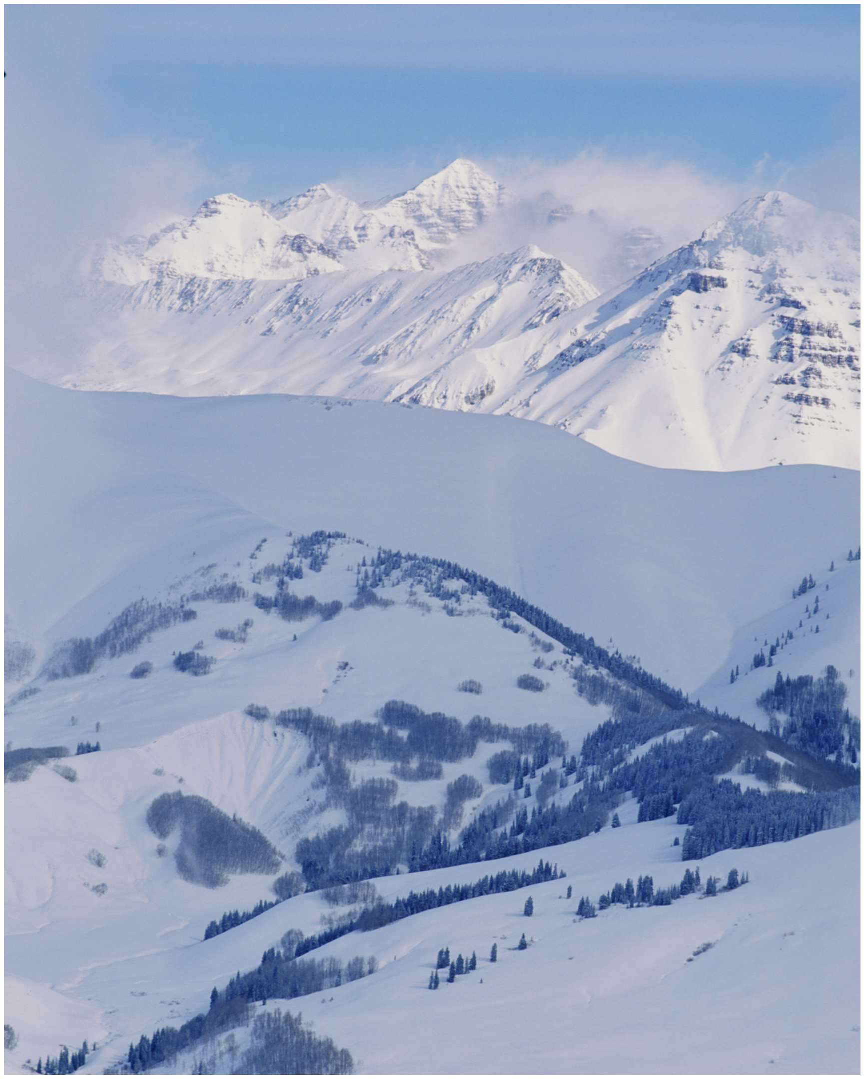
CLIMATE CHANGE IN THE HEADWATERS
WATER AND SNOW IMPACTS



A report to the Northwest Colorado Council of Governments

the ROCKY MOUNTAIN CLIMATE Organization

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Tom Easley

2018

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Water and Snow Impacts

By
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A report by the
Rocky Mountain Climate Organization

To
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The Rocky Mountain Climate Organization works to reduce climate disruption and its impacts to help keep the Interior West the special place we cherish. We do this in part by spreading the word about what an altered climate can do to us here and what we can do about it, including through reports such as this.

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Northwest Colorado Council of Governments is a voluntary association of county and municipal governments that believes in the benefits of working together on a regional basis. NWCCOG serves 26 member jurisdictions in a five-county region of northwest Colorado.

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Contents

1. INTRODUCTION

This report summarizes existing information on how climate change may affect the snow and water resources of six Colorado counties that include the headwaters of the Colorado River and its tributaries. These headwaters counties are Eagle, Grand, Gunnison, Pitkin, Routt, and Summit counties.

The water and snow resources of this six-county region are essential ingredients of its spectacular natural resources, opportunities for recreation and tourism, local economies, and quality of life, all of which are treasured locally and worldwide. To begin with, there is the Colorado River itself—starting here, draining one-twelfth of the contiguous United States, providing the largest source of water in the country's driest region, but still being diverted beyond its basin to meet other needs across the West. Altogether, the Colorado provides drinking water for 22 of the 32 largest cities across the West[1] and irrigation water for some of America's most productive growing areas.

Another hallmark of the headwaters counties is their 16 ski resorts, which include seven of the 10 most-visited ski areas in the nation. One quarter of the nation's skiing is on Colorado slopes,[2] and most of that in the headwaters counties.

Truly, the water and snow resources of these counties are something special.

But as this report documents, the water and snow of the headwaters counties and the many economic and social values that depend on them are at risk as the climate changes.

Temperature. In Colorado, all but one of the last 40 years have been hotter than the 20th century average and this century has had seven of the state's ten hottest years on record. Mid-century temperatures are projected to average 1.5° Fahrenheit* to 6.5° hotter than in 1971–2000, and late-century temperatures 1.5° to 9.5° hotter, depending on future levels of heat-trapping emissions.

Precipitation. To offset the impacts of higher temperatures on snow and water resources, there would need to be large increases in total precipitation and snowfall. But only the wettest 10 percent of climate projections suggest that Colorado precipitation amounts could increase by even six to nine percent.

Water and snow resources. Across the West, less winter precipitation is falling as snow and more as rain, snowpacks are declining, and snowmelt is occurring earlier. Colorado's mountains, with the highest terrain in the West, are buffered somewhat against the larger changes happening at lower elevations, but changes are happening in the headwaters, too. The flows of the Colorado River, fed mostly by mountain snow, have recently been the lowest in the past century—driven in large part by the evaporative effects of higher temperatures. Projections are that these changes will become more pronounced, with greater shifts from snowfall to rainfall, earlier snowmelt, decreased river flows, and increased likelihood of water restrictions and curtailments.

Impacts on winter recreation and tourism. If Colorado snowfall and snowpacks decline as projected, the state's skiing, snowboarding, and other opportunities for snow-dependent winter recreation could suffer. This could have economic consequences throughout the state, as the skiing/snowboarding industry alone contributes about $5 billion to the state's economy.

Impacts on warm-season recreation and tourism. If climate change projections materialize, fishing, boating, rafting, and other warm-season, water-dependent outdoor recreation could be adversely affected by hot temperatures, low water levels, and other manifestations of climate change.

Impacts on water quality. Climate change may lead to decreases in water quality, including violations of water quality standards that specify maximum stream temperatures to protect fish and other resources. Further, climate change is projected to lead to major increases in wildfires, which in turn can increase flooding and sedimentation from burned areas.

On these topics, this report primarily summarizes existing information to document what has happened and what could happen in the headwaters counties as a result of climate change and what is at stake there if projected changes materialize. (One piece of new analysis is of headwaters snowpack levels.) The report's emphasis is on presenting, as much as possible, local, specific information focused on the headwaters region.

*All temperatures presented in this report are in degrees Fahrenheit.

This report follows up on a 2011 report, *Water and Its Relationship to the Economies of the Headwaters Counties*, prepared for the Northwest Colorado Council of Governments by Coley/Forrest, Inc.[3] NWCCOG commissioned this new report because of the importance of potential climate change impacts on the resources and values identified in that earlier report.

Figure 1 below shows the six headwaters counties, addressed both in the 2011 report and in this one.

The Headwaters Counties

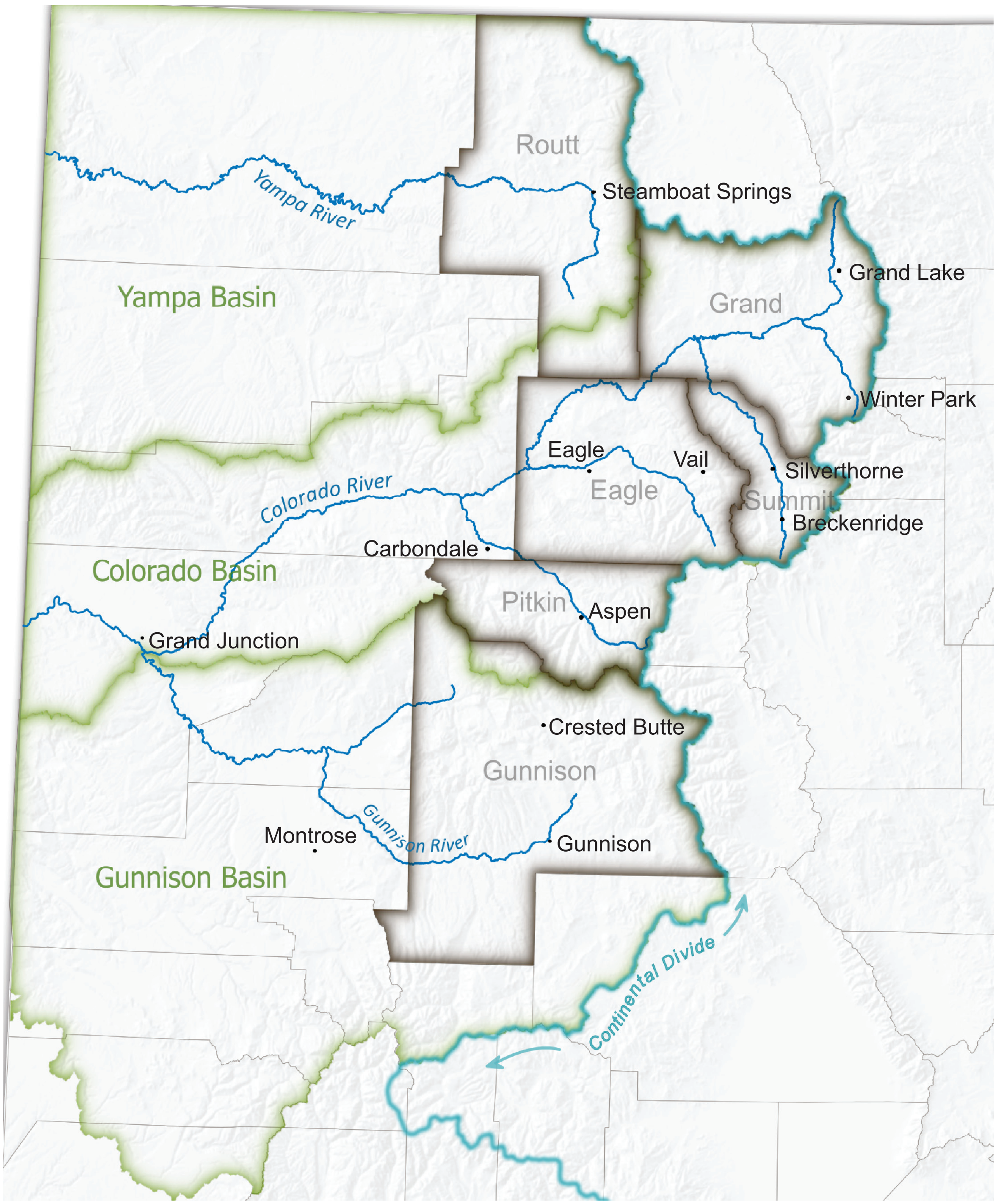

Figure 1. The six headwaters counties, bordered in gray. Also shown are river basins (bordered in light green) and the Continental Divide (in dark green). Map by Lotic Hydrological.

2. TEMPERATURE

Higher temperatures are the most obvious manifestation of an altered climate and also drive other changes. Temperatures clearly have already increased, and further increases are expected, with the extent depending on future levels of heat-trapping emissions.

What Has Happened

Average temperatures

A 2014 U.S. government national climate assessment opens, “Climate change, once considered an issue for a distant future, has moved firmly into the present.”[4] The changes in the climate now unfolding begin with higher temperatures. Globally, the last 41 years have all been above the 20th century’s average temperature.[5] Three of the last four years have set new records as the hottest year on record, and the other year (2017) has now gone into the books as the third hottest ever.[6] Global average temperatures have increased 0.3° per decade since 1970, with 2016’s record temperature having been 1.7° above the 20th century average.

Colorado statewide temperature changes have been similar. According to the Rocky Mountain Climate Organization’s examination of data from the National Oceanic and Atmospheric Administration, all but one of the last 41 years in Colorado have been above the 20th century average. The first 18 years of this century averaged 1.4° hotter than 1971–2000, and include eight of the state’s ten hottest years on record.[7] Statewide temperatures have increased 0.6° per decade since 1970, with 2012’s record temperature reaching 3.7° above the 20th century average.

In the headwaters counties, there is an unfortunate shortage of reliable long-term weather data, as there is across Colorado’s central mountains. Individual weather stations in the mountains often have limited periods of records, and the stations also have often been relocated over time, limiting their usefulness for analyzing long-term temperature trends. One exception is a Steamboat Springs weather station with data since 1908. It is among 38 weather stations identified by the Colorado Climate Center at Colorado State University as “better quality” stations in the state suitable for analysis of long-term climate trends, and among the nine stations selected from that list by the Western Water Assessment program at the University of Colorado, Boulder, for analysis in its 2008 and 2014 reports on climate change in Colorado.[8] In the 2014 report, Western Water Assessment determined that the Steamboat Springs weather station was among the seven of those nine representative, high-quality stations that had statistically significant trends of increasing average temperatures over both 30- and 50-year periods.

Another source of sub-state, regional temperature data is a climate division dataset that combines records from all weather stations in a particular part of a state—in the West, typically a watershed. However, river basins are often highly varied. For example, the entirety of Colorado’s Western Slope is one climate division, although it spans major changes in elevation and climate. For this reason, for its 2014 report on climate change in Colorado, Western Water Assessment used an updated, alternate set of sub-state climate divisions chosen for having generally similar climate. Of these alternate divisions, the one that best overlays the headwaters counties is the North Central Mountains division. The WWA report indicates that this area had statistically significant trends of increasing division-wide average temperatures over 100- and 50-year trends, but not over the most recent 30-year period (1993–2012).[9] (The analysis has not been updated to cover the five most recent years.)

What Could Happen

Average temperatures

Colorado’s recent temperature increases could be dwarfed by those to come, according to global climate models that have been “downscaled” to produce local projections, with the future increases largely determined by future levels of global heat-trapping emissions. According to Western Water Assessment, by mid-century

Colorado could average 1.5° to 6.5° hotter than the 1971–2000 average, and by late in the century 1.5° to 9.5° hotter, depending on emission levels, as shown in Figure 2 below.[10] The figure also shows actual statewide temperatures since 1895, as context for the projections.

Historical and Projected Colorado Temperatures

Comparisons to 1971–2000 Averages

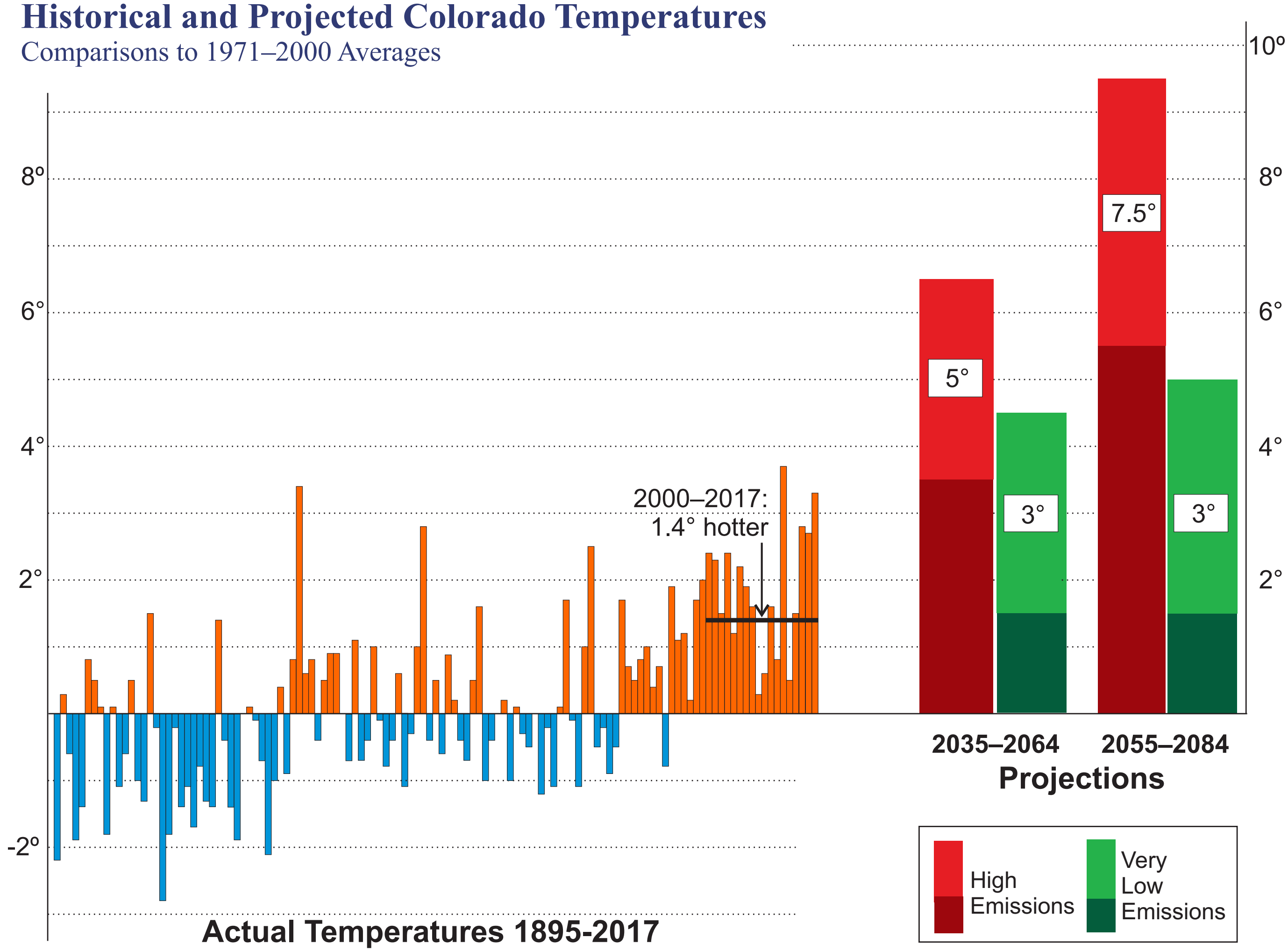

Figure 2. On the left, historic statewide Colorado temperatures, and on the right, projections of statewide temperatures, for two future periods and in each period for two alternative emission scenarios (see the scenario explanation on page 8.) Comparisons to 1971–2000 averages are shown. Temperatures in 2000–2017 averaged 1.4° higher. For the projections, as illustrated below, the brighter portions of columns show the middle 80 percent of individual projections, which are from 34 climate models for the high-emissions scenario and 23 models for the very low scenario, and the numerals show their medians. Table 1 on the next page includes the numerical values for the projections. Historical data are from the National Oceanic and Atmospheric Administration,[11] and the projections are from the Western Water Assessment, University of Colorado, Boulder.[12] The analysis of the historical data and the figure are by the Rocky Mountain Climate Organization.

Figure 3. Illustration of how the above figure combines values from multiple projections, hypothetically here from 10 models, into a single column. The middle 80 percent of the individual projections is represented by the brighter portion of the single column. This means that 90 percent of all projections project at least the value dividing the brighter and darker portions of the column (which is the 10th percentile of the projections). The numeral shows the median (or midpoint) of all projections.

How Multiple Projections Are Represented Above

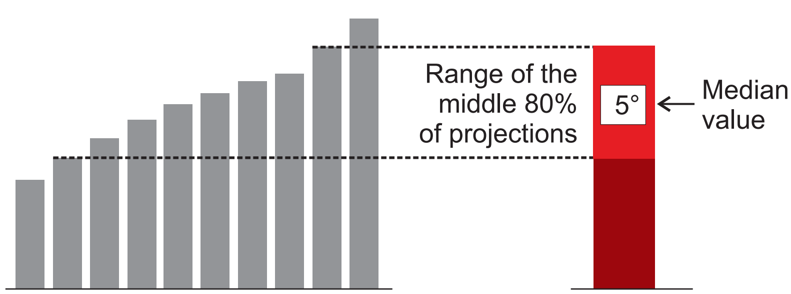

Table 1 below shows the data for projected increases in statewide average temperatures—based not just on the two emission scenarios illustrated in Figure 2 on the previous page but also on the two intermediate scenarios out of the four latest-generation emission scenarios now used for climate projections (see page 8).

Projected Changes in Statewide Average Temperature

Comparisons to 1971–2000

Time Period	High Emissions	Medium #1 Emissions	Medium #2 Emissions	Very Low Emissions
2035–2064	+5° (+3.5° to +6.5°)	+3.5° (+2.5° to +4.5°)	+3° (+2.5° to +5°)	+3° (+1.5° to +4.5°)
2055–2084	+7.5° (+5.5° to +9.5°)	+5° (+3.5° to +7°)	+4.5° (+2.5° to +6.5°)	+3° (+1.5° to +5°)

Table 1. Projected changes in Colorado statewide average temperatures, compared to 1971–2000 levels, from the latest global climate models and emission scenarios, for four alternative scenarios of future levels of heat-trapping emissions (see page 8). For each scenario/time period pairing, the higher row in the table shows the median (mid-point) of the multiple individual projections (up to 34 per scenario) and the lower row shows the range of the middle 80 percent of the individual projections. The projections for high emissions and very low emissions are the same as illustrated in Figure 2 on the previous page. Data from Western Water Assessment, University of Colorado, Boulder.[13]

The extent of future temperature increases will be largely determined by future levels of heat-trapping emissions.

A change of a few degrees in average temperatures may not seem like much. But the average projected increase with continued high emissions by mid-century (+5°) would make Aspen as warm as Golden, and that for later in the century (+7.5°) would make Aspen as warm as Fort Morgan.[14]

Projections of future average temperatures for some specific locations on Colorado's Western Slope are included in an analysis done for the Colorado Water Conservation Board.[15] The four projections for localities in the headwaters counties are shown in Table 2 below.

Projected Changes in Local Average Temperatures

Results from five representative projections, comparisons to 1950–2005

Time period	Grand Lake	Gunnison	Hayden	Yampa
2025–2054	+3.4° (+1.6° to +5.0°)	+3.6° (+1.7° to +5.2°)	+3.5° (+1.7° to +5.1°)	+3.5° (+1.7° to +5.1°)
2055–2084	+6.1° (+3.9° to +7.5°)	+6.4° (+4.1° to +8.0°)	+6.2° (+4.1° to +8.0°)	+6.3° (+4.0° to +8.0°)

Table 2. Projected changes in selected local average temperatures, compared to 1950–2005 levels, from five projections chosen to represent the range of 112 pairings of the latest global climate models and emission scenarios, for four locations within the headwaters counties. For each location/time period pairing, the higher row in the table shows the average of the five projections and the lower row shows the range of the middle 80 percent of the individual projections. Note that the baseline period used for comparisons in this table is different from that used in Table 1. Data from AECOM.[16]

An assessment of local climate impacts in Aspen made for the City of Aspen included other temperature (and precipitation) projections, but they are for a multi-state region much larger than the headwaters counties or even the Colorado mountains.[17]

Extreme temperatures

Extremes in daily high temperatures are projected to increase substantially across the United States, especially with continued high increases in heat-trapping emissions.[18] Nationwide studies showing local projections indicate that in the Colorado mountains both extremely high and extremely low temperatures could become higher, with the extremely low temperatures projected to increase more than extremely high ones.[19]

There has not yet been an analysis done of projected changes in extreme temperatures for the headwaters counties. (Projecting extremes requires a much more extensive analysis of far more data than is required to project average conditions.) The closest location for which such a detailed analysis has so far been done is an area in the mountainous part of Boulder County, an area of approximately 7 miles by 9 miles with elevations ranging from about 6,500 feet to about 8,500 feet. For this area, the Rocky Mountain Climate Organization prepared projections of future climate, with an emphasis on extreme conditions, for a report commissioned by the Colorado Department of Local Affairs.[20] The temperature projections for that area, which may be somewhat suggestive of what could occur in the headwaters counties, include that with continued high emission growth:

- Days of extreme heat could become more frequent, with days 90° and hotter going from an average of none in recent years to an average of three per year by mid-century and 20 per year late in the century.
- Days entirely below freezing (in other words, with highs below 32°) could become much less frequent, going from 42 per year in recent years to an average of 23 per year in mid-century and then only 12 per year late in the century.

Table 3 on the next page includes additional details from these projections.

Boulder County Mountains: Temperature Extremes

Actual values for 1970–1999 and projections with climate change

	1970-99	Projections with Different Emission Levels: 2040–2059				2080–2099			
	Actual	**High**	**Med. #1**	**Med. #2**	**Very Low**	**High**	**Med. #1**	**Med. #2**	**Very Low**
Daily high temps									
Days per year 80° or hotter	14	61 *51–73*	49 *39–56*	54 *37–64*	40 *30–52*	96 *86–118*	73 *60–91*	59 *49–79*	39 *29–57*
Days per year 90° or hotter	0	3 *1–6*	1 *0–3*	1 *1–3*	1 *0–2*	20 *10–50*	5 *1–11*	2 *1–5*	0 *0–1*
Hottest day of year	85°	92° *90–94°*	90° *90–91°*	90° *90–92°*	89° *88–91°*	97° *95–102°*	93° *91–95°*	92° *90–94°*	89° *88–91°*
Days per year with highs below 32°	42	23 *16–32*	29 *21–33*	26 *21–32*	29 *23–36*	12 *7–20*	20 *14–27*	24 *15–31*	30 *21–34*
Daily low temps									
Hottest night of year	52°	59° *56–60°*	57° *56–58°*	57° *56–59°*	56° *55–58°*	63° *61–67°*	60° *57–62°*	58° *56–61°*	56° *55–58°*
Nights per year below 32°	230	194 *184–205*	203 *196–210*	203 *194–213*	206 *196–214*	165 *146–183*	180 *172–198*	195 *181–206*	206 *196–214*

Table 3. Actual values for 1970–1999 and projections for mid-century and late century for daily high temperatures (top four data rows) and low temperatures (bottom two rows) averaged for an area of mountains and foothills in Boulder County (see text on the previous page). Projections are for two time periods and four alternative emission levels (see the next page). For each emission/time period pairing, the higher row in the table shows the medians of the multiple individual projections (up to 34 per scenario) and the lower row shows (in italics) the range of the middle 80 percent of those projections. Adapted from a report by the Rocky Mountain Climate Organization.[21]

Background: Possible Future Heat-Trapping Emissions

Scientists use scenarios of possible, alternative future levels of heat-trapping emissions to make projections of the extent of upcoming climate change and its impacts. The four latest-generation scenarios include one assuming continued high growth in emissions, two medium-level scenarios, and a fourth assuming very low levels of future emissions, the last approximately as needed to meet international climate-protection goals. Each scenario is a representation of a plausible future. Figure 4 below illustrates the four scenarios.

Emission Scenarios

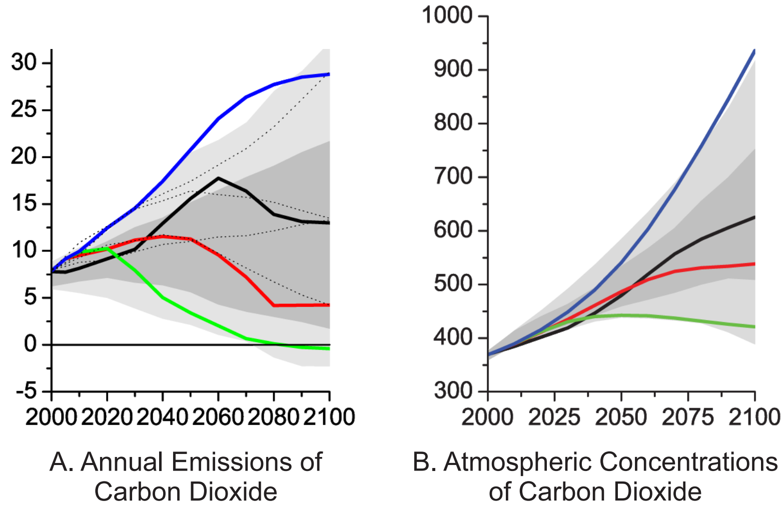

Figure 4. Key values for the four latest-generation emissions scenarios being used for climate projections. Figure 4A (on the left), annual global emission levels of carbon dioxide, the principal (but not only) heat-trapping pollutant, in gigatons of carbon; 4B, atmospheric concentrations of carbon dioxide, in parts per million. The blue lines represent the scenario identified as “high” in this report; the black lines, “medium #1”; the red lines, “medium #2”; and the green lines, “very low.” Figures provided by Detlef van Vuuren.[22]

This report sometimes refers to a previous generation of emission scenarios used in earlier studies. One scenario described in this report as having “medium-high” emissions has continuing increases in annual emissions, but at a lower trajectory than the newer scenario identified above as having “high” emissions. Other previous-generation scenarios used for the projections shown in Figure 7 on page 18 include a single medium-level scenario and a “medium-low” scenario that assumes slowly increasing rates of annual emissions.[23]

3. PRECIPITATION

The amount of precipitation falling in an area obviously is important to its water and snow resources. Less obvious but also important in the headwaters region is that a major increase in precipitation would be needed to cancel out the ways that higher temperatures otherwise could reduce water and snow resources.[24] Climate models are mixed, however, about whether there will be increases or decreases in precipitation in Colorado, and only a few suggest precipitation increases of even six to nine percent.

What Has Happened

For statewide precipitation amounts in Colorado, there are no long-term trends of change. Of the nine high-quality representative weather stations analyzed by Western Water Assessment in 2014 (see page 3), none had a statistically significant trend (for either an increase or a decrease) over 100, 50, or 30 years.[25] Instead, year-to-year and decade-to-decade variability dominates, with annual precipitation amounts varying by factors of three or four.[26]

What Could Happen

Precipitation amounts

Projections from climate models vary on how climate change may affect total precipitation amounts in Colorado, including on whether precipitation will increase or decrease.[27] (By contrast, temperature projections are in much greater agreement). Colorado lies between areas where precipitation projections are more consistent. For the very northern part of Colorado and even more so for areas farther north, most projections are for increases in annual precipitation. For areas south and especially to the southwest of Colorado, most projections are for decreases.

For Colorado, the statewide averages of the varied projections, across all emission scenarios, are for small increases in precipitation amounts, as shown in Table 4 below.

Projected Changes in Statewide Precipitation
Comparisons to 1971–2000 Averages

Time Period	High Emissions	Medium #1 Emissions	Medium #2 Emissions	Very Low Emissions
2035–2064	+2% (-3% to +8%)	+1% (-3% to +6%)	+1% (-6% to +6%)	+3% (-3% to +9%)
2055–2084	+1% (-7% to +9%)	+2% (-5% to +8%)	+3% (-4% to +8%)	+3% (-3% to +9%)

Table 4. Projected changes in Colorado statewide average precipitation amounts per year, compared to 1971–2000 levels, from the latest global climate models and emission scenarios, for four alternative scenarios of future levels of heat-trapping emissions (see page 8). For each time period/scenario pairing, the average of projections is shown in the top row and the range of the middle 80 percent of the projections in the bottom row, in parentheses. Analysis by Western Water Assessment, University of Colorado, Boulder.[28]

As Table 4 shows, the median projections for all four emission scenarios are for slight increases in statewide precipitation, both in mid-century and late in the century. There is variation, however, among individual projections, with the middle 80 percent of the projections including both projected decreases and projected increases for all scenarios and for both time periods.

The upper end of the precipitation projections in Table 4 is worthy of particular attention because future temperature increases are likely to reduce water flows unless counteracted by large precipitation increases (see page 15). The high end of the middle 80 percent of all individual projections is for six to nine percent increases, depending on future emissions and the time period. This means that only 10 percent of all projections—the ones above the middle 80 percent—project increases larger than six to nine percent. This does not offer much hope of precipitation increases large enough to cancel out the effects on water supplies of higher temperatures.

Seasonal precipitation

For winter, most climate projections across all four current emission scenarios indicate there will be an increase in statewide seasonal precipitation, both in mid-century (2035–2064) and later (2055–2084), with higher emissions generally projected to lead to larger projected increases.[29] For other seasons, projections are mixed and projected trends are not clearly associated with emission levels.

Western Water Assessment's 2014 report included projections of precipitation change for each month, for the Central Mountains and the Yampa Valley (both in the headwaters) and for six other sub-state regions, based on the medium #2 emission scenario (see page 8). For both the Central Mountains and the Yampa Valley, precipitation amounts in both January and March were projected to increase by 10 to 15 percent—in both cases, the largest projected monthly increases. Increases of 5 to 10 percent were projected for the Central Mountains in February, July, and December, and for the Yampa Valley in February, April, July, August, and December. Decreases of 5 to 10 percent were projected for the Central Mountains in May and October, and for the Yampa Valley in May and June.[30]

Extreme storms

Across most of the nation and the world, the frequency of extreme storms has increased and is projected to increase further as the climate continues changing.[31] This is expected under the basic laws of physics, as warmer air can hold more moisture. However, across the southwestern six states, including Colorado, there has been less of a trend of an increase in extreme storms, and there is greater uncertainty than elsewhere in the nation about the extent to which extreme storms will become more frequent.

There has been no analysis focused on the headwaters counties, or more broadly for the Colorado mountains, of what climate models project for local or regional increases in extreme storms. The location closest in elevation and proximity to the headwaters counties for which such localized projections of future precipitation have been analyzed is the same area of mountains and foothills of Boulder County referred to on page 6, considered in the same Rocky Mountain Climate Organization report for the Colorado Department of Local Affairs referred to on that page. That analysis suggests that for that area of Boulder County mountains, the frequency of heavy storms (those with a half an inch or more of liquid precipitation in a day, whether as rainfall or snowfall) could increase. The median projections based on high future heat-trapping emissions are for a 16 percent increase in the frequency of heavy storms by mid-century and for a 36 percent increase late in the century. By contrast, the frequency of everyday storms, with less than a quarter-inch of precipitation in a day, would be essentially unchanged.[32]

Two important caveats about these projections, however, are in order. The first is that individual projections of such specific types of events vary widely, much more than for projections of annual precipitation amounts events (which themselves also vary, as shown in Table 4 on the previous page). Second, the Boulder County location analyzed in this report is located east of the Continental Divide, while the headwaters counties are all on the Western Slope. As is well understood in Colorado, storm patterns can be very different on either side of the Divide. Still, these are the specific, localized projections for the area closest to the headwaters counties and may be somewhat suggestive of future changes that could occur there.

4. WATER AND SNOW

It is now "well documented" that there has been "profound change in the hydrology of snowmelt-driven flows in the western United States."[33] Projections based on further climate change indicate that future changes could be even more profound.[34]

What Has Happened

In pioneering studies published in the early years of this century, scientists first reported changes in the West's snow and water resources, which appeared to be linked to the unfolding alteration of the climate. Since then, study after study has confirmed these results, they now have been clearly linked to climate change, and some similar results have been found in Colorado, too.

Snowfall versus rainfall

One change in western hydrology that has occurred in recent times is a shift in winter precipitation, with less falling as snow and more as rain.[35] This was first established in 2006 when a study documented that from 1949 through 2004 there were significant trends at three-quarters of 200 studied sites in western mountains of less winter precipitation falling as snow and more falling as rain.[36] The greatest changes were at lower-elevation sites, where changes of a few degrees would more often push temperatures above freezing.

Snowpacks

About the same time, an analysis of snowpack measurement sites across the West showed that snowpack levels had declined at most of those sites from 1950 to 1997, again with the greatest decreases at lower elevations.[37] The scientists who did this analysis concluded, "the West's snow resources are already declining as Earth's climate warms." This study has been followed by many others documenting similar results.[38] Recently, several studies statistically linked the changes to human-caused climate change, through formal, statistical attribution analyses.[39]

These West-wide studies often showed no change, or less of an effect, in Colorado's mountains, which generally are higher in elevation and have colder temperatures than in other parts of the West.[40] In its 2014 report on climate change in Colorado, Western Water Assessment assessed records over the full history of the state's snowpack measurement sites and found no statistically significant trends of increases or decreases in snowpacks, either for the most recent 30 years or for the most recent 50 years.[41]

For this report, the Rocky Mountain Climate Organization similarly analyzed April 1 snowpack levels at the 18 snowpack measurement sites in the headwaters counties that have records going back to at least 1961 and no more than five years of missing data since then.[42] Consistent with the statewide results referred to above, we found no significant trend of either decrease or increase in snowpack values over the last 30 years (1988 through 2017) or 50 years (1968 through 2017).

In a new analysis for this report, the Rocky Mountain Climate Organization found no trends in the headwaters counties that local snowpacks have changed. This is consistent with an earlier, broader study done for the Colorado Water Conservation Board.

However, a more sophisticated study by a U.S. Geological Survey scientist found that annual maximum levels of Colorado snowpacks have declined by one-fifth over the 29 years ending in 2007.[43] In its 2014 report, Western Water Assessment acknowledged that the difference between WWA not detecting a trend and the USGS scientist finding one may result from the different method of statistical analysis he used, which is "more sensitive" in detecting trends than the linear regression used by WWA (and also by RMCO in our new but geographically limited analysis for this report).[44]

Snowmelt timing

In 2004, a study first documented that across most of the West's snowmelt-dominated rivers and streams the timing of snowmelt and peak flows had become earlier, with peak flows coming 10 to 30 days earlier in many cases.[45] Again, the changes were greater at low elevations than in Colorado. However, the study by the USGS scientist referred to on the previous page clearly demonstrated that the timing of snowmelt and peak runoff has shifted earlier in the spring by 1–4 weeks across Colorado's river basins over the 29 years through 2007.[46] Thirteen of 14 sub-state regions had significant trends toward earlier snowmelt, and (surprisingly) the trends were not significantly related to elevation.

Across Colorado, spring snowmelt now comes one to four weeks earlier than it did about three decades ago.

In portions of the Upper Colorado River Basin, especially in the San Juan Mountains, a further contributor to earlier runoff is windblown desert dust, which appears to be increasing because of human activities.[47] Dust that settles on snow reduces its reflectivity and accelerates snowmelt.

Stream flow and water supplies

In the six states (including Colorado) comprising the Southwest region for the U.S. government's national climate assessments, river flows across the region generally declined from 1901 through 2008, making this the only such region (of six regions in the contiguous United States) where flows have diminished.[48] In 2000–2014, the Colorado River had its lowest flows in more than a century, about 19 percent below the long-term average flow.[49] From 1999 to 2005, Colorado River water stored at Lake Powell fell from 99 percent of capacity to 33 percent, falling more quickly than an analysis of previous droughts suggested was possible.[50]

Recent high temperatures have been identified as playing an unprecedented role in reducing Colorado River flows, according to three recent studies. The first study concluded that abnormally high temperature (1.6° above the 20th century average) accounted for one-sixth to one-half of the Colorado River's shortfall in 2000–2014.[51] Previous comparable low flows, the study found, were driven by a lack of precipitation, not high temperatures.

A second study assessed the factors contributing to six major droughts in the Colorado River basin over the past century.[52] This study found that recent droughts have been amplified by higher temperatures that exacerbate the effects of relatively modest precipitation deficits, with the latest drought driven by the smallest decline in precipitation but the largest increase in temperature.

Still a third study estimated that higher temperatures in the Upper Colorado River Basin have, by themselves, reduced the river's flows by seven percent.[53]

High temperatures already have reduced Colorado River flows. Water levels now depend on how hot a year is, not just on how wet it is.

Water Demand

It is widely recognized that higher temperatures increase the need for water for nearly all types of water use, including uses for landscapes, crops, livestock, some industrial uses, and also increase water take-up by natural vegetation and evaporative losses from reservoirs and other water bodies.[54] So far, however, there has been relatively little analysis of the extent to which water demands have actually increased in recent years. (By contrast, changes in water supplies are much more studied.)

One exception is the U.S. Bureau of Reclamation's study of the Colorado River, which reported that from 1971 to 1999 agricultural uses of Colorado River water grew by 4 percent, consuming another 300,000 acre-feet per year.[55] (An acre-foot is the water needed to cover one acre to a depth of one foot—roughly enough to supply two families for a year.) Municipal and industrial uses grew by 57 percent, consuming another 800,000 acre-feet, and reservoir evaporation losses grew by 35 percent, consuming another 600,000 acre-feet. Of these changes, though, only the reservoir losses would have resulted solely from temperature increases.

What Could Happen

Snowfall versus rainfall

The U.S. government's fourth national climate assessment report, published in November 2017, declares, "Reduced U.S. snowfall accumulations in much warmer future climates are virtually certain as frozen precipitation is replaced by rain"—regardless of whether there are changes in total winter precipitation amounts.[56]

One recent study of changes from snowfall to rainfall includes results broken out for individual watersheds across the West.[57] The projections covering three watersheds in the headwaters counties are shown in Figure 5 below. As it indicates, if heat-trapping emissions continue increasing at a high rate (the assumption on which these projections are based), the share of winter precipitation falling entirely as snow is projected to decrease sharply.

Snowfall as Share of Winter Precipitation

Projections with high emissions

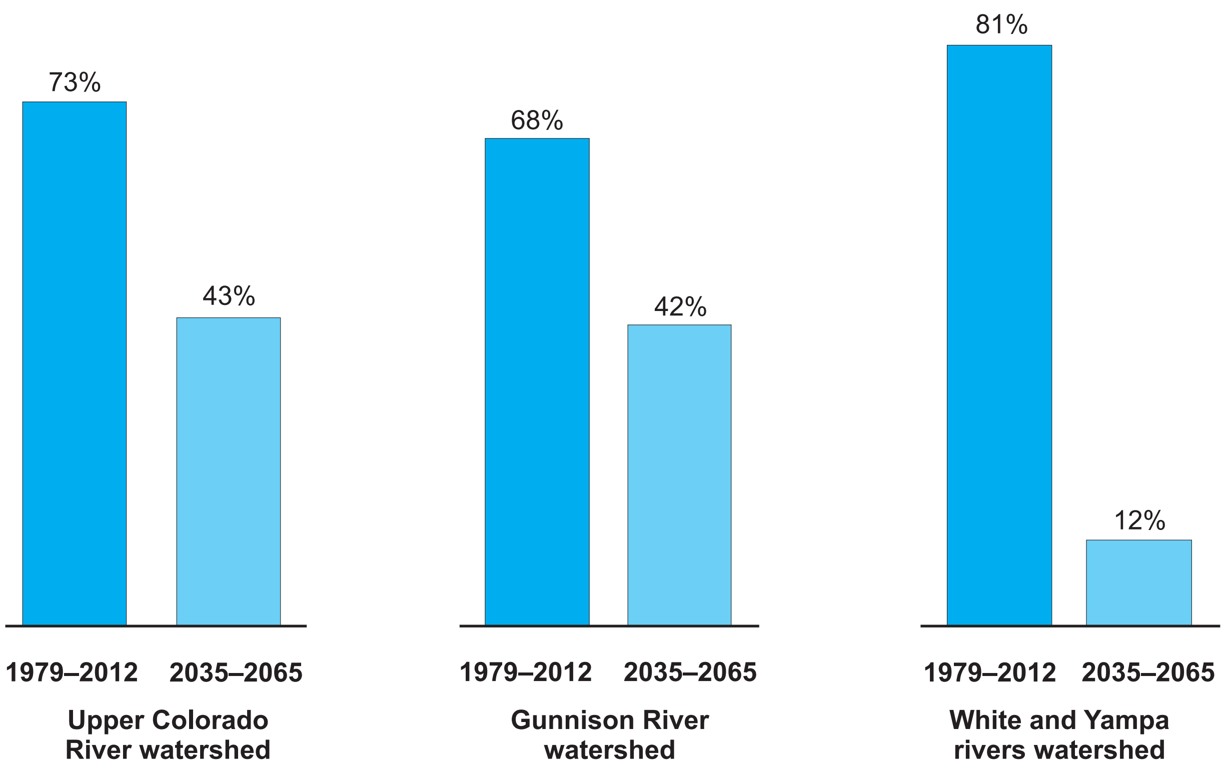

Figure 5. The share of winter precipitation falling as all snowfall in the indicated watersheds. For 2035–2065, shown are averages of 20 projections based on a high rate of future heat-trapping emissions (see page 8). The remaining share of winter precipitation is either mixed snowfall/rainfall or all rainfall. Data from Klos (2017).[58] The watersheds are as defined by the U.S. Geological Survey.[59] The Upper Colorado River watershed is of the main stem of the Colorado River in Colorado and its immediate tributaries. The White and Yampa watershed contains the drainages of both rivers, and the values shown are combined averages across both.

Snowpacks

The U.S. government's fourth national climate assessment report also declares it "virtually certain" that snowpacks in the nation will shrink in the future,[60] and in support cites two particular studies (out of several[61]) projecting smaller future snowpacks. The first cited study projects changes in snowpacks for each of the West's major mountain ranges, assuming continued high increases in future levels of heat-trapping emissions. For the Rocky Mountains, the projections are that the snow-water equivalent of all winter snow will decline by 17 percent by mid-century and by 65 percent by the end of the century, compared to late 20th century levels.[62]

The other set of projections called out in the 2017 national assessment is for future statewide spring snowpacks with future medium-high levels of heat-trapping emissions (see page 8) for the six states shown in Figure 6 below.[63] For Colorado, the average projections (of multiple models) are that spring snowpacks will be 13 percent smaller in 2041–2070 and 26 percent smaller in 2070–2099, compared to late in the 20th century.

Projected Snowpacks

Projections with medium-high future emissions
Comparisons to 1971–2000

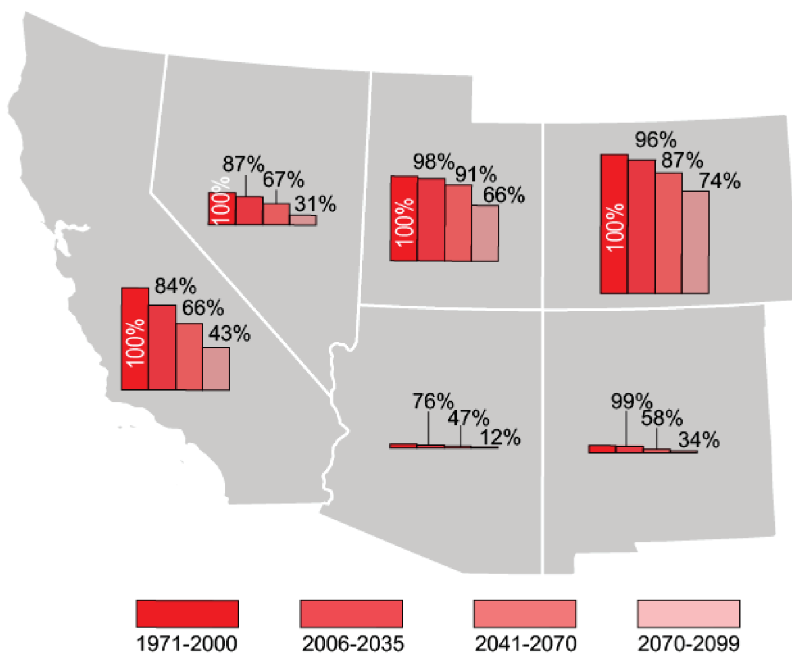

Figure 6. Projected average statewide snowpack, measured as snow water equivalent (the amount of water held in a volume of snow), based on medium-high future heat-trapping emissions (see page 8), and expressed in percent change from 1971–2000 levels. Column heights are in proportion to the amount of snow each state contributes to the regional total; thus, the columns are highest for Colorado, which contributes the most to region-wide snowpack, and the columns are smallest for Arizona, which contributes the least. The figure is from the third national climate assessment, illustrating data from the Scripps Institution of Oceanography.[64]

One scientific projection is that Colorado's average statewide snowpack could decline by 13 percent by 2041–2070, and by twice that later in the century.

Snowmelt timing

One of the most likely impacts of continued climate change is a continued shift in the timing of runoff to earlier in the year.[65] Studies project that peak runoff will shift up to 2–3 weeks earlier by mid-century.[66]

One study suggests that increased deposition of dust on snow could double the shift of snowmelt timing, to a total of as much as six weeks earlier than historically.[67]

> "Runoff timing is particularly sensitive to warming, and nearly all projections, even ones with increased precipitation, show the peak of runoff shifting earlier, with the extent of that shift ranging from 1–3 weeks by 2050."
>
> *Western Water Assessment, University of Colorado*[68]

Stream flow and water supplies

Perhaps most troubling of all impacts on western water resources is that climate change may reduce overall flows of rivers in the arid and semi-arid West, continuing the recent trends documented earlier in this report.

Even with the uncertainty regarding future precipitation levels, projected future temperature increases would tend to reduce streamflows, as higher temperatures cause greater direct losses of water from snow and ice into the atmosphere, without going through a liquid state (a process called sublimation) and from evaporative losses from lakes, reservoirs, streams, irrigation ditches, soils, and vegetation.[69] This would continue the trends already documented for the Colorado River (see page 12). To overcome these effects, large increases in precipitation amounts would be required.[70] However, most climate-change-based projections suggest that large precipitation increases will not occur (see pages 9–10) and that streamflows will decrease across all or nearly all of the state's water basins.[71]

Unlike with respect to snowpacks, for which Colorado may fare better than other western states, our state is highly vulnerable to future losses of stream flow and water supplies. According to an analysis by the U.S. Bureau of Reclamation of the eight major river systems where the Bureau operates, both the Colorado River and the Rio Grande are likely to have their flows reduced by climate change, while the other six rivers are likely to see little change or increased flows.[72]

> "Basins in the southwestern U.S. and southern Rockies (for example, the Rio Grande and Colorado River basins) are projected to experience gradual runoff declines during this century."
>
> *Third National Climate Assessment*[73]

In the headwaters counties, the greatest local impact of future reductions in stream flow would be if those reductions led to water use curtailments, locally and across much of Colorado, to comply with the Colorado River Compact. That potential impact is addressed in the next section.

Effects of changes in forest cover

Studies of past tree harvesting and bark-beetle infestations show that widespread tree mortality increases total runoff and accelerates the timing of runoff, as a result of changes in snow accumulation, snowmelt, and water uptake by trees, creating an expectation that recent widespread insect infestations could change future runoff.[74] Recent studies, however, have failed to detect any such changes. One projection suggests that future infestations could increase the amount of runoff by about 5 to 10 percent but not change its timing.

Future forest cover in Colorado's mountains could also be reduced by increased wildfires (see page 27), increased tree mortality from future heat and drought, and loss of future climatic suitability for the tree species now widespread in Rocky Mountain forests.[75] There apparently have not been studies documenting the extent to which changes in forest cover driven by those factors could affect runoff.

Flooding

In snowmelt-dominated rivers, flooding usually results from heavy rainfall falling on melting snow, or from a rapid springtime warm-up leading to sudden snowmelt.[76] For the six-state Southwest region considered in U.S. government climate assessments, flooding is generally expected to increase.[77] For Colorado mountains, however, there are no specific projections of the extent (if any) to which more substantial or more frequent flooding may occur.

Water demand

The higher temperatures projected to come with further climate change are likely to increase demands for nearly all types of water uses.[78]

Climate-change-driven impacts on water demand "may be as or more important than changes to water supply," according to Western Water Assessment.[79] Higher temperatures would tend to increase the consumption of water by plants—crops, native vegetation, yards, and other landscaping. Lower summer precipitation levels, as projected by most models, would aggravate this, by increasing the need for supplemental water for crops and landscaping.

The Colorado Water Conservation Board commissioned an analysis of future water availability from the Colorado River that included an assessment of climate change impacts on agriculture on the Western Slope.[80] (This is the same study that included the temperature projections shown in Table 2 on page 6.) That study extrapolated projected longer growing seasons into changes in crop irrigation requirements for pasture grass, the primary agricultural crop on the Western Slope, at 14 locations, for two time periods—2025–2054 and 2055–2084. Projections were made using five separate climate model/emission scenario pairings, chosen in an attempt to cover the middle 80 percent of all available such pairings on a scale of how hot and dry they are. The projected changes in crop water demands, expressed as changes from historic values for 1950–2005, are:

- For 2025–2054, an average of a 19 percent increase, with the five projections ranging from increases of 8 percent to 29 percent;
- For 2055–2084, an average of a 32 percent increase (range: from a 31 to a 43 percent increase).

Climate change impacts on water demands "may be as or more important than changes to water supply."

Western Water Assessment, University of Colorado[81]

Other waters users besides farms are also expected to use more water in a hotter future. One important example among industrial users is coal-fired power plants, since they use water for cooling and that use is expected to increase as temperatures rise.[82] The headwaters counties include one coal-fired, water-cooled plant, the Hayden plant in Routt County.

Drought

Across the American Southwest including Colorado, drought conditions are expected to become more frequent and intense than in recent times.[83] If large increases in average precipitation were to materialize, the impacts of droughts could be counteracted. But only the wettest 10 percent of all projections suggest increases in precipitation of just six to nine percent or more (see pages 9–10). And the models that do project decreases in streamflow also suggest that stretches of consecutive years with below-average streamflow will become more frequent, intense, and long-lasting.

Analysis of tree-ring records that show tree growth over time indicates that in pre-historic times the Colorado River basin has experienced droughts lasting for decades at a time, longer than those that have been experienced since European settlement of the region. It is reasonable to assume that such a mega-drought could reoccur in the future. If one does, and operates atop new normals of reduced streamflow and increased temperatures, then it could be even more severe and consequential than the mega-droughts of the past.[84]

5. WATER SHORTAGES

What Has Happened

The West's recent hotter and drier conditions have already reduced water flows, as explained in the previous section. So far, though, unusual water restrictions in Colorado have mostly been avoided.[85]

What Could Happen

In the headwaters counties, as anywhere in Colorado, in times of water shortages, municipal water utilities may impose restrictions on local water use by households and other customers. Secondly, under the fundamental principle of western water law, holders of individual junior (newer) water rights (often, farmers or ranchers) may have to curtail their water use if needed to allow those with senior (older) water rights to continue exercising their full, historic use of water. Both types of water restrictions become more likely as water supplies fall, as projected to happen with climate change.

Colorado River Compact restrictions

Potentially the most significant water restrictions in the headwaters counties could be curtailments on water usage triggered by the Colorado River Compact. Any such restrictions would not be locally targeted just at the headwaters area, and would instead be shared with others across Colorado and other Upper Basin states. But any compact-triggered restrictions, even if region-wide, still would matter in the headwaters counties.

The Colorado River Compact allocates river water among the states in the river basin.[86] In brief summary, under the compact:

- The basin is divided into an Upper Basin, above Lees Ferry, Arizona, and a Lower Basin, below that. Each basin is granted a right to the consumptive use of up to 7.5 million acre-feet of water per year, and the Lower Basin may increase its usage by up to an additional 1 million acre-feet per year.
- The Upper Basin states of Colorado, New Mexico, Utah and Wyoming may not cause the flow passing Lees Ferry to be depleted below 75 million acre-feet in any consecutive 10-year period.
- In addition, the Upper Basin must deliver, if needed, one half of the water necessary to fulfill a treaty with Mexico—an amount that can vary, particularly in times of extraordinary drought.

It is not clear what would happen if the Upper Basin's use of the water to which it is entitled under one provision of the compact causes the flow at Lees Ferry to fall below the level guaranteed to the Lower Basin by another provision. It is clear, however, that the effects of climate change on both natural river flows and on water demands in the Upper Basin increase the chance that the flows at Lees Ferry could fall below the amounts promised to the Lower Basin and Mexico.

What could happen under the Colorado River Compact could be similar to what happens under the familiar operation of western water law. Those in the Upper Basin using Colorado River water, whether in-basin or through a transbasin diversion, could face water restrictions to the extent necessary to keep Colorado River flows at Lees Ferry from falling too low—much as junior water rights can be restricted to satisfy senior rights.

How likely is a compact-triggered curtailment? In the Colorado River basin, recent uses and losses (from evaporation and system inefficiencies) of river water have exceeded the river flows for the first time. By 1999, the combination of water uses, losses, and deliveries to Mexico had reached 16 million acre-feet per year, compared with historic average flows of 15 million acre-feet per year.[87] Reservoir releases of stored water have, so far, been sufficient to overcome this deficit and avoid compact issues. But the population using Colorado River water (now about 40 million people) is expected to continue growing. And climate change impacts are projected to increase, too (see Section 4). According to the U.S. Bureau of Reclamation, by mid-century the average projected impacts on both Colorado River water supplies and the demand for that water would push water demand another 1.7 million to 2 million acre-feet above water supplies. That climate change effect would be equivalent to an 11 percent to 13 percent reduction in the river's historic average flow.[88]

The extent to which Colorado River flows decrease and demand for that water increases depends in part on future levels of heat-trapping emissions. The Bureau of Reclamation in its Colorado River basin water supply and demand study did not break out projected increases in *demands* by emission scenario. (It seems inevitable, though, that more emissions and therefore higher temperature increases—see Section 2 of this report—will increase water demand more than lower emissions and smaller temperature increases.) The Reclamation study did, though, break out its projections for future water *supplies* by different emission scenarios, as shown in Figure 7 below.[89]

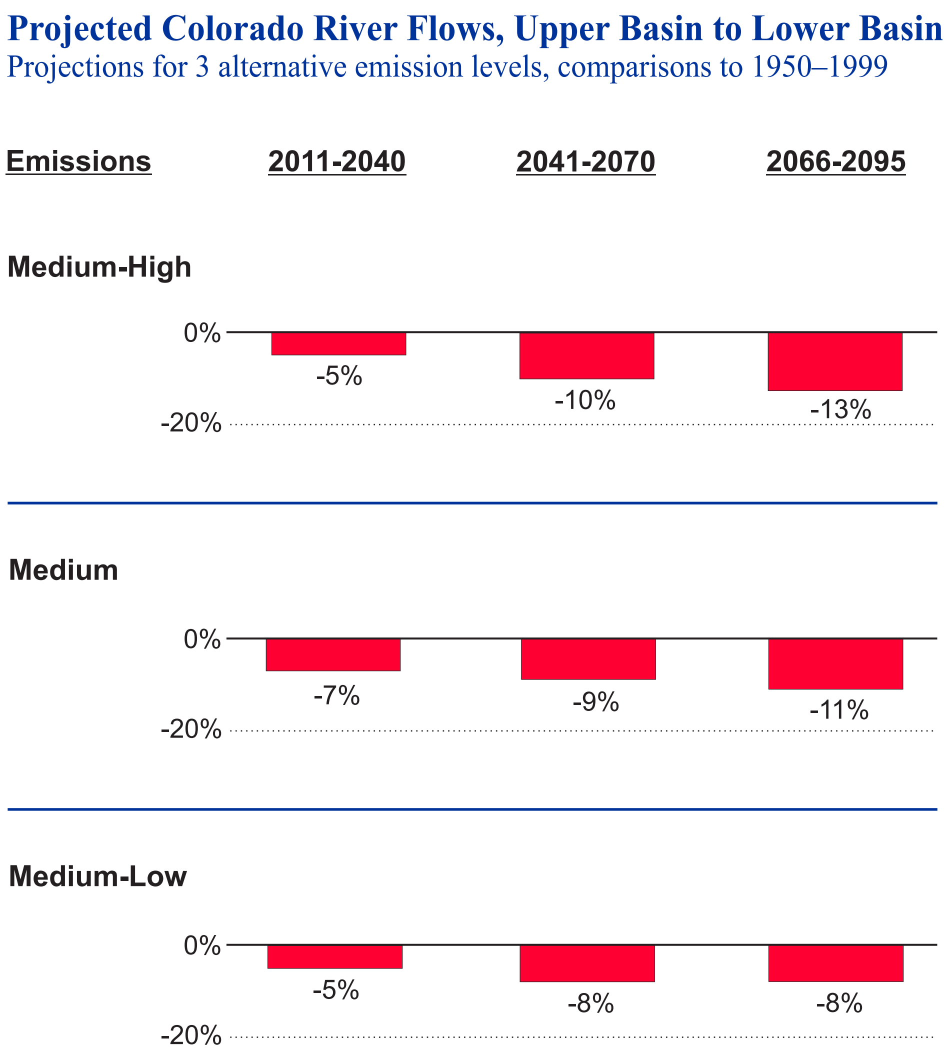

Figure 7. Projected change in Colorado River natural flows (without storage or diversions) at Lees Ferry, Arizona, showing averages of projections for each of three alternative scenarios of future heat-trapping emissions, compared to 1950 through 1999 historic flows. Total projections include 36 for the medium-high scenario, 39 for the medium, and 37 for the medium-low (see page 8). Despite the labels used here, the "medium" scenario has the highest level of emissions in the first time period (see Figure 4A on page 8); consistently across the projections, therefore, higher emissions are associated with greater flow reductions. As these projections are of modeled natural flow without storage or diversions, changes in water demands (see page 16) are not factored into these projections. Data source: U.S. Bureau of Reclamation.[90]

To translate the projected percentage reductions in Figure 7 above into water amounts, the projected 10 percent reduction in Colorado River flows for 2041–2070 with medium-high emissions, for example, would mean the loss of about 1.5 million acre-feet per year.

“By late century, the differences between simulated streamflows across emission scenarios become substantially larger, reflecting both the response time of the climate system and the higher emissions.”

U.S. Bureau of Reclamation[91]

For the state of Colorado’s contribution to future Colorado River flows, the best information to date comes from a study done for the Colorado Water Conservation Board.[92] That study used a representative sample of five pairings of climate models and possible future levels of future heat-trapping emissions as inputs to a model of Colorado River flows. The five pairings were chosen to reflect the range of the middle 80 percent of the projected flow changes that likely would result from the full suite of 112 such pairings used in the Bureau of Reclamation’s study. As with the Reclamation projections shown in Figure 7 on the previous page, the projections done for the CWCB address climate change’s impacts only on water supplies, not also on demands for water use.

The study done for the CWCB identifies river flow projections for many locations on the Western Slope. The projection for the Colorado River main stem near the Colorado-Utah state line is most important with respect to the Colorado River Compact, because that is our state’s largest contribution to flows at Lees Ferry. The projections for future flows at that point are shown in Figure 8 below.

Projected Colorado River Flows, Colorado to Utah

Projections for 5 representative possible futures, comparisons to 1950-2005

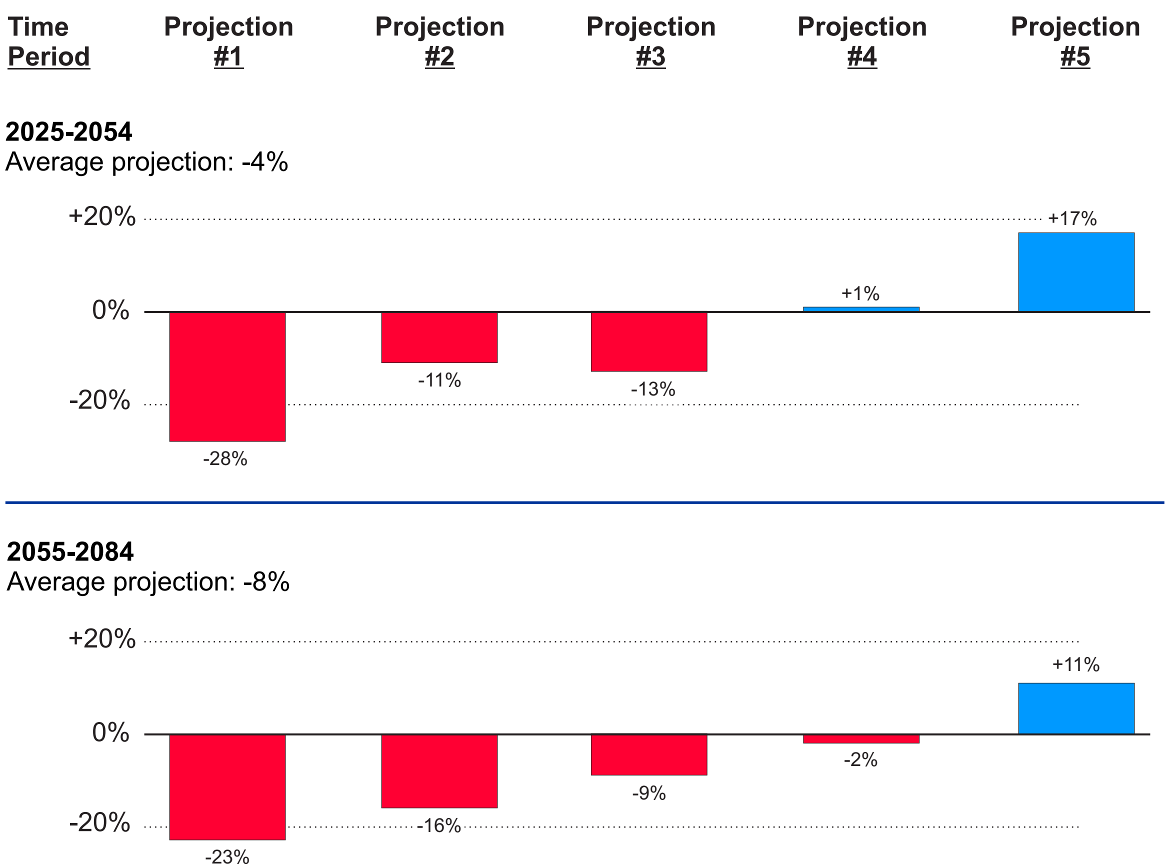

Figure 8. Projected changes in modeled natural flows (without storage or diversions) of the Colorado River near the Colorado-Utah state line, compared with historical values for 1950-2005. Results from five climate model/emission scenario combinations, chosen to approximate the range of the middle 80 percent of 112 such combinations from one database. Source: AECOM.[93]

As Figure 8 on the previous page shows, of the five representative projections for Colorado River flows into Utah, at least three suggest future flow reductions. Only one scenario, chosen to represent a warm (not hot) and wet future, is projected to lead to an increase in flows.

The Yampa River also drains portions of the headwaters counties and flows separately out of Colorado and into Utah (before joining the Green River, which in turn later merges with the Colorado River). The Yampa is the state of Colorado's second largest contributor to Upper Colorado River Basin flows into the Lower Basin. For the Yampa, the projections corresponding to those for the main stem of the Colorado (shown in Figure 8 on the previous page), are illustrated in Figure 9 below.

Projected Yampa River Flows, Colorado to Utah

Projections for 5 representative possible futures, comparisons to 1950-2005

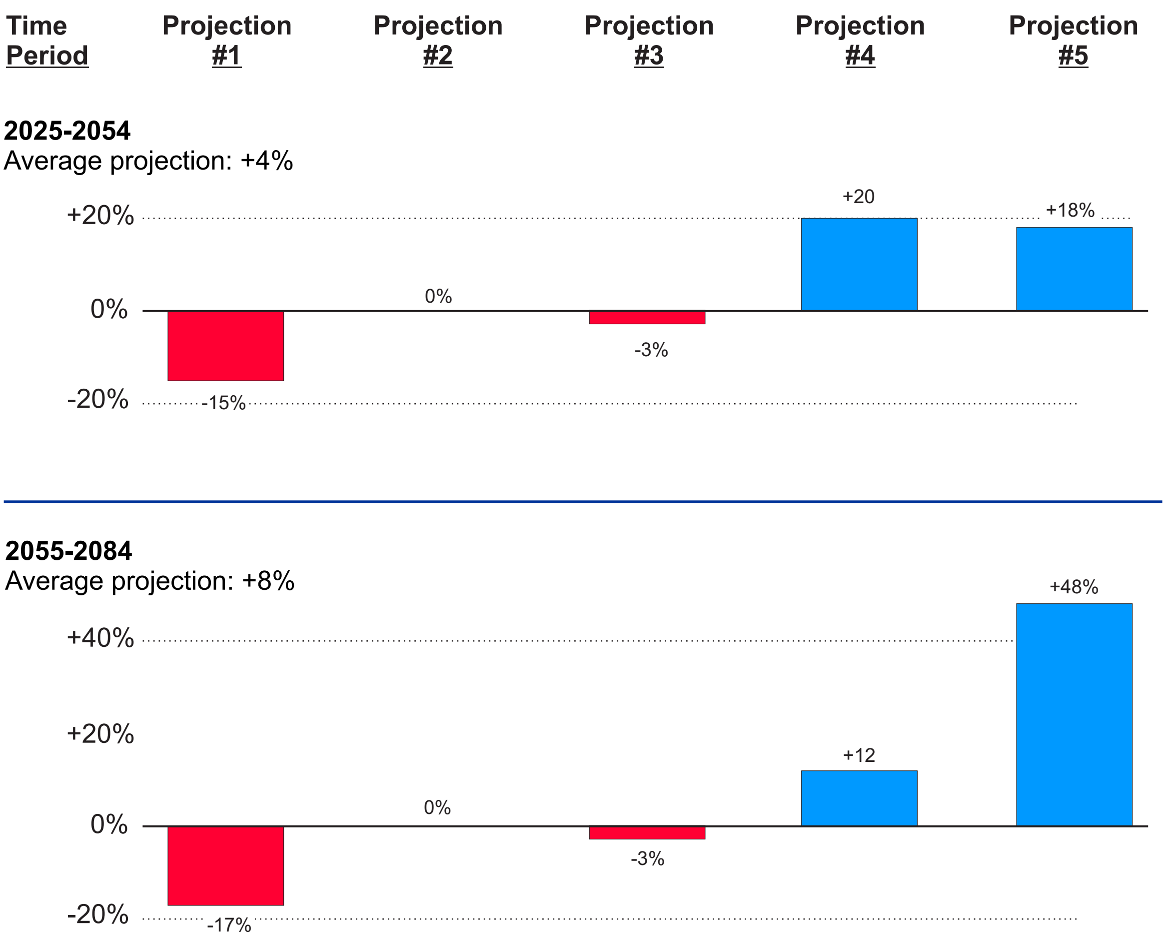

Figure 9. As Figure 8, but with respect to the Yampa River at its last modeled point before flowing from Colorado into Utah (at Deerlodge Park, where the Yampa enters Dinosaur National Monument, which is below virtually all diversions in Colorado). Source: AECOM.[94]

As is readily evident from a comparison of figures 8 and 9, this study suggests that the main stem of the Colorado River as it flows from Colorado into Utah is more likely to see reductions in river flows than the Yampa River as it flows into Utah. This is consistent with precipitation projections from the same climate change models used for the flow projections, which suggest that northernmost Colorado may see a precipitation increase in the future (see page 9.)

Future temperature increases, independent of future precipitation amounts, could be more important in affecting water supplies in the Colorado River basin than elsewhere. As indicated on page 12, researchers have already documented that temperature increases, not just precipitation amounts, contribute to lower flows of the Colorado River. Another study projects that a given future temperature increase would lead to greater flow reductions in the Colorado River basin than in the Columbia River basin or in northern or southern Sierra Nevada basins.[95] This does not bode well for future Colorado River flows, as climate models are very consistent in projecting continuing and increasing further temperature increases. According to still another study, reductions in Colorado River flows resulting simply from further temperature increases may exceed 20 percent by mid-century and 35 percent by the end of the century.[96] This suggests that future climate-change impacts on the Colorado River could be greater than the current assumptions illustrated by Figure 7 on page 18.

What Is At Stake

If the Lower Basin states do not receive their entitled river flows under the Colorado River Compact, they could issue a compact "call" for the Upper Basin states to release more water. This has never happened, and nobody knows exactly what actions, potentially including water restrictions across much of Colorado, could result. But Coloradans, including those in headwaters counties, could face unprecedented limits on their abilities to exercise their current water rights (other than rights that pre-date the compact, which are protected by it). Any such restrictions could be triggered even if there appears to be plenty of water in our rivers and streams to meet local needs, because the flows that could trigger the restrictions are those well downstream, at Lees Ferry, Arizona. And if restrictions were to be imposed across the Upper Basin, Colorado apparently would have to do what would be necessary to provide more than half of the Upper Basin's required delivery to the Lower Basin.[97]

"There is concern over a potential compact shortage during severe and sustained drought and the potential effects to in-basin supplies."

Colorado's Water Plan[98]

6. WINTER RECREATION AND TOURISM

What Has Happened

With no clear evidence of any change yet in Colorado snowpacks (see page 11), it is not surprising that there is no indication yet of any climate-change-driven trend in conditions for skiing in Colorado. As many as 13 million downhill skiers and snowboarders continue to visit the state's resorts every year, with numbers fluctuating depending on a variety of factors, including the strength of the national economy and a winter's snowfall.[99]

What Could Happen

If Colorado snowpacks decline as projected (see page 14), Colorado's skiing certainly could suffer.

The impacts, however, could be affected by other factors besides the amount of snow. In particular, ski resorts in other states are usually at lower elevations and may more quickly experience significant impacts from climate change, putting the Colorado resorts at a competitive advantage that would help to keep them economically viable.[100] In the 2005–2006 season, for instance, low snowfall in the Southwest brought ski visits in New Mexico down by almost 50 percent and in Arizona down by more than 80 percent compared to the previous year.[101] Colorado's skiing, however, was not affected in a similar fashion.

A recent study made projections of changes in national skiing (both alpine and cross country) and snowmobiling recreational activity for two different possible levels of heat-trapping emissions, using five climate models for each scenario.[102] The projections were based on a range of climate-related factors, including local snow accumulation, season length, and, for downhill skiing and snowboarding, conditions suitable for snowmaking. The average projected changes in the winter recreation visits for mid-century and late century are shown in Table 5 below.

Projected National Changes in Winter Recreation Visits

Comparisons to 2006–2007 through 2015–2016 seasons

	2040–2059	2080–2099
High emissions		
Downhill skiing	- 35%	- 65%
Cross-country skiing	- 24%	- 57%
Snowmobiling	- 30%	- 64%
Medium #2 emissions		
Downhill skiing	- 28%	- 37%
Cross-country skiing	- 18%	-26%
Snowmobiling	- 28%	- 32%

Table 5. Projected changes in winter recreational visits (defined as one person for one day) for skiing and snowmobiling at 247 winter recreation locations across the United States. Shown are averages of projections from five climate models, for two emission scenarios (see page 8), and for mid-century and late-century time periods, compared to average values from 10 recent seasons. The baseline visitation numbers are 56 million downhill skiing visits, 3.6 million cross country skiing visits, and 2.8 million snowmobiling visits. The projections are based on an assumed constant population over time, and an assumption that all businesses operating ski resorts remain in operation through the century. Data source: Wobus and others (2017).[103]

Importantly, the projections in Table 5 are for changes in skiing and snowmobiling activity across the nation, not for changes in Colorado or the headwaters counties. The study presenting these projections includes figures illustrating, for example, that the projected reductions in downhill ski season length are smaller for resorts in Colorado than for most resorts in other states (as expected due to the higher elevations and colder temperatures in the Colorado mountains), but the study does not include reportable numerical values.

The first specific projection of climate change impacts on skiing in a Colorado location is in a 2006 local climate change vulnerability assessment for City of Aspen.[104] As summarized in a 2014 update to that study:

> In the 2006 Aspen Study, results . . . projected deteriorating skiing conditions on Aspen Mountain over the course of the 21st century among high, medium, and low emissions scenarios. For the highest emissions scenario considered, an end to skiing in Aspen was projected by 2100. . . . Historical observations and projected future changes in the Aspen area reinforce findings from 2006.

In the updated 2014 assessment, the Aspen Global Change Institute presented new estimated impacts on local skiing, this time based on two current-generation emission scenarios.[105] With the medium #2 emission scenario (see page 8):

- By 2030, the start of snow accumulation on Aspen Mountain could be delayed at the top of the mountain by about two weeks and at the base by one week. It could be challenging to open the resort by Thanksgiving.
- By 2100, snow accumulation at the top will be pushed back by four weeks. Opening may be pushed back to mid-December.
- In spring, when the timing of the season's end is driven more by changing visitor interest than by snow cover, adequate snow may persist long enough in the future to keep skiing going until Easter, but the quality of skiing could deteriorate and the risks of slab avalanches could increase.

By contrast, with high future emissions (see page 8), by 2100 "skiing in Aspen could be a thing of the past."[106]

Ultimately, the determining factor in how long skiing lasts will be not snow amounts but instead the economic viability of the businesses that operate the resorts—in particular, whether the season lasts long enough for them to make a profit. As one ski resort official has said, "[S]ki resorts operate in deficit until March, when we make most of our profit. If you shorten our season on either end—take away March, for example—we go out of business. The problem: a shortened season is one of the most reliable predictions of the climate modeling and science."[107]

> If emissions continue unchecked, by the end of this century "skiing in Aspen could be a thing of the past."
>
> *Aspen Global Change Institute*[108]

What Is At Stake

The headwaters counties are home to the largest concentration of skiing in the nation, with 16 downhill ski resorts, including seven of the 10 most-visited resorts in the nation—Vail (number 1), Breckenridge (2), Keystone (4), Steamboat (5), Winter Park (6), Beaver Creek (7), and Copper Mountain (9).*[109]

Although visitation numbers are not available for all individual resorts, the ski areas in the headwaters counties certainly offer most of the skiing in Colorado, which adds up to 13 million skier and snowboarder visits a year.[110] (Just the four Vail Resorts ski areas in headwaters counties—Beaver Creek, Breckenridge, Keystone, and Vail—by themselves host about 40 percent of Colorado's skiers and snowboarders.[111]) And Colorado provides nearly one-quarter of all skiing in the nation.[112]

*The other resorts in the headwaters counties are Arapahoe Basin, Aspen Buttermilk, Aspen Highlands, Aspen Mountain, Crested Butte, Granby Ranch, Howelson Hill, Snowmass, and Sunlight Mountain.

According to a 2015 study, the skiing and snowboarding industry in Colorado generates $4.8 billion in economic activity.[113] Among the details from that study are:

- Skiing and snowboarding support more than 46,000 jobs in the amusement and recreation, lodging, food services, retail, and other sectors. These jobs generate $1.9 billion per year in salaries and wages for Coloradans.
- In the 2013-2014 season, the 500,000 Coloradans who skied here were joined by more than seven million out-of-state skiers, who were responsible for 8.4 million nights of stays in hotels, motels, and other accommodations and for 8 percent of all airline passengers arriving at the Denver airport.
- The ski industry is a major contributor to state and local government revenue. Since the 2002–03 ski season, state taxable retail sales in Colorado's six leading ski counties in winter have grown by 62 percent for hotels and other accommodation services, 75 percent for food and drinking services, and 106 percent for real estate, rental, and leasing services.

As anybody familiar with real estate values in Colorado mountain communities knows, property values are higher if skiing is available nearby. One study projected that medium-high future heat-trapping emissions (see page 8) could reduce snowfall intensity enough by mid-century (2040–2059) to lower property values in ski resorts in the West.[114] The projected losses are as high as 44 to 55 percent reductions in home values in the most affected areas, but in most of Colorado (including all the headwaters counties) the projections are for declines of 14 percent or less. Again, Colorado's colder climate provides protection against the greatest impacts, but not all impacts.

> "A related economic effect of decline in the ski industry could be falling private-property values. . . . [A] significant decline in skiing, or certainly its complete demise, would mean serious economic loss to the resorts, and to the economies of communities heavily dependent on skiing."
>
> *Rocky Mountain/Great Basin Regional Climate-Change Assessment*[115]

7. WARM-SEASON RECREATION AND TOURISM

What Has Happened

Fishing, boating, rafting, and other warm-season, water-dependent outdoor recreation can be adversely affected by hot temperatures and low water levels. As yet, there is evidence of only sporadic impacts on these specific pursuits, which may serve as harbingers of future risks. For example, in 2012, a drought year, Colorado's rafting had a 17 percent decline in usage compared to the year before, and the lowest level since 2002, another drought year.[116]

(The underlying impacts on the headwaters region's foundational natural resources are beyond the scope of this report. These impacts include increases in bark beetle and other insect infestations in forests, increases in wildfires, and increases in tree mortality, all detailed in a 2014 report by the Union of Concerned Scientists and the Rocky Mountain Climate Organization, and other natural resource impacts summarized in the University of Colorado and Colorado State University's *Colorado Climate Change Vulnerability Study* (2015).[117])

What Could Happen

Trout populations, and therefore trout fishing, could be disrupted by climate change. Coldwater fish species including trout are vulnerable to stream temperatures exceeding the tolerance levels of the fish. Reduced stream flows also lead to high temperatures (as smaller bodies of water experience greater temperature increases) and restrict the ability of fish to escape to cooler waters. These changes are likely to appear first and be greater in lower-elevation, warmer waters, but depending on the extent of future changes could also occur in higher elevations.[118] Many coldwater fish including trout may be lost from lower-elevation streams. Across the West, a 47 percent loss of habitat for all trout species is projected late in the century if future heat-trapping increase at a medium-high rate, with cutthroat trout projected to decline by 28 percent in the 2040s and 58 percent by the 2080s, and rainbow trout projected to decline by 13 percent and then by 35 percent.[119] The Colorado River cutthroat trout, the only native trout subspecies left on the Western Slope, is already limited to seven percent of its historic range.[120]

Before trout are eliminated from streams, fishing can be curtailed to protect stressed fish. Colorado has not yet had any restrictions on fishing similar to those in Montana in recent years, but that state has had repeated stream closures, extensive time-of-day fishing prohibitions, and other restrictions on fishing to protect fish stressed by high water temperatures and low streamflows, with resulting declines in fishing and economic losses.[121] This suggests what could happen in Colorado in the future.

Higher temperatures can lead to more people participating in boating and rafting to escape the heat.[122] If water levels in lakes and reservoirs drop enough, though, demand for boating and other activities there may drop.[123] For rafting, the vulnerability is much greater and clearer—low river levels lead to less rafting.[124]

> "If average streamflow decreases in the future—a likely outcome across the climate projections—resulting competition for diminishing resources could impact rafting, fishing, and other recreation activities along with aquatic habitats."
>
> *Colorado Climate Change Vulnerability Study*[125]

What Is At Stake

The headwaters counties are the epicenter of Colorado's premier opportunities for warm-season outdoor recreation and tourism, which are even more important to the state's economy than winter recreation and tourism. Statewide, outdoor recreation across all four seasons generates per year:

- $28.0 billion in consumer spending,
- 229,000 direct jobs,

- $9.7 billion in wages and salaries, and
- $2.0 billion in state and local tax revenue.[126]

Although these economic benefits are statewide, they are largely driven by the headwaters counties, which contain an extraordinary collection of special places which draw local and in-state residents and out-of-state tourists. The six headwaters counties contain the following special places, all dependent on their water and snow resources:

- Rocky Mountain and Black Canyon of the Gunnison national parks;
- Arapaho, Gunnison, Routt, and White River national forests;
- Lakes and reservoirs with boating opportunities, including Blue Mesa Reservoir (Colorado's largest reservoir), Morrow Point Reservoir, and Crystal Reservoir, all part of Curecanti National Recreation Area; Grand Lake, Colorado's largest natural lake; Lake Granby, Shadow Mountain Lake, Monarch Lake, Willow Creek Reservoir and Meadow Creek Reservoir, all part of Arapaho National Recreation Area; Elkhead Reservoir; Lake Dillon; Stagecoach Reservoir; and Steamboat Lake;
- Gold medal fishing streams, including stretches of the Blue, Colorado, Fryingpan, and Gunnison rivers and of Gore Creek, plus North Delaney and Steamboat lakes.
- Stretches of the Blue, Colorado, Eagle, Gunnison, Roaring Fork, Taylor, and Yampa rivers that offer rafting; and
- Nearly half—21 out of 43—of Colorado's congressionally designated wilderness areas—the Black Canyon of the Gunnison, Byers Peak, Collegiate Peaks, Eagles Nest, Flat Tops, Fossil Ridge, Gunnison Gorge, Holy Cross, Hunter-Fryingpan, Indian Peaks, Maroon Bells-Snowmass, Mount Massive, Mount Zirkel, Never Summer, Powderhorn, Ptarmigan Peak, Raggeds, Rocky Mountain National Park, Sarvis Creek, Uncompahgre, and West Elk wilderness areas.

For a few of these areas that are under federal management, there is specific information on local usage levels and economic benefits, which powerfully illustrates how popular and economically important they are.

- The White River National Forest is the most visited national forest in the nation, with 12 million annual recreational visits—which in 2014 supported 14,300 local jobs and $460 million in income for workers and sole proprietors.[127] Much of this visitation is driven by skiing, but the national forest in 2007 had 53,425 primary visits specifically for fishing, with untold others for hiking, camping, and sightseeing. Fishing and hunting in the forest, alone, contribute $4.4 million in labor income to the local economy.[128]
- Rocky Mountain National Park in 2016 had 4,517,586 recreational visits, supporting 4,575 local jobs and adding $273 million to local economies.[129]
- Curecanti National Recreation Area in 2016 had 982,498 recreational visits, supporting 565 local jobs and adding $29 million to the local economy.[130]

> "Outdoor recreation is among our nation's largest economic sectors. From the smallest rural towns to the most densely packed cities, outdoor recreation powers a vast economic engine that creates billions in spending and millions of good-paying American jobs."
>
> *Outdoor Industry Association*[131]

8. WATER QUALITY

Across the nation, water quality is at risk to increasing air and water temperatures; more extreme storms, runoff, and floods; and lower water flows, which can making waters too hot and increase their sediment, nutrient, and contaminant concentrations.[132] In the West, including in the headwaters counties, a particular concern is how increases in wildfires can cause erosion and sedimentation that adversely affect water quality.[133]

What Has Happened

There now is clear evidence that there has been “a profound increase” in the frequency and extent of wildfires across the West, which has been documented in several studies.[134] However, there apparently has been no analysis yet of the extent to which sedimentation from wildfires may have already increased. Similarly, there apparently is no documentation of the extent to which other effects on water quality from climate change may have already occurred.

What Could Happen

Sedimentation from wildfires

Several studies have projected increases in wildfires in Colorado, which in turn could lead to increases in sedimentation and other water quality problems.[135] The wildfire projections range from about a doubling of historic area burned to more than a fivefold increase, depending on the region, time frame, methods, and assumptions for future levels of heat-trapping emissions.[136] A summary of six recent scientific projections, based on future climate change, of changes in future wildfires in regions including the Colorado mountains follows. The six scientific studies project:

- Across the Rocky Mountains region, by mid-century very large wildfires would be about five times more frequent with either medium or high future heat-trapping emissions. By the end of the century, they would stay about five times more frequent with medium emissions, or become 15 times more frequent with high emissions.[137]
- In the Southern Rocky Mountains by 2070, the area burned would increase by 3–5 times with high emissions and by 5–6 times with lower emissions. (Yes, this study actually projects greater impacts with lower emissions.)[138]
- In the Southern Rocky Mountains, a 1.8° increase in global temperature could increase the area burned nearly sevenfold.[139]
- In Rocky Mountain forests in eight states by mid-century, the area burned would increase nearly threefold.
- In Colorado by late in the century, the area burned would nearly double, compared to the 20th century.[141]
- In Colorado mountains across this century, the number of days of high fire danger would not increase significantly if humidity does not drop here—the projection from the one model used in this study.[142]

One study estimating future erosion rates in the first year following wildfires in the West projected that the southern Rocky Mountains would have higher amounts of exposed soil and lower amounts of remaining vegetation following wildfires, compared to other areas in the West, but would actually have lower erosion rates that most other areas.[143] In this study, the lower erosion rates were linked to two factors—relatively low overall precipitation and much precipitation falling as snow rather than rain, both of which limit erosion.

Another study assessing future increases in stream sedimentation from wildfires projects that in nearly 90 percent of western watersheds post-fire sedimentation will increase by at least 10 percent by 2041–2050.[144] This study assumed an unusually small change in area burned in Colorado mountains, but still projected average increases of about 10 percent to 200 percent in sedimentation in the state.

Other water quality effects

Climate change may lead to other impacts on water quality (in addition to increased sedimentation from wildfires), including:

- Decreased river and stream flows can lead to increases in in-stream concentrations of metals, sediments, nutrients and other contaminants, as the same amount of pollution would represent a higher relative concentration in less water.[145]
- Higher water temperatures can lead to production of more organic matter in waterways, requiring increased use of disinfection by-products, which must in turn be removed to meet water quality standards.[146]
- Higher water temperatures can exceed water quality standards. Colorado's standards include water temperature standards to keep water pollution discharges from raising stream temperatures so much that coldwater fish species are stressed.[147] If background stream temperatures rise in a hotter climate, permit restrictions on discharges may have to become stricter to maintain acceptable stream temperatures.

What Is At Stake

Increased sedimentation from wildfires can lead to major new costs to protect water supplies. For example, the Hayman fire of 2002 along the Front Range led to the erosion of an enormous amount of sediment into a reservoir used by Denver Water.[148] The water utility had to spend $25 million to protect its water supplies from this erosion.[149]

Two other telling examples are from the U.S. government's 2014 national climate assessment, which details the water quality effects of 2011 wildfires in Arizona and New Mexico, the largest fires in the history of those states.[150] Subsequent heavy rainstorms led to major flooding and erosion, including at least ten debris flows; evacuations of downstream recreation areas; and contamination of half of the drinking water for Albuquerque. Withdrawals from the Rio Grande to supply water to the city had to be stopped entirely for a week.

Climate-change-driven increases in water temperature could lead to more frequent, or even unprecedented, restrictions on discharges to maintain the water temperatures specified in state standards. A study by the U.S. Department of Energy has identified thermoelectric power generation facilities (of which there is one, the Hayden power plant, in the headwaters counties) as being vulnerable to such restrictions.[151] That study documented that heat waves in this century have led to water temperatures too high for discharges from power plants in at least three states, leading to curtailments of operations. In other situations, curtailments were avoided only because special exceptions from water quality standards were granted.

"Lower and more persistent low flows under drought conditions as well as higher flows during floods can worsen water quality. Increasing precipitation intensity, along with the effects of wildfires and fertilizer use, are increasing sediment, nutrient, and contaminant loads in surface waters used by downstream water users and ecosystems."

Third National Climate Assessment[152]

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