date that 50% of cumulative water year flow was recorded at stream gages. Source: U.S. Geological Survey National Water Information System (https://waterdata.usgs.gov/nwis)
9. Peak Discharge CV—Coefficient of variation, representing variation in peak daily discharge among years. Source: U.S. Geological Survey National Water Information System (https://waterdata.usgs.gov/nwis)
10. Peak Date CV—Coefficient of variation, representing variation in peak discharge date among years. Source: U.S. Geological Survey National Water Information System (https://waterdata.usgs.gov/nwis)

11. Center of Flow Mass CV—Coefficient of variation, representing variation in center of flow mass timing among years. Source: U.S. Geological Survey National Water Information System (https://waterdata.usgs.gov/nwis)
12. Cutthroat Trout Reaches—Number of stream reaches with managed populations of cutthroat trout. Source: Inland Cutthroat Trout Program (https://icp.wygisc.org)
13. Perennial Stream Miles—Total length of perennially flowing stream reaches. Source: U.S. Geological Survey National Hydrography Dataset (https://www.usgs.gov/core-science-systems/ngp/national-hydrography/nhdplus-high-resolution)
14. Intermittent Stream Miles—Total length of stream reaches with surface flows occurring only during periods of runoff. Source: U.S. Geological Survey National Hydrography Dataset (https://www.usgs.gov/core-science-systems/ngp/national-hydrography/nhdplus-high-resolution)
15. Mapped Wetlands—Acres of wetlands mapped and classified by the National Wetland Inventory and the Colorado Natural Heritage Program. Source: Colorado Natural Heritage Program (https://cnhp.colostate.edu/cwic)
16. Mapped Fens—Acres of fens calculated using numerous datasets compiled by the Colorado Natural Heritage Program. Source: Colorado Natural Heritage Program (https://cnhp.colostate.edu/cwic)
17. Mapped Springs—Number of known springs. Source: Spring Stewardship Institute (https://springstewardshipinstitute.org/)
18. Forest Service Fishing and Boating Sites—Recreation sites primarily used for access to streams and lakes. Source: U.S. Forest Service National Dataset (https://data.fs.usda.gov/geodata/)
19. Active Ditches and Pipelines—Structures used to divert water from streams and springs. Source: Colorado's Decision Support System (https://dwr.state.co.us/Tools)
20. Active Reservoirs—Impoundments created for water storage. Source: Colorado's Decision Support System (https://dwr.state.co.us/Tools)
21. Active Wells—Sites developed for groundwater use. Source: Colorado's Decision Support System (https://dwr.state.co.us/Tools)

22. Change in Maximum Summer Air Temperature—Projected change in maximum air temperature during June, July, and August between the historical period (1985-2015) and a future period (2035-2050) under four climate scenarios. Source: U.S. Bureau of Reclamation Climate and Hydrology Projections (https://gdo-dcp.ucllnl.org/downscaled_cmip_projections/)
23. Change in Spring Snow Water Equivalent—Projected change in snow water equivalent during March, April, and May between the historical period (1985-2015) and a future period (2035-2050) under four climate scenarios. Source: U.S. Bureau of Reclamation Climate and Hydrology Projections (https://toolkit.climate.gov/tool/downscaled-cmip3-and-cmip5-climate-and-hydrology-projections)
24. Change in Spring Runoff—Projected change in runoff during March, April, and May between the historical period (1985-2015) and a future period (2035-2050) under four climate scenarios. Source: U.S. Bureau of Reclamation Climate and Hydrology Projections (https://toolkit.climate.gov/tool/downscaled-cmip3-and-cmip5-climate-and-hydrology-projections)
25. Change in Summer Runoff—Projected change in runoff during June, July, and August between the historical period (1985-2015) and a future period (2035-2050) under four climate scenarios. Source: U.S. Bureau of Reclamation Climate and Hydrology Projections (https://toolkit.climate.gov/tool/downscaled-cmip3-and-cmip5-climate-and-hydrology-projections)
26. Change in Annual Runoff—Projected change in runoff between the historical period (1985-2015) and a future period (2035-2050) under four climate scenarios. Source: U.S. Bureau of Reclamation Climate and Hydrology Projections (https://toolkit.climate.gov/tool/downscaled-cmip3-and-cmip5-climate-and-hydrology-projections)
27. Change in Fire Danger—Projected change in number of fires between the historical period (1985-2015) and a future period (2035-2050) under four climate scenarios. Source: Multivariate Adaptive Constructed Analogs Climate Projections (http://www.climatologylab.org/maca.html)
28. Change in Drought Frequency—Projected change in frequency of severe droughts like 2012 between the historical period (1985-2015) and a future period (2035-2050) under four climate scenarios. Source: Multivariate Adaptive Constructed Analogs Climate Projections (http://www.climatologylab.org/maca.html)

29. Change in Extreme Rainfall Events—Projected percent change in extreme rainfall events between the historical period (1985-2015) and a future period (2035-2050) under four climate scenarios. Source: Multivariate Adaptive Constructed Analogs Climate Projections (http://www.climatologylab.org/maca.html)
30. Change in Cold-water Cutthroat Trout Habitat—Projected change in miles of thermally suitable cutthroat trout streams between the historical period of 1970-1999 and two projection periods (2030-2050 and 2070-2099) under the A1B climate scenario. Source: U.S. Forest Service Climate Shield (https://www.fs.usda.gov/rm/boise/AWAE/projects/ClimateShield.html)
31. Change in Mean Summer Stream Volume—Projected change in mean daily stream flow volume during the summer months between the historical period of 1970-1999 and two projection periods (2030-2050 and 2070-2099) under the A1B climate scenario. Source: U.S. Forest Service Climate Western Streamflow Metrics (https://www.fs.usda.gov/rm/boise/AWAE/projects/modeled_stream_flow_metrics.shtml)
32. Change in Center of Flow Mass Timing—Projected change, in number of days, of the center of flow mass timing between the historical period of 1970-1999 and two projection periods (2030-2050 and 2070-2099) under the A1B climate scenario. Source: U.S. Forest Service Climate Western Streamflow Metrics (https://www.fs.usda.gov/rm/boise/AWAE/projects/modeled_stream_flow_metrics.shtml)
33. Change in Mean Annual Stream Volume—Change in mean annual stream flow volume between the historical period of 1970-1999 and two projection periods (2030-2050 and 2070-2099) under the A1B climate scenario. Source: U.S. Forest Service Climate Western Streamflow Metrics (https://www.fs.usda.gov/rm/boise/AWAE/projects/modeled_stream_flow_metrics.shtml)