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.