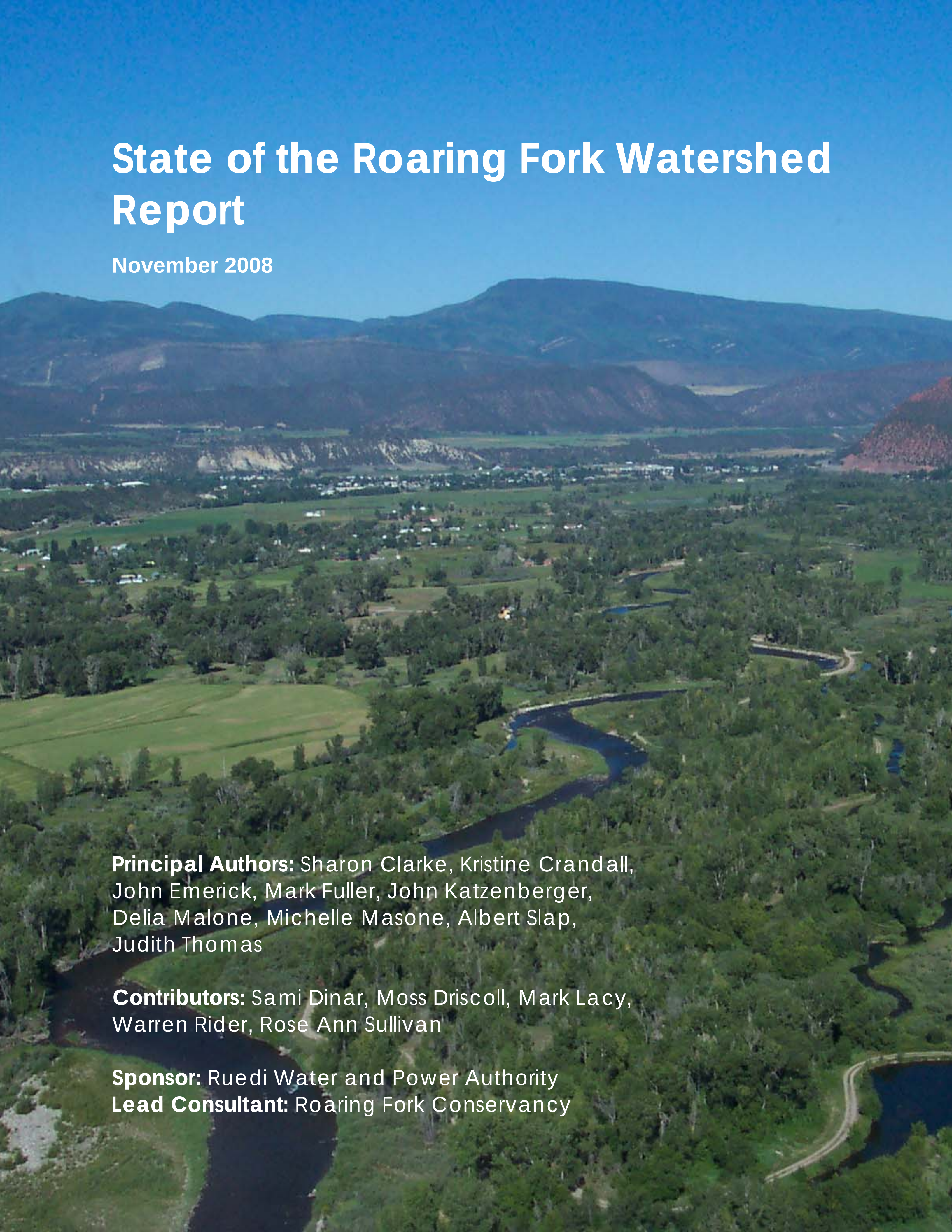
State of the Roaring Fork Watershed Report

November 2008



Principal Authors: Sharon Clarke, Kristine Crandall, John Emerick, Mark Fuller, John Katzenberger, Delia Malone, Michelle Masone, Albert Slap, Judith Thomas

Contributors: Sami Dinar, Moss Driscoll, Mark Lacy, Warren Rider, Rose Ann Sullivan

Sponsor: Ruedi Water and Power Authority
Lead Consultant: Roaring Fork Conservancy

3.5 Climate Change

Global warming from greenhouse gas (GHG) emissions and land use changes affects the temperature, precipitation, and streamflow of the Roaring Fork Watershed and the greater Colorado River Basin. These physical climate changes will impact the ecosystems and socioeconomics of the Roaring Fork Watershed. A recent review of six major studies on the Colorado River finds that stream flows will likely be reduced due to climate change (Udall, 2007). This has major significance for resource management: although demand is increasing, supply is projected to decrease. High-elevation tributaries such as the Roaring Fork River provide 85 percent of the total Colorado River Basin flow (IPCC, 2008; Milly et al., 2005). This critical water resource makes settlement in much of the Southwest possible, serving the water needs of seven U.S. states, two Mexican states, and 34 Native American tribes – a total population of 25 million that is expected to exceed 38 million by the year 2020 (Pulwarty et al., 2005; IPCC, 2008). It is imperative that a better understanding of how climate change will alter the hydrology, ecosystems, and socioeconomics of the Roaring Fork Watershed be incorporated in its emerging watershed planning process.

Present-day climate modeling techniques have limited accuracy at the scale of the Upper Colorado River Basin and even greater limitations at the scale of the Roaring Fork Watershed; however, because of the importance of the Upper Colorado River Basin to the entire Southwest, many climate modeling studies have focused on this region. During the last decade climate studies have been done for the western U.S., Colorado River Basin, Upper Colorado River Basin (Mote et al., 2005; Hamlet et al., 2005, 2007; Barnett et al., 2005; Udall, 2007; Christensen et al., 2004; Barnett et al., 2008; IPCC, 2008), and the upper part of the Roaring Fork Watershed (AGCI, 2006). These studies reflect a growing consensus on how climate change may affect these regions, and, although concerned with various spatial scales and using varying methods, they are generally consistent in their overall findings. Models show confidence in the direction of temperature change, but exhibit less confidence in projections of precipitation.

Climate research indicates that, by 2050, major droughts in the Southwest U.S. – as occurred in the 1950s – could become the norm (IPCC, 2008). One study characterizes water availability in the western U.S. as “a coming crisis” with shortages, lack of storage, and shifting demand from agricultural to urban uses (Barnett et al., 2008). As global warming unfolds over the course of the 21st century, it will give rise to greater weather and climatic extremes surpassing those planned for under existing water management framework, and will create a new set of management challenges for assessing future risk, reducing vulnerability, and devising workable watershed management plans.

The nexus of global warming, natural variability, and human population growth will put unprecedented pressure on water resources in the West in the 21st century, and set a broader context for assessing the present state of Roaring Fork Watershed and planning for the management of its future.

Key direct effects of climate change projected for the Roaring Fork Watershed are:

- Warmer temperatures,
- More precipitation as rain, with less as snow,

- Decreased snow cover and snowpack,
- Earlier snowmelt and runoff, and
- Decreased runoff.

These changes will drive secondary changes within the watershed, such as:

- Earlier drying of soil moisture and riparian habitats;
- Increase in evapotranspiration and water demand;
- Increase in fire risk and insect outbreaks;
- Elevational shifts in plant and animal communities and reduction or loss of alpine tundra;
- Shifts in the geographic ranges, reproductive timing, competitive interactions, and relative abundances of aquatic species;
- Potential for more extreme weather events (e.g. droughts and floods); and
- Less insulating snow cover leading to greater risk of frost exposure to roots and soil organisms.

Change to the physical and biological aspects of the river system will also impact the built environment and affect how water resources are managed. Some of these effects will include altered timing and amount of water available for irrigation and groundwater recharge, stresses on municipal water supplies and other consumptive uses such as snowmaking, and greater demand from diversions and downstream calls. Overall, competition for water will increase among municipal, agricultural, recreational, industrial, and ecological uses.

3.5.1 Climate Observations and Projections

This sub-section provides specific data about observed and projected changes in climate from various models and studies. Global and continental-scale climate models predict that temperatures will be warmer and the overall amount of runoff will be reduced. However, these models also predict that more extreme precipitation and rain on snow events could increase the risk of floods. A recently completed study for the upper Roaring Fork River Watershed couples past and projected climate variability data for the Upper Colorado River Basin with local data to make localized snowmelt and runoff predictions. For the Roaring Fork Watershed, the combination of past dry conditions and future predicted warming with related impacts on flows presents a new challenge in assessing and planning for future water availability and demand. This process may necessitate development of new strategies to increase resiliency and reduce risk.

Warming in the West

The world as a whole is getting hotter. The latest Intergovernmental Panel on Climate Change (IPCC) assessment of climate science – which represents the consensus of more than 2000 scientists from around the world working together since 1990 – says that warming is “unequivocal.” The map shown in Figure 3.5.1 illustrates global temperature trends at the surface of the Earth based on observations since 1970. The observations generally show more warming in the continental areas and a greater rate of change in the western U.S. compared to the rate of change for the U.S. as a whole. IPCC model projections for the 21st century show a continuation of this warming trend (IPCC, 2007a).

Using a medium IPCC greenhouse gas emissions scenario (A1B), data from 21 climate models project a 3.9 °C (6.9 °F) increase in annual temperature and a 3 percent decrease in precipitation for our region by 2080-2099 (change is from the 20-year mean of 1980-1999). On the other hand, if worldwide emissions follow a lower IPCC emissions scenario (B1), models project a 2.6 °C (4.7 °F) temperature increase (AGCI, 2006). This more conservative projection still exceeds the 2 °C (3.6 °F) threshold that some experts estimate could lead to “dangerous interference” in the climate system. It should be noted, however, that the introduction of policies to lower emissions to specific stabilization targets is not included in any of the Special Report on Emissions Scenarios (SRES), including the IPCC B1 scenario.

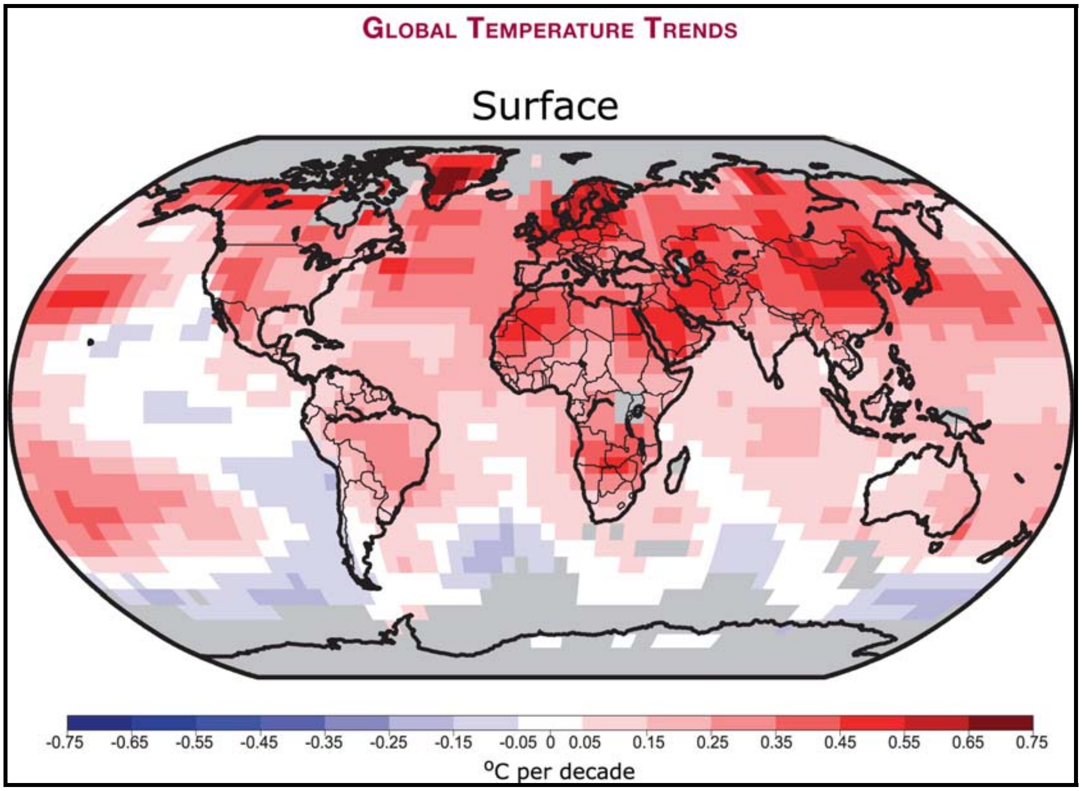


Figure 3.5.1. Global map of temperature trends since 1970. The colors represent the rate of change per decade in degrees C. Blue colors represent a cooling, red a warming. Darker colors represent greater rates. White areas show no change. The interior West of the U.S. shows a regional rate of change per decade of 0.35 to 0.45 ˚ C (0.63 to 0.81˚F) (Source: IPCC, 2007a).

Changes in Runoff

The 2007 IPCC Working Group II report looked at the projected change in annual runoff by mid-21st century for North America, with results shown in Figure 3.5.2. The figure shows a significant change in runoff for the western U.S.

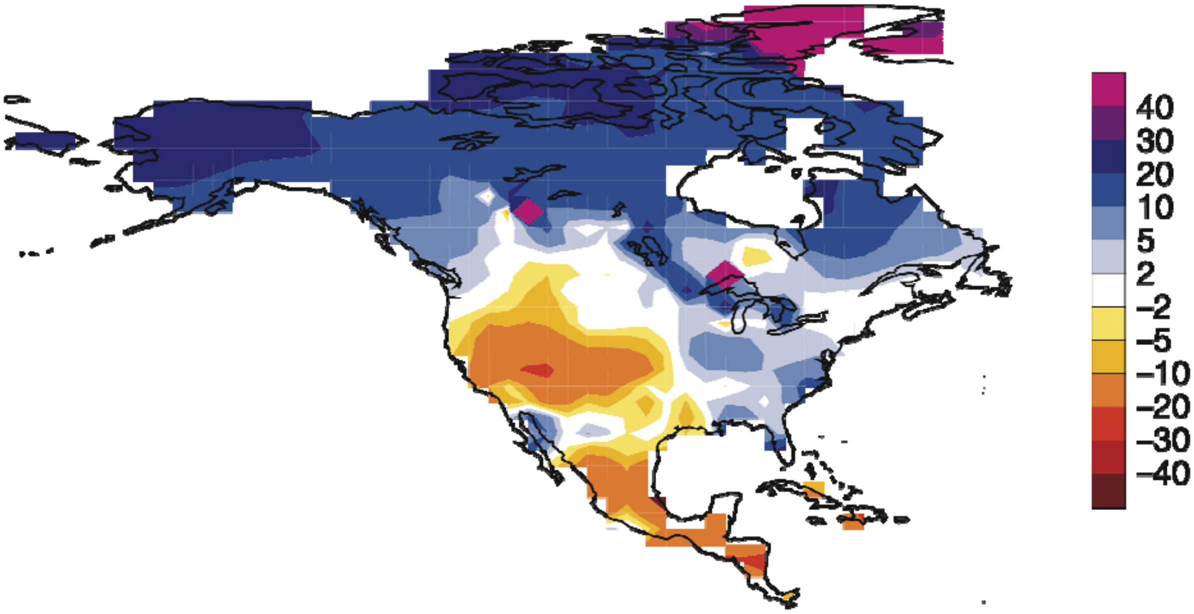


Figure 3.5.2. Percentage change in average annual runoff by 2041-2050, relative to 1900-1970, using the middle of the IPCC standard emissions scenarios (A1B). Shown is the North American portion of the world map. Source: Milly et al., 2005; IPCC, 2007b.

As snowmelt driven systems, upper basin tributaries of the Colorado River, such as the Roaring Fork River, are particularly prone to disruption in the historical pattern of spring runoff as a consequence of increasing temperature (Barnett et al., 2005; IPCC, 2007b). While precipitation and temperature both contribute to runoff, studies indicate temperature is likely to dominate. A study of the overall Colorado River Basin projects a slight decrease in precipitation during the 21st century (Christensen et al., 2004). Udall, in an overview of recent climate studies of the Colorado River, states that current models indicate “precipitation will remain approximately the same” and, when combined with temperature increases, where stronger agreement exists, indications are that “runoff will be reduced” (Udall, 2007). Aggravating the effect of higher temperatures on snow cover and snowpack is the increased rate of melt that results from darkening of the snowpack through deposition of windblown dust (Painter et al., 2007; Neff et al., 2008).

If projections are correct and annual precipitation remains about the same or somewhat less, it is not clear how this translates to flood risk. Even if total annual precipitation is reduced, individual precipitation events can be extreme, leading to flooding. Flooding associated with spring melt of the snowpack, particularly if it is above average, is tied to spring temperature fluctuations. A rapid spring warm-up and sustained high temperatures pose a serious risk, while a gradually warming spring can melt an above average snowpack without flooding. Another important consideration is rain on snow events that can cause flooding by rapidly melting the snowpack. The climate modeling conducted for the Aspen study (AGCI, 2006) indicates a greater possibility for mid-winter and early spring temperatures to produce rain events on snow. For a full discussion of flood risk based on observed warming in the 20th century and how it has affected flood risk in the western U.S. (including the Colorado River Basin) see Hamlet and Lettenmaier, 2007.

Warmer temperatures mean that a greater proportion of annual precipitation will fall as rain rather than snow. This is a widespread phenomenon; 74 percent of the mountains in the western U.S. already experienced this shift between 1949 and 2004 (Knowles et al., 2006). Increased temperatures melt snowpack earlier in the spring, leading to earlier peak runoff and a potential decrease in annual flow as warming continues (AGCI, 2006; IPCC 2007a).

Climate Variability: Past and Projected

Major climate patterns such as the Pacific Decadal Oscillation, the El Nino Southern Oscillation, and prevailing storm track and jet stream patterns are all sources of natural variability and play a critical role in Colorado's climate. To best project future variability, climate scientists first look to the past. Techniques such as tree ring analysis establish long-term stream flow records to understand better the natural variability. Colorado River flows reconstructed from tree ring data from the year 800 to the present were compared to the 1906-2004 mean of observed natural flows (i.e. periods where flows were above or below 10 to 15 percent of the past 100-year mean – see Figure 3.5.3). These data indicate considerable variability with approximately eight wet and dry periods. This reconstructed record shows evidence of a prolonged major drought in the mid-1100s (Meko et al., 2007), and shows that the natural variability of the past far exceeds infrastructure and allocations based upon flows of the 20th century alone. As described in Section 2.1.2, for the Colorado River Basin the water management legal stipulations (established in the 1922 Colorado River Compact and 1948 Upper Colorado River Compact) and infrastructure development were based on flows from a wet period.

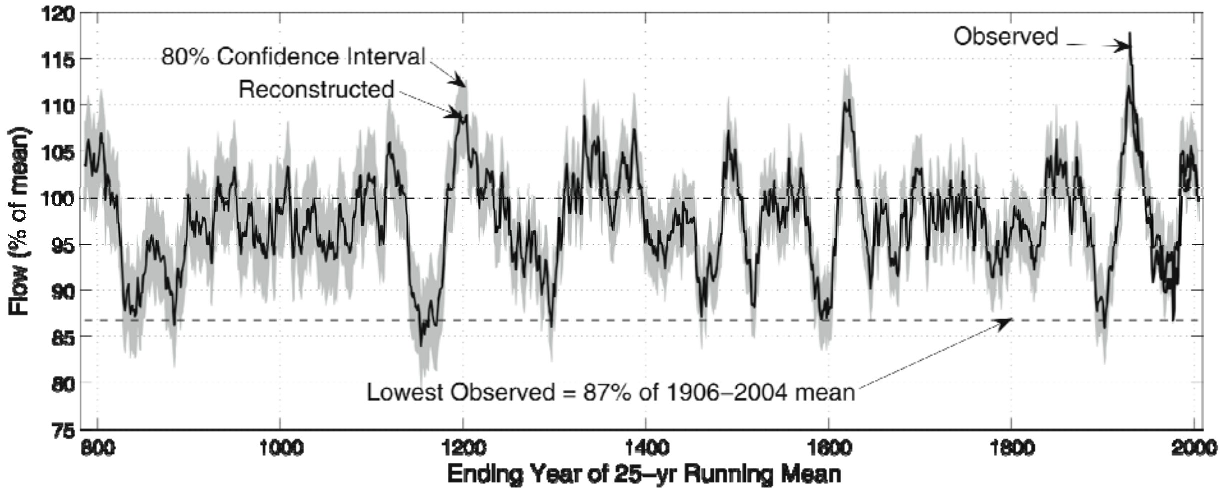


Figure 3.5.3. Upper Colorado River Basin flows reconstructed from tree ring data plotted as a percentage of the 1906-2004 mean of observed natural flows (dashed line at 100%). Lowest of the dashed lines is the 25-year running mean of observed flows for 1953-1977. Source: Meko et al., 2007.

In a related study, McCabe and Wolock modeled how a 0.86 and 2.0˚C (1.6 and 3.6˚F) increase in temperature commensurate with low and middle emission climate projections for the 21st century would affect flows in the Upper Colorado River Basin if added to the temperatures of the driest 100 years (1573-1672) in the 500 year record (1490-1998). They found that flows would not satisfy the water allocation amounts of the 1922 Colorado Compact more than 50 and 75 percent of the time, respectively. The same study showed that the effect of a 2.0˚C (3.6˚F) increase in temperature on the 20th century flows would result in insufficient flows to meet the Compact quotas more than 35 percent of the time. For a more complete description of the method and analysis see McCabe and Wolock, 2007.

Upper Roaring Fork Watershed Snowmelt and Runoff

A 2006 study by the Aspen Global Change Institute (AGCI), "Climate Change and Aspen: An Assessment of Impacts and Potential Responses," used the IPCC low, medium, and high emission scenarios combined with climate models and a snowmelt model to simulate how Roaring Fork River flows at the confluence with Woody Creek could be altered by climate change by 2030 and 2100. [For a complete discussion of the IPCC emission scenarios, see the 2000 IPCC "Special Report on Emission Scenarios." For more detailed information on climate models and their application in the Aspen report, see AGCI 2006 and the Working Group II's contribution to the IPCC's Fourth Assessment Report, "Climate Change 2007: Impacts, Adaptation and Vulnerability."] As shown in Figure 3.5.4, the projected runoff results for the low, medium, and high emissions scenarios indicate a clear shift to an earlier peak runoff of about one month. This figure also portrays a mid-winter runoff in all three scenarios and the retention of a summer monsoon.

As mentioned earlier, it is important to keep in mind, however, that the skill of climate models, while improving, is limited at the regional scale and very limited at the sub-regional scale. Serious limitations exist in downscaling climate models to project changes in climate for geographic areas as small as the Roaring Fork Watershed; however, by placing the study in the context of larger scale studies, much can be ascertained about future climate and potential vulnerabilities of the Colorado River and the Upper Colorado River Basin with direct relevance to the Roaring Fork Watershed.

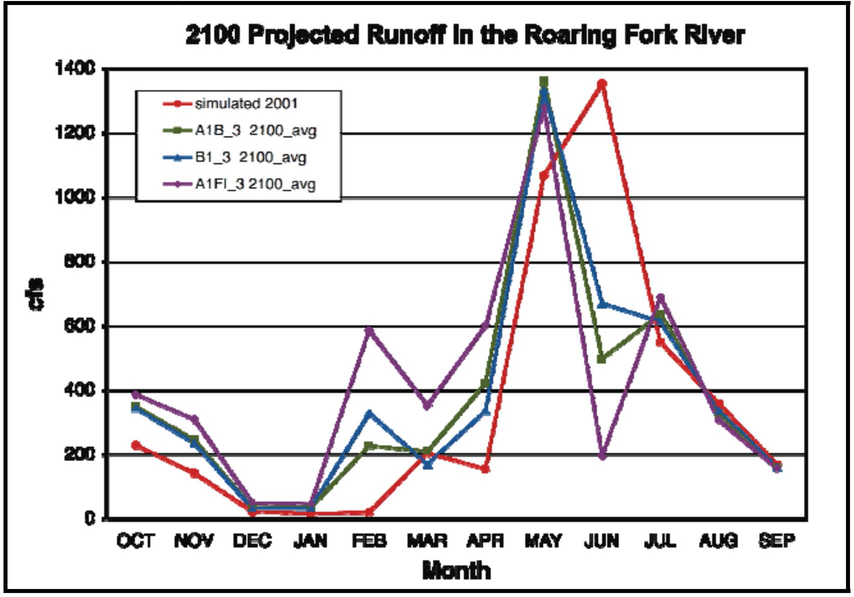


Figure 3.5.4. Projected runoff in the Roaring Fork River at the Woody Creek confluence for the year 2100 with low (B1), medium (A1B), and high (A1FI) IPCC emission scenarios. Note that this does not include base flows and is a snowmelt/runoff projection utilizing the Snow Runoff Model. Source: AGCI, 2006.

3.5.2 Impacts to Ecosystems

Watershed Interactions

The types of climate changes underway drive a complex set of interactions for the Roaring Fork Watershed. The flow chart in Figure 3.5.5 illustrates these interrelationships. Local environmental impacts such as land use change now are compounded by the regional effects of global-scale climate change. As the 21st century progresses, aquatic and terrestrial habitat will be increasingly impacted by warmer air and water temperatures, earlier spring runoff, and altered soil moisture and precipitation patterns. Traditional management strategies need to be modified to accommodate these new factors.

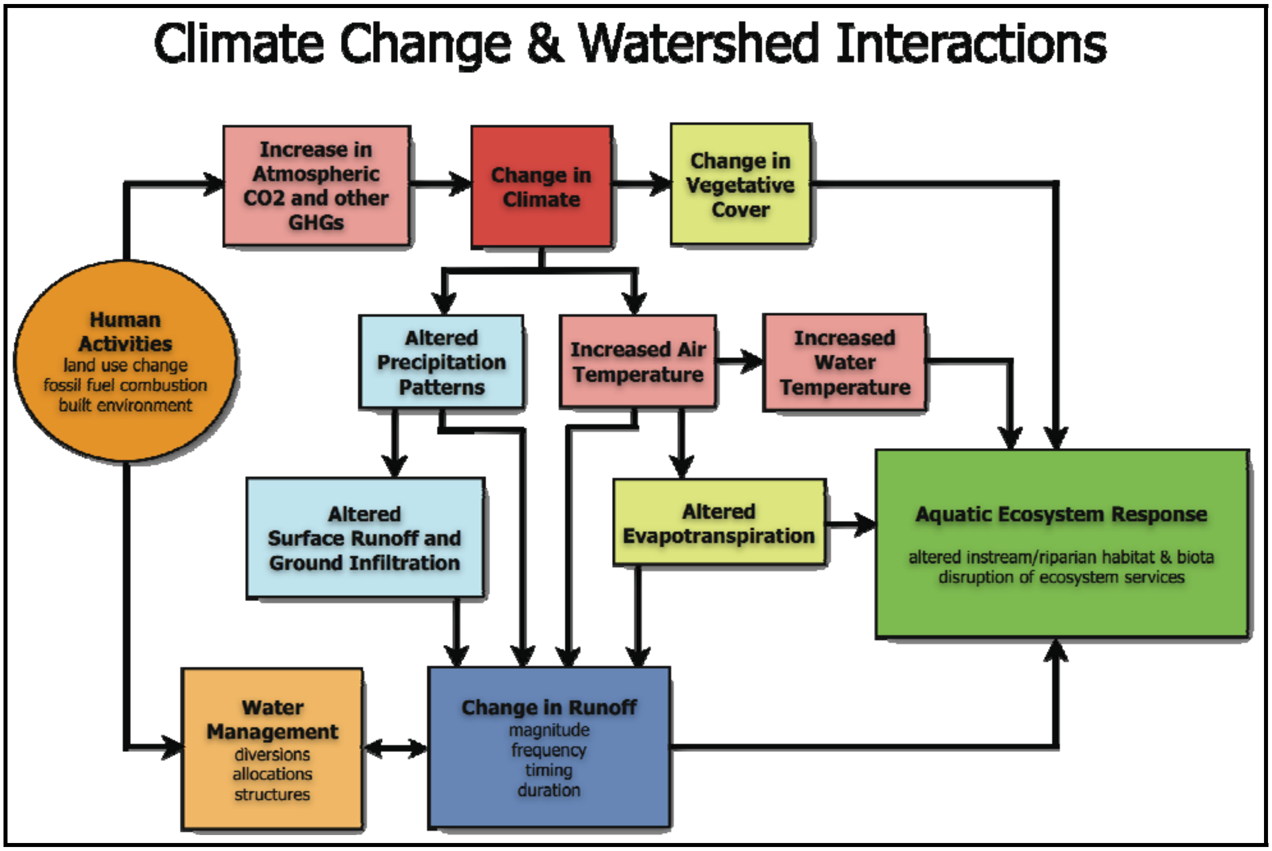


Figure 3.5.5. The complex interactions between human and natural systems in the Roaring Fork Watershed. Adapted from Poff et al., 2002.

Some of the most pronounced evidence of climate change already occurring in the U.S. has been observed in the Colorado River Basin (Saunders et al., 2008). Within the lower 48 states, the Colorado River Basin has experienced greater temperature increases than any other region in the last 30 years (NRCNA, 2007). As a result of continued change, aquatic and terrestrial ecosystems of the Roaring Fork Watershed will experience stress and transformation over the course of the 21st century. Over time, human-driven changes to the Earth's climate will alter the physiochemical properties of instream and terrestrial areas as well as the geographic distribution, relative abundances, and types of species within them (Poff et al., 2002; Robinson and Covich, 2003). Climate change will likely intensify the effects from other anthropogenic stressors that are already disrupting local alpine aquatic environments, including invasive species, stream depletions from diversions, municipal stormwater drainage, altered landscape runoff, and habitat fragmentation from development. All of these burden fragile ecosystems and contribute to biodiversity loss (Fahrig, 2003; Smith, 2001; Lockwood, 2004). Global warming in the 21st century will likely become an additional stressor (Poff et al. 2002), potentially driving conditions beyond the range of natural variability to which present-day species are best suited. The following discussion looks at how global climate change may affect terrestrial and instream areas within the Roaring Fork Watershed.

Terrestrial Areas

Site-specific research is needed to project specific ecological changes to the Roaring Fork region. Vegetation and fire risk modeling for the upper watershed was conducted as part of the upper Roaring Fork/Aspen climate change study (AGCI, 2006), with results summarized below. In the absence of more extensive local studies, the following section also includes a literature review of projected climate change impacts for western and alpine terrestrial ecosystems. Research suggests that combined ecological effects from changes to snowpack, wildfire frequency, insect outbreaks, soil moisture and temperature, and evapotranspiration may be equally as important as total change in temperature and precipitation. Expected temperature-driven changes in water demand by plants should be a paramount concern for resource planners charged with assessing future water requirements and availability. Despite the possibility of speciation occurring in response to changing conditions, the prime concern for alpine ecosystems is that the rate of change will outpace the ability of species to adapt (Smith and Tirpak, 1990). The growing body of evidence suggests that genetic variation will be lost. Many alpine species are particularly sensitive to climatic changes, including those that are habitat specialists, slow reproducers, poor dispersers, geographically isolated, or at the edge of their range (AGCI, 2006). An inability of individuals to adapt via migration or other behavioral modification will result in the reduction or extinction of single populations, whole species, distinct communities, or – in the most extreme cases – complete ecosystems. Warming in the Southern Rocky Mountains is likely to result in a population contraction of cold-adapted species sensitive to temperature increases, such as many mammals and birds, while more temperature-tolerant species like reptiles and amphibians may increase in number (Hansen et al., 2001).

Snow Cover and Soils

As snow cover retreats, surface albedo (a measure of the amount of solar radiation reflected from a surface) decreases considerably (IPCC, 2007a). Exposed dark ground absorbs more solar radiation than ground covered with white snow, amplifying warming and melt rates. Climate models suggest significant decreases in winter and spring water storage (in snow and soil) as a consequence of reduced snowpack (Hall et al., 2008). This in turn affects summer soil moisture. Summer drying is compounded by the direct effects of higher temperatures on soil moisture content. Moreover, a large enough reduction in summer soil moisture can suppress evapotranspiration, thereby further enhancing warming (Manabe et al., 2004).

Snowpack is also an important insulator and helps to protect soil biota against winter freeze events (Marchand, 1987; Jones, 1999; Groffman et al., 2001). Satellite observations from 1966-2005 show an appreciable decline in snow cover in the Northern Hemisphere, most notably during the spring and summer (IPCC, 2007a). The largest changes have occurred in the lower reaches of high-elevation sites such as the Rocky Mountains and Swiss Alps (IPCC, 2007a).

Areas with current temperature ranges close to the rain/snow temperature threshold will experience the greatest changes in snowpack (Cooley, 1990).

In the future, the Aspen area is likely to face both a delay in early season snow accumulation and an earlier spring melt. Models project the snow season to be 1.5 weeks shorter by 2030 and four to 10 weeks shorter by 2100. More radical temperature increases in the second half of the century indicate that lower elevation areas, including the base area of Aspen Mountain, are unlikely to have sustained winter snowpack by 2100 in the absence of a swift and rigorous reduction in global emissions (AGCI, 2006).

Shifts in Biotic Communities and Migrations

Climatic factors like temperature and moisture are prime determinants of the distribution of plant and animal species. Research has shown that observed changes to mountain snowpack and snowmelt timing can be correlated to parallel shifts in vegetation (Stewart et al., 2005; Mote et al., 2005; Breshears et al., 2005). Over the last several decades, the mountainous regions of the West have witnessed shifts in temperature and precipitation patterns accompanied by a gradual disappearance of alpine tundra (NAST, 2000; IPCC, 2007a; Diaz and Eischeid, 2005). Changes in snowpack and spring melt, reduced soil moisture, and hotter summers will affect riparian habitats from Glenwood Springs to Independence Pass.

Model projections indicate that continued anthropogenic warming will give rise to widespread biome shifts (Watson et al., 1997). Temperature-sensitive species are likely to seek out cooler conditions in higher altitude and/or latitude locations in response to warming. Paleoclimatology evidence supports most scientists’ opinion that the projected rate of climate change will exceed the dispersion potential of most forest tree species (Roberts, 1989).

Within the mountain environment of the Roaring Fork Watershed, the uneven topography combined with human-caused habitat fragmentation can impede the ability of species to adapt to climate change via migration. On the other hand, mountains offer higher-elevation escapes that may facilitate successful migration for certain species (NAST, 2000), although these species will be restricted to smaller and smaller geographic areas and will likely face population squeezes as they move higher and higher upslope (AGCI, 2006). If global warming is allowed to progress unchecked, some alpine species – and eventually entire alpine ecosystems – will vanish completely.

High-elevation headwater ecosystems such as alpine meadows and subalpine forest are predicted to gradually decline and eventually disappear from some areas. Vegetation modeling conducted for the Aspen area projects a transformation of dominant vegetation from taiga-tundra to boreal conifer forest in as few as 20 years (AGCI, 2006). Analysis by the U.S. Environmental Protection Agency suggests that tree lines in the Southern Rocky Mountains will migrate 350 feet upwards in elevation for every 1°F (0.56°C) increase in temperature (USEPA, 1997b).

Vulnerable Species

Many alpine species such as those found in the Roaring Fork Watershed possess characteristics that make them especially vulnerable to environmental changes. Mountain animal species are often poor dispersers and slow reproducers with low productivity and long generation times, making rapid adaptive response to new climatic conditions difficult (Krementz and Handford, 1984). Within the watershed, populations currently inhabiting the highest elevations and/or those located at the edge of their geographic range are at the greatest risk from warming (AGCI, 2006). Specialist species – those species requiring a narrow range of ecological conditions to survive and whose diet is often limited to only one or two food sources – are also generally less capable of adapting to change. Although specialists thrive in reasonably stable conditions as a result of highly specialized co-evolution with other organisms, they are greatly dependent on the habitat characteristics of the ecological niches to which they have acclimated. Generalist species like mice and coyotes, on the other hand, are able to survive in a broad range of habitats and use a varied diet. These species can be found throughout the watershed at elevations anywhere from 6,000 – 13, 000 feet (AGCI, 2006). Consequently, habitat specialists face greater risk of extinction than generalist species under changing environmental conditions (Benayas et al., 1999). Two such specialists expected to face population extirpation from climate change are the American pika and white-tailed ptarmigan (Beever et al., 2003; AGCI, 2006; Saunders et al., 2008).

Because plants and animals initiate certain behaviors based on climatic signals (including temperature, precipitation, and runoff), an earlier spring melt can upset the normal timing of biological events, triggering earlier migrations, breeding, emergence from hibernation, and flowering (Saunders et al., 2008; AGCI, 2006). Varied responses among predator, prey, and competitor species will weaken existing ecological relationships and define new ones. The IPCC reports that such phenological changes are already being observed in the West and can be directly attributed to local temperature increases (IPCC, 2007a). In the second half of the 20th century, accelerated phenology ranging from a few days to several weeks has been documented in the egg lay date of tree swallows, migration by American robins, hatching in white-tailed ptarmigan, nesting by Mexican jays, and emergence from hibernation of yellow-bellied marmots (Dunn and Winkler, 1999; AGCI, 2006; Hobbs et al., 2003; Li and Brown, 1999; Inouye et. al., 2000). Across species, chicks are now emerging at a time when food supplies are less readily available.

Some mountain species have seasonal ranges, inhabiting higher elevations during the summer and migrating to lower elevations in the winter to escape cold temperatures and deep snowpack. Warmer winter conditions in the future could allow these animals – which include Rocky Mountain bighorn sheep, mule deer, and Rocky Mountain elk – to remain at higher elevations year round. Modeling suggests that while warmer winters would result in a contraction of overall range, population sizes would increase substantially (AGCI, 2006).

Invasive Species

Non-native invasive species already pose a threat to many Rocky Mountain ecosystems (NAST, 2000), and climate change stands to increase the likelihood of invasions. Because they are capable of reproducing and dispersing rapidly, invasive plant species are well suited to respond and adapt to climatic disturbances. Certain weeds may also benefit from increased CO_2 concentrations, including Canada thistle, field bindweed, leafy spurge, and spotted knapweed - all of which appear on the 2005 Pitkin County Noxious Weed List (AGCI, 2006; Ziska, 2003). Meanwhile, native vegetation will be stressed by higher temperatures. Competition from invasive species will likely jeopardize native species' ability to adapt successfully to climatic changes.

Forests

Another important terrestrial biotic community to examine is that of forests, which play an important role in the hydrological cycle. Alterations to forest coverage or composition – as those caused by drought, fires, or insect infestation – can affect water flow, storage, and filtering (Lemmen et al., 2004).

As temperature rises, plant evapotranspiration and water demand increases (Goyal, 2004). When that demand is not met – such as during periods of drought – trees undergo stress. The recent and dramatic decline of aspen trees in Colorado has been attributed to high temperatures and dry conditions (Worral et al., 2008). This trend is expected to accelerate with global warming. Stands on south- and west- facing slopes, which receive the most solar radiation and thus experience the highest temperatures during the growing season, are most vulnerable (Saunders et al., 2008).

Climate change increases the likelihood of insect outbreaks (IPCC, 2007b). Recent warming trends in alpine areas have improved the overwinter survival of insect species that kill trees and make forests more susceptible to fires (Ebi et al., 2007). In the past, sustained cold winter temperatures have kept beetle populations in check (Saunders et al., 2008), but higher summer temperatures are expected to enable epidemic level population increases (Hansen et al., 2001). Research needs to be undertaken to compare temperature thresholds for alpine insect species to the current climate of the Roaring Fork Watershed.

As to wildfires, since 1980 the annual acreage of U.S. land burned from wildfires has increased 70 percent from the average for the 1920-1980 period (IPCC, 1997). Global warming is likely to accelerate this trend in the West (NAST, 2000). According to the Pew Center on Climate Change, severe western fires, like those in Yellowstone in 1988 and Hayman in 2002, were triggered by "extreme climate signals, which could become more dominant in a warmer future" (Ebi et al., 2007). Slopes disturbed by fire are more vulnerable to erosion, which has profound implications for stream water quality.

Westerling et al. (2006) reported a high correlation between increased fire risk activity in the western U.S. and warmer temperatures (about 1.0°C/1.8°F warmer), and also between wildfire activity and earlier spring snowmelt (one to four weeks earlier) (Figure 3.5.6). Increased temperatures and earlier spring snowmelt are both trends being observed in the Upper Colorado River Basin (Ebi et al., 2007; Westerling et al., 2006; AGCI, 2006). The same study also found that the greatest increase in western U.S. wildfire activity since the mid-1980s has occurred at elevations near 7,000 feet (Figure 3.5.7). Greater variability in precipitation can also increase fire risk regardless of a positive or negative change in total precipitation; wetter years increase plant productivity, thereby prompting a buildup of the organic matter that fuels fires in drought years (NAST, 2000).

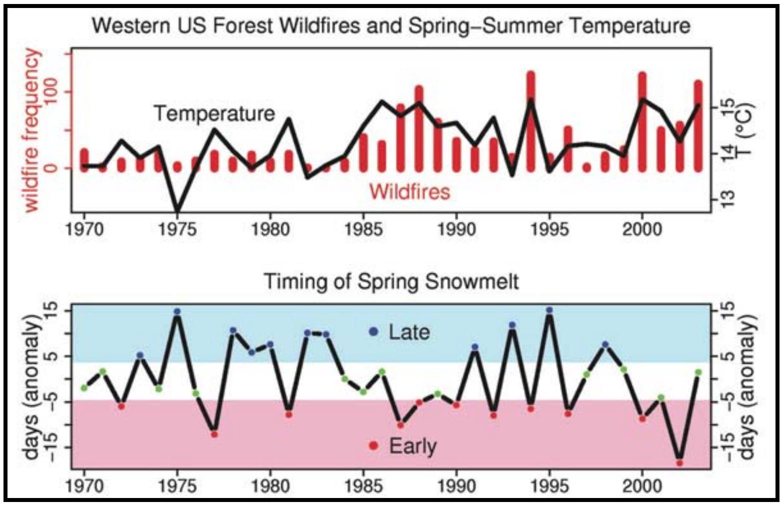


Figure 3.5.6. Western U.S. forest fires and spring-summer temperature. Correlations between temperature, timing of spring snowmelt, and wildfire frequency are shown. Note that both the top and bottom graphs are on the same time scale, and that during early melt years (pink band), the frequency of wildfires goes up. Warming trends indicated for the western U.S. are mirrored in local data reported in AGCI 2006. Source: Westering et al., 2006.

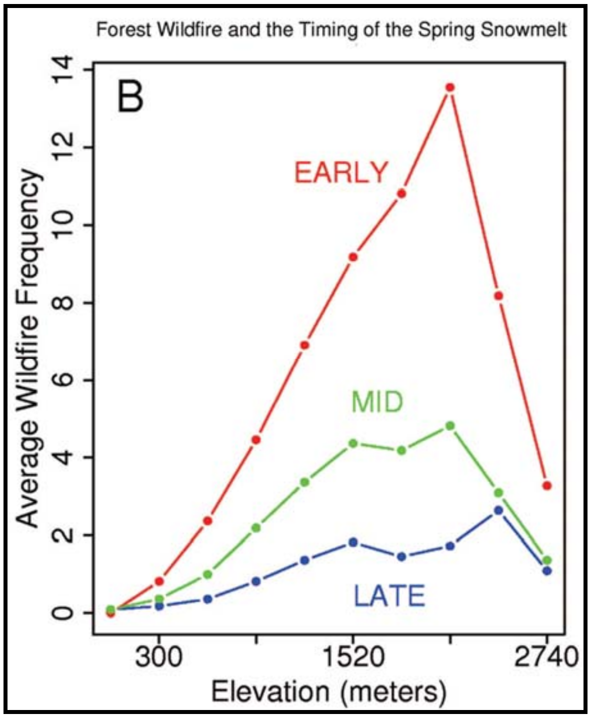


Figure 3.5.7. Forest wildfire and the timing of spring snowmelt. Average western U.S. wildfire frequency from 1970-2002 is shown by elevation for early, mid, and late snowmelt years. Fire frequency during early snow melt years peaks at 2130 meters, or about 7000 feet. An earlier peak flow is projected for the Roaring Fork Watershed (AGCI 2006). Source: Westering et al., 2006.

Climate modeling conducted for the greater Roaring Fork Watershed region projects temperature increases of 1.7-2.2 °C (3-4 °F) by 2030, and roughly 2.8-9.4 °C (5-17 °F) by 2100 (largely dependent on how quickly and seriously the world responds to the climate crisis); summer temperatures are predicted to increase more than winter temperatures, and precipitation is projected to decrease slightly (ACGI, 2006). Such conditions would worsen drought and increase the risk of high-elevation forest fires (NAST, 2000; Seager et al., 2007). Fire risk modeling conducted for the Aspen area predicts larger average fire sizes during the first half of the 21st century, and more frequent but smaller fires during the second half of the century (AGCI, 2006).

Instream Areas

The relationship between climate change, water temperature, stream flows, and instream habitat and species is multi-faceted and complicated. This sub-section offers an overview of this relationship and related potential effects within the watershed. A more in-depth discussion of the potential implications of climate change on instream areas, particularly trout species and populations, is provided in Appendix 3.5.1.

Aquatic species' physiological processes and geographic ranges are tied directly to water temperatures. Since the 1970s, rising air temperatures in high altitude locations have been mirrored in rising alpine stream temperatures; these changes are expected to accelerate in the coming decades (Hari et al., 2006). Since snowmelt runoff can mediate otherwise warmer water temperatures, higher elevation stream reaches – those in closest proximity to snowpack – will have an advantage over lower elevation reaches as air temperatures warm. However, because global warming will reduce the extent of snowpack feeding cool meltwater into streams, stream temperatures in the Roaring Fork Watershed are expected to track more closely with air temperatures in the future.

Compounding direct temperature impacts, a projected shift in the timing and seasonal volume of runoff in the upper Roaring Fork River related to future climate trends could prove disruptive to flora and fauna communities throughout the watershed (AGCI, 2006). Crucial aquatic habitat components such as dissolved oxygen, water temperature, water depth and velocity, and availability of food supply are highly correlated with streamflow (Ptacek et al., 2003). Additionally, aquatic species have evolved behavioral survival strategies based on existing, natural flow regimes. Any alteration to this flow regime as a result of warming temperatures and precipitation change will be mirrored in alterations to aquatic ecosystems, creating opportunity for some species and increased vulnerability for others. Both the extent and rate of change are equally important in determining the ability of freshwater species to successfully adapt.

The 2007 IPCC report reconfirmed model projections of more extreme precipitation events during the course of the 21st century (IPCC, 2007a). Accordant with these findings, the upper Roaring Fork/Aspen climate change study projected the occurrence of possible, but not certain, July monsoons toward the end of the 21st century for the greater Roaring Fork Watershed area. While such precipitation events could help alleviate the impact of otherwise low summer flows, intense rains can generate heavy, disruptive stream flows that cause channel erosion, sedimentation, and bank instability – all of which affect aquatic habitat (AGCI, 2006). The projected increase in precipitation variability also suggests a greater risk of prolonged drought periods, as more rainfall will be concentrated into fewer rain days. In arid mountain regions, more frequent drought events associated with climate change will exacerbate low flow conditions, leading to reduced aquatic habitat and biological diversity (Poff et al., 2002).

Trout are an important aquatic species within mountain stream ecosystems. These coldwater fish are considered to be keystone species, meaning that without equivalent replacement by another species, the removal of trout from a river system would leave an ecological gap causing a ripple effect throughout the food chain. For example, the disappearance of trout from a stream could result in an overpopulation of the insects on which they feed, while land vertebrates that prey on trout would lose an important food source (Willson and Halupka, 1995).

Trout are dependent on clear and cold water – both at risk from global warming. Of all the freshwater fish species, salmonids (which include trout, salmon, and whitefish) are likely to face the greatest negative impacts from climate change (IPCC, 2007b). Extended periods of high temperatures and low flows in summer months may leave streams too warm and too shallow to provide sufficient fish habitat (AGCI, 2006). Secondary changes to stream cover, food supply, and competitive interactions will further influence trout populations. The IPCC projects a 15 to 40 percent loss in total fish habitat in the Rocky Mountains, depending on global emissions levels (IPCC, 2007b). A recent report by Trout Unlimited projected that trout populations in the western U.S. could be reduced by more than 60 percent in some areas (Williams et al., 2007). A 1996 study by Keleher and Rahel found that Rocky Mountain salmonids were restricted to streams in regions where average July air temperatures remained below 22 °C (72 °F), corroborating findings from similar studies. Projected increases in summer maximum temperatures and even greater increases in winter minimum temperatures are likely to cause an upstream shift in the boundaries of fish ranges (Meisner, 1990). Coldwater species may be excluded from presently inhabited downstream stretches of the river, while more heat-tolerant species may expand their range (Chu et al., 2005). Habitat fragmentation that acts as a barrier to migrations may increase the likelihood of local population extinctions.

While no significant trends in water temperature are evident from the available historical data for the Roaring Fork River, data collected from the Roaring Fork at Glenwood Springs gage shows 2002-2007 average maximum water temperatures peaking in August at around 15 °C (59 °F) (maximum water temperature data dates back to 1980, but a data gap exists between 1985 and 2002; analysis of the 1980-1984 data shows average maximum water temperatures for this period also to be near 59°F). Therefore, taking into consideration the positive but less than 1:1 correlation between air and water temperatures (See Appendix 3.5.1 for more on the air-water temperature relationship), a 1.7-2.2 °C (3-4 °F) increase in air temperatures in the Roaring Fork Watershed region by the year 2030, as projected by AGCI 2006, could potentially put brook trout, cutthroat trout, and brown trout fry into suboptimal thermal ranges during the warmest portion of the year. A medium emissions scenario projection of 3.9-6.1 °C (7-11°F) warming by the end of the century would come closer to, but not exceed, the lethal limits of brook and cutthroat trout, and might approach the suboptimal ranges for rainbow and brown trout. Once the upper limit to the optimal range has been exceeded, mortality rates rise with increasing temperature (Hickman and Raleigh, 1982; Raleigh, 1982; Raleigh et al., 1986; Raleigh et al., 1984). Although many fish are capable of adapting to new thermal regimes by varying their lethal and optimal temperatures by a few degrees, this process occurs over time. The rate and degree of temperature change dictates the success of acclimatization.

The reproductive success of Roaring Fork Watershed trout populations in a warmer climate will vary greatly by species. Low overwinter temperatures, likely to be compromised by global warming, are often necessary for successful spawning of coldwater salmonids (Gerdaux, 1998), while extreme temperatures during incubation can cause mortalities. Alterations to flow during the reproductive window may affect the frequency of scouring and/or dewatering events, with implications for young survival. Brown and brook trout are fall or early winter spawners, with incubation occurring over the winter. Rainbow and cutthroat trout are spring spawners, with fry emerging in the late spring/summer in rhythm with spring runoff flows. The cumulative effects from alterations to streams' thermal regimes and flow patterns will likely affect the spawning activities of these trout species.

3.5.3 Socioeconomic Impacts

Climate-driven physical and ecological changes – both local and regional – will have financial consequences for municipal, agricultural, and recreational users in the Roaring Fork Watershed. As part of the upper Roaring Fork/Aspen climate change study, potential socio-economic impacts to the Aspen area were assessed, including those associated with alterations to the Roaring Fork River. In interviews conducted for the report, discussions with community representatives, including elected officials, ski mountain managers, resource managers, ranchers, and river-based business owners, revealed that future change to the river was consistently the greatest stakeholder concern (AGCI, 2006).

The Ski Industry and Snowmaking

Although the Aspen and Snowmass ski areas are positioned more favorably than many other U.S. and European ski resorts because of their higher elevation and colder temperatures, the local ski industry will become increasingly vulnerable to the progressive impacts of climate change in the second half of the 21st century. In the watershed, lower elevation ski areas, such as Sunlight and Buttermilk, are most vulnerable.

Modeling conducted for the upper Roaring Fork/Aspen climate change study indicated that as more precipitation falls as rain rather than snow due to warming temperatures, early season snow depths will decrease (potentially delaying the opening day target date - a threat to Aspen's holiday season). An earlier spring melt will likewise shorten the ski season. In interviews, mountain managers identified several strategies for coping with shortened snow seasons and degraded conditions, including moving snowmaking to higher elevations, extending the snowmaking season, stockpiling more snow, building more water storage, and obtaining more water rights. These adaptations will require more energy, water, and money, and will put additional stress on local water resources. For example, adding snowmaking on top of Aspen Mountain is estimated to require an additional 5 million gallons of water per year; this quantity would increase at higher temperatures (AGCI, 2006). Currently, Aspen Skiing Company obtains water for snowmaking from Maroon, Castle, and Snowmass creeks. According to AGCI (2006):

> "Withdrawing water from streams in November and December prolongs normal late-summer low flows for months, and leaves streambeds and aquatic communities, like the prized trout fisheries in Aspen, more exposed and vulnerable to cold temperatures and freezing and drying. Anchor ice, which forms in shallow water, adheres to stream bottoms affecting egg viability…And with dewatering there are fewer deep pools for fish to overwinter. The absence of flushing flows can lead to sedimentation and problems related to algal growth."

Instream Recreation

Future growth in instream non-consumptive uses (e.g. fishing and boating) is tied to patterns of peak runoff, turbidity, and temperature. The threat of increased out-of-basin diversions in a warmer West could further complicate flow issues, potentially leaving inadequate water levels for whitewater rafting or for sufficient fish habitat to support a fishing industry. The upper Roaring Fork/Aspen climate study indicated that projected earlier peak runoff and lower flows might negatively impact whitewater rafting outfitters by forcing an abbreviated and earlier rafting season to a time of year typically not favored by tourists. Likewise, recreational fishing outfitters may need to adjust their operations to adapt to changing river conditions. As noted earlier, lower summer flows and warmer water temperatures (because of lower volumes, loss of stream cover, and warmer surface air temperatues) could adversely impact trout populations and cause shifts in the timing of trout spawning (AGCI, 2006).

Flood Risk

Climate-driven changes to the hydrological system will likely increase the frequency, magnitude, and financial costs of extreme weather events. Snowmelt-driven basins like the Roaring Fork Watershed are at especially high risk from increased flooding (Frederick and Gleick, 1999). Compounding this risk, valley-wide development has placed an increasing number of structures in the floodplain. Structures in the floodplain are costly to relocate, and vulnerabilities should be reassessed in the context of an altered hydrograph.

Municipal Supply

Future warming in the West could result in substantial water supply shortages for Colorado River Basin communities (McCabe and Wolock 2007; Steiner 1998). Notwithstanding potential climatic changes, the City of Aspen already anticipates an increased demand on municipal water that will reduce flows below instream flow designations. Although the total annual water supply available to municpal users in the watershed is not projected to change significantly under global warming, seasonal availablity will likely shift. Anticipated warmer temperatures leading to increased snowmelt in winter would alleviate surface water demand during winter months when the City of Aspen generally needs to pump water from its alluvial acquifer. However, surface water availablity would decline in June due to earlier runoff, which might require additional use of the acquifer stores. Tapping this underground source ultimately lowers the instream flow of the Roaring Fork River (AGCI, 2006).

Agriculture

The agricultural sector is likely to experience lower soil moisture content at the same time that instream water resources are reduced. Earlier peak runoff (May) is predicted to saturate soils initially but leave them desiccated by peak growing season. Therefore, more irrigation might become necessary, but water availability will likewise shift, potentially straining irrigation abilities. Higher temperatures will also have a direct impact on the transpiration rate of crops and, at the same time, create additional competition for irrigation of lawns and golf courses (AGCI, 2006).

Tourism

Alterations to the natural aesthetics of the watershed are another economic concern related to climate change. The watershed likely will become more vulnerable to beetle outbreaks because of increased overwinter insect survival rates (due to warmer winter temperatures) and weakened stands of trees experiencing drought-related stress (AGCI, 2006). Warmer summer temperatures and more frequent extreme heat waves, combined with increased tree damage from insect infestations, will make forested areas, including riparian forests, more susceptible to fires (Westerling et al., 2006; Ebi et al., 2007). Such environmental damage arising from climate-driven aggravation of natural conditions may negatively impact the tourist experience in the watershed. It should be noted, however, that Aspen's higher elevation and cooler climate relative to other popular resort destinations may work in favor of the local summertime economy.

Water Rights and Regional Demand

The recent inflation in the price of water rights in the watershed is likely to become an enduring trend in the future. Global warming will exacerbate water scarcities that drive up demand and value of water. In 2007, 200 shares of water in the Salvation Ditch were put up for sale for $1.2 million, with a final selling price of about $6,860 per acre foot (Gilman, 2008). In Summit County, water rights already sell for as much as $40,000 per acre foot (Gilman, 2008). During the summer months, a coincident decrease in supply (due to low flows) and increase in demand (due to warmer temperatures) will exert additional upwards pressure on the value of water.

In addition to local factors, changing climatic conditions beyond the watershed may impact local supply. Transmountain diversions on the upper Roaring Fork River redirect water to Front Range communities like Colorado Springs and Pueblo, where approximately 80 percent of that water is utilized for municipal and industrial uses and 20 percent for agriculture (Condon, 2005). Municipal demand for Upper Colorado River Basin water is also growing further downstream among Arizona, Nevada, and California users. Although the Bureau of Reclamation maintains that water levels in Lake Mead will be sufficient for years to come, some climate scientists contend that Lake Mead will be "operationally empty" by 2020 (Thompson, 2007). With both in- and out-of-basin municipal and agricultural water needs projected to rise due to population growth and likely to increase further with global warming, the demand for Roaring Fork Watershed water resources is expected to increase.

In very dry years, it is possible for the Cameo Call, representing a group of senior water rights holders in Grand Junction, to prevent diversions within the Roaring Fork Watershed by certain users. In August 2003, the Cameo Call prevented Twin Lake Reservoir and Canal Company (Twin Lakes) from diverting water through the Independence Pass Transmountain Diversion System. Withdrawals from the upper Roaring Fork River by the Twin Lakes reduce native flows (as measured above Aspen at the USGS stream gage station) by 40 percent (AGCI, 2006). Therefore, although the call negatively affected Front Range municipal users and Arkansas Valley farmers, the result for Roaring Fork Valley users was positive because more water remained in the river (Condon, 2003; AGCI, 2006). Projected drier summers in the future may increase the likelihood of the Cameo Call.

In contrast to the Cameo Call, the Shoshone Hydro Plant in Glenwood Springs makes a call on the Colorado River throughout most of the year (Sloan, 2004) to assure sufficient flow for the plant to operate efficiently. According to ACGI (2006): "Because the Shoshone Call results in increased flows through Glenwood Springs and down to Grand Junction, the call may delay the Cameo Call and demand for water to protect the Colorado River Endangered Fish Recovery

Program. Otherwise, without the Shoshone Call in place, water from the Roaring Fork River would be required to augment flows to meet the Colorado River demands leaving more water instream. When the Roaring Fork River flows are not required to be released downstream to the Colorado River for fish habitat protection or use by Grand Valley farmers, they can be diverted elsewhere. Thus, the Shoshone Call mainly benefits Roaring Fork transmountain diversions. The resulting lower flows in the upper Roaring Fork River can negatively impact Roaring Fork instream users, such as rafters, and negatively affect fish and riparian habitat."

Climate-driven alterations to the hydrograph of the Colorado River could vary the current pattern of calls administered by the Shoshone hydroplant. For additional discussion about the Cameo and Shoshone calls, refer to Section 2.1.1.

Separate from concerns over local and regional diversions, the recent boom in biofuel production (including corn-based ethanol and soy-based biodiesel) spurred by climate-energy concerns threatens to accelerate the disappearance of groundwater reservoirs on the East Slope. Colorado corn farmers seeking prosperity from the state's $500 million ethanol industry planted 20 percent more acres of corn in 2007 than in 2006 (Moscou, 2008). Corn requires approximately 4,000 gallons of water to produce one bushel (USGS, 2007a). These growing agricultural water demands, when combined with East Slope population growth, intensify efforts to divert more West Slope water to the East Slope.

Colorado's West Slope, expanding oil and gas drilling operations are projected to require additional withdrawals from the Colorado and other rivers in the near future (Webb, 2007). Potential "in-situ" oil shale development may harbor the greatest threat to water resources. While it is not known exactly how much water would be required for full scale oil shale production, experts have projected water needs of 105 to 315 million gallons per day (Webb, 2007). This does not include water required to meet additional demands from regional population growth associated with a sizeable and growing energy industry.

Overall, competing demand from East Slope diversions, urban growth in the western part of the state, and Colorado's growing energy industries, compounded by warmer and drier conditions stemming from climate change, will further drive water prices up and availability down.

3.5.4 Watershed Management

Improved understanding of the vulnerabilities and risks associated with climate change can lead to adaptations that are anticipatory rather than reactive. Unlike many aspects of the Roaring Fork Watershed that are a product of local changes such as increased settlement and development, the climate of the watershed now responds to forces global in scope and external to local jurisdictions and institutions. This creates new challenges for local resource managers and planning efforts. In *Science's* Policy Forum, Milly and a senior group of hydrologists and climatologists caution about a tendency to base infrastructure and management decisions on past variability, a management approach they label "stationarity." They reject this as a workable approach given climate change, noting that global warming will "push [the] hydroclimate beyond the range of historical behaviors." They note that other strategies are needed, such as using probabilistic models to identify ways to optimize water systems undergoing change (Milly et al., 2008).

Although this report on the “State of the Watershed” is an important step, an in-depth integrated climate impact assessment utilizing recent developments in regional climate and hydrologic modeling could help identify and quantify potential vulnerabilities beyond the more qualitative assessment provided here. Assessments that identify vulnerabilities are a critical step toward adaptations which can reduce risks and increase resiliency to the impacts of change. Just as the impacts of human settlement in the West drove the establishment of our legal and water resource management institutions during the 19th and 20th centuries, the effects of climate change will likely force a re-evaluation of infrastructure and management practices at all scales of jurisdiction within the Colorado River system. The many changing variables and interactions require dynamic systems analysis and active stakeholder involvement to help guide policies and procedures. One innovative example of this type of approach was conducted by Cohen et al. for the Okanagan region in British Columbia. The approach joins stakeholders with local experts and scientists first to assess and then to develop adaptation strategies. The general framework consists of:

1. Climate change scenarios (global to regional)
2. Hydrological scenarios (snowpack, stream flow, annual cycle)
3. Water supply and demand scenarios/land use patterns (requirements, case studies)
4. Adaptation options/case studies/costs
5. Adaptation dialogue with stakeholders

The Okanagan assessment incorporated information on regional planning and water management processes, and directly engaged local practitioners and decision makers, leaving a legacy of shared learning that should influence future planning beyond the completion of this assessment (Cohen et al., 2006; Cohen and Neale, 2006).

By the end of this century, future change in annual temperature for the Roaring Fork Watershed region could be 5.6°C (10°F) or more if global emissions follow the higher of the IPCC emission scenarios (AGCI, 2006). On the other hand, if mitigation is aggressively pursued worldwide, global average temperatures could be held at or below the 2 to 2.5°C (3.8 to 4.5°F) increase that many scientists estimate would be enough to avoid “dangerous interference” in the climate system. It is probable we have passed the point where the climate of the 21st century can be like that of the 20th century. Projections for the end of this century range from modest change to radical change. The climate of the 21st century is dependent on the path global greenhouse gas emissions take, which is a question of political will and the technical capability to dramatically reduce emissions on a worldwide scale.

Adding human-induced climate change to the list of critical factors addressed in traditional management plans and watershed assessments and plans is essential for devising sound strategies for watershed management in the future. The impact to the watershed of a changed global, regional, and local climate will be unprecedented and far-reaching. These effects will include altered hydrology, change in aquatic and riparian habitat, and a shift in species composition. The combination of natural variability with human-induced climate change will likely alter water supply and demand in ways new to existing institutions. Climate change will impact human uses of local water resources from irrigation and municipal supply to hydroelectricity generation and recreational uses like snowmaking, boating, and fishing. It will also alter riparian and instream habitat and the plant and animal communities of the entire watershed. It is important to pursue mitigation locally, thus sending the message that jurisdictions in the watershed take climate change seriously. Sound management must also face the reality of climate change. The challenge is to identify and quantify these potential changes in advance so that adaptations can be built into the planning process, management practices, and infrastructure, thereby reducing risk and building greater resilience.

3.5.5 Data and Knowledge Gaps

As noted earlier in this section, regional climate change modeling is in its early stages. Once higher resolution models become available, we will learn more about how to model at the watershed and regional scale. Along with this, resource managers will benefit from better projections of change in seasonality, timing and magnitude of runoff, and overall change in temperature and precipitation. The following points cover, more specifically, data gaps and management approaches that should be addressed in order to prepare adaptation and mitigation strategies in response to climate change.

- A comprehensive climate impacts assessment for the entire Roaring Fork Watershed is needed. Although the Aspen climate impacts study completed in 2006 included snowpack runoff modeling of the upper Roaring Fork Watershed, it did not incorporate full-scale hydrological modeling, and was limited in scope to impacts on the Aspen area. A watershed-wide integrated assessment would require in-depth hydrological modeling coupled to a high resolution regional climate model. In addition to hydrologic and climate modeling, such an assessment would need to bring together stakeholders and local experts in order to develop more complete understanding and guide appropriate responses to climate change in the context of other watershed issues.

- Existing watershed management plans and operational procedures should be re-evaluated to take into consideration long-term past climate variability and future climate projections related to the timing and magnitude of stream flows. Gaps identified can be incorporated in Phase II management plans.

- Maintenance of existing river-related infrastructure and all new projects should incorporate future projections of stream flows based upon climate change research, and should not rely solely on interpretation of 20th century historical flow variability.

- Basic knowledge of how tightly coupled the economies of the watershed are to climate change is lacking. Research to assess the impact that significant global warming may have on present economic trends (real estate, tourism, recreation, and energy) in the watershed and beyond could help to fill this gap and lead to more sustainable economic strategies.

- Site-specific research and modeling needs to be conducted in order to understand better the complex interactions at work within the Roaring Fork Watershed (see Figure 3.5.5) and improve projections of impacts to the overall watershed.

- Gaps in the current monitoring network for physical, chemical, and biological properties of the watershed should be assessed and used to serve as the basis for developing an integrated, long-term observational database – a critical requirement for future assessments.

Appendix 3.5.1. Climate Change Influence on Water Temperature, Stream Flow, and Trout

By John Katzenberger and Michelle Masone, Aspen Global Change Institute

Temperature

Stream temperatures correlate positively with air temperatures (Ducharne, 2007; Stephan and Preud'homme, 1993), although the majority of streams appear to exhibit less than a 1:1 relationship (Morril et al., 2005). Since the 1970's, rising air temperatures in high altitude locations have been mirrored in rising alpine stream temperatures; these changes are projected to accelerate in the coming decades (Hari et al., 2006). In general, stream temperatures are dictated by the amount of heat exchange at the water/air interface, and to a second degree by the temperature of precipitation, surface runoff, and groundwater. Water temperatures can be further influenced locally by streamcover/shade, proximity to snowpack, and upstream diversions (below which lower flows result in shallower and therefore warmer waters which are more heavily influenced by the sun and air temperature). High alpine stream temperatures typically correlate more loosely with air temperatures because they are dominated by snowmelt (Mohseni and Stefan, 1999; Brown et al., 2005). Since snowmelt runoff can mediate otherwise warmer water temperatures, higher elevation stretches – those in closest proximity to snowpack – will have an advantage over lower elevation reaches as air temperatures warm. However, because global warming will reduce the extent of snowpack that feeds cool meltwater into streams, stream temperatures in the Roaring Fork (particularly the downstream reaches) are likely to track more closely with air temperatures in the future.

Higher temperatures already being witnessed can reduce streamflow volumes through increased evaporation – even if total precipitation goes unchanged (Saunders et al., 2008). A 1993 report by the EPA which assessed the impacts of climate change to water supply in the Colorado River basin found that if precipitation was held constant, a 7.2°F (4°C) increase in temperature could produce enough evaporative loss to decrease runoff by 9-21% (Nash and Gleick, 1993). Alterations to runoff volume are of particular concern since flow is a prime determinant of the physical characteristics of rivers, which in turn shapes biotic composition (Bunn and Arthington, 2002). Additionally, lower flows are generally accompanied by warmer stream temperatures, which – on top of already elevated temperatures – could have a negative impact on both insect development and fish health.

Under a 1°C (1.8°F), temperature increase, the IPCC projects an 8% loss in total North American freshwater fish habitat, and a 15% loss in the Rocky Mountains. A 16% and 28% loss respectively is projected under a 2°C (3.6°F) temperature increase, and a 24% and 40% loss respectively is projected under a 3°C (5.4°F) temperature increase (IPCC, 2007b).

Streamflow

A projected shift in the timing and seasonal volume of runoff in the Upper Roaring Fork River (AGCI, 2006) could prove disruptive to flora and fauna communities throughout the watershed (AGCI, 2006). Crucial aquatic habitat components such as dissolved oxygen, depth, velocity, water temperature, and availability of food supply are highly correlated with streamflow (Ptacek et al., 2003). Additionally, aquatic species have evolved behavioral survival strategies based on existing, natural flow regimes. Any alteration to this flow regime as a result of warming temperatures and precipitation change will be mirrored in alterations to aquatic ecosystems. Because low flows are less effective at diluting pollutants, lower instream flows in summer months could contribute to lowered water quality (especially if the timing of pollution events coincide with reduced flows), resulting in decreased macro-invertebrate and fish populations (Davies, 1978; IPCC, 2001).

Lower flows can also result in a loss of vegetation along the riparian zone. This vegetation provides cover and shade that regulates stream temperatures. Extended periods of high temperatures and low flows in summer months therefore may leave streams too warm and too shallow to provide sufficient fish habitat (AGCI, 2006). In winter, more frequent rain-on-snow events could increase the incidence and magnitude of winter flooding in snow dominated basins (Wigmosta and Leung, 2003); flooding degrades water quality by transporting silt into stream areas, and can also scour the streambed, washing away small organisms and organic matter that serve as important food resources for other species (Waters, 1995; Poff et al., 1997).

The 2007 IPCC report reconfirmed model projections of more extreme precipitation events over the course of the 21st century (IPCC, 2007a). Accordant with these findings, the 2006 AGCI study projected the occurrence of possible, though uncertain, July monsoons towards the end of the 21st century for the greater Roaring Fork watershed area. While such precipitation events could help alleviate the impacts of otherwise low summer flows, intense rains can generate heavy, disruptive streamflows that cause channel erosion, sedimentation, and bank instability – all of which affect aquatic habitat (AGCI, 2006). The projected increase in precipitation variability also suggests a greater risk of prolonged drought periods, as more rainfall will be concentrated into fewer rain days. In arid mountain regions, more frequent drought events associated with climate change will exacerbate low flow conditions, leading to reduced aquatic habitat and biological diversity (Poff et al., 2002).

Trout

Trout are considered to be 'keystone' species; without equivalent replacement by another species, the removal of trout from a river system would leave an ecological gap causing a ripple effect throughout the food chain. For example, the disappearance of trout from a stream could result in an overpopulation of the insects on which they feed, while land vertebrates that prey on trout will lose an important food source. (Willson and Halupka, 1995)

Trout are dependent on clear, cold water – both of which are at risk from global warming. Of all the freshwater fish species, salmonids (which include trout, salmon, and whitefish) are likely to face the greatest negative impacts from climate change (IPCC, 2007b). A recent report by Trout Unlimited projected that western trout populations could be reduced by more than 60% in some areas (Williams et al., 2007). Trout survival is dependent to a great extent on the physical characteristics of a stream, including water temperature, water velocity, instream cover/overwintering habitat, and flow pattern. The combined effects from an increase in water temperatures (particularly in the post peak runoff months), a decline in snowpack, and earlier peak runoff as a consequence of climate change could transform trout communities in the Roaring Fork Valley.

Water temperature

Water temperature can impact fish directly through physiological processes, or indirectly through interactions with other species (Ficke and Myrick, 2004).

Physiology

Incipient upper and lower lethal temperatures are temperatures that fish can tolerate for only a few minutes to a few days before eventually perishing (Myrick and Cech, 2000). A narrow optimal range exists where temperatures are most conducive for reproduction, growth, and efficient metabolism. A shift in temperature away from the optimal range impedes physiological function and the ability to maintain homeostasis. Fish exposed to high enough temperatures become stressed, leading to a reduction in swimming performance and lowered reproduction and growth rates (Ficke and Myrick, 2004). Although many fish are capable of adapting to new thermal regimes by varying their lethal and optimal temperatures by a few degrees, this process occurs over time. The rate and degree of temperature change dictates the success of acclimatization.

Geographic range

The range of a fish species is dictated by thermal gradients; fish are limited to temperature zones where summertime growth (energy storage) is sufficient to meet overwinter energy demand. A major ramification of climate change will be increases in summer maximum temperatures and an even greater increase in winter minimum temperatures, which would cause an upstream shift in the boundaries of fish ranges (Meisner, 1990). Coldwater species may be excluded from presently inhabited downstream stretches of the river, while more heat-tolerant species may expand their range (Chu, 2005).

A 1996 study by Keleher and Rahel found that Rocky Mountain salmonids were restricted to streams in regions where average July air temperatures remained below 22 °C (72 °F), corroborating findings from other similar studies. The study indicated that increases of 1, 2, 3, 4, or 5 °C (1.8, 3.6, 5.4, 7.2, or 9 °F) in average July air temperatures in Rocky Mountain regions would decrease the amount of suitable trout habitat by 16.8, 35.6, 49.8, 62.0, or 71.8% respectively (Keleher and Rahel, 1996). Another study, which measured water rather than air temperature, found that salmonids did not persist in headwater streams with maximum water temperatures above approximately 21 °C (Rahel et al., 1996). As the climate warms, lower elevation trout will likely migrate to higher elevations in search of cooler waters. Fragmented habitats that prevent such upstream migration may experience local extinctions. In particular, reaches heavily impacted by diversions, such as the area below Salvation Ditch, may experience more frequent dewatering in the future, creating a barrier to upstream movement. Even successful migrants will experience a reduction in total habitat due to the fact that stream size decreases with altitude (Hubert and Kozel, 1993; Hari et al., 2006). Eventually, coldwater trout could face a habitat “squeeze” as headwater temperatures approach upper thermal limits and fish have nowhere left to go.

Disease and parasitism

Observations of temperature effects on fish immune function and transmission rates indicate that global warming may increase parasite outbreaks and the persistence of certain fish pathogens (Ficke and Myrick, 2004). According to Hiner and Moffitt (2001), warmer summertime water temperatures in the Rocky Mountains are likely to exacerbate the impact of whirling disease on cutthroat and rainbow trout.

Toxicology

Increased temperatures could also affect the toxicity and bioaccumulation of heavy metals and other pollutants. Studies have shown that both toxicity and uptake of pollutants into fish tissue increase with increasing temperature (Roch and Maly, 1979). The ability to effectively metabolize pollutants under conditions of increased temperature varies by species.

Habitat suitability indicators

Tables 1 and 2 provide habitat suitability indicators by life stage for two of the most dominant trout species in the Roaring Fork Watershed: rainbow and brown trout. This data, from the U.S. Fish and Wildlife Service, represents a synthesis of research literature and expert panel review. While less complete data is available for cutthroat trout, selected studies indicate that cutthroat trout prefer a slightly cooler average temperature range, from 48-54 °F (9-12 °C), and typically do not persist at temperature in excess of 72 °F (22 °C) (Bell, 1973; Benke and Zarn, 1976). Table 3 shows average *maximum* water temperatures for four Roaring Fork trout species at the adult/juvenile/fry life stages during the warmest period of the year. Table 4 presents the same data for embryos.

Trout Habitat Suitability Indicators: Rainbow Trout

Life stage	Average Temperature (°F)			Mean Water Column Velocity (ft/s)			Depth (ft)
	Optimal	**Min**	**Max**	**Optimal**	**Min**	**Max**	**Optimal**
Adult	55-70	32	84	0.5-2.2	–	3.5	1.5+
Juvenile	50-72	32	84	0.0-0.8	–	3.5	2.0+
Fry	57-66	32	77	0.0-0.5	–	3.0	0.82-1.64
Spawning/ Embryo	36-60	35	61	1.6-3.0	0.9	3.1	0.7-8.2

Table 1: Habitat Suitability Indicators for Rainbow Trout. Optimal habitat ranges for average temperature and depth are given for a sustainability index (SI) of 1.0; optimal velocity ranges use an SI of 0.8+. All minimums and maximums assume an SI of 0.0 (fatal). Data estimated from SI curves. (Source: Raleigh et al., 1984)

Trout Habitat Suitability Indicators: Brown Trout

Life stage	Average Temperature (°F)			Mean Water Column Velocity (ft/s)			Depth (ft)
	Optimal	**Min**	**Max**	**Optimal**	**Min**	**Max**	**Optimal**
Adult	54-72	32	75	0.3-0.9	–	6.0	2.6
Juvenile	43-75	32	79	0.1-1.3	–	4.3	3.0
Fry	57-66	32	77	0.7-1.3	–	2.9	1.31-1.61
Spawning/ Embryo	43-48	32	55	0.6-1.7	0.3	3.9	0.8+

Table 2: Habitat Suitability Indicators for Brown Trout. Optimal habitat ranges for average temperature and depth are given for a sustainability index (SI) of 1.0; optimal velocity ranges use an SI of 0.8+. All minimums and maximums assume an SI of 0.0 (fatal). Data estimated from SI curves. (Source: Raleigh et al., 1986)

Average Maximum Water Temperatures: Adult, Juvenile and Fry

Species	Average Maximum Water Temperature (°F)	
	Optimal Range	**Lethal**
Rainbow Trout Adult, Juvenile & Fry	54-64	79
Brown Trout		
Adult & Juvenile	54-66	81
Fry	45-59	79
Brook Trout Adult, Juvenile & Fry	50-61	72
Cutthroat Trout Adult, Juvenile & Fry	52-61	72

Table 3: Optimal and Lethal Average Maximum Water Temperatures for Four Roaring Fork River Trout Species During the Fry, Juvenile and Adult Life Stages. Shown are average maximum water temperatures for adult, juvenile and fry during the warmest period of the year. Optimal temperature ranges assumes a sustainability index (SI) of 1.0; lethal temperatures correspond to an SI of 0.0. Data estimated from SI curves. (Source: Hickman and Raleigh, 1982; Raleigh, 1982; Raleigh et al., 1984; Raleigh et al., 1986)

Average Maximum Water Temperatures: Embryo

Species	Average Maximum Water Temperature (°F)	
	Optimal Range	**Lethal**
Rainbow Trout	46-54	68
Brown Trout	45-55	59
Brook Trout	39-54	68
Cutthroat Trout	45-54	68

Table 4: Optimal and Lethal Average Maximum Water Temperatures for Four Roaring Fork River Trout Species During the Embryo Stage. Shown are average maximum water temperatures during embryo development. Optimal temperature ranges assumes a sustainability index (SI) of 1.0; lethal temperatures correspond to an SI of 0.0. Data estimated from SI curves. (Source: Hickman and Raleigh, 1982; Raleigh, 1982; Raleigh et al., 1984; Raleigh et al., 1986)

While no significant trends in water temperature are evident from the available historical data for the Roaring Fork River, data collected from the Glenwood Springs USGS gage station shows 2002-2007 average maximum water temperatures peaking in August at around 15 °C (59 °F) (maximum water temperature data dates back to 1980, however a data gap exists between 1985 and 2002; analysis of the 1980-1984 data shows average maximum water temperatures for this period also to be close to 59°F). Therefore, taking into consideration the positive but less than 1:1 correlation between air and water temperatures (See Appendix for more on the air-water temperature relationship), a 1.7-2.2 °C (3-4 °F) increase in air temperatures in the Roaring Fork Watershed region by the year 2030, as projected by AGCI 2006, could potentially push brook trout, cutthroat trout, and brown fry into suboptimal thermal ranges during the warmest portion of the year. A medium emissions scenario projection of 3.9-6.1 °C (7-11°F) warming by the end of the century would come closer to, but not exceed, the lethal limits of brook and cutthroat trout, and may approach the suboptimal ranges for rainbow and brown trout. Once the upper limit to the optimal range has been exceeded, mortality rates increase with increasing temperature

(Hickman and Raleigh, 1982; Raleigh, 1982; Raleigh et al., 1984; Raleigh et al., 1986). Although many fish are capable of adapting to new thermal regimes by varying their lethal and optimal temperatures by a few degrees, this process occurs over time. The rate and degree of temperature change dictates the success of acclimatization.

The variation in temperature sensitivities between the four Roaring Fork trout species will influence the relative abundances of these fish as temperatures rise over the next several decades. Because brook and cutthroat trout appear to be best adapted to slightly cooler waters (and less tolerant of high maximum temperatures), in the future these species will likely face greater risk of depressed physiological function and – in extreme cases – temperature induced mortalities. However, research to date underscores the fact that thermal sensitivity should not be the only factor considered when assessing climate change impacts.

Water chemistry

Increases in global temperature can be directly tied to changes in water chemistry including dissolved oxygen levels, nutrient concentrations, toxicity and accumulation of pollutants, and pH. As far as fish health is concerned, the most important water chemistry variable is dissolved oxygen (DO) concentration (Davis, 1975; Alabaster and Welcomme, 1962; USEPA, 1973). Trout, aquatic insects, macrophytes, and algae are all dependent on sufficient DO levels. As temperature increases, DO in the water decreases (oxygen is less soluble in warm water than in cold water). Meanwhile, elevated water temperature increases the metabolic rate of fish, which in turn increases DO requirements. Consequently, a species' thermal tolerance is typically a reflection of its sensitivity to dissolved oxygen concentrations. Temperature increases are also known to accelerate macrophyte production, which can contribute to eutrophic conditions when nutrients are released during decomposition. Such high concentrations of nutrients can further reduce DO levels. Kankaala et al. showed that a dramatic 300-500% increase in macrophyte biomass could result from a 2-3°C (3.6-5.4 °F) increase in water temperature (Kankaala et al., 2002). Consequently, global warming is expected to increase macrophyte biomass, reduce dissolved oxygen levels, and increase the demand for oxygen, raising the probability of hypoxia-induced fish mortalities.

Hypoxic conditions have been shown to reduce feeding activity and growth rates, suppress immune function, reduce swimming speeds, and limit tolerance of other environmental stresses (Doudoroff and Shumway, 1970; Ficke and Myrick, 2004). Fish can tolerate short periods of reduced oxygen, and studies have shown that trout can acclimatize to reduced DO concentrations if declines occur gradually over time, however abrupt declines or several days of sustained oxygen depletion can often lead to fish kills (Davis, 1975). Fish may respond behaviorally to avoid depleted oxygen conditions by physically moving out of an area.

At sites already experiencing low DO levels, only a moderate drop in DO can impair physiological performance (Morrill et al., 2005). Projected increases in July and August temperatures may reduce DO below minimum required concentrations for some aquatic species. For coldwater trout species, the lower boundary for optimal summertime DO concentrations appears to be around 9mg/l, but this number is debatable (Hickman and Raleigh, 1982; Raleigh, 1982; Raleigh et al., 1984; Raleigh et al., 1986). Prolonged exposure to concentrations below 6.0 mg/l can be harmful or fatal to stream biota (Ferguson, 2003). According the USGS Roaring Fork Watershed Water-Quality Data, data for the Roaring Fork River collected at Glenwood Springs shows that DO levels in August (the warmest month of the year) have averaged 9.4 mg/L over the period of 1973-2001.

Stream flow

Research has shown that fluctuations in streamflow can be a limiting factor in trout growth (Hunter, 1991). In a warmer climate, a greater percentage of winter precipitation falls as rain rather than snow; the result is more runoff in winter and less snow for the spring melt. Modeling for the Roaring Fork Watershed region projects reduced snowpack, earlier peak runoff, lower summer flows, and more variable seasonal flow (due to an increase in extreme precipitation events) over the course of the 21st century (AGCI 2006; IPCC, 2007b).

Changes to the hydrograph will impact trout habitat by influencing the frequency and extent of scouring and dewatering events. In winter, high flow events and flooding can scour the streambed, displacing trout and making them easy prey. Therefore a surge in peak daily flow as a result of midwinter melting could become an additional stressor to trout communities in the future.

Dewatering occurs when flows are too low to persist above the permeable streambed, leaving fish "high and dry." Diversions can already do this in some reaches of the Roaring Fork. Under warmer summer conditions and greater risk of heat waves, the likelihood of dewatering goes up, and the reach of affected areas will likely increase. Lower summer flow will reduce total habitat area.

Warming may also reduce seasonal formation of ice dams and their subsequent release. Observation supports a correlation between ice-jam flood frequency and spring snowpack depth/extent. These flash flood events have a significant impact on stream habitat including riparian vegetation, water quality (temperature, dissolved oxygen, nutrients and pollutants), sediment transport and substrate, aquatic plants, the food cycle, and fish habitat. Recent research by Beltaos et al. utilized temperature and precipitation outputs from a climate model to simulate the impact of climate change on ice in the Peace River Basin, a freshwater river system in northern Alberta, Canada, Their analysis indicated thinner ice cover and an abbreviated ice season under both high and low emissions scenarios, suggesting a significant reduction in ice-jam flooding and subsequent loss of aquatic habitat. (Beltaos et al., 2006)

At the same time, increased winter flows from snowmelt may produce secondary effects that could benefit trout. The build up of anchor ice – which forms under extreme cold and is an indirect effect of low flow conditions – would be reduced. This would have a positive impact on fish species: anchor ice slows water velocities at the bottom of the river, which depletes oxygen concentrations, and can cause hypoxia in fish embryos. Death can result when anchor ice collapses and deflects water out of the stream (Hunter, 1991).

Stream cover

Altered patterns of riverside vegetation resulting from shifts in hydrology are particularly critical to aquatic ecosystems (Meyer et al., 1999). Extended periods of low flows can increase water stress in riparian plants and ultimately result in a loss of riverside vegetation (Smith et al., 1991), which shades passing waters and moderates stream temperatures. Overhead vegetation also plays a critical role in supplying logs, root wads, branches, and other large organic debris to the stream that provides instream cover for fish, protecting them from predation (Wilzbach et al., 1986). Fast moving floodwaters, which can cause displacement – particularly in winter – are slowed by instream debris. Furthermore, debris aids in the creation of pools (as water passes over top and carves out the riverbed on the downstream side), the deeper and colder waters of which fish seek out in the summertime to escape higher temperatures elsewhere. Because a direct relationship exists between trout population and stream cover (Hunter, 1991), a reduction in riparian green zones due to climate change may limit trout populations. Because trout will likely become more dependent on deep pools as stream temperatures increase, stewardship of these habitats could help to mitigate declines in trout populations sustained from climate change. A recent report by Trout Unlimited recommended management projects that deposit more woody debris and variable-sized boulders within rivers as a way to mitigate the effects of global warming on aquatic ecosystems (Williams et al., 2007).

Apart from overhead stream cover, surface ice cover (and ice with snow cover) insulates fish from winter temperatures and provides protection from predators. A growing body of evidence derived from both historical trends and climate models suggests a decline in future river ice cover as a result of warming air temperatures (Magnuson et al., 2000). According to the IPCC, annual river and lake ice cover has already been reduced by an average 12 days over the past 150 years (IPCC, 2007a). Reduced ice cover can increase energy deficiencies – a key factor in winter mortality – by affecting metabolism and feeding behavior (Finstad et al., 2004). A study which examined the ability of salmonids to adapt to changes in ice cover found that responses can vary greatly between species, and thus could directly influence species composition (Finstad, 2007).

Climate variability and extremes

While change in the direction and magnitude of precipitation for the Roaring Fork Valley is less certain than change in temperature (AGCI, 2006), total precipitation will likely be less evenly distributed across time, coming instead more in the form of extreme events (Palmer and Räisänen, 2002; Bell and Sloan, 2006; NAST, 2000; Hamlet and Lettenmaier, 2007). Intense rains cause flooding that can lead to erosion, bank instability, sedimentation, and scouring in aquatic systems. Longer, more frequent heat waves (like those seen in 2003 and 2006 in Europe and North America) fueled by global warming can shrink rivers. A reduction in habitat, combined with extreme maximum daytime temperatures and nighttime temperatures that do not cool down (preventing thermal recovery), could increase the likelihood of thermal stress and the potential for fish kills.

Trout food supply

Climatic changes will induce similar (but not necessarily parallel) shifts in the rates of production and timing of emergence of prey trout species (e.g. invertebrates and microbes). Paleo evidence reveals that past changes to the earth’s climate have catalyzed changes in species interactions, including predator-prey relationships. Warmer stream temperatures and earlier peak runoff are already having an impact on food supply in Rocky Mountain streams. Insects like mayflies, a key food source for trout, are already hatching earlier in the year (Williams et al., 2007) and have been shown to undergo accelerated development (thus shortening the life cycle) at warmer sites compared to colder ones (Pritchard and Zloty, 1994). Within other aquatic insect species, females are producing fewer eggs, which have obvious ramifications for fish populations (Saunders et al., 2008; IPCC, 2007b). In addition to altered reproductive patterns, migrations could eliminate an important predator/prey species in one reach of a stream, and introduce a new one in another.

Because temperature influences the physiological processes of aquatic organisms, shifts in the timing of life events can lead to altered competitive interactions, with profound implications for macroinvertebrate diversity (Sweeney, 1984; Vannote and Sweeney, 1980). However, existing research into the effects of temperature on freshwater macroinvertebrates is limited, and previous studies vary in their results. In studies where temperature was experimentally manipulated, some have found a strong link between stream temperature and macroinvertebrate diversity (Petchey et al., 1999). Others, meanwhile, have shown no effect of elevated temperatures on species richness, but a reduction in densities (Hogg and Williams, 1996).

In contrast to the experimental temperature manipulation studies, a 2006 study by Burgmer et al. examined observed temperature trends and macroinvertebrate populations in Northern European streams over periods of 10-15 years. Although a large amount of variation was observed (attributed to other regional environmental factors), increases in mean temperature over the last two decades corresponded to substantial alterations to species composition. Results suggested that macroinvertebrate responses to global warming are highly species-specific; some taxa benefited from warming by expanding their range or increasing in abundance, while others nearly disappeared from the study region. Study authors pointed out that, while weak, the observed effects are "potentially highly important as they became evident over a rather short time period and upon moderate increases in mean temperature," and "[t]herefore, aquatic invertebrates are likely to show strong responses to climate warming." (Burgmer et al., 2006)

Hydrological changes accompanying reduced snowpacks are also likely to impact aquatic macroinvertebrate communities, however little work has been done linking alpine stream biota and stream flow. One study of note by Brown et al. established a connection between macroinvertebrate diversity and snowmelt runoff in an alpine stream in the French Pyrenees. They demonstrated that a reduction in meltwater volume increased macroinvertebrate diversity and overall abundance at a single site, but decreased diversity between sites. Changes in macroinvertebrate populations were attributed to reduced suspended sediment concentrations, higher stream temperatures, and altered pH. As with temperature, optimal meltwater conditions varied greatly between species. The authors predicted extinction of selected native alpine species under future conditions of reduced snowmelt runoff. (Brown et al., 2007)

Both magnitude of change and prey availability will be a critical factor in trout survival. A transition to a warmer climate will be accompanied by local food chain disruptions, albeit the specific mechanisms are not well understood as complex ecosystem interactions make it difficult to predict the precise effects of warming on food availability. The aforementioned studies provide a general indication of the sort of changes to macroinvertebrate communities that predator species such as trout could face in a warmer future. Caution should be taken, however, when evaluating the results from manipulation experiments in the context of a complete system; In a real world ecosystem facing climatic warming, a shift in species richness, for example of a plant species, could be counteracted by another previously unaccounted for variable, such as a population increase in grazers (Klein et al., 2004). As anthropogenic climate change gives rise to new ecological regimes, some prey species may experience population explosions while the viability of other species could become threatened. Site-specific research is needed to make more explicit projections for the effects on Roaring Fork macroinvertebrate diversity and subsequent impacts to local trout populations.

Native vs. non-native species competition

Non-native Roaring Fork trout species, such as brown, rainbow, and brook trout, compete with native cutthroat trout for food sources and habitat space. Because non-native species are often better able to adapt to higher temperatures, these fish may out-compete native populations under warmer conditions. Global warming could allow non-natives, particularly brown and rainbow trout (which are better adapted to slightly warmer water temperatures) to expand their range and displace native cutthroat. (Willams et al., 2007)

Reproduction and development

Spawning and incubation

The reproductive success of Roaring Fork trout populations in a warmer climate will vary greatly by species. Low overwinter temperatures – likely to be compromised by global warming – are often necessary for successful spawning of coldwater salmonids (Gerdaux, 1998), while extreme temperatures during incubation can cause mortalities. Within the seasonal spawning window, the exact spawning date is determined largely by temperature, but can be delayed by high flows (Jager et al., 1999). It is well documented that high water velocities that accompany floods can wash away eggs and newly emerged fry (Fausch et al., 2001). With more precipitation coming as rain rather than snow in alpine areas, a subsequent increase in winter flood disturbances may lead to a decrease in young survival rates. Moreover, length of the incubation period is highly dependent on both temperature and runoff (Ficke and Myrick, 2004). Elevated temperatures could encourage faster embryonic development and earlier hatching (Kwain, 1975) at a time when food sources may be scarcer. Warmer water also increases maintenance metabolism, taking energy away from growth and producing smaller fry which are more vulnerable to predation.

Brown and brook trout are typically fall or early winter spawners, with incubation occurring over the winter. Rainbow and cutthroat trout on the other hand are spring spawners, with fry emerging in the late spring/summer. It stands to reason therefore that that winter spawners are adapted to lower incubation temperatures than spring spawners (Elliot, 1981). Spring spawners are further isolated by the timing of spring runoff; cutthroat trout spawn just after the peak runoff and rainbow trout spawn just before (Williams et al., 2007). An earlier spring runoff could create a “squeeze’ effect whereby rainbow trout, unable to spawn any earlier, encroach on earlier cutthroat spawners (Williams et al., 2007). Increased opportunity for hybridization and a potential loss of distinct species would result.

A 1999 study by Jager et al. which modeled the consequences of climate change on trout in Sierra Nevada streams found that the combined effects from a 2 °C (3.5 °F) increase in temperatures and a shift in peak flow from spring to winter affected brown and rainbow trout abundance by decreasing the age at which fish became reproductively mature. The same model indicated an abbreviated spawning season for brown trout (later onset and earlier emergence), and a three month earlier shift for rainbow trout. In addition, the model suggested that although a future shift in the timing of spawning and incubation could negatively impact winter spawning trout by exposing redds to scouring from higher winter flows, a decrease in dewatering may more than compensate for this effect. Meanwhile, spring spawners may suffer from more frequent dewatering events. More research is needed to accurately predict scouring and dewatering mortalities from hydrological shifts.

The same study found that the combined effects from streamflow and temperature changes were not additive; considered alone, neither factor was an accurate predictor of population size. When changes to both stream flow and temperature were taken into account, the model projected a dramatic increase in Rainbow trout in upstream reaches; the multivariable simulation indicated a reduction in both species in downstream reaches (Jager et al., 1999). The cumulative effects from climate-driven changes to flow patterns, temperature, dissolved oxygen, and stream cover will give rise to an array of complex physiobiological interactions. Such complexity warrants further research in order to make useful predictions on how these kinds of changes could alter trout habitat in the Upper Colorado River Basin and Roaring Fork River.

Although the Jager study did not model Rocky Mountain streams and cannot be used as a precise predictor of what will happen in the Roaring Fork, it highlights the myriad of complex interactions that must be accounted for when assessing climate change-driven impacts to fish species. Similar research/modeling should be conducted for the Roaring Fork Watershed in order to best approximate local impacts. It is likely, however, that temperature-induced shifts in the timing of spawning and incubation will almost certainly affect the four Roaring Fork trout species differently, potentially driving shifts in the relative abundances of these populations and increasing the likelihood of hybridization.

Growth

In the fall and spring , a small increase in water temperatures could extend the growing season of trout. Fish in high elevation streams, where cold temperatures currently limit productivity, may benefit (Ries and Perry, 1995). However, higher growth requires the availability of sufficient food resources to support an increase in consumption (Shuter and Meisner, 1992). Because metabolic demand increases with temperature, summer fish growth is often limited by food supply. Therefore, in addition to direct trout impacts, climate-driven changes to the abundance and availability of prey species will play an important role in trout growth and related overwinter survival.

Studies on brown trout have demonstrated that the optimal temperature range for growth decreases as fish food rations are reduced (Elliot, 1975a; Elliot, 1975b). If temperatures increase above a certain threshold where metabolic demand cannot be met by adequate food supply, growth rates will decrease, and starvation-related deaths will increase. Research indicates that trout could benefit from increased growth rates in the spring and fall, but may experience reduced growth rates in the summer – especially under more extreme warming (Ries and Perry, 1995). A study which simulated the effects of global warming on a high elevation stream in the Appalachian Mountains found that an increase in up to 2°C (3.6°F) in stream temperature increased brook trout growth, while more severe temperature increases had more variable effects as a result of a greater dependence on prey abundance; bioenergetic modeling indicated that a 15-20% increase in food consumption would be necessary to support higher growth rates under a 2°C (3.6°F) increase in temperature, whereas a 30-40% increase in food consumption would be necessary to achieve current growth rates with 4°C (7.2°F) of warming (Ries and Perry, 1995).

Once temperatures drop below 50 °F (10 °C), trout seek out stations in slow-moving areas on the bottom of the stream where they remain "lazy" in order to conserve energy during the cold winter months (Hunter, 1991). By restricting energy storage, lower summertime growth can therefore lead to a decrease in overwinter survival; conversely, milder winters could increase overwinter survival by alleviating stress from extremely cold temperatures – which factor will dominate in a warmer Roaring Fork River remains uncertain.