STRATUS CONSULTING

The Potential Consequences of Climate Change for Boulder Colorado’s Water Supplies

Prepared for:

Nancy Beller-Simms, PhD
NOAA Climate Program Office
1315 East West Highway, Room 12221
Silver Spring, MD 20910-5603

The Potential Consequences of Climate Change for Boulder Colorado's Water Supplies

Prepared for:

Nancy Beller-Simms, PhD
NOAA Climate Program Office
1315 East West Highway, Room 12221
Silver Spring, MD 20910-5603

Prepared by:

Joel B. Smith
Stratus Consulting Inc., Boulder, CO

Prof. Kenneth Strzepek
University of Colorado, Boulder, CO

Lee Rozaklis
AMEC Inc., Boulder, CO

Carol Ellinghouse
City of Boulder, Boulder, CO

Kathleen C. Hallett[1]
Applegate Group, Denver, CO

February 3, 2009
SC11511

1. Ms. Hallett was formerly with Stratus Consulting where she worked on this project.

Contents

Appendices

A Climate Change Scenarios Data
B K-Nearest Neighbor

Figures

Table

Abstract

This study combines the potential impacts of climate change with long-term climate variability to examine their effects on the water supply of one community. The study team examined outputs from general circulation models (GCMs; supplied by the National Center for Atmospheric Research) for grid boxes that include Boulder, Colorado, and selected the wettest model, the driest model, and a middle model. Estimates of climate change for 20-year periods centering on 2030 and 2070 were used. In addition, 437-year (1566-2002) reconstructions of streamflow in Boulder Creek, South Boulder Creek, and the Colorado River (conducted by Connie Woodhouse) were used. A "nearest neighbor" approach was used to select years in the observed climate record that resemble the paleoclimate reconstructions. Average monthly GCM changes in temperature and precipitation for 2030 and 2070 were combined with multiple recreations of the paleoclimate record to simulate the combined effects of change in climate and paleoclimate variability.

Increase in temperature alone was estimated to have little effect on the total annual volume of runoff, but by 2070 would shift peak runoff one month earlier. This results in higher late winter and spring runoff and lower summer runoff. Indeed, these seasonal changes (e.g., higher winter runoff, lower summer runoff) were estimated even with increased or decreased precipitation. Annual runoff is quite sensitive to change in precipitation, with runoff decreasing with reduced precipitation and increasing with higher precipitation.

Using Boulder's water management model (which incorporates supply and demand for water and water rights) and accounting for population growth in Boulder and changes in demand for crop irrigation, the study found that wet and "middle" scenarios had little effect on the reliability of Boulder's water supply. But reduced precipitation scenarios resulted in violations of some of Boulder's water supply reliability criteria, which give goals for the frequency of providing specified levels of service (e.g., for indoor use, lawns). By 2070, higher greenhouse gas emissions scenarios increase the risk of supply disruptions more than the lowest emissions scenario. Although an earlier study found that Boulder's water supplies would be reliable with a repeat of climate conditions from hundreds of years ago, this study found that the *combination* of climate change imposed on a reconstruction of events from the 16th and 17th centuries would cause more frequent violations of the city's water supply criteria. Demand for irrigation was projected to increase substantially, but very little of the increased demand would be met under the middle or dry scenarios.

In general, Boulder is in a relatively good position to adapt to climate change because it has relatively senior water rights and can fill its reservoirs during later winter and spring months when runoff is projected to increase. Other municipalities without reservoirs or with junior water rights that will more frequently not be allowed to divert in late summer months would likely be at greater risk due to climate change. Boulder will work to increase the flexibility of operations for its water system and examine means to reduce demands and enhance supplies.

Acknowledgements

This project was funded by grant NA05OAR4311123 from the National Oceanographic and Atmospheric Administration Office of Atmospheric Research Climate Program Office. We wish to thank our project officer, Dr. Nancy Beller-Simms, for her continued support, encouragement, and patience on this project.

We appreciate the support and collaboration by the City of Boulder. Carol Ellinghouse, Water Resources Coordinator for the City of Boulder, participated from the beginning to the end of the project, from project conceptualization, through analysis to review of results. Her involvement provided a critical to a key stakeholder, the City of Boulder.

Our efforts were greatly helped by the sound advice and thoughtful guidance provided by a number of people. The advisors included Dr. Tom M. L. Wigley of the National Center for Atmospheric Research, Dr. Connie Woodhouse of the University of Arizona (formerly at NOAA), Dr. Klaus Wolter of NOAA, and Brad Udall of the Western Water Assessment.

The University of Colorado provided extensive support for the project with minimal compensation. Dr. Kenneth Strzepek built a runoff model and estimated change in runoff. Dr. Strzepek also participated in project meetings and presentations. He and Dr. Balaji Rajagopalan applied the nearest neighbor approach that enabled us to combine climate change scenarios with the reconstructed streamflow.

Tsasha Christopoulos was the Support Associate for Stratus Consulting. Erin Miles at Stratus Consulting prepared the report for publication. Christina Thomas was the technical editor on the report.

Executive Summary

Incorporating knowledge of the effects of climate change into water resource management is a challenge for several reasons. Among the challenges are the long time frames over which climate change will happen and uncertainty about the changes. Projections of climate change are typically done at a geographic scales far larger than the scale on which water management decisions are typically made. Further, changes in climate variability are often not considered in studies of climate change impacts. And often, decision makers on water resources are not closely involved in studies, whose results may thus not be applicable to decision making.

This study focused on the vulnerability of the water supply of Boulder, Colorado to climate change. Boulder is a city serving the water needs of 113,000 people. Like many cities in the West, Boulder depends on snowpack for its water supplies. Seventy percent of Boulder's treated water supplies come from the eastern slopes of the Rocky Mountains west of the city. The other 30% comes from the Upper Colorado River on the West Slope of the Rockies and is transported via tunnels cut through the mountains.

In 2003, Boulder examined its vulnerability to a 285 -year reconstruction (1703-1987) of streamflows in Boulder Creek based upon tree ring data. The study found that Boulder's water supply reliability would not be threatened by a repeat of climate variability over several centuries. However, the City also examined a long-term reduction (15%) in average streamflows and found that such a change would significantly reduce reliability of the water supply system.

This new study, which was funded by a grant from the National Oceanographic and Atmospheric Administration's Office of Global Programs, builds on the previous study in two ways. First, climate change scenarios are combined with the paleoclimate reconstructions to effectively examine the impacts of human induced climate change imposed on a repeat of long-term variability. Second, an updated and lengthened tree ring-based reconstruction was completed shortly before this study was initiated, a 437-year record (1566-2002) and was used in this study.

A key aspect of this study was the close collaboration between the researchers and key water management staff in the City of Boulder. Carol Ellinghouse, Water Resources Coordinator for the City, was involved in this study from its conception through structuring of the study, development of scenarios, conduct of the study, and analysis of results.

Methods

The study has four main analytic components: (1) climate scenarios; (2) runoff modeling; (3) water management modeling; and (4) policy analysis.

Climate scenarios. The climate scenarios had two components: average change in long-term climate, and combined average change and long-term climate variability. The study examined climate change impacts in 2030 and 2070 by examining estimated changes in climate in the central Rocky Mountains using 21 general circulation models (GCMs). These models all project higher temperatures. Roughly half the models project decreased precipitation in the central Rockies, and half the models project an increase. The models tend to project wetter winters and drier summers. Four GCMs were selected to reflect a wide range of potential changes in precipitation. One model had one of the largest reductions in annual precipitation for the region, one had one of the largest increases in precipitation for the region, and one was close to the middle of the projections. All of those three models project wetter winters. The fourth model projects decreased winter precipitation.

Three scenarios of greenhouse gas emissions were used, drawing on the Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios (Nakićenovic et al., 2000). The scenarios were B1, A1-B, and A2 and reflect a wide range of future emissions of greenhouse gases. The precipitation and temperature changes projected using the A1B emissions scenario are displayed in Figures S.1 and S.2.

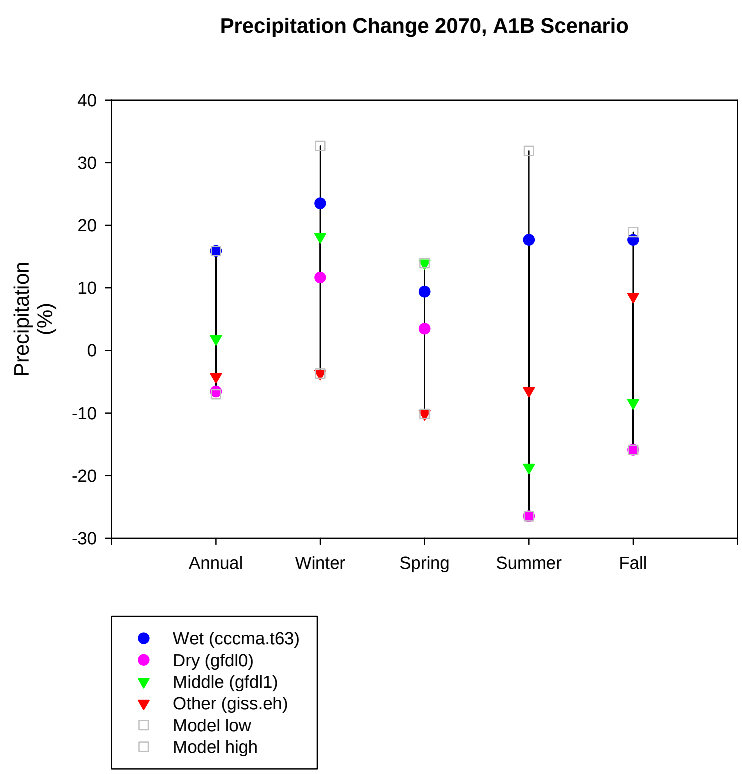

Figure S.1. Climate change scenarios on precipitation for 2070 for A1B scenario.

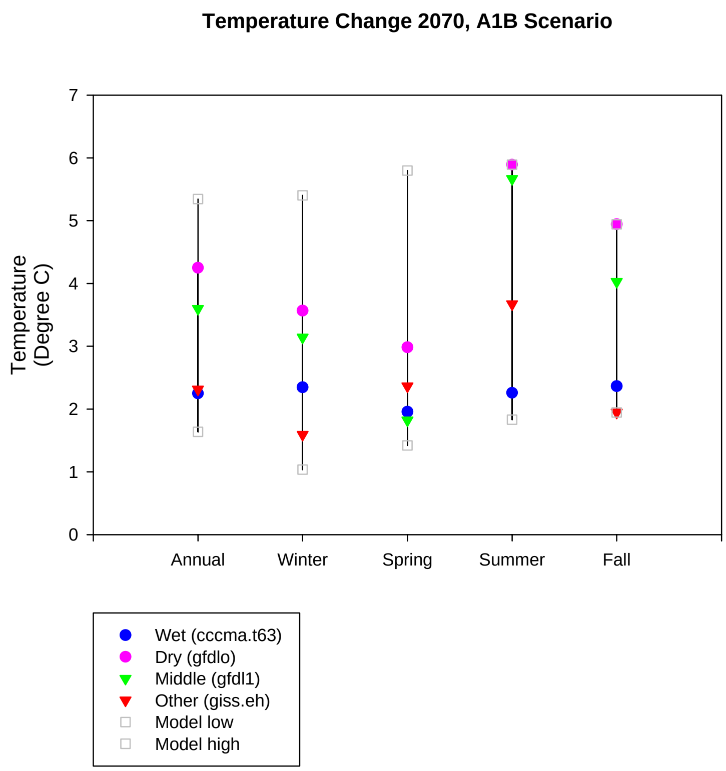

Figure 3.2. Climate change scenarios on temperature for 2070 for the A1B scenario.

This study is, as far as the authors can tell, the first in the United States to combine long-term climate change and long-term variability. The climate change scenarios were combined with the 437-year reconstruction of streamflow in Boulder Creek. The reconstructed streamflows are displayed in Figure S.3. The nearest neighbor approach was used to match streamflows in the period before 1953, when accurate climate records began in the mountains above Boulder. Years between 1953 and 2004 were then used as proxies for the pre-1953 years. Temperature and precipitation changes from the GCMs were then added to, or multiplied by in the case of precipitation, the temperature and precipitation record derived from this procedure.

Runoff modeling. A new runoff model for Boulder Creek, CLIRUN2, was developed for this project. It builds on previous models such as CLIRUN and WATBAL. This model was reconfigured for wet, middle, and dry runoff conditions.

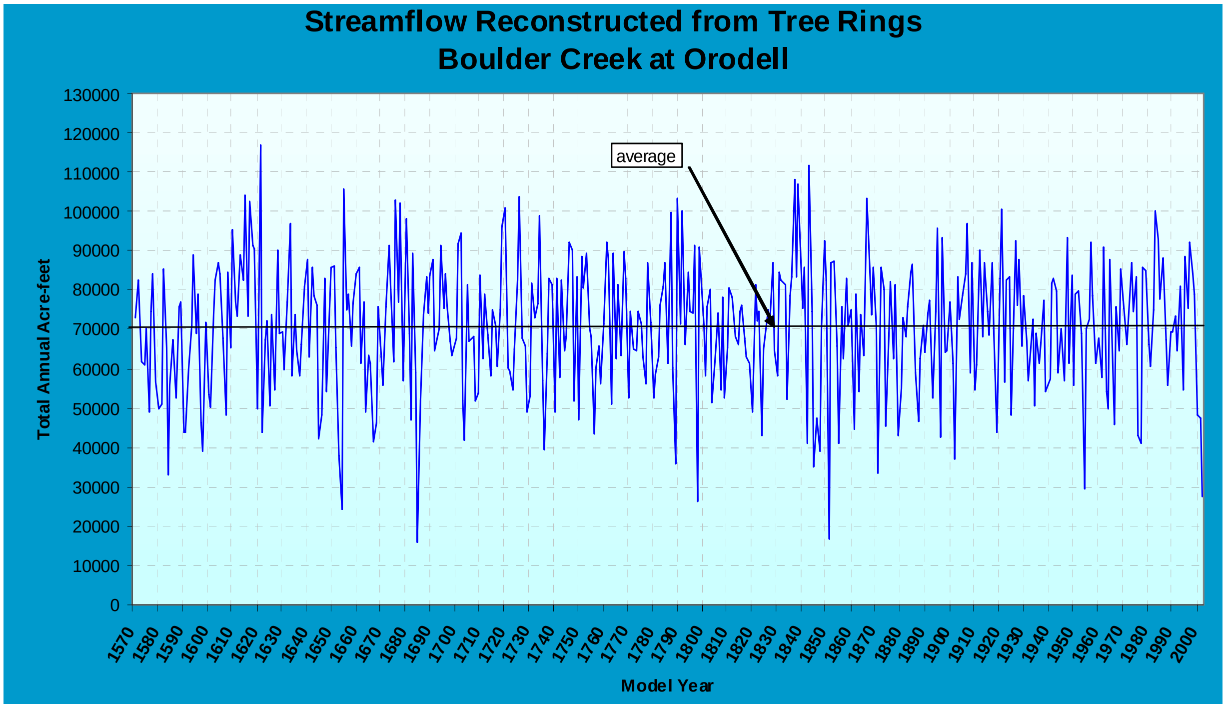

Figure 3.3. Reconstructed streamflows for Boulder Creek. Data provided by Connie Woodhouse.

Water management modeling. Boulder has a well developed management model that it has used for years to analyze water supplies and demands. The Boulder Creek Model is a network model that uses a linear programming algorithm to allocate water supplies among competing demands. It optimizes allocation of water based on relative water rights priorities or operating rules as objective function drivers. Changes in crop irrigation demand (downstream from Boulder) were also estimated.

The impacts of climate change were assessed based on whether they would increase or decrease risk of triggering drought restrictions. Boulder plans for increasing levels of reductions in water deliveries based on frequency of droughts. Restrictions are increased from relatively mild to severe depending on whether a drought is a 1 in 20 year event, a 1 in 100 year event, or a 1 in 1,000 year event. If the frequency of imposing these restrictions increases above these targets, Boulder is essentially violating its drought reliability criteria.

The team then analyzed the implications of the potential impacts for the City's water management, and in particular drought management, policies. Results were presented to the City Council, city advisory boards, and other water users.

Results

Runoff. The most robust finding of the runoff modeling was that under all climate change scenarios the hydrograph for Boulder Creek will shift because peak snowmelt will happen earlier than it does now. This is displayed in Figure S.4 for 2070. Runoff is projected to increase in February through May and decrease from June through September. Peak runoff shifts from June to May in all scenarios but one. Table S.1 displays annual and seasonal changes in runoff. Note that whether runoff increases or decreases annually is indeterminate. Generally, the wet scenarios increase runoff and the dry scenarios decrease runoff. No change in precipitation results in a slight decrease in runoff. But virtually all the scenarios project increased winter and spring runoff and decreased summer runoff.

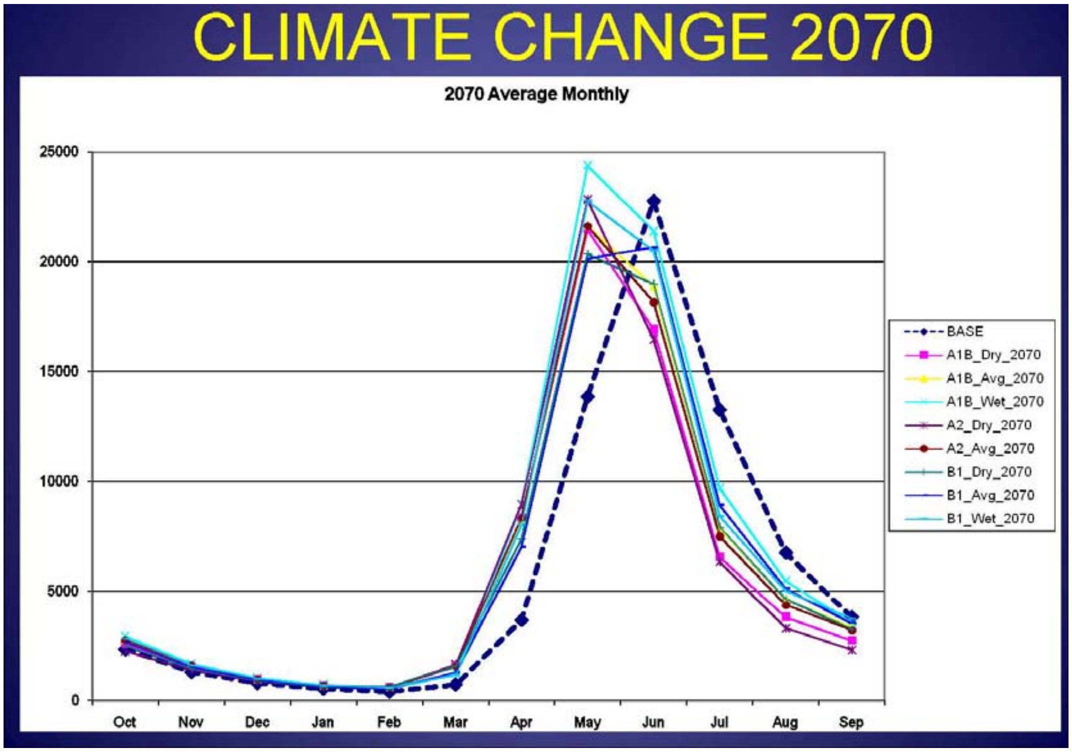

Figure S.4. Boulder Creek runoff under current climate and climate change in 2070.

Table S.1. Estimated change in runoff in Boulder Creek

	Seasonal change				
Scenario	**Annual**	**Winter**	**Spring**	**Summer**	**Fall**
Base case	0%	0%	0%	0%	0%
B1 Wet 2030	7%	19%	19%	-18%	15%
B1 Mid 2030	-2%	4%	13%	-28%	-7%
B1 Dry 2030	-3%	9%	7%	-21%	-1%
A1B Wet 2030	12%	21%	24%	-8%	14%
A1B Mid 2030	-2%	5%	13%	-25%	-12%
A1B Dry 2030	-4%	19%	8%	-26%	6%
A1B Dry3 2030	-6%	-3%	2%	-23%	0%
A2 Mid 2030	-1%	8%	10%	-22%	4%
A2 Dry 2030	-5%	8%	7%	-28%	-2%
B1 Wet 2070	9%	38%	27%	-28%	23%
B1 Mid 2070	0%	23%	16%	-27%	2%
B1 Dry 2070	0%	62%	15%	-34%	9%
A1B Wet 2070	16%	45%	35%	-21%	27%
A1B Mid 2070	5%	46%	25%	-35%	16%
A1B Dry 2070	-4%	65%	15%	-44%	12%
A1B Dry3 2070	-3%	32%	13%	-35%	7%
A2 Mid 2070	0%	47%	20%	-41%	11%
A2 Dry 2070	-4%	62%	19%	-49%	0%

Management modeling

The impacts of climate change on the management of Boulder's water supplies depend largely on whether annual runoff increases or decreases, but also on change in timing of peak runoff. An increase in runoff results in an increase in water supply and a decrease in demand. (Change in flood risks was not assessed in this study.) Earlier peak runoff would allow Boulder to capture a larger percentage of available annual streamflow due to less competition from downstream agricultural water users during the critical spring reservoir fill season.

Irrigation demand from agricultural water users downstream of Boulder would increase with higher temperatures because with earlier runoff, the "natural overlap" between stream flows and irrigation demands would be reduced, resulting in relatively greater shortages to irrigation uses. Irrigators would have relatively minor impacts under the wet and middle scenarios. However, under the dry scenarios, a smaller share, and in some cases a substantially smaller share, of irrigation demand would be unmet.

The likelihood of triggering drought restrictions in Boulder's water supply system moves in the opposite direction as changes in runoff. If runoff increases, then the likelihood is reduced. For most of the scenarios involving little change in precipitation, the likelihood of triggering drought restrictions does not increase. However, for the high emissions scenario (A2) with little change in precipitation in 2070, risk of triggering the 1:20 drought criteria rises. It is under all the reduced precipitation scenarios that potential for violating drought criteria rises. The increases are more likely in 2070 than in 2030 and more likely under the higher greenhouse gas emissions scenarios than under the lower emissions scenarios.

Policy analysis. The results of this study and the 2003 study have been presented to Boulder citizens, City Council, city advisory boards, and other water users. Among the main policy conclusions are the following:

- Boulder is well positioned to adapt to the estimated change in runoff patterns because it will have an increased ability to fill City reservoirs in the spring before downstream agricultural users with senior rights make their calls as the peak runoff period moves earlier in the year. Also, the City's senior direct flow water rights will allow continued diversions in late summer if streamflow decreases. Other water users may have higher risks under climate change than Boulder.

- The combination of a warmer climate and past variability poses more risk to Boulder's water supply reliability than either a repeat of the past variability without climate change or a change in average climate conditions imposed on the observed climate record.

- The City of Boulder will examine "no regrets" actions that will increase reliability of its water supplies. It also will pursue monitoring of climate as well as developments in the science of climate change. In particular, the city will monitor projections of climate change in the central Rocky Mountains. The city will also continue to educate its water users on risks from climate variability and change.

1. Introduction

There is often a disconnect between the projections of climate change and the ability of water managers to examine the risks that climate change poses at a scale appropriate for policy making. Climate projections are most reliable on very large geographic scales, much larger than the geographic scales on which water management decisions are typically made. Climate projections on such finer geographic scales are typically not reliable. In addition, substantial uncertainty exists about the magnitude and direction of climate change: How much will temperatures rise? Will precipitation increase or decrease? Beyond this, climate change is not the only aspect of climate that concerns water managers. They are also concerned about climate variability such as the potential for deep or persistent droughts.

Climate change studies are often conducted by researchers not connected to policy makers. The selection of the geographic area, the variables to be studied, and the scenarios and the interpretation of results are typically made by researchers without input from policy makers. But policy makers need to be closely involved in such studies from the beginning to ensure that the outputs of such studies are worthwhile for policy making.

This study addresses how risks to water supplies from climate change can be addressed by one community, Boulder, Colorado. City water utility staff was closely involved in this study. In addition, this study built on an earlier study of Boulder's water supply vulnerability to long-term climate variability by considering the combined effects of climate change and variability.

1.1 Boulder's Water Supply, Growth Plans, and Drought Management Plans

The Boulder Creek basin is situated within the larger South Platte basin of Colorado. Most of the city's water is from snowpack melt from the Rocky Mountains. The water is drawn from two sources. About 70% of the treated water supplied to the City of Boulder is diverted from North Boulder Creek and Middle Boulder Creek, which produce the majority of the stream flow in Boulder Creek. The natural flow of Boulder Creek near Orodell is 71,000 acre-feet per year (City of Boulder, 1988; see Figures 1.1 and 1.2).

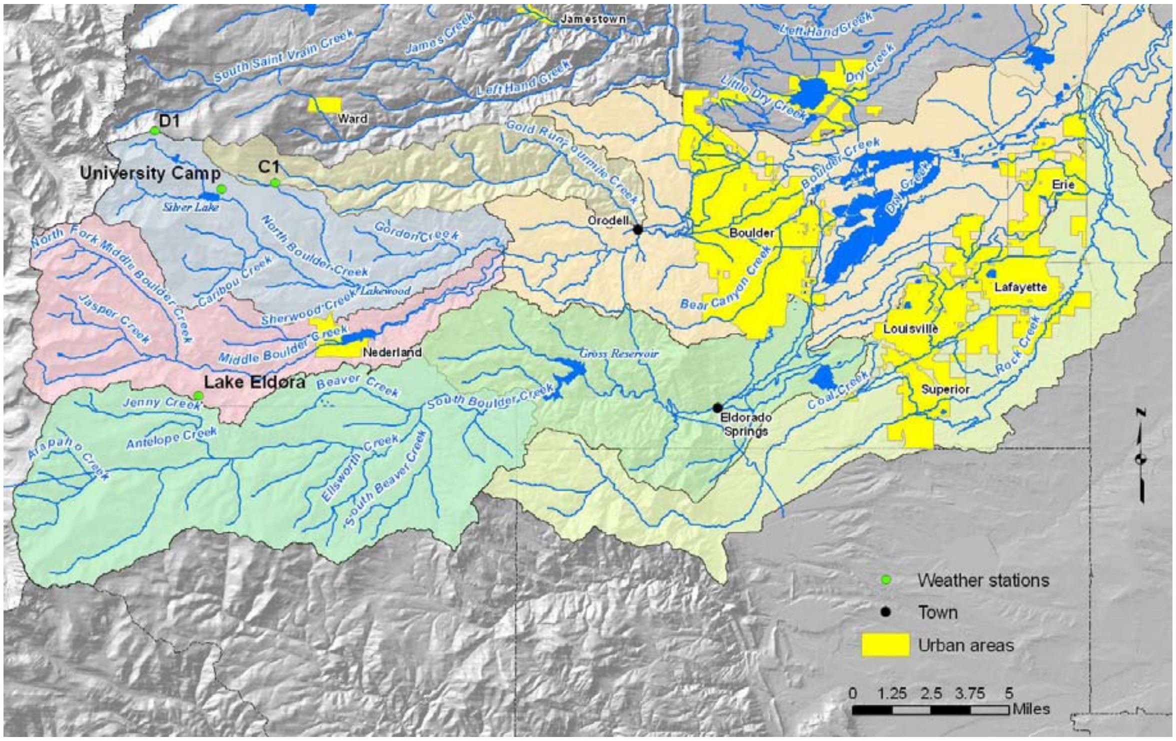

Figure 1.1. Map of the Boulder Creek basin and the C1 site.

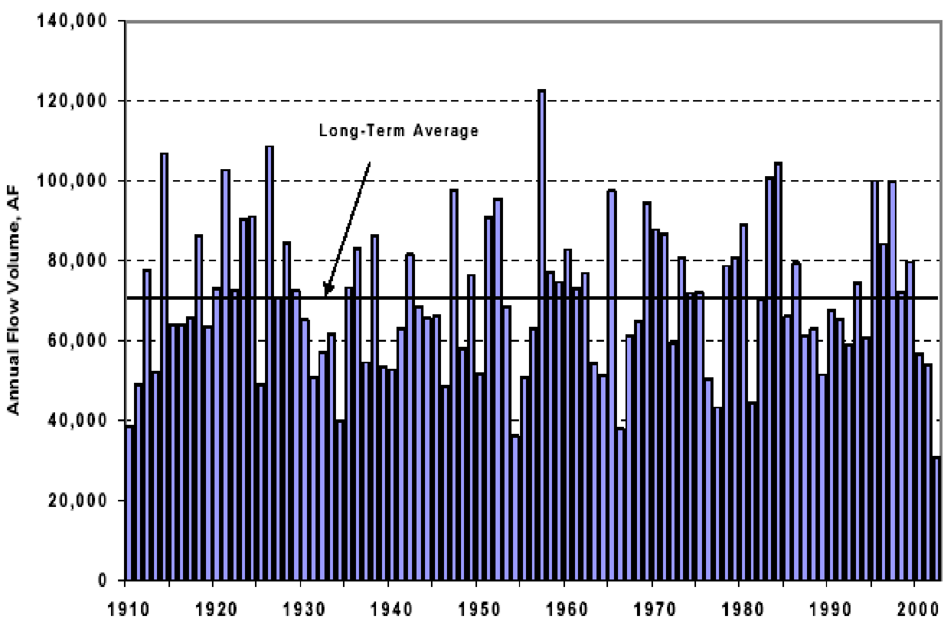

Figure 1.2. Reconstructed natural flow for Boulder Creek near Orodell.

Source: City of Boulder, 2008a.

The natural water supply of the Boulder Creek basin is supplemented by water imported into the basin from the Colorado-Big Thompson (CBT) and Windy Gap projects, which divert water from the headwaters of the Colorado River (on the West Slope of the Rocky Mountains) into the South Platte basin. This water is managed by the Northern Colorado Water Conservancy District (NCWCD; City of Boulder, 2004). A portion of that water is delivered to CBT and Windy Gap project allottees located in the Boulder Creek basin. Annual allotments, or “quotas,” of CBT and Windy Gap supplies are determined each spring by the governing organizations of those projects based on reservoir storage levels and expected runoff conditions. One-half of Boulder’s water supply is dependent on these projects with three-fifths of the city’s imported water allocations treated for direct use (30% of the city’s total treated water supply) and two-fifths exchanged for additional Boulder Creek water. Note that Colorado River water is subject to the Colorado River Compact, which guarantees the lower Colorado River basin states up to 75 million acre-feet in any ten-year period, which translates to an average annual delivery of 7.5 million acre-feet per year. A compact call on Colorado River water by lower basin states could reduce delivery of water to Boulder (and other Front Range water users).

Because Boulder’s water supply is mainly from snowpack, and in the semi-arid western United States year-to-year variability in precipitation is relatively high, an extensive reservoir and transfer system is used to capture runoff and store water for when it is most needed as well as to carry over supplies from year to year. Most of Boulder’s annual supply of water is stored in May and June during the spring snowmelt period for the high mountain elevations where the city’s reservoirs and diversions are located. This stored water supply supplements direct diversions once streamflows drop in late summer and through the winter. In addition, the reservoirs regulate water supplies between wet and dry years because both occur with greater frequency than average years in Colorado’s semi-arid climate. The city’s water rights yield different amounts every year depending on hydrologic conditions and on calls for water by more senior water rights owners.

Boulder currently provides water to 113,000 people living within and nearby the city. The city’s water is also consumed by more than 100,000 employees working in the area, 50,000 of whom commute to the city from other areas (City of Boulder, 2008a, 2008b); Boulder’s current population is about 103,000 (City of Boulder, 2008b). In the 1990s annual consumption of water varied from 20,000 to 25,000 acre-feet (see Figure 1.3). Following the 2002 drought restrictions and other conservation measures undertaken by the city, annual consumption has dropped to just under 20,000 acre-feet per year. The city considers water demand under various “build-out” scenarios in its water planning. The scenario with the highest water demand has the population in the service area growing to 125,000, employees increasing to 172,000 (City of Boulder, 2008a), and water demand rising to 28,600 acre-feet, which includes a 10% demand safety factor (City of Boulder, 2008a).

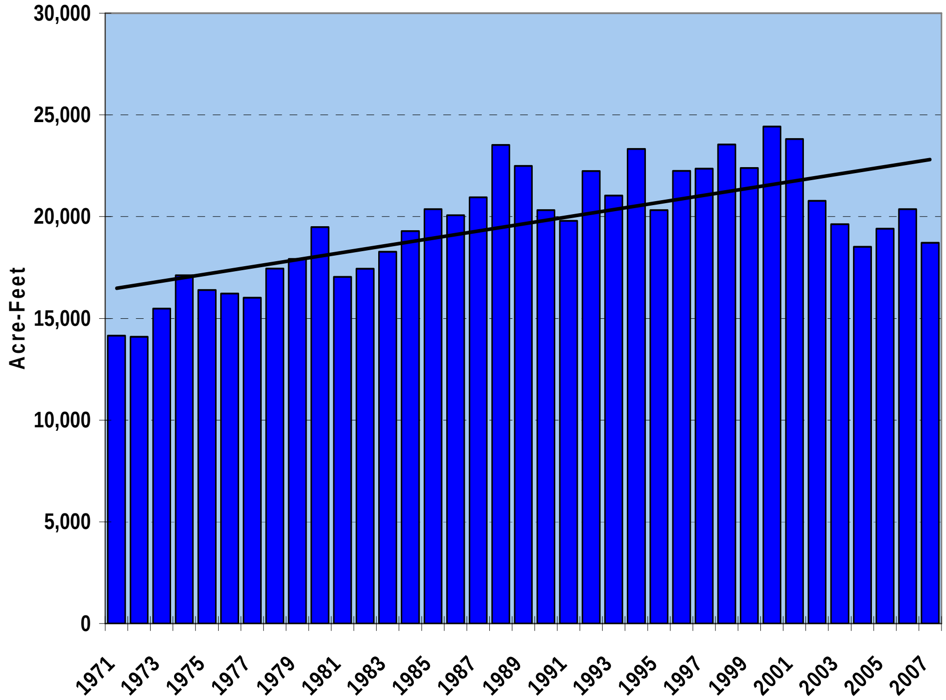

Figure 1.3. Boulder's annual water use. Note reduction following the 2002 drought.

Source: City of Boulder, 2008a.

Unlike most Front Range communities, which use a majority of their water for irrigation, Boulder uses two-thirds of its water for indoor and industrial uses and one-third for irrigation (City of Boulder, 2003). This difference likely occurs because Boulder is an older city with smaller residential lots, many multi-family units and a compact urban form. But its smaller share of water used for irrigation gives the city less flexibility in responding to droughts than its neighbors.

Boulder has donated some of its water rights to a state agency for providing minimum instream flow levels in Boulder Creek and its tributaries to protect aquatic habitat during low flow periods when the creeks would otherwise be dry due to diversions by senior water rights. The goal for minimum flow rate allowed varies by stream reach and increases as the streams drop in elevation. On main Boulder Creek as it runs through Boulder, the donated water usually prevents the stream from dropping below 15 cubic feet per second (cfs) during most of the summer and 4 cfs during other low flow times of the year. Streamflows naturally flow at a rate of hundreds of cfs during the spring runoff period and just a few cfs during the winter (City of Boulder 2008a).

There are many agricultural water users in the Boulder Creek basin downstream of Boulder and further downstream along the South Platte River, many of whom have water rights that are senior to some of the city's rights. Therefore, the city's water rights are sometimes affected by the competing demands of senior water rights ("calls") from downstream locations. Up to 70% of the water physically available at the city's high-elevation Boulder Creek basin diversion points is bypassed each year, either because the city's reservoirs and pipelines are full or because of downstream senior calls.

Boulder's water system performance is judged based on reliability criteria for the water supply established by City Council in 1989. Boulder's water planning does not provide for supplying all water that may be needed for all water uses in all years. Instead, the city anticipates reduced water deliveries in drought years within specified limits of occurrence. Boulder's water reliability standards involve having interruptions of municipal supplies depending on the frequency of droughts.

- For droughts occurring no more frequently than once in 20 years, water for landscaping would be reduced
- Water for landscaping would be substantially reduced (such that permanent damage to landscaping could happen) for droughts that are expected to happen no more frequently than once in 100 years
- Droughts occurring less often than once in 1,000 years would result in reductions of water deliveries for indoor uses and fire fighting.

The drought in 2002 was a 1 in 300 year event, and 57% of outdoor watering needs were met.

These reliability criteria became the basis for developing the city's Drought Plan, which delineated drought response triggers for the city's four Drought Stages, which range from moderate to extreme. The Drought Plan provides for the implementation of increasingly more stringent water use restrictions for each stage. Modeling of 285 years of the city's water system operations and water rights yields based on past hydrology, as extended from gauge records using tree ring data, was completed in 2003. The effort showed that 9 years of water supply restrictions would occur in the 285 modeled years. Only one of these 9 years required restrictions so severe that lawns and gardens would be permanently damaged. The city's adopted reliability criteria allow up to 14 years with water use restrictions in a 285-year period, with up to 2 years of those years requiring severe restrictions.

1.2 Vulnerability of the West to Climate Change

The literature shows that water resources in the West will be (and may already be) quite sensitive to climate change. Gleick (1990) found that compared to the rest of the country, river basins in the West are the most sensitive to changes in supply. This work was reinforced by Hurd et al. (1999). One of the key concerns is that higher temperatures will most likely reduce the size of snowpacks on which western water users mainly depend for water supplies. In addition, the snowpack will melt earlier, meaning that there will be a longer dry season during which water will need to be supplied to users. Smith et al. (2001), as part of the U.S. National Assessment, found that change in water supply is one of the major climate change concerns facing the western United States.

Reviewing the literature on freshwater resources in North America, Field et al. (2007) found that snowpack is generally projected to decrease, peak runoff will shift earlier, and summer flows will decrease. Christensen and Lettenmaier (2007) examined output from 11 climate models and estimated that a projected rise in temperature combined with small changes in precipitation would yield a range of change in runoff from no change to up to a 11% reduction.

More recent literature has shown that the West's climate and Colorado's climate in particular have been changing, and the changes in climate are affecting water supplies. Mote et al. (2005) found that across the West, snowpack as of April 1 has been decreasing. The trend in the central Rocky Mountains is more equivocal. However, from 1945-1955 to the 1990s, the water content of April 1 snowpack in the Rockies declined. Across the West, Barnett et al. (2008) find that most of the observed warming and change in snowpack are human induced.

Using climate change information in water resource management

At first glance, the literature appears to be pessimistic about the likelihood that water managers will use information on climate change in their long-term management of water resources. Studies of how water managers use relatively short-term forecasts of climate conclude that, for various reasons, such information is generally not incorporated in planning or management. A pilot study in the Northwest found that scientific and technical information competes with local knowledge, political mandates, stakeholder pressures, and internal organization needs (Lach et al., 1994; Lach and Quadrel, 1995).

Rayner et al. (2005) found that the rational choice approach, which suggests that an institution will assimilate, compare, and weigh new information to arrive at the best alternative, does not necessarily apply to institutional decision-making for water resource planning. They looked at why water resource planners in several regional water resource management institutions generally do not use probabilistic forecasts of seasonal and interannual climate variability. The reasons fell into two general categories: qualities (or perceived qualities) of the forecasts themselves and institutional design. Water managers most frequently stated that the (perceived) unreliability of forecasts was a reason for not using them, even if the interviewee had no direct experience, positive or negative, with probabilistic forecasts. Water managers also said that the spatial and temporal resolutions of these forecasts are not fine enough to be helpful in their planning processes.

Issues regarding institutional design include overlapping jurisdictions, water rights issues, and the fact that oftentimes other infrastructure construction or maintenance projects will take precedence over overhauling forecasting procedures that are seen to be working “well enough.” These institutions tend to be highly conservative and risk averse, and avoid institutional change unless they are experiencing heightened public or political scrutiny, such as during a drought or contaminant outbreak.

Callahan et al. (1999) also found that the primary obstacle to incorporating climate forecasts into water resource management lies within the resource management institutions. In their survey of Columbia River Basin management organization, the most frequently cited reason for not using long-range forecasts was inadequate skills for interpreting and implementing the forecasts. Managers in their survey also frequently cited management’s resistance to changing procedures as a major barrier to implementing long-range climate forecasts.

There is scattered anecdotal information that climate change is starting to be factored into planning in some sectors sensitive to a change in climate. For example, Easterling et al. (2004) point out examples of sea level rise being factored into coastal infrastructure design. But there are no examples of water resource managers in the United States incorporating possible change in freshwater supply or quality into their long-term planning for water resource management. This may be because sea level is not highly variable (although it does vary), sea level rise involves one variable (sea level), and the direction of change is certain (it will rise). In contrast, runoff is highly variable. In addition, climate models are not in agreement about how precipitation will change at the scale of regions such as the western United States (Houghton et al., 2001). Even though an increase in temperature is highly likely, which makes it highly likely that snowpacks will melt earlier, the uncertainty about change in precipitation makes it impossible to accurately forecast the size of future water supplies.

City of Boulder and consideration of climate change

In an effort to reduce the high level of unknowns about how future hydrologic changes caused by climate change might affect Boulder’s water supply, in 2003 the city commissioned a sensitivity study by Hydrosphere Resource Consultants (now AMEC), the city’s water resources consultant (Hydrosphere, 2003). One of the most novel aspects of the study is that it examined the vulnerability of Boulder’s water supply to the most recent 300-year climate record (as opposed to examining vulnerability to the drought of record in the observed climate data, such as the 1950s or 1930s droughts). The year record consisted of stream flows reconstructed from tree ring data for 1703-1987 (Woodhouse, 2001, 2003) and observed stream flow data for 1988-2002. The study also considered a 25% increase in interannual variability in the 300-year reconstructed record to test sensitivity to an increase in supply variability and a 15% decrease in average supply to test sensitivity to a long-term change in supply. Both of these sensitivity tests were prompted by concerns about climate change, but did not consider changes in the timing of runoff because of earlier snowmelt.

The results of the study showed that the city's water supply could be more vulnerable to the possibility of reductions in streamflow than increases in variability. Although both scenarios resulted in violation of the city's reliability criteria for the modeled 300-year sequence, the increase in variability resulted in more years with minor shortages that required a response based on voluntary water use reductions (14 years as compared to the 5 that occurred using the base hydrology). The decreased streamflow scenario caused a violation of all stages of the reliability criteria, including 6 years when the city's essential indoor water use needs could not be met even with severe mandatory water rationing. The study did not consider changes in seasonal stream flow patterns that could result from changes in snowpack due to higher temperatures, changes in demand for water, or how much of a change in supply or timing would exceed Boulder's coping capacity. In addition, it did not use climate model output to examine changes in supply or likelihood of exceeding coping thresholds. This modeling capability has created confidence in the ability to supply the city's water needs in all but the most severe drought conditions under scenarios similar to past hydrology.

Based on climate research that indicates that average temperatures in the intermountain western United States are likely to increase in the next 100 years, city staff, advisory boards, and the Boulder City Council had concerns about the continued adequacy of the city's water supplies under future hydrologic conditions. Although available information is less certain about whether future precipitation in the Boulder Creek basin will increase or decrease or whether Boulder Creek streamflows will increase or decrease on an annual volumetric basis, it is likely that mountain snowmelt will occur earlier in the year and that late summer flows will be significantly lower. Hydrologic changes are also likely to occur in the Western Slope basins that supply almost one half of the city's water supply. The resultant effects for Boulder's water system could be anything from an increased average water yield to a decreased yield depending on the timing of seasonal streamflow changes and their interaction with the city's ability to divert water in priority under Colorado's water administration system.

If future climate change occurs in a manner that leads to no changes in future streamflow conditions as compared to past streamflow, such as a scenario where increased precipitation offsets higher evaporative losses due to higher temperatures and little change in spring runoff timing occurs above 2,440 meters (8,000 feet) in elevation, the city's current water rights portfolio would be sufficient to supply water in conformance with the Council-adopted water system reliability criteria. However, if global warming were to cause severe reductions in streamflow or detrimental changes in streamflow patterns in the basins feeding Boulder's water supply, it could impair the city's ability to meet future water needs by reducing the yield of its water rights.

This study

The intent of this study was to work closely with the City of Boulder to assess long-term consequences of climate change. The study was conceived in consultation with city officials and designed to provide them with useful information on climate change. The intent was to see if what is known and not known about climate change could be conveyed and used by the city in long-term planning.

The study was funded by a grant to Stratus Consulting Inc. by the National Oceanographic and Atmospheric Administration's (NOAA). Stratus Consulting signed a Memorandum of Agreement with the city to cooperate on the study. Stratus Consulting worked closely with a representative of the city, Ms. Carol Ellinghouse, of the Water Utilities Department. Stratus Consulting subcontracted with Hydrosphere Inc. (now part of AMEC) to run the city's water management model and with Prof. Kenneth Strzepek of the University of Colorado to estimate change in runoff.

The study relied on a team of scientific and technical advisors. These included Dr. Tom Wigley of the National Center for Atmospheric Research (NCAR) on climate change scenarios; Dr. Connie Woodhouse of Arizona State University on the streamflow reconstructions; Dr. Klaus Wolter of NOAA on observed climate data; and Brad Udall of the University of Colorado on western water issues and assessment of climate change impacts.

Study structure

The focus of the study is on whether climate change poses a threat to the long-term reliability of Boulder's water supplies. The potential effects of climate change on flooding were not examined. (Note that the risk of flooding could increase because of a combination of larger winter snowpack and earlier snowmelt or the potential for increased intensity of precipitation events.)

Figure 1.4 displays the main elements of the study. The study began with an analysis of Boulder's current vulnerability to drought. Current drought criteria were used. Change in baseline demand was also considered. The study team decided to examine impacts in 2030 to capture impacts within a few decades, and impacts in 2070 to capture larger, but longer term impacts.

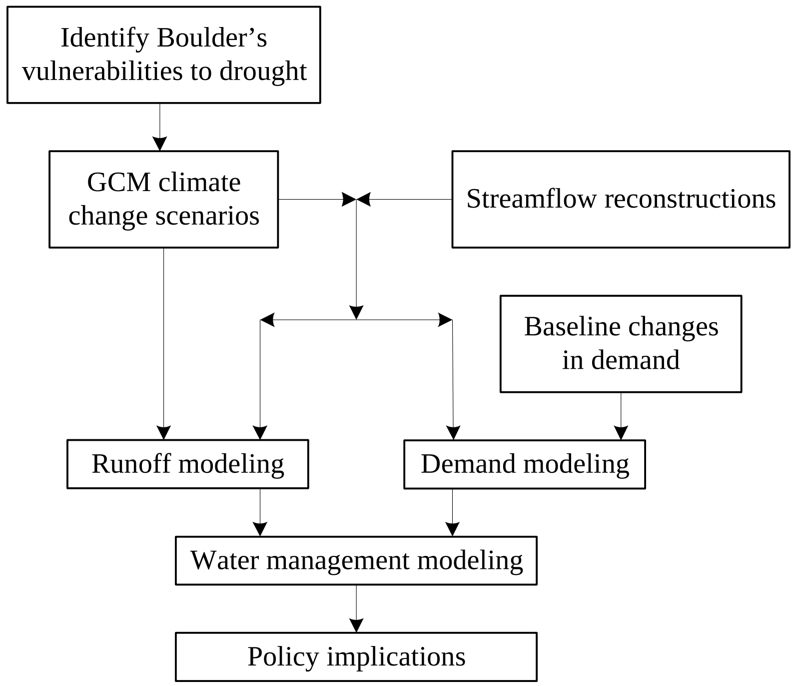

Figure 1.4. Structure of the Boulder study.

General circulation model climate change scenarios. Climate change scenarios were identified based on an analysis of output from general circulation models (GCMs). GCMs are models of the entire earth and project climate change in grid boxes that are typically several hundred miles across. As is discussed in more detail subsequently, downscaling was not used in the study. This is because only a limited number of models are available for downscaling, whereas output from about 18 GCMs was available. This presents a wider range of possible climate changes for decision making.

Streamflow reconstructions. A novel feature of this study was to combine average long-term changes in climate caused by increased greenhouse gas concentrations with a potential repeat of climate variability that happened over past centuries. Climate change studies often combine long-term mean estimates of climate change with observed data from recent decades. This effectively imposes a mean change in climate on a repeat of recent years. Even without change in atmospheric greenhouse gas concentrations, it is possible that climate variability that happened in past centuries rather than just in past decades could repeat itself. The climate variability was taken from a 437-year reconstruction of streamflow in Boulder Creek. As far as the authors are aware, this combination of a streamflow reconstruction and climate change scenarios has not been done in the United States. A similar approach was applied in the United Kingdom (Jones et al., 2006a, 2006b) and its implications for water resource management in Britain were assessed in Wade et al. (2006).

A “nearest neighbor” approach, hereafter referred to as K-NN, was used to create a temperature and precipitation record based on the streamflow reconstruction. The approach matches the reconstructions of streamflow before 1953 with observed streamflow from 1953 to 2004 (the process includes randomization so different traces are developed). Temperature and precipitation are taken from the observed record. These roughly recreate the paleoclimate record but in particular capture year to year variability from the reconstructions.

Runoff modeling. The study then estimated change in runoff in Boulder Creek. An updated version of the CLIRUN model (Kaczmarek, 1993; Yates, 1996; Strzepek et al., In preparation) was developed for the study and calibrated to historical data. The historical data included weather data from the Niwot Ridge C1 station located west of Boulder (see Figure 1.1) and natural stream flow data reconstructed from stream gages and diversion records on Middle Boulder Creek, North Boulder Creek and Boulder Creek. This model better simulates extreme wet and dry periods than previous versions of the model. The model was first run with average monthly changes in climate imposed on the observed climate record from 1952 to 2004 (e.g., adding average monthly temperature increases and multiplying percentage change in precipitation to the observed daily record).

Demand modeling. The same climate information was used to estimate change in irrigation demand from farmers downstream of Boulder.

Water management modeling. The estimated changes in runoff and demand were integrated using the Boulder Creek Model (BCM). Hydrosphere (now part of AMEC) developed and maintains the BCM for the City of Boulder. The model simulates all significant aspects of hydrology, water rights, water storage, and diversion facilities as well as water uses and return flows in the Boulder Creek basin. The model also simulates the operation of the CBT and Windy Gap projects, from which Boulder obtains a significant portion of its water supply. The model was run assuming no changes in demand other than for downstream irrigation and assuming an increase in Boulder’s demand for water to 28,600 acre feet per year (assuming build out plus another 10% increase in water demand). The analysis did not consider reducing water demand through implementation of further water conservation measures.

Policy implications. The team then analyzed the results and presented them to the City of Boulder for consideration.

Climate data and current climate

Current data are from the C1 data site maintained by the University of Colorado's Institute for Artic and Alpine Research (INSTAAR) program and is part of a Long Term Ecological Research (LTER) site. The site is at 3000 meters above sea level and is located at 40º 02' 09'' N; 105º 32'

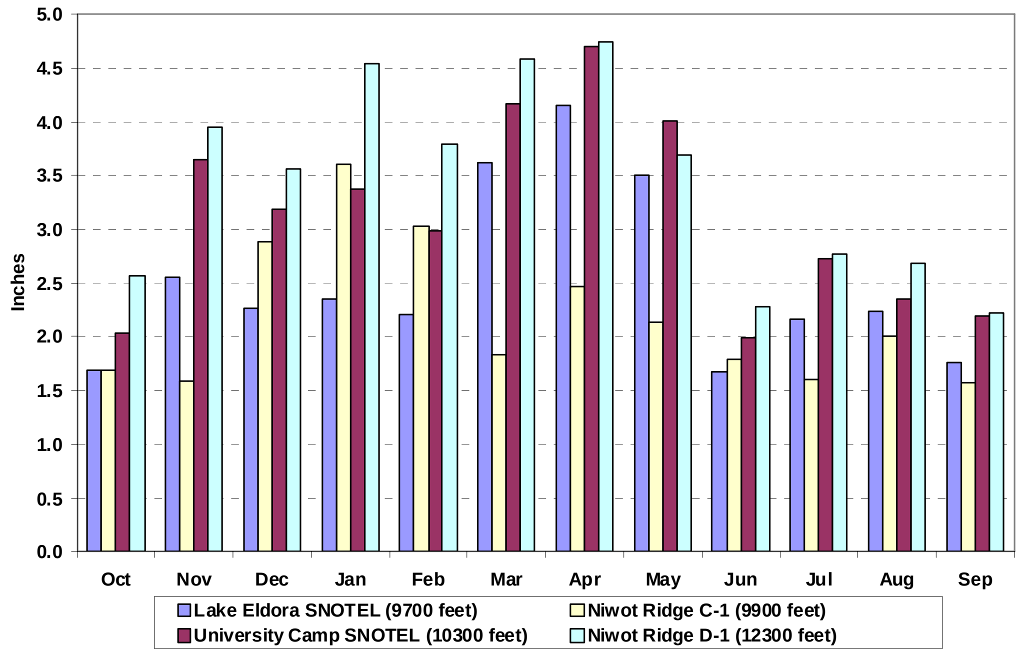

Figure 1.5. Current precipitation in Boulder Creek headwaters.

Source: City of Boulder, 2008a.

09'' W. Data on temperature, precipitation, and other variables have been continuously recorded since 1953 (University of Colorado, 2008).

Current monthly precipitation in Boulder Creek headwaters is shown in Figure 1.5 and snowpack in Figure 1.6. Precipitation typically peaks in the spring and is at a minimum in the fall. Snowpack typically begins to accumulate in the fall and peaks in April and May as higher temperatures lead to snowmelt. The city of Boulder itself typically receives 20 inches of precipitation per year (City of Boulder, 2008a).

Climate change in Colorado

Colorado's climate has warmed in recent decades. Eastern Colorado has seen a decadal temperature rise of about 0.1 to 0.3°C (0.25 to 0.4°F) per decade since the 1940s. Western Colorado has warmed at a faster rate. On the other hand, the state has generally become wetter since the 1930s, with the largest increase in the northeastern portion of the state (NOAA, 2008). Peak streamflow is happening somewhat earlier, as displayed in Figure 1.7.

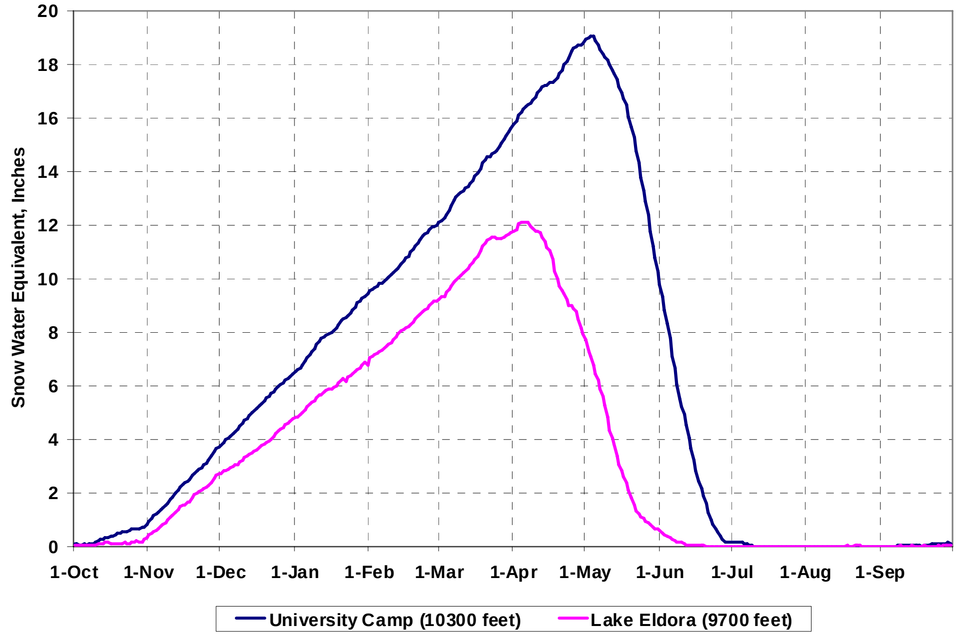

Figure 1.6. Average Snowpack in Boulder's SNOTEL sites.

Source: City of Boulder, 2008a.

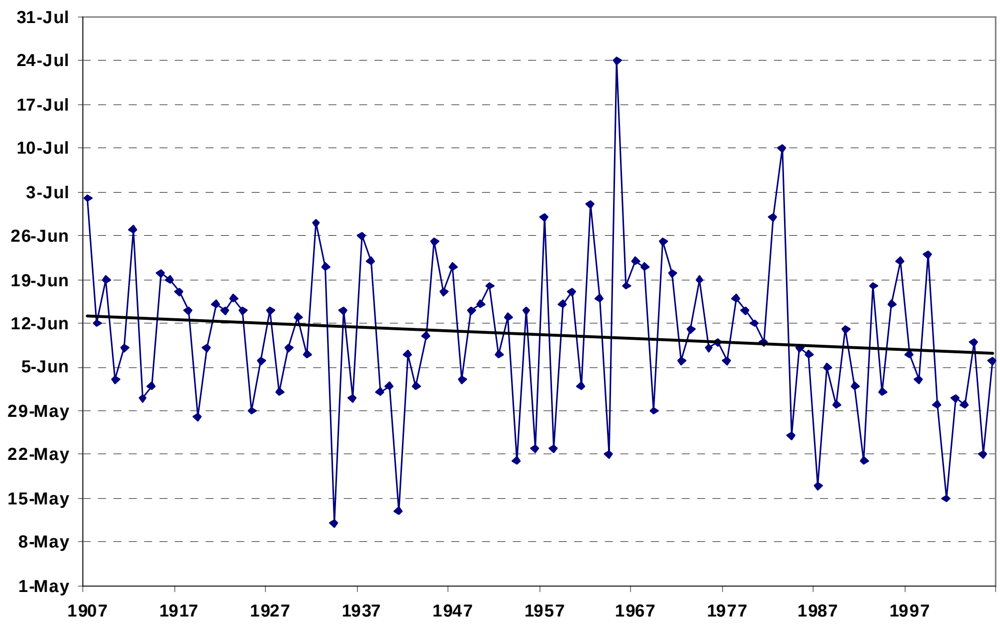

Figure 1.7. Peak streamflow in Middle Boulder Creek in Nederland.

Source: City of Boulder, 2008a.

In all likelihood, temperatures in Colorado will continue to increase, mainly because greenhouse gas emissions are projected to continue rising and for at least several decades to do so at an accelerated rate (Nakićenovic et al., 2000). The Intergovernmental Panel on Climate Change (IPCC) projects in its latest assessment a general warming across all of North America. Of the 21 GCMs run for the latest IPCC assessment, all project Colorado (and the entire lower 48 states) to warm this century (Christensen et al., 2007).

Change in precipitation is much harder to project. On average, the 21 GCMs examined by the IPCC project that the southwestern United States will see a decrease in precipitation. Based on this and other information, the IPCC concluded that it is "likely" (which means there is a two out of three chance the projection is correct) that the Southwest will be drier. The geographic domain of the Southwest is not defined by the IPCC. On average, the models show almost no change in precipitation for Colorado, but individual models differ quite considerably. Indeed, a few models project a wetter Southwest. Even those that project a drier Southwest project different patterns of change, with some areas projected to be wetter in some models and drier in others. The models tend to project circulation patterns carrying precipitation to shift poleward. Whether this shift is far enough north to reduce precipitation is not clear. In addition, the models tend to project wetter winters and drier summers, but the models have difficulty simulating the current monsoon.

The report is structured as follows:

- Chapter 2 describes the climate change scenarios including how the streamflow reconstruction was used to create scenarios which combine long-term climate change from the climate models with long-term climate variability
- Chapter 3 discusses the modeling of runoff and the change in runoff as estimated using the climate change scenarios
- Chapter 4 covers the analysis of implications for Boulder's water supplies. It describes the management modeling including implications for downstream irrigation demands and meeting Boulder's drought reliability criteria
- Chapter 5 discusses the potential policy implications of climate change for the City of Boulder and consequences for other Front Range water users
- Chapter 6 presents conclusions of the report
- The bibliography follows chapter 6.

The appendices are as follows:

- Appendix A contains the climate change scenarios
- Appendix B contains a description of the "K Nearest Neighbor" approach.

2. Climate Change Scenarios

It is critical that climate change scenarios reflect a broad range of potential changes in climate, particularly with regard to precipitation. Whether annual precipitation increases or decreases in the mountains west of Boulder will have a critical impact on net changes to Boulder's water supplies. Because this study is intended to aid in policy making, it must capture a plausible range of changes in climate that will affect Boulder. If, for example, it is uncertain how precipitation changes, but the scenarios include only increases, then users of this analysis could wrongly conclude that an increase in precipitation is likely. A similar outcome derives should the scenarios be selected from the dry end of the range of possibilities.

Precipitation is not the only key uncertainty. Future emissions and atmospheric concentrations of greenhouse gases are also uncertain. Using a range of plausible scenarios of greenhouse gas concentrations, the IPCC projected that atmospheric concentrations of carbon dioxide (CO_2), the major human increased greenhouse gas in the atmosphere, will rise from the present concentration of just of 380 parts per million (ppm) to 500 to more than 900 ppm (Solomon et al., 2007). Such differences in concentrations can result in significant differences in warming. The more temperatures increase, the more precipitation changes as well.

To capture the uncertainties about future emissions, this study used a wide range of emissions scenarios. The three scenarios (Nakićenovic et al., 2000) used are as follows:

- The B1 scenario assumes global population peaks at 9 billion by midcentury and then declines to 8 billion by 2100. There is a pronounced transition to a service- and information-based economy with clean technologies and low material intensity. CO_2 concentrations are the lowest of the SRES scenarios: more than 500 ppm by 2100.

- The A1B scenario has the same population assumption as B1. But it has the most rapid technological development and highest per capita income of the scenarios developed by IPCC. The scenario assumes a mix of fossil intensive and nonfossil fuel energy sources. CO_2 concentrations would be about 700 ppm by 2100. Note this scenario is quite widely used, although the IPCC gave no projections on which scenario is most likely to happen.

- The A2 scenario assumes very high population growth (about 15 billion people by 2100) and slower economic growth and technological development than the others. There is also less convergence in the standard of living and technology between developed and developing countries than in the other storylines. It results in the lowest per capita income of the IPCC emissions scenarios. CO_2 concentrations would be more than 800 ppm by 2100[1] (Nakicenovic et al., 2000).

For any given atmospheric concentration of greenhouse gases, there is substantial uncertainty about the regional pattern of change. This uncertainty is particularly pronounced at the geographic scale of Boulder's water supply. A minimum range of uncertainty about regional patterns of climate change is captured across the climate models, in particular across the GCMs. That is, the extent to which model projections do not yield consistent projections of regional climate change is a minimum indicator of uncertainty about future climate change. Agreement among models indicates a lower range of uncertainty, yet even then the models could be consistently in error.

For Boulder's water supply, the models consistently project that temperatures will increase but are inconsistent about precipitation. To assess the degree to which the model projections are consistent or inconsistent with each other (by consistency, we focus on the direction of change, e.g., does precipitation increase or decrease), we obtained GCM output from NCAR.[2] NCAR has put the GCM output on a standard grid and computed probability density functions (pdf) (Tebaldi et al., 2004, 2005). These should not be interpreted as a distribution function of future possibilities of climate change, but as reflecting how the GCMs project regional change.

NCAR provided data for the geographic area displayed in Figure 2.1. The colored area is the entire grid from which the date were drawn. The dotted lines connect the centers of four grid boxes used in the analysis.

Figure 2.2 shows the pdf on change in annual mean temperature for 21 GCMs in this geographic domain. The projections are for the A1B scenario and display the temperature increase in 2070 compared to 1990. Note that the years denote long-term averages (e.g., 20 years) around those dates. The differences are between model estimates of temperatures circa 1990 and projections of temperatures in 2070. Note that all of the models project an increase in temperature, but the warmest model is about three times warmer than the coolest model.

1. Note the IPCC has an even higher emissions scenario, A1-FI, in which CO_2 concentrations exceed 900 ppm by 2100. GCM model output for this scenario was not available.

2. Data and analysis provided by the Institute for the Study of Society and Environment at NCAR, based on model data from the World Climate Research Programme's Coupled Model Intercomparison Project phase 3 (WCRP CMIP3) multi-model dataset. More information about the RCPM analysis can be found at http://rcpm.ucar.edu.

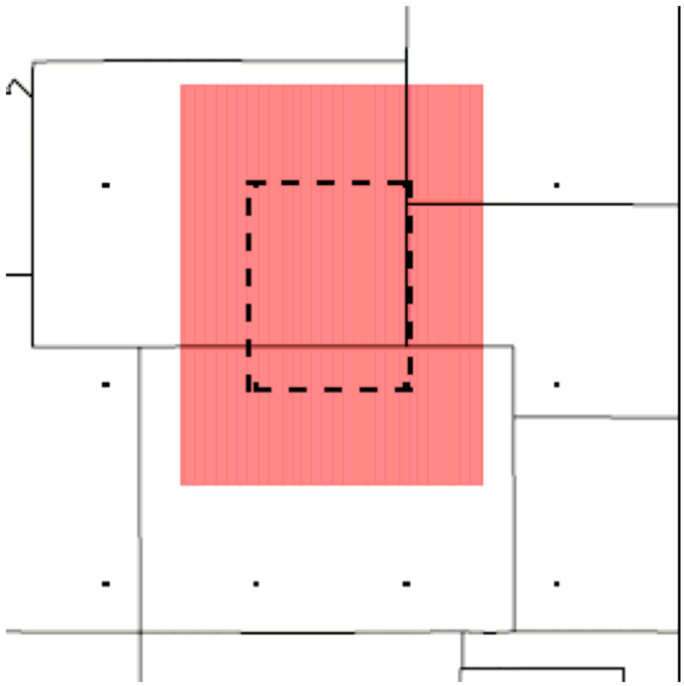

Figure 2.1. Domain of geographic area used by NCAR.

Figure 2.3 contains the pdf on precipitation: the node of the probability curve falls almost exactly over zero change. Of the 18 models in the figure, 9 project a decrease in annual precipitation, 1 projects no change, and the remaining 8 project an increase. This essentially means half the models project increased precipitation and half project decreased precipitation. Were we to examine model output for a region more to the south, the tendency would be for the models to project decreased precipitation. Were we to go farther north, the tendency would be toward projections of increases in precipitation. The area containing Boulder appears to be in the transition zone from drier to wetter.

Given this uncertainty, it is critical that the selection of models to use to examine potential climate change reflect this broad range. After examining the GCM output, the team decided to select three scenarios: a relatively wet model, a relatively dry model, and one in the middle. After analysis of model output and consultation with Dr. Wigley, we selected the following models:

- Wet model: Canadian Climate Model (CCCMA)
- Middle model: Geophysical Fluid Dynamics Laboratory (GFDL1)
- Dry model: Geophysical Fluid Dynamics Laboratory (GFDL0).

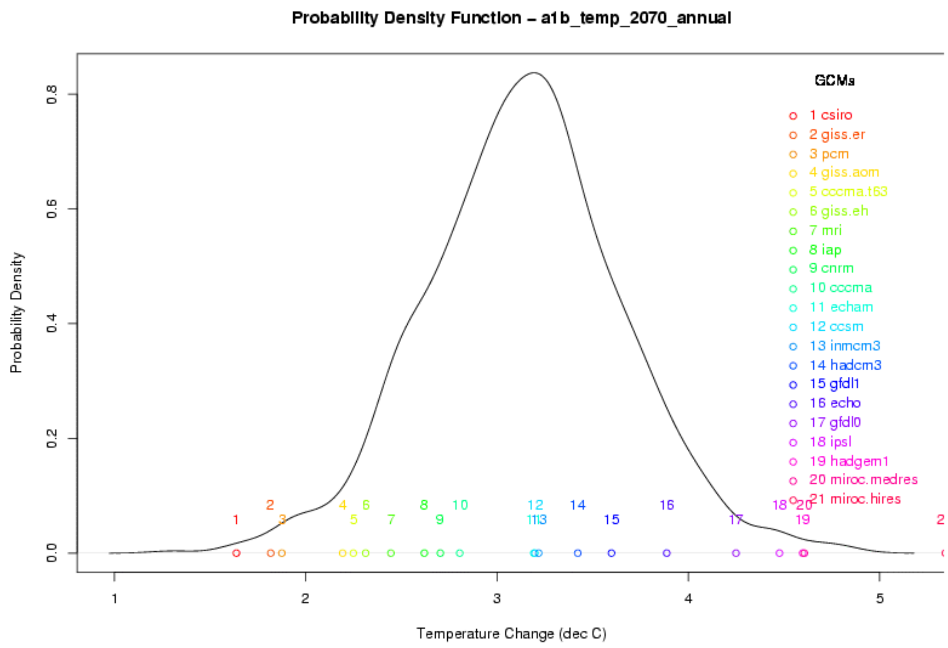

Figure 2.2. Probability density function for GCM temperature projections for Central Rocky Mountains in 2070 under A1B scenario.

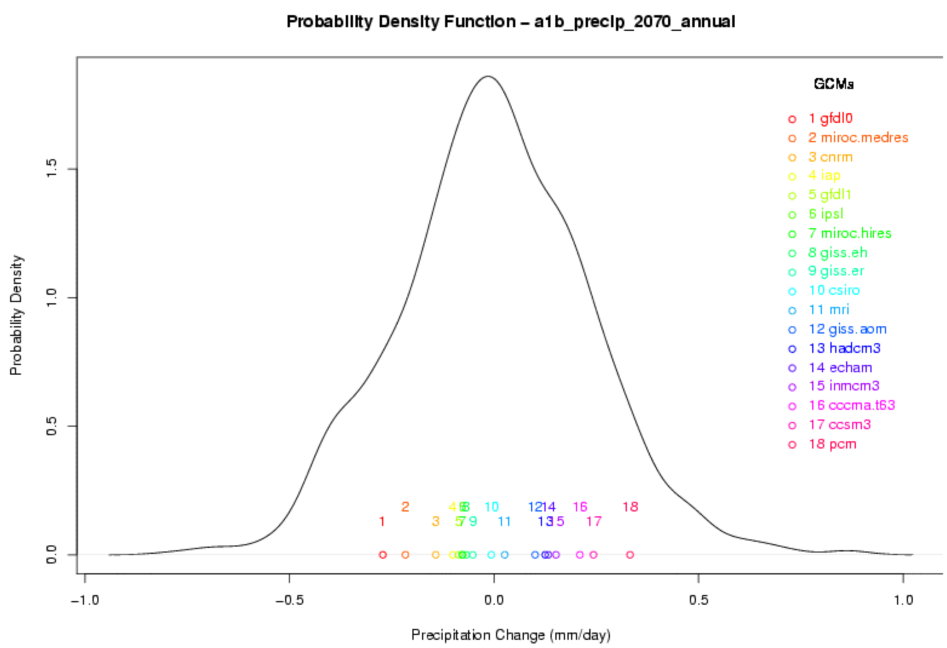

Figure 2.3. Probability density function for GCM precipitation projections for Central Rocky Mountains in 2070 under A1B scenario.

As the project proceeded, we noticed that all three models tend to project relatively wetter winters and drier summers. Indeed, most of the models project this, but not all; some models project drier winters. Given the importance of winter precipitation for Boulder's water supply, we decided to use a fourth model, the Goddard Institute for Space Studies (GISS EH) model, which projects a drier winter.

In Figure 2.3, GFDL0 is model #1, GFDl1 is model #5, CCMA is model #16, and GISS EH is model #9. The selection of models captures a wide range of precipitation output, although the "middle" model is on the wetter side of the distribution.

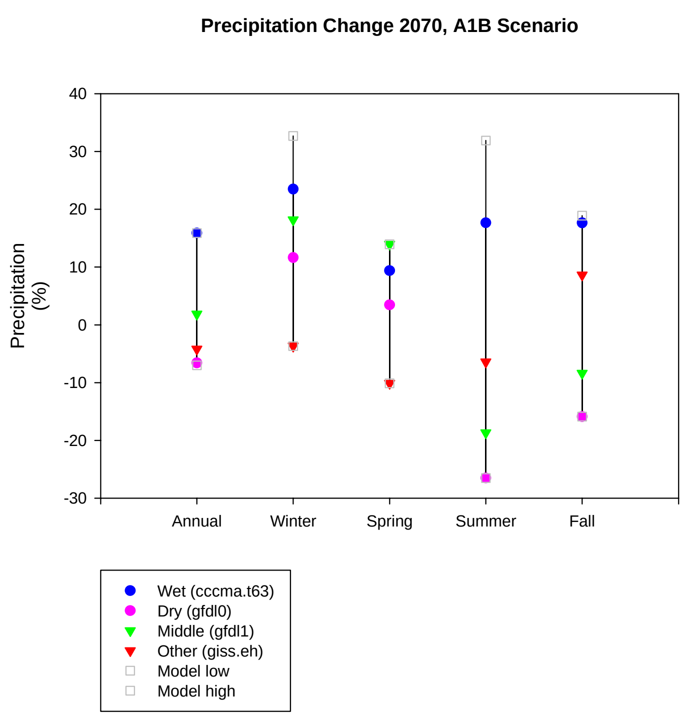

Figure 2.4. Climate change scenarios on precipitation for 2070 for A1B scenario.

Seasonal and annual projections of change in precipitation for the four models under the A1B scenario in 2070 are displayed in Figure 2.4 Two of the models project a decrease in annual precipitation, one projects a slight increase, and the fourth (CCMA) projects a larger increase. Three of the models project a wetter winter, and three project a drier summer.

Figure 2.5 displays temperature increases for the A1B scenario. The annual temperature increases range from over 2.2°C to about 4.2°C. The range of changes across all of the GCMs is much broader, ranging from 1.6°C to 5.3°C. The models project more warming in the summer than the other seasons. The four scenarios selected happen to be on the lower end of the range of models for the winter and spring seasons. Thus, the impact of higher temperatures on snowpack in winter and spring may be more significant than is discussed here.

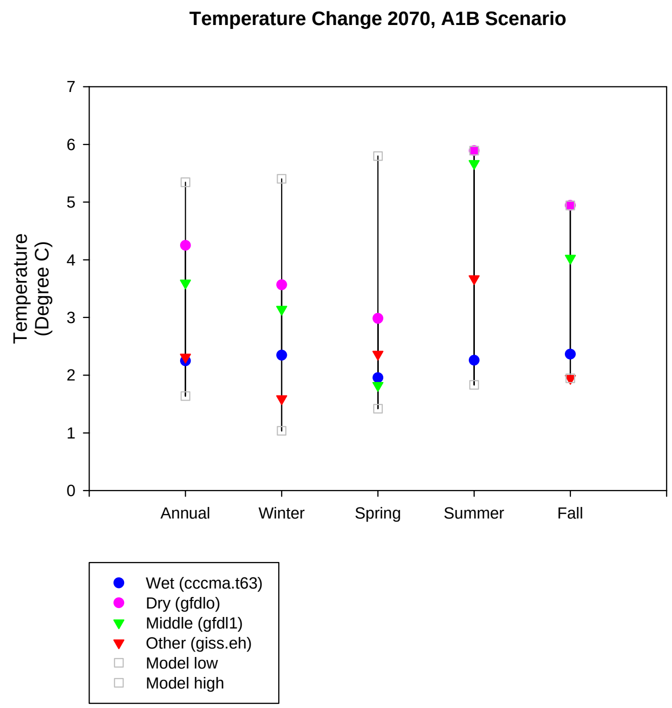

Figure 2.5. Climate change scenarios on temperature for 2070 for the A1B scenario.

Numerical scenario projections are in Appendix A. Baseline scenarios

Boulder has a buildout scenario of 125,000 people with 170,000 jobs (City of Boulder, 2008a). Annual demand for water was assumed for this analysis to increase to 28,600 acre-feet per year under buildout conditions.

2.1 Combined Climate Change and Streamflow Reconstructions

One of the unique aspects of this study was to examine the sensitivity of Boulder's water supplies, not just to a long-term change in average climate conditions (e.g., warmer temperatures) but also to a return to climate variability of past centuries.

Although there is no record of observed temperature or precipitation from past centuries (from which to draw information from past climate variability and on which to impose climate change scenarios), scientists have developed paleoreconstructions of streamflow from past centuries. Such paleoreconstructions provide information about the variability in annual streamflow. Streamflow is directly influenced by climate, both temperature, which affects the timing of snowmelt and amount of evaporation, and precipitation. Variability in streamflows, therefore, reflects climate variability.

The principal streamflow record used in this study was a 437-year reconstruction of streamflow at Orodell in Boulder Creek from 1566 to 2002 (Woodhouse and Lukas, 2006; Figure 2.6). This streamflow reconstruction is based on tree-ring data from the basin and neighboring basin. The reconstructed series represents the statistically "most-likely" annual flow for each year based on the set of tree-rings. Note that the approach estimates 65%[3] of the variance in the recorded streamflow record. So, developing a monthly climate based on this single estimate does not provide a robust estimation of the possible temperature and precipitation. The solution to this is to generate an ensemble of reconstructed historical climate that span the statistical range.

Climate models yield changes in temperature and precipitation, yet the reconstructed streamflow provides only an estimate of annual streamflow. It is not possible to combine the changes from the climate models directly with a streamflow record. The challenge was to develop an approach that could provide monthly scenarios (because the hydrology models estimate runoff on a monthly basis) of temperature and precipitation that would be consistent with variability in the paleoreconstruction of streamflow. The technique developed for this study used the available observed climate record in the higher elevation portion of the Boulder Creek watershed (1953-2004) and the reconstructed streamflow record (1566-2006) to yield new, 437-year proxy temperature and precipitation records consistent with the streamflow reconstructions.

In developing a monthly paleoclimate record from the annual paleostreamflow reconstruction, it was not important to exactly replicate monthly temperature and precipitation that would produce the streamflow reconstructions. It was more important to capture interannual variability and persistence of wet and dry periods from the paleoclimate record. It was not critical to exactly replicate the long-term droughts from the reconstruction, with warmer temperatures from climate

3. It has an R^2 of 0.65.

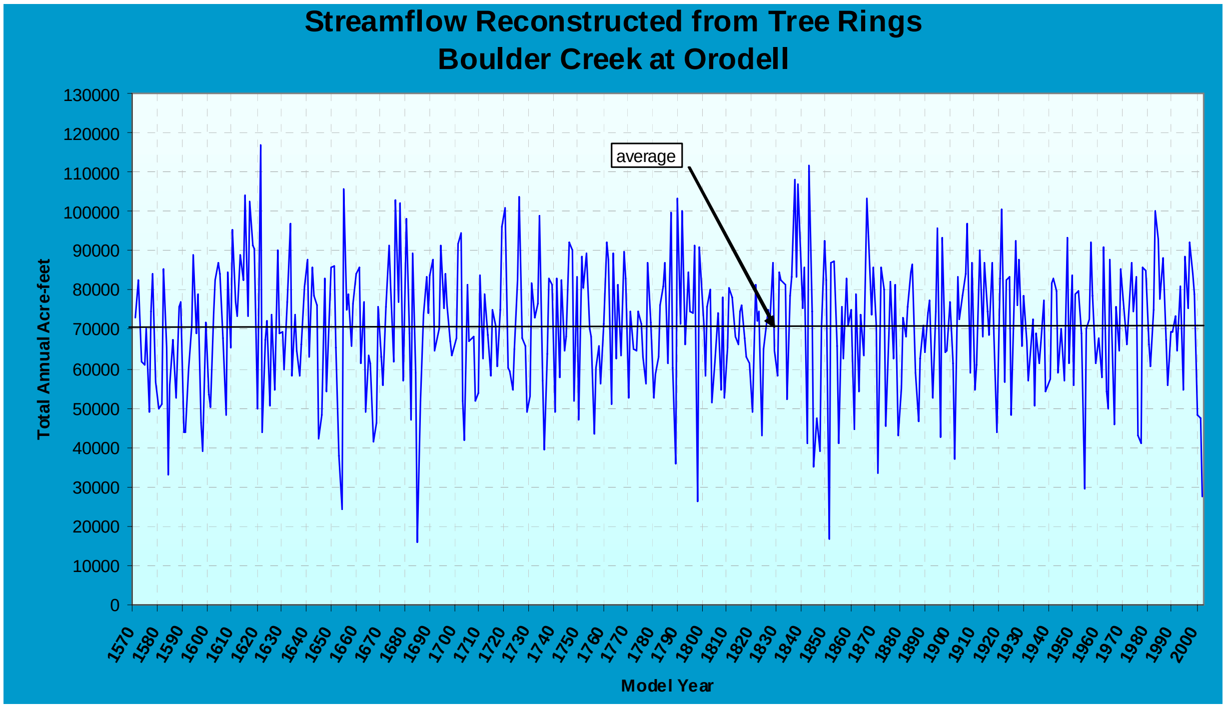

Figure 2.6. Reconstructed streamflows for Boulder Creek.

Source: Woodhouse and Lukas, 2006.

change added in. We can match these modern measured streamflows with years from the reconstructed record and assume that the temperature and precipitation in the modern record would approximately produce the streamflow of reconstructed year. Creating a climate record that could approximate the paleoclimate record was sufficient for this analysis. This develops a long-term monthly climate record that repeats the occurrence of long-term droughts from the reconstructed streamflow record with sufficient statistical accuracy and provides a monthly climate time series that can be joined with GCM generated monthly climate changes in temperature and precipitation.

We used a "non-parametric nearest neighbor" approach.[4] Reconstructed streamflows in the period before 1953 (when climate observations at the C1 monitoring station began) were compared to reconstructed streamflows from 1953 to 2004. The "nearest neighbor" in the recent record is then selected as a proxy for the pre-1953 streamflow. The temperature and precipitation record from C1 is then used to approximate the climate of the past.

4. We are indebted to Dr. Rajagopalan Balaji of the University of Colorado for advice and guidance on applying this procedure.

The “K-NN” approach is a statistical approach. The methods select a set of years in the 1953-2004 record which best matches the pre-1953 streamflow. The number of neighbors is a parameter of the method. The method then selects from the set of years “neighbors” via randomization procedure. This allowed for creation of any number of historic climate traces grouped together as an ensemble. For this analysis over one thousand traces were generated to span the statistically likely the paleoclimate record. The procedure is described in more detail in Appendix B.

3. Runoff Modeling

3.1 Model Description

CLIRUN-II was used to estimate runoff in South, Middle, and North Boulder Creeks as well as the Upper Colorado River basin. CLIRUN-II is the latest model in a family of hydrologic models developed specifically for analyzing the impact of climate change on runoff. Kaczmarek (1993) presents the theoretical development for a single-layer lumped watershed rainfall runoff model-CLIRUN, and Kaczmarek (1998) presents the application of CLIRUN to the Yellow River in China.

Yates (1996) expanded on the basic CLIRUN by adding a snow-balance model and a suite of possible PET models, and packaged it in a tool called WATBAL. WATBAL has been used on a wide variety of spatial scales from small to large watersheds and globally in 0.5 × 0.5° grid (Strzepek et al., 1999; Huber-Lee et al., 2005; Strzepek et al., 2005).

CLIRUN-II (Strzepek et al., In preparation) is the latest in the “Kaczmarek School” of hydrologic models. It incorporates most of the features of WATBAL and CLIRUN but was developed specifically to address extreme events at the annual level, modeling low and high flows. CLIRUN and WATBAL did very well in modeling mean monthly and annual runoff, important for water supply studies, but did not model well the tails of runoff distribution.

CLIRUN-II has adopted a two-layer approach following the framework of the SIXPAR hydrologic model (Gupta and Sorooshian, 1983, 1985) and a unique conditional parameter estimation procedure was used.

Spatial and temporal scale: CLIRUN-II models runoff as a lumped watershed with climate inputs and soil characteristics averaged over the watershed simulating runoff at a gauged location at the mouth of the catchment. CLIRUN-II can run on a daily or monthly time step. For this study, climate and runoff data were available only on a monthly basis, so monthly was used.

Snow-balance model: The snow accumulation and melt model used is based on concepts frequently used in monthly water balance models (McCabe and Wolock, 1999). Inputs to the model are monthly temperature (T) and precipitation (P) The occurrence of snow is computed as function of average watershed temperature and two parameters: Temp_snow and Temp_rain. These two parameters are calibrated for each watershed. Snowmelt is added to any monthly precipitation to form effective precipitation available for infiltration or direct runoff.

Water balance: Figure 3.1 is a schematic of the water flows of CLIRUN-II, showing the mass balance of water in the CLIRUN-II system. Water enters via precipitation and leaves via evapotranspiration and runoff. The difference between inflow and outflow is reflected as change in storage in the soil or groundwater.

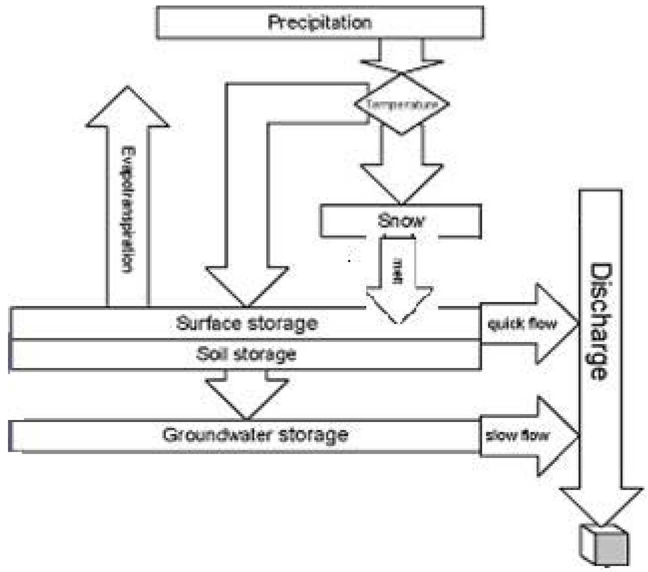

Figure 3.1. CLIRUN-II conceptual hydrologic model schematic.

Evapotranspiration: A suite of potential evapotranspiration models are available for use in CLIRUN-II. For this study, the Blaney-Criddle (temperature based) method (FAO, 1996) was used to be consistent with State of Colorado practices. Actual evapotranspiraton is a function of potential and soil moisture state following the FAO method (FAO, 1996).

Soil water modeling: Soil water is modeled as a two layer system: a soil layer and groundwater layer. These two components correspond to a quick and a slow runoff response to effective precipitation.

1. Quick runoff: The soil layer generates runoff in two ways. First there is a direct runoff component, which is the portion of the effective precipitation (precipitation plus snowmelt) that directly enters the stream systems. The remaining effective precipitation is infiltration to the soil layer. The direct runoff is a function of the soil surface and modeled differently for frozen soil (winter and spring) and nonfrozen (summer and fall).

The infiltration then enters the soil layer. A nonlinear set of equation determines how much water leaves the soil as runoff, how much is percolated to the groundwater, and how much goes into soil storage. The runoff is a linear relation of soil water storage and percolation is a nonlinear relationship of both soil and groundwater storages.

2. Slow runoff. The ground water receives percolation from the soil layer and runoff is generated as a linear function of groundwater storage.

The soil water processes have six parameters similar to the SIXPAR model (Gupta and Sorooshian, 1983) that are determined via calibration of each watershed.

Modeling dry and wet years

When CLIRUN-II is calibrated in a classical rainfall-runoff framework, the results are very good for the 25th to 75th percentile of the observed streamflows, producing R^2 of 0.3 to 0.7.[1] However, for most water resource systems, the tails of the streamflow distribution are important for design and operation planning. To address this issue, a concept developed by Block and Rajagopalan (2008) for hydrologic modeling of the Nile River known as localized polynomial was extended to calibrate rainfall runoff modeling in CLIRUN-II (Strzepek et al., In preparation).

Briefly, each observed year is categorized as to whether it falls into a dry year (0-to 25% of the distribution), a normal year (25% to 75%), or wet year (greater than 75%). A separate set of model parameters were estimated for the three different classes of annual streamflow. This increased the R^2 from 0.7 to 0.92.

Modeling the snowpack and its runoff is critical because three-quarters of the runoff in Boulder Creek above Boulder is from snowpack (see Figure 3.2). Precipitation is at least 40 mm in all months and peaks in April. Runoff, however, is barely above zero in the winter and peaks in June.

CLIRUN-II was calibrated to flow at 14 separate locations using estimated virgin flow (1907-2006). The goal was to model the relationship between climate and flow, so observed climate from 1953 to 2004 from the C1 monitoring station was used.

It was critical to capture extreme dry and wet years, so three versions of the model were calibrated: one for “middle” or normal years, one for drought or relatively dry years, and one for flood or relatively wet years. With the three models, the R^2 for estimating flow at Orodell was 0.91.

1. R^2 is the amount of observed variance explained by a model.

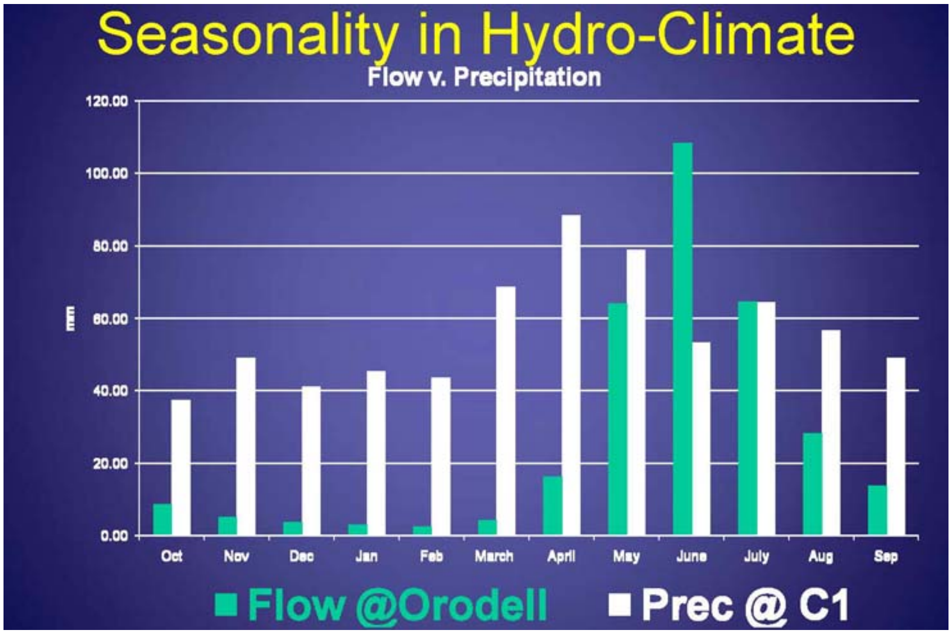

Figure 3.2. Precipitation and runoff for Boulder Creek.

Sensitivity analysis

The model was run assuming arbitrary annual increases in temperature and changes in precipitation (see Figure 3.3). The purpose of this analysis is to examine the sensitivity of annual flow and timing of runoff to changes in temperature and precipitation. Runoff in Boulder Creek currently peaks in June. A 3°C (5.6°F) temperature increase with no change in precipitation results in a 4% reduction in annual flow, but with a 3 % increase in Spring runoff and a 28% decrease in summer runoff. Note that annual water supply in the basin is not very sensitive to temperature because it either precipitates as rain or snow. If it comes as winter or spring rain it runs off quickly because the soil is either frozen or fully saturated due to snow melt. The effective precipitation has little opportunity to evaporate and runs off quickly.

In sensitivity runs, annual precipitation was held constant, runoff increased in winter and decreased in summer. A 20% reduction in winter precipitation results in only an 8% decrease in winter runoff because of the earlier snowmelt. When such a change is combined with a 30% increase in summer precipitation, there is a 1% increase in summer runoff, but a 4% decrease in annual runoff.

If annual precipitation is reduced 20%, 20 % in winter and 18% in summer the annual reduction in runoff is only 13%.

The results show three important features of the Boulder Creek hydrologic system:

1) Due to its altitude runoff response to precipitation is very different between the Winter/Spring season as compared to the Summer/Fall season.

2) Runoff in both seasonal regimes behaves non-linearly with precipitation.

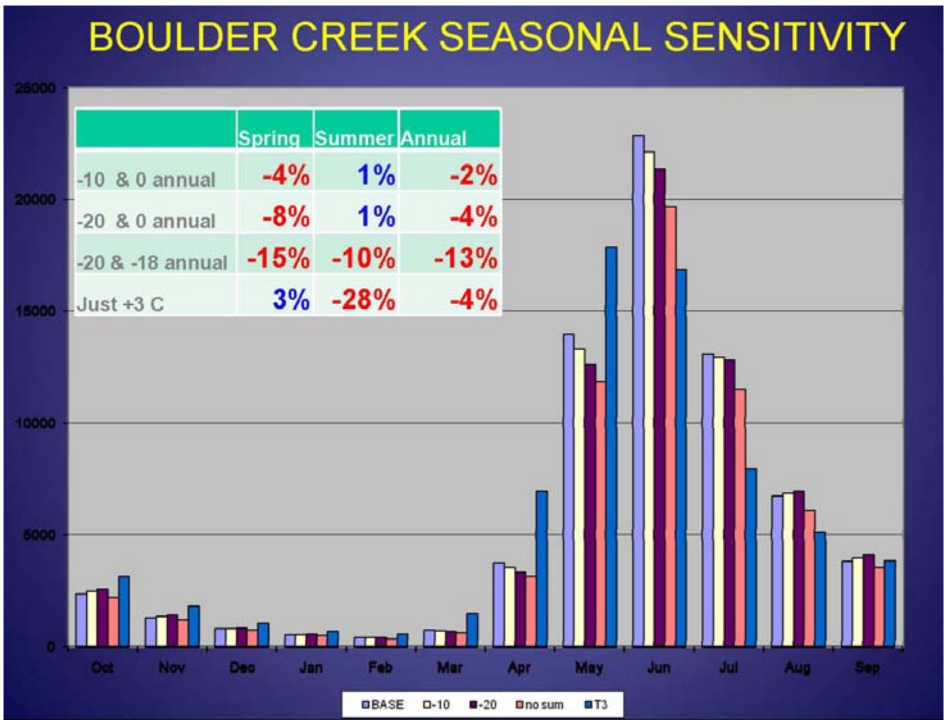

Figure 3.3. Sensitivity of Boulder Creek runoff to climate change.

3) The magnitude of temperature increase estimated by the models for 2070 shifts peak runoff at least one month earlier.

GCM scenarios

Perhaps more important, a 3°C increase in temperature shifts peak runoff from June to May. Indeed, runoff is projected to increase from October through May because more snow is melted off or precipitates as rain. From June through August, however, runoff drops. September remains virtually unchanged.

The effect of the GCMs in 2030 is displayed in Figure 3.4. All the scenarios result in higher runoff in April and May and lower runoff in July and August. There is little change from October through March. For other months, whether runoff increases or decreases depends on change in precipitation.

The effect of the GCM scenarios for 2070 is displayed in Figure 3.5. By 2070, the temperature increase is large enough to shift peak runoff a month earlier than in current conditions.

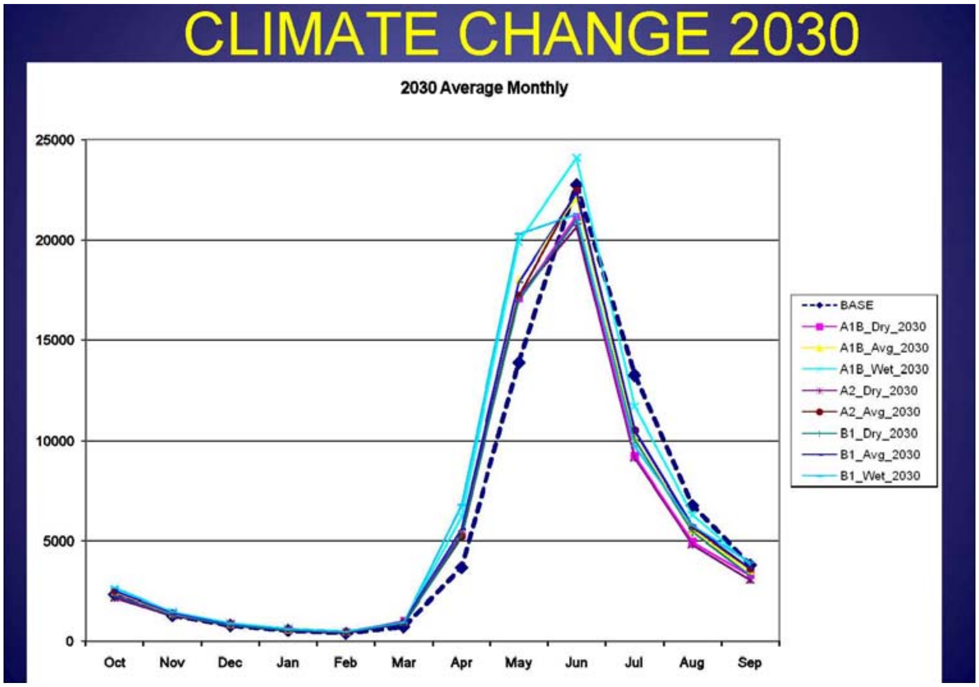

Figure 3.4. Boulder Creek runoff under current climate and climate change in 2030.

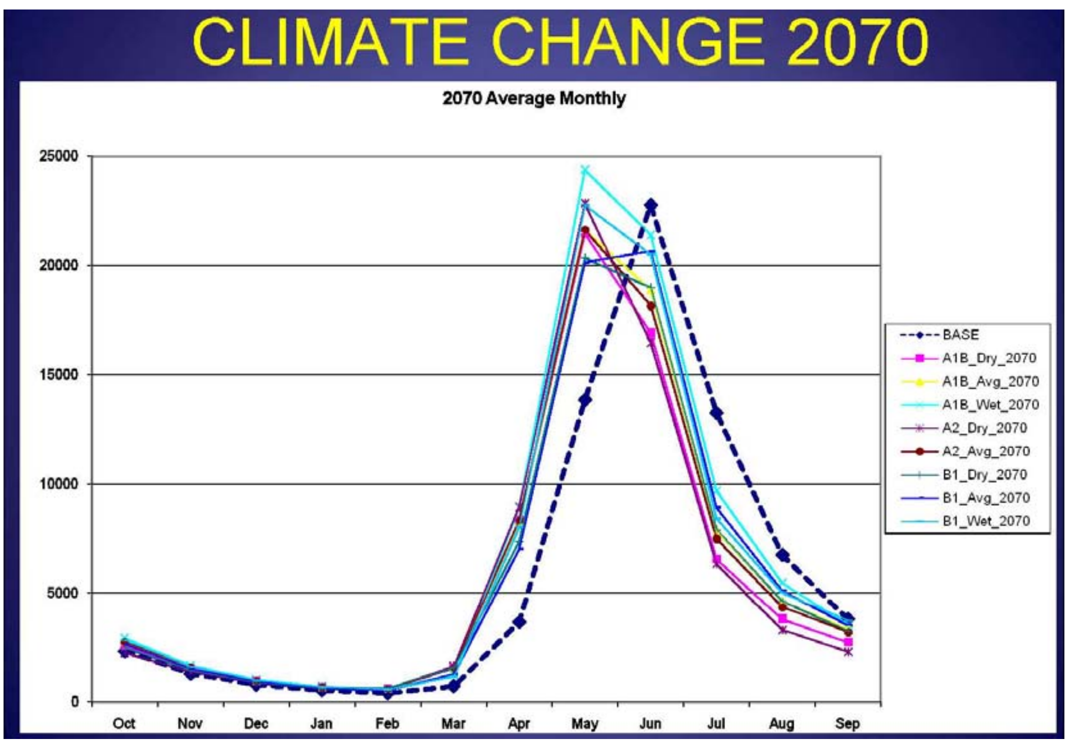

Figure 3.5. Boulder Creek runoff under current climate and climate change in 2070.

Analysis of combination of climate change and prerecorded climate

Figure 3.6 displays the combination of the proxy climate and GCM output compared to simulated runoff assuming no climate change. The wet scenario results in much higher runoff, particularly in very wet years. This is because the additional precipitation goes almost exclusively to runoff as actual evapotranspiration is almost at potential or maximum levels.. The dry scenario results in generally lower runoff. However, in dry years, paradoxically, the effect is less pronounced. This is because in those years the potential evapotranspiraration is so high that

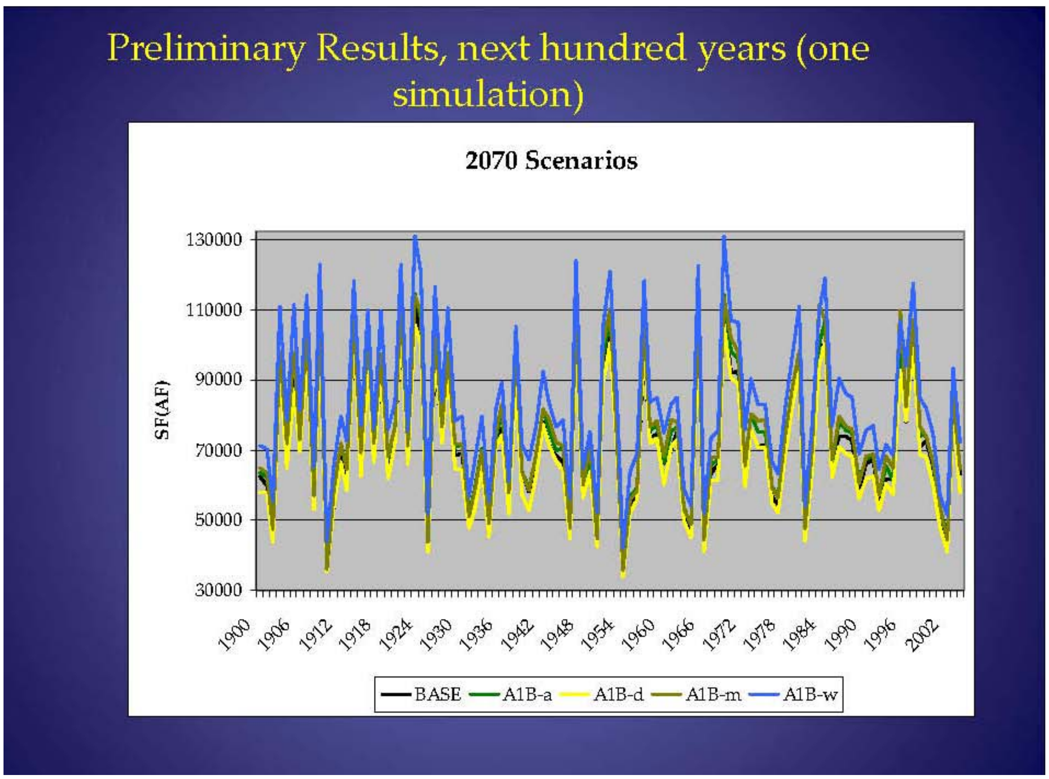

Figure 3.6. Combined reconstruction with 2070 climate change scenarios.

there is little runoff in the basin. Reducing the rainfall makes little difference in runoff since most precipitation has been lost to the atmosphere.

Table 3.1 summarizes annual and seasonal changes in runoff using the combined 437-year and climate change calculations.

Table 3.1. Estimated change in runoff in Boulder Creek

	Seasonal change				
Scenario	**Annual**	**Winter**	**Spring**	**Summer**	**Fall**
Base case	0%	0%	0%	0%	0%
B1 Wet 2030	7%	19%	19%	-18%	15%
B1 Mid 2030	-2%	4%	13%	-28%	-7%
B1 Dry 2030	-3%	9%	7%	-21%	-1%
A1B Wet 2030	12%	21%	24%	-8%	14%
A1B Mid 2030	-2%	5%	13%	-25%	-12%
A1B Dry 2030	-4%	19%	8%	-26%	6%
A1B Dry3 2030	-6%	-3%	2%	-23%	0%
A2 Mid 2030	-1%	8%	10%	-22%	4%
A2 Dry 2030	-5%	8%	7%	-28%	-2%
B1 Wet 2070	9%	38%	27%	-28%	23%
B1 Mid 2070	0%	23%	16%	-27%	2%
B1 Dry 2070	0%	62%	15%	-34%	9%
A1B Wet 2070	16%	45%	35%	-21%	27%
A1B Mid 2070	5%	46%	25%	-35%	16%
A1B Dry 2070	-4%	65%	15%	-44%	12%
A1B Dry3 2070	-3%	32%	13%	-35%	7%
A2 Mid 2070	0%	47%	20%	-41%	11%
A2 Dry 2070	-4%	62%	19%	-49%	0%

Note that annual changes in runoff are relatively insensitive to temperature changes and quite sensitive to precipitation changes. In the table and in some figures, "Dry3" is the alternate scenario with decreased winter precipitation. The wet scenarios result in increased runoff, the dry scenarios decreased runoff, and the middle scenario (with close to no change in annual precipitation) results in little change. All of the scenarios result in increased spring runoff and decreased summer runoff, demonstrating the relative importance of temperature compared to precipitation in affecting the seasonality of flow. Winter runoff increases in all of the scenarios except the 2030 alternate scenario. There, the decrease in winter precipitation more than offsets the higher runoff from increased temperatures. By 2070 even in this scenario, the effect of higher temperature on snow melt more than offsets the decrease in winter precipitation. Figure 3.7

displays the changes in May and July runoff. All scenarios cause an increase in May runoff and a decrease in July runoff.

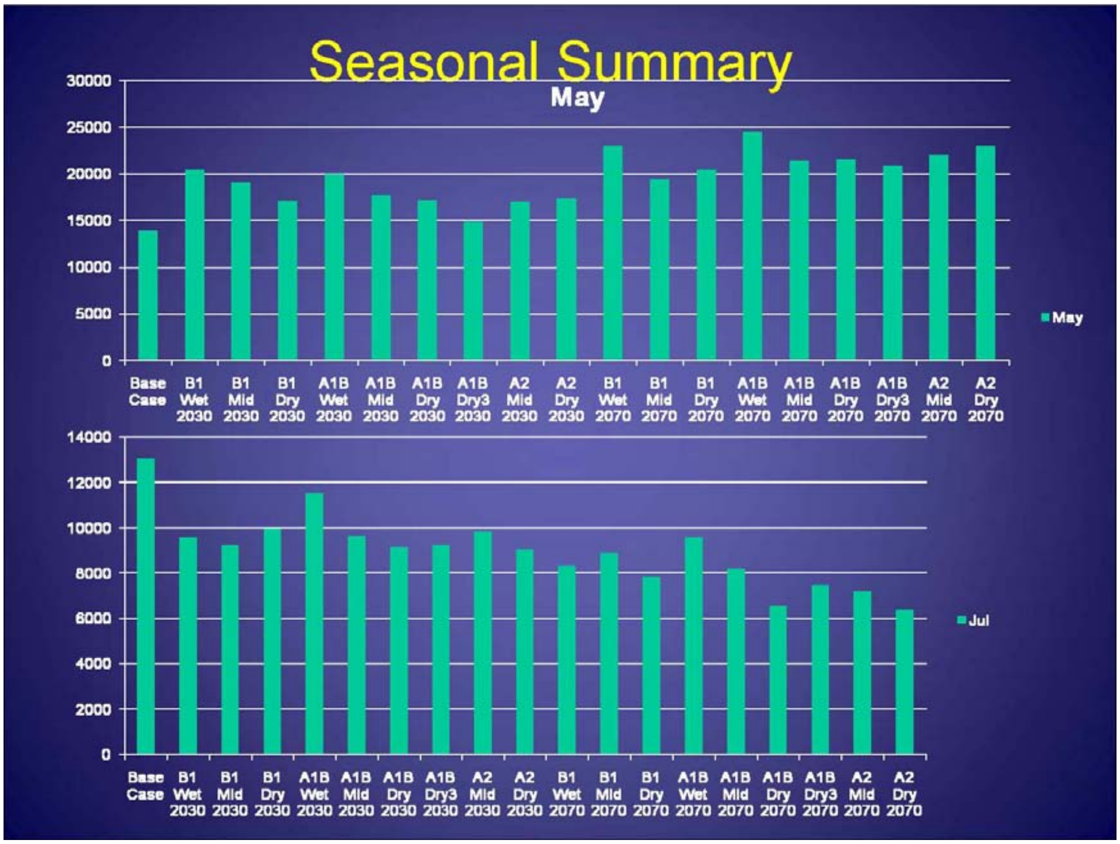

Figure 3.7. May and July runoff in Boulder Creek.

4. Water Management Modeling

The study team evaluated the effects of the climate change scenarios on the City of Boulder's water supply system and on regional water supplies using an existing model of the management of the City's water system, the Boulder Creek Model (BCM). Time series outputs of natural stream flows from CLIRUN-II and temperature and precipitation from the GCMs combined with the 437 year paleo-climate reconstruction of streamflow in Boulder Creek were incorporated into BCM. BCM was used to evaluate each of the 18 climate change scenarios, with each scenario represented by 11 alternate traces of hydrologic and temperature/precipitation time series.

BCM is a water management model developed by Hydrosphere (now AMEC Earth & Environmental) for the City of Boulder to simulate the operation of Boulder's water supply system for a range of planning purposes. It is a well-developed computer model that has allowed considerable evaluation of the adequacy of the city's water rights portfolio. This model simulates operation of the city water system as it meets a specified annual demand level over a variable time series of climate and natural flow hydrology data, and evaluates the ability of the City's water rights and water supply system to meet that demand.

This network model uses a linear programming algorithm to allocate water supplies among competing demands. It optimizes allocation of water based on relative water rights priorities or operating rules as objective function drivers. It incorporates the requirements of mass balance, stream topology, facilities capacities, water rights limits, and demands as side constraints. The model operates on a quarter-monthly time step and uses hydrological inputs (e.g., gauge data or estimated runoff from CLIRUN-II). Each time step is iteratively solved, first to allocate natural stream flows among competing water rights based on relative priorities, then to simulate other aspects of water management including allocation of immediate return flows and operations of exchanges and reservoir releases.

BCM simulates all major physical and institutional aspects of stream flow hydrology, water rights administration, and water use within the 439 square mile Boulder Creek basin. Physical aspects include natural stream flows and stream segments, water imports into the basin, reservoirs, ditches and raw water pipelines, water demands, consumptive use, and return flows. Institutional aspects include water rights, reservoir operating rules, and water supply system operation rules.

Boulder's municipal raw water supply system is represented in detail, including the city's surface water diversions, reservoirs, raw water pipelines, and water and wastewater treatment plants. Customer demands are represented as three separate components, reflecting the city's three distribution pressure zones, which allow water system pressure to be maintained in acceptable ranges across elevation changes from the western foothills area of Boulder to the eastern-most area of the city on the plains. The model emulates Boulder's reservoir operating rules as well as its drought recognition thresholds and response triggers.

Other competing water uses in the Boulder Creek basin are individually and explicitly represented, including irrigation ditches and reservoirs, and other municipal (Lafayette, Louisville, Denver) and industrial (Xcel Energy) water supply systems.

Calls by water rights diverting downstream of the Boulder Creek basin in other parts of the larger South Platte basin are represented in BCM as a time series of unlimited demands at the bottom of the Boulder Creek network with ranks corresponding to the priorities of calls from downstream water rights. When the model is run using historical hydrology, the priorities of such calls reflect historical call records. When the model is run using synthetic hydrology, the priorities of such calls are estimated based on historical relationships between climate and natural stream flow as independent variables and downstream calls as the dependent variable.

BCM simulates deliveries from the Colorado-Big Thompson and Windy Gap projects (from the Upper Colorado River) to project allottees in the Boulder Creek basin using a separate operating module (cooperatively developed with Mr. Andy Pineda of NCWCD) that emulates the operations and quota-setting policies of the those projects based on project inflows. This study assumed adequate CBT replacement supplies in Green Mountain Reservoir and no Colorado River Compact calls.

The principal use of BCM is to assess the reliability of Boulder's water supply system given assumptions regarding climate and associated natural stream flow hydrology, Boulder's municipal water demands, and water rights and facilities available to Boulder. The model attempts to meet a specified annual municipal water demand over given time series of variable natural stream flows, climate data, and transbasin imports. In the model, Boulder's municipal demands are reduced during droughts according to Boulder's adopted drought response triggers and water use reduction goals. Each model run is "scored" based on Boulder's adopted water supply reliability criteria.

The BCM originally operated using 1950-1985 historical natural flow hydrology reconstructed from records of stream gauges and upstream diversions. In 2002, an alternate set of tree ring-derived hydrologic data covering the period of 1703-1987 was developed for use in the model in cooperation with Dr. Connie Woodhouse of NOAA. In 2006, the gauge-based natural stream flow data were extended to cover 1907-2006 and the tree ring-based data were extended to cover 1566-2003 based on the extended periods of available gauge-based natural stream flow data and new tree ring data that had been collected to include three rings laid down during the recent and extreme drought year of 2002.

4.1 Application to this Study

BCM was modified for use in this study to incorporate the following inputs:

- Higher elevation hydrology inputs from CLIRUN-II
- Eleven traces for each scenario
- Temperature, precipitation inputs directly from GCMs
- New temperature and precipitation-driven algorithms developed to generate time series data not obtained directly from CLIRUN-II and GCMs: lower elevation runoff, unit agriculture demands, agriculture return flows, and South Platte calls.

CLIRUN-II estimated runoff in the following locations in the Boulder Creek basin (see Figure 1.1 in Chapter 1):

- North Boulder Creek at Silver Lake
- North Boulder Creek gains at Lakewood
- Middle Boulder Creek at Nederland
- Boulder Creek gains at Orodell
- South Boulder Creek at Gross Reservoir
- South Boulder Creek gains at Eldorado Springs

CLIRUN-II was also run to estimate change in runoff in the Colorado River near Hot Sulphur Springs. That information was used to estimate changes in CBT and Windy Gap deliveries.

Direct output from the GCMs was used to estimate the following:

- Boulder Creek gains at lower elevations (Orodell to 75th Street)
- Irrigation demands and return flows in Boulder Creek Basin
- South Platte calls.

Boulder Creek gains from Orodell to 75th Street are caused by precipitation, local inflows, return flows, and groundwater interactions. These gains are relatively minor compared to Boulder Creek natural flows at Orodell (approximately 17,000 acre-feet per year vs. 71,000 acre-feet per year, respectively), but are important in modeling the allocation of stream flows among water rights. Gains from Orodell to 75th Street can be readily quantified via mass balance analysis using stream flow gage records and diversion records. Historical gains correlate reasonably well (R^2 = 0.46) with local precipitation as measured at the Boulder weather station over the period of 1987-2006, for which data are available for all mass balance components. In this study, estimated changes in precipitation from the GCMs were used to estimate the Boulder Creek gains based upon this historical correlation.

In the BCM, irrigation demands in the Boulder Creek basin are calculated on a crop unit basis, applied to crops and acreages served by individual irrigation rights. The calculations employ the modified Blaney-Criddle method (USDA, 1970) which utilizes frost dates, mean monthly temperature and mean monthly precipitation. The growing season is sensitive to changes in frost dates, temperature and precipitation, and crop coefficients are sensitive to changes in temperature and precipitation. Incorporation of climate model output resulted in shifts in seasonal irrigation demand patterns. Because climate model output did not include specific frost dates, frost dates were generated via correlation with monthly mean temperatures from the climate models. Irrigation return flows in the Boulder Creek basin are explicitly modeled based upon historical relationships between irrigation diversions and return flows to lower Boulder Creek, which were quantified via mass balance techniques. The study assumed no changes in crop mixes.

In order to reasonably evaluate the effects of climate change scenarios, South Platte calls in the BCM were based upon historical call patterns but were responsive to climate change. In this study, we generated separate South Platte calls for the irrigation (April through September) and non-irrigation seasons (October through March). For irrigation season calls, we categorized historical Orodell natural flows into six “year types:” very wet, wet, average, dry, very dry, and year following very day. We correlated historical Orodell natural flow year types with South Platte calls during the irrigation season ($R^2 = 0.98$). This correlation reflects the relationship between supply and demand. Irrigation season calls are more senior and extensive in dry years than in wet years, and natural flows at Orodell are generally indicative of overall stream flow conditions throughout the South Platte basin. We generated irrigation season South Platte calls using this “flow year” type/seasonal call pattern relationship and scenario-derived Orodell natural flows.

South Platte calls during the non-irrigation season are driven by the filling of several large off-channel irrigation reservoirs on the Lower South Platte. These reservoirs begin filling at end of irrigation season (typically October) and reach maximum levels between March and June. The length of time required for the Lower South Platte reservoirs to fill each year is a function of both natural stream flows and irrigation demands over the previous irrigation season or seasons. Lower-than-average stream flows combined with higher-than-average irrigation demands over one or more years typically result in relatively low return flow volumes during the ensuing reservoir filling seasons and vice versa. The date by which the Lower South Platte Reservoirs historically filled each year is reasonably correlated with a “supply index,” comprised of Orodell natural flow and Longmont ET for the two previous years (R2 = 0.49). We generated non-irrigation season South Platte calls using this supply index/”fill date” relationship and scenario-derived Orodell natural flows and Longmont temperature and precipitation.

4.2 Key Assumptions

This study did not consider reduced CBT deliveries resulting from potential Colorado River Compact calls because such an analysis would be beyond the scope and resources of this study. Previous studies such as Christensen and Lettenmaier (2007) found that average runoff in the Colorado River could be reduced by climate change. Whether such a reduction in runoff would eventually lead to a Compact Call is uncertain. Such a call has not happened and there are uncertainties in the "Law of the River" as to how shortages will be handled. Furthermore, the entire State of Colorado would have to address a Compact Call, not Boulder alone. By not considering the possibility of a Compact Call, the results of the particularly dry scenarios may be optimistic.

Other important model run assumptions are as follows:

- Boulder's "build-out" municipal water demand was modeled at 28,600 acre-feet per year, which includes a 10% safety factor, and is based on a build-out demand number from a now-outdated population and employment projection that is probably overstated (conservative).
- Boulder is not allowed to carry over its CBT water in CBT project storage. Such carry-over has been allowed as an operating practice for the last 15 to 20 years but is not an official permanent policy (conservative).
- Boulder's diversions are not allowed to dry up certain segments of Boulder Creek during droughts. In practice, such dry-up practices are allowed and have occurred (conservative).
- No attempt was made to modify Boulder's drought recognition thresholds, drought response targets, or system operating rules to respond to climate change.
- The study did not examine the effect of adaptations within Boulder's water supply system such as conservation measures that can temporarily or permanently reduce demand (e.g., replace bluegrass with no or native vegetation).
- Similarly, the study did not examine the effect of adaptations by irrigated agriculture such as switching to a different crop mix.
- The model does not consider other limitations on CBT's ability to divert entire physical supply except for local bypass requirements.

4.3 Results

Boulder's water supply system appears to be sufficiently robust to meet its more severe reliability criteria, regarding survival of landscaping and supplying essential indoor needs, in most of the future possible climate conditions modeled. About half of the scenarios show an increased likelihood of drought years requiring minor, likely voluntary, water use reductions for the city's water customers if no effort is made to adapt to the changing climate conditions in other ways. The scenarios based on the Canadian climate model (the wettest GCM selected) result in an increase in yield to the city's water system. GFDL0 (the driest GCM scenario) showed that Boulder would have difficulty supplying sufficient water for even a greatly restricted level of municipal water needs during the most severe drought years by 2030. Two of the nine modeled scenarios result in reliability criteria violations for more severe droughts by 2070. The GISS EH model, which estimates very dry winters, showed significant losses in yield for the city's water rights by 2030. However, by 2070, much of this loss was regained because of earlier spring snowmelt allowing the city to capture more runoff in its reservoirs before interruption by calls from downstream senior agricultural water rights.

Figure 4.1 displays the results in terms of the city's reliability criteria under the different climate change scenarios. Cells highlighted in red indicate the reliability criteria are not met. Yellow means reliability is reduced but the criteria are still met and green indicates that the criteria are met more frequently than in the base case. Boulder's reliability criteria are met in most of the scenarios. The more serious 100 and 1,000 year criteria are met in all but three of the scenarios. By 2070, the risks of violating the reliability criteria increase with the A1B and in particular the A2 scenarios. These are higher greenhouse gas emission scenarios than the B1 scenario.

Emission Scenario	Model Type	Year	1-in-20 year criterion met?	1-in-100 year criterion met?	1-in-1000 year criterion met?	% of years with reduced deliveries		# of "events" (1 or more consecutive years with reduced deliveries)		maximum event length, years		maximum delivery reduction (AF)		average of delivery reductions, (AF)	
						Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg	Max
Drought Plan (300 years)			yes	yes	yes	3%		6		4		6552		3313	
BASE CASE			yes	yes	yes	2%	3%	3	5	4.8	7	2526	5334	1247	1604
B1	Wet	2030	yes	yes	yes	0%	0%	0	2	0.5	2	524	1573	1159	1573
B1	Mid	2030	yes	yes	yes	4%	5%	5	8	6.6	11	2848	5334	1369	1899
B1	Dry	2030	no	yes	yes	5%	7%	7	11	6.3	10	4138	9377	1419	1800
A1B	Wet	2030	yes	yes	yes	0%	0%	0	2	0.3	1	295	1573	719	982
A1B	Mid	2030	yes	yes	yes	4%	5%	5	7	5.8	7	3120	5334	1371	1724
A1B	Dry	2030	no	yes	yes	7%	11%	10	16	7.1	10	3953	5838	1448	1864
A1B	Dry3	2030	no	no	no	23%	27%	27	36	11.3	14	10120	12130	1847	2232
A2	Mid	2030	yes	yes	yes	3%	5%	5	6	5.2	6	2736	5334	1286	1656
A2	Dry	2030	no	yes	yes	13%	18%	16	22	8.5	11	4426	5838	1484	1716
B1	Wet	2070	yes	yes	yes	0%	0%	0	2	0.5	2	426	1573	893	1234
B1	Mid	2070	yes	yes	yes	2%	3%	3	6	4.2	6	2533	5334	1217	1713
B1	Dry	2070	yes	yes	yes	3%	5%	4	6	4.8	6	3098	5838	1414	2044
A1B	Wet	2070	yes	yes	yes	0%	0%	0	2	0.3	1	295	1573	719	982
A1B	Mid	2070	yes	yes	yes	2%	3%	3	6	3.7	6	2531	5652	1106	1818
A1B	Dry	2070	no	yes	no	14%	16%	18	26	8.9	13	9657	11398	1857	2253
A1B	Dry3	2070	no	yes	yes	4%	6%	6	10	5.5	7	3829	5838	1481	1755
A2	Mid	2070	no	yes	yes	5%	6%	7	10	5.8	7	5933	9036	1431	2078
A2	Dry	2070	no	no	no	21%	26%	23	29	12.8	17	10475	12332	2153	2467

Figure 4.1. Summary of model results. Averages and maxima for the eleven 437-year traces in each scenario.

It is interesting to note the Dry3 (alternate) model. In 2030, the pattern of temperature increase is not strong enough to accelerate runoff to a significant degree, but enough to increase irrigation demands in June. The result is that Boulder's reservoirs do not store as often as in current conditions. By 2070, temperatures have increased enough to accelerate runoff to a greater degree than irrigation demands. Consequently, Boulder's reservoirs store more reliably.

Figure 4.2 displays one of the 11 traces in the base case. It shows how reduced deliveries are distributed over time. Note that the occurrences of such reductions are not uniform. None occur during period of record except for 2002 (see far right). Most are in the early part of the reconstruction, i.e., the 16th and 17th Centuries.

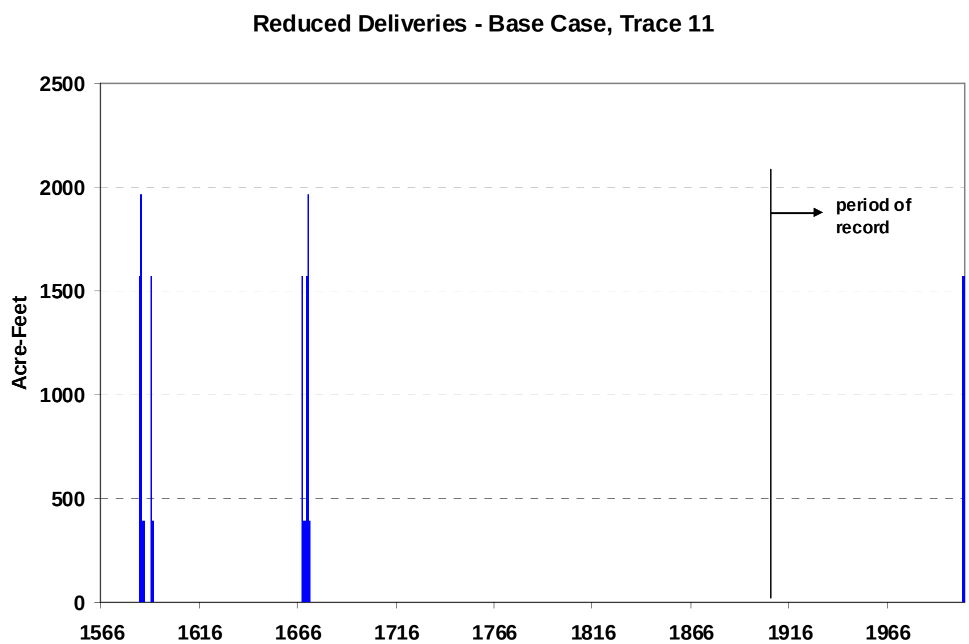

Figure 4.2. Summary of model results. Averages and maxima for the eleven 437-year traces in each scenario.

Figure 4.3 is a wet scenario under the lowest greenhouse gas emissions scenario (B1). There are fewer and less severe shortages, none in period of record.

Figure 4.4 is one of the most negative scenarios. It is the dry scenario under the highest greenhouse gas emissions scenario examined (A2). The 16th and 17th Centuries have the most frequent violations and a substantial increase in violations compared to the base case. There are very few violations in the most recent 100 years.

This analysis shows how looking just at period of record would not show vulnerability nearly as well. It is interesting that the combination of long-term average climate change and the reconstructed streamflow record (long-term climate variability) decreases Boulder's water supply reliability more than considering each one separately. Thus, studies that examine only climate change or long-term climate variability can underestimate vulnerability to a combination of climate variability and climate change.

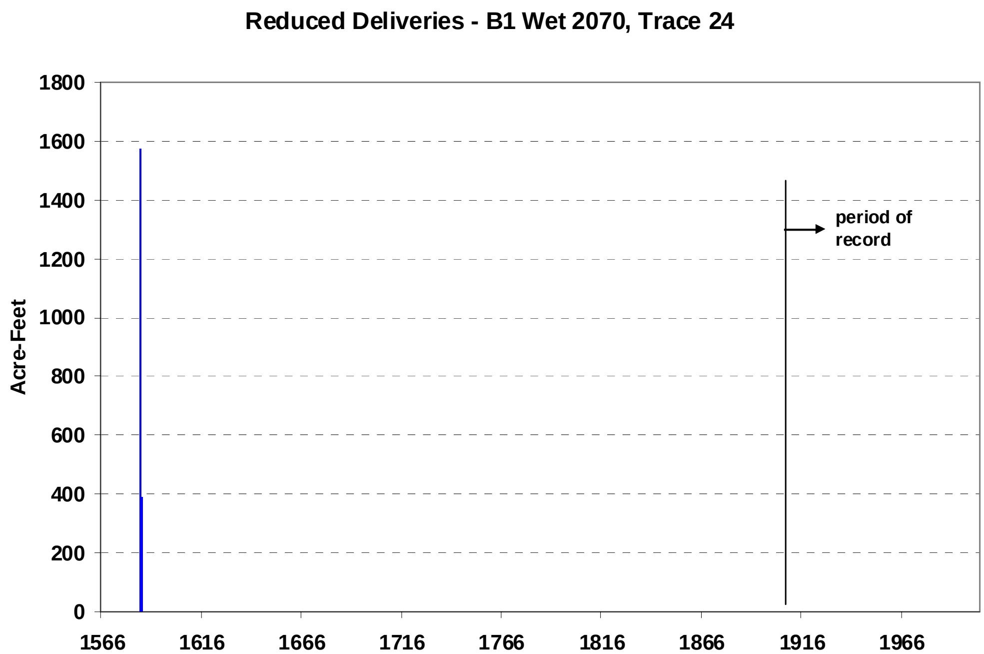

Figure 4.3. B1 2070 wet scenario delivery reductions.

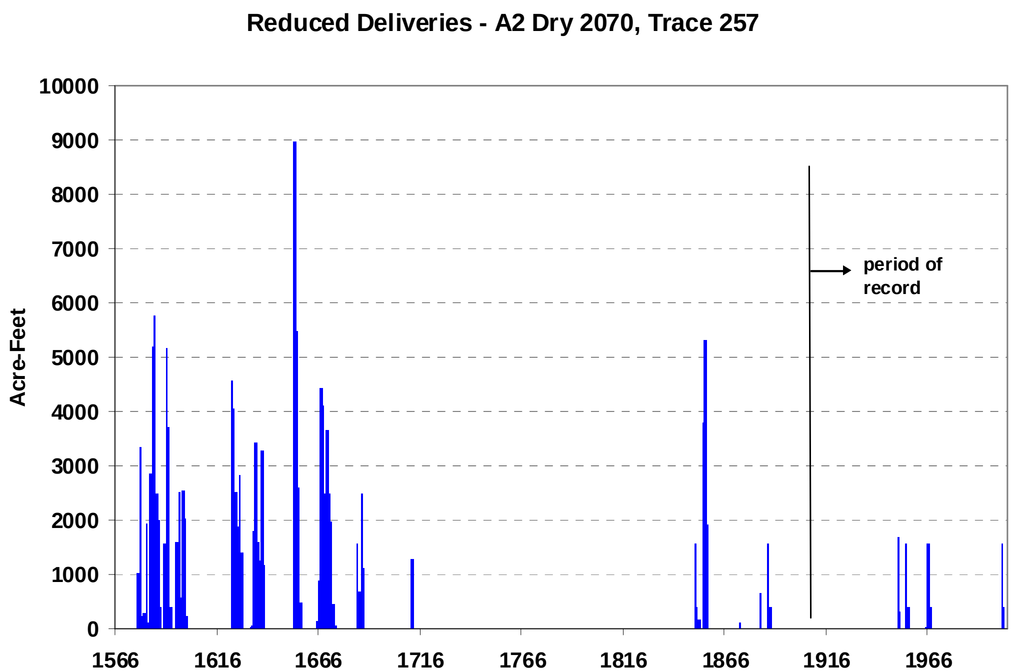

Figure 4.4. 2070 A2 dry scenario delivery reductions.

From an agricultural perspective, irrigation demands were estimated to increase in all scenarios (see Figure 4.5). But the increase varies considerably depending on the amount of temperature increase and change in precipitation. In general, demands in 2070 are estimated to be higher than demands in 2030. But, the A1B wet scenario in 2070 has a lower demand than many of the 2030 scenarios.

One of the most certain effects of climate change is to reduce the "natural overlap" between supplies (natural flow hydrograph) and demands. Figure 4.6 displays the base case, i.e., with June runoff peak. In the base case there is a 72% overlap in the monthly timing of natural flow versus irrigation demand.

Figure 4.7 displays the estimated impact of the alternate (reduced winter precipitation) A1B scenario in 2030. Runoff has increased only slightly in April and May, is unchanged in June, and has declined significantly in July-September. Irrigation demands increase drastically in June. The result is there is now only a 57% overlap in the monthly timing of natural flow versus irrigation demand.

The A1B dry scenario in 2070 (Figure 4.8) would be very negative. The runoff peak is now in May, and irrigation demands are much greater in July through September. There is now only a 38% overlap in the monthly timing of natural flow versus irrigation demand.

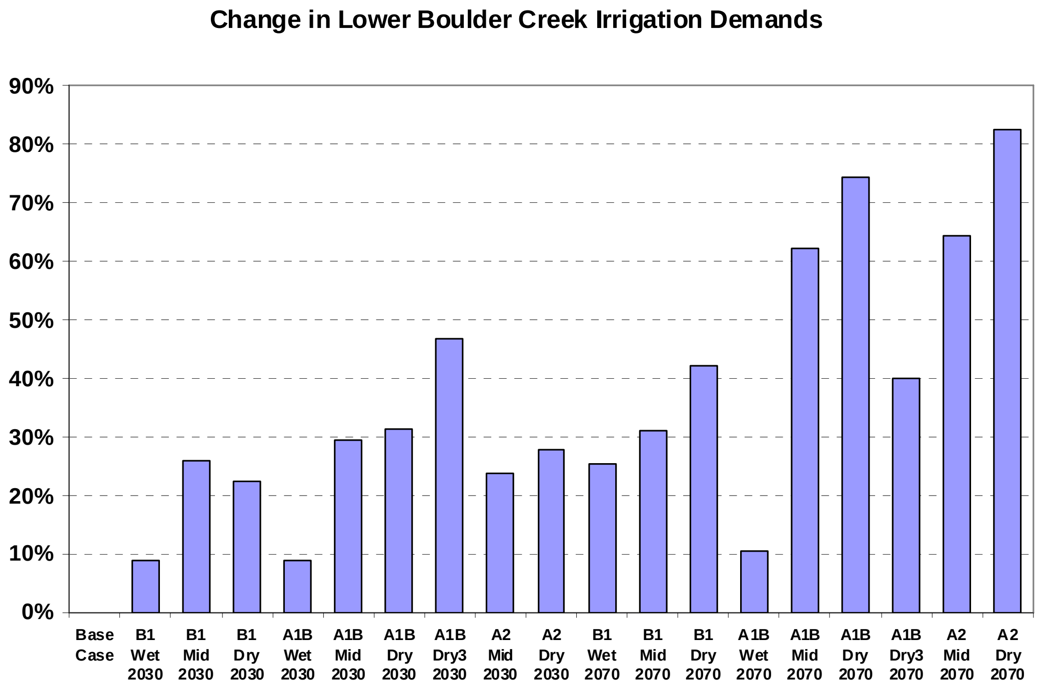

Figure 4.5. Change in lower Boulder Creek irrigation demands.

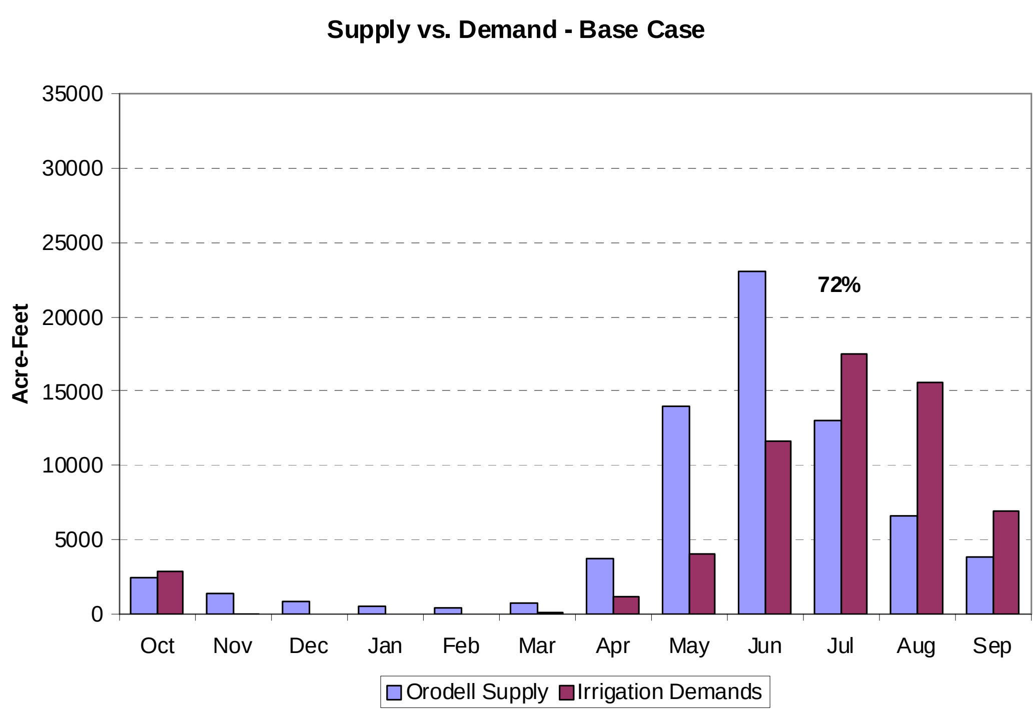

Figure 4.6. Current water supply and irrigation demand.

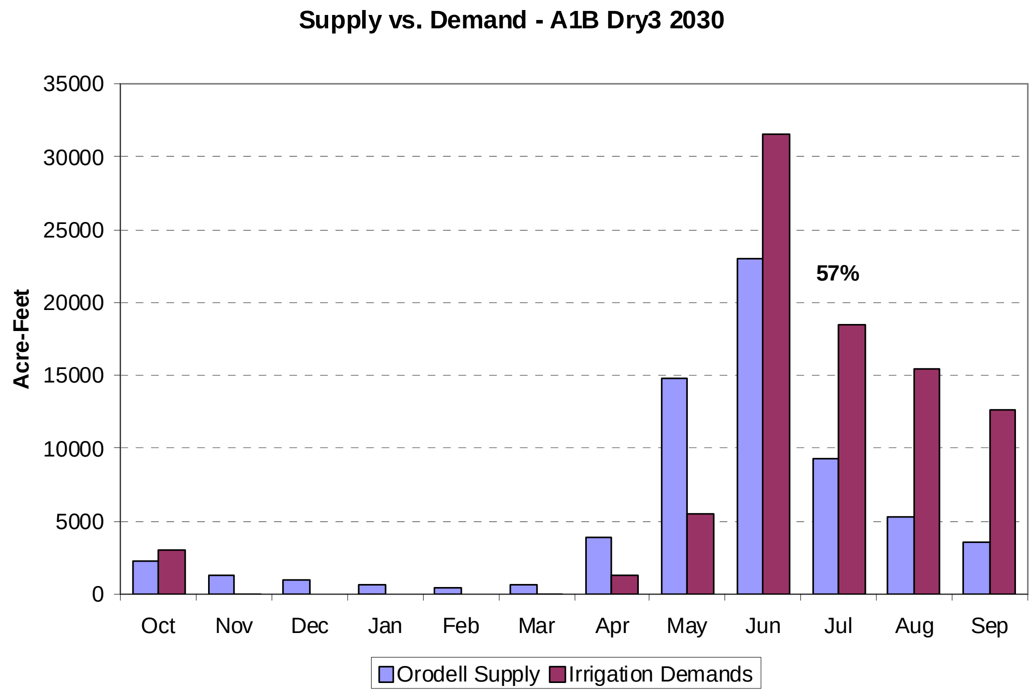

Figure 4.7. 2030 A1B alternative scenario runoff and irrigation demand.

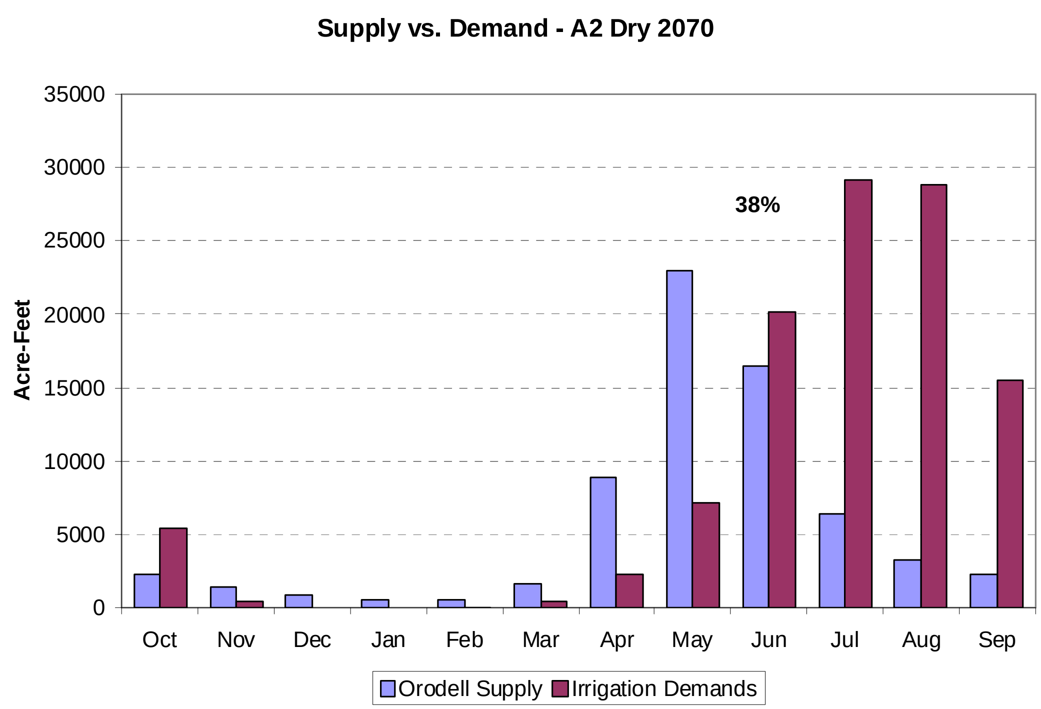

Figure 4.8. A2 2070 alternative scenario runoff and irrigation demand.

Although demands increase significantly, irrigation diversions remain basically the same. There are more diversions in June and less in July-September. This would have significant implications with respect to the proportions of hay-type crops vs. crops requiring a longer irrigation season. Essentially this means that, except for scenarios in which runoff increases, agriculture could receive roughly the same water supplies it currently gets, but with climate change, irrigation demand will be higher and there would be less natural overlap between supply and demand. Effectively, a smaller share of agriculture's irrigation needs will be satisfied. The implications for crop production and yields, and the potential for irrigators to adapt to such changes, were not studied.

5. Use and Policy Implications of the Climate Study

5.1 Conveying Study Results to Decision-Makers and Public

The results of this study and the 2003 study were presented to Boulder citizens, City Council, the city's Water Resources Advisory Board, and other water users. When discussing the adequacy of the city's water supplies and possible climate change effects on supply reliability, the common concerns expressed by the city's water customers tend to fall into three categories:

- Type of regional changes in the environment that might occur
- Continued availability of water for irrigation
- Cost of water supplies.

In general, the public seemed to appreciate the city's effort to provide specific information on a range of possible futures for Boulder's water supplies, even though perhaps preliminary and uncertain, in preference to dealing with generalized information, which often led to an assumption that higher future temperatures could only result in extreme decreases in future water supplies for the city. Although some citizens wanted a projection of a single scenario, most of the public seemed to appreciate receiving information on a range of possibilities that might only be narrowed from the full spectrum.

The climate studies have given those making decisions regarding Boulder's future water supplies a better understanding of the scope of possible future climate changes, the data that will be necessary to understand the extent of regional climate changes as they occur, and the range of the possible responses that may be required. For the general public, the availability of the studies has helped to moderate extreme views of climate change possibilities. Both groups have gained insight into the complexities of the water system response to changing conditions, including the effects on water rights yields and possible infrastructure limitations.

A few lessons were learned about what could be gained from studies of this nature and how the results should be presented to the public. The study results were very useful in conveying the range of possible future conditions, although some members of the public wanted probabilities assigned to the various scenarios. During presentations, the public was asked not to interpret the results too literally because the future will not look exactly like any one modeled scenario. In distilling the results for presentation, sometimes important elements of the water system response were lost when conveying data in terms of averages. A correlating concern arose when presenting modeled extreme events. Some citizens focused intently on the severe, but very rare events, with the expectation that these events should become the basis for water system changes.

Inclusion of information on modeling strengths and weaknesses could increase understanding that modeled infrequent extremes should be interpreted with caution.

5.2 Water Rights Implications of Possible Climate Change Effects

All of the climate change scenarios could have impacts on water rights yields under Colorado's prior appropriation water rights system, which satisfies senior water rights prior to junior rights during times of shortage. Even if the average annual precipitation amount remains the same, a change in the pattern of streamflows will cause a redistribution of water supplies because of differences in allowable diversion times or places within water rights decrees. A significant unknown factor that could affect about half of Boulder's water supply is changes that might be triggered in the administration of the Colorado River Compact because of decreased streamflow in the Colorado River basin.

The complexity of factors affecting water rights yields and the highly interactive nature of the Colorado water rights administration system can make it difficult to predict the impact of changes in temperature or precipitation patterns on the yield of a particular water right or portfolio of water rights. A change in the timing or amount of available streamflow due to climate change will alter which water rights are satisfied and to what degree. Some water rights decrees, such as older water rights used for the originally decreed purposes, will allow water users to shift diversion practices with changing climatic conditions, while other decrees, such as water rights that have been changed in use and given a fixed yearly start date for diversions, could see water yields shrink. Climate change is likely to create water rights winners and losers, and the question is to what degree water reallocation will occur within the existing Colorado water allocation system.

Given the uniformity with which higher average temperatures are predicted to occur in Boulder's source watersheds, a few changes that could have an effect on the yield of the city's water rights can be predicted with some confidence. One of these likely outcomes is the occurrence of earlier spring snowmelt and runoff in the mountain watersheds feeding Boulder's water system. This change could be beneficial for the city because of the water rights administration issues affecting Boulder's water yields. At present, the city has a four to eight week window in the spring to fill its high mountain reservoirs with the water that will carry the city through the rest of the year once streamflows drop in late summer. This window usually occurs from late April until June between the start of snowmelt in high elevation areas and when the city's relatively junior water storage rights are called out by senior direct flow water right owners using the water for agricultural irrigation. Most of Boulder's reservoir storage water rights do not have a fixed start date to begin accounting for the allowed annual diversion amount, so accounting for the year's fill begins when the reservoir levels start to rise from initiation of snowmelt. Many downstream agricultural water rights do not have a fixed start date for initiation of diversions either, so water must be allowed to bypass the city's reservoirs at the time that growing conditions result in agricultural water users placing water rights calls that are senior to Boulder's reservoir rights. If the start of Boulder's reservoir diversion window occurs earlier, but the onset of irrigation demand does not advance as much because of limitations on crop growth from hours of daylight, then the city may be able to increase its reservoir water yields.

Another change due to higher temperatures could be the form of annual precipitation with more coming as rain than snow. This change might not have as great an impact to the portion of water supplies derived from the lower elevation areas of the South Platte River basin where most water supplies are used. However, it could have a significant impact on the pattern of runoff from the higher elevation areas that feed the entire South Platte River basin. The snowpack that accumulates in the mountains throughout the winter serves as a pseudo-reservoir that releases water throughout the growing season and might need replacement with actual reservoirs under changed conditions.

The combination of earlier runoff and an increased percentage of winter precipitation coming as rain might lead to even lower streamflow levels in late summer because of the snowmelt-driven hydrology of regional streams. This change would trigger an increase in the seniority of calling water rights in late summer and close out diversions by more junior rights that receive some yield under current conditions. For junior water users, the situation could be made worse by greater irrigation water demands caused by higher temperatures. Boulder is fortunate to have some very senior direct flow water rights that should allow continuation of diversions during low streamflow periods.

5.3 Water Policy Adjustments due to Climate Change

Some of the water policy adjustments that might be expected to develop because of climate change can be anticipated now, but others may become apparent only as the extent and character of future climate change effects are revealed. Given the expectation of higher temperatures, changes in landscaping and agricultural practices are likely.

Many municipalities in Colorado have already altered urban landscaping requirements for new development to encourage greater use of drought-tolerant plantings and reduced areas of lawn grass. In the future, low water demand landscapes may gain wider acceptance in established neighborhoods. The increasing cost and effort associated with maintaining large expanses of water-intensive lawn grass under higher temperature conditions may overcome the lack of public acceptance and associated limited use of alternative landscaping and native plantings in some existing neighborhoods. There may be increased pressure to change covenant restrictions that require lawns to be kept very green even in the heat of August.

Agricultural producers may select different crops that have greater spring frost tolerance to make better use of the earlier spring runoff period. However, this adaptive approach will be limited because many crops require a certain number of daylight hours and associated amount of solar energy for germination are early growth, which depends on location and latitude, not climate. Farmers may also look for crops that mature earlier in the season to adapt to extended late summer low streamflow periods. Hay and alfalfa producers may have fewer cuttings each year owing to decreases in irrigation water in the late season. Crop selection may change to favor crops that are less water-intensive, which could lead to fewer locally produced fruits and vegetables. This outcome would hinder efforts by those who are attempting to buy more local produce to reduce the contribution of consumer products transportation to greenhouse gas emissions. Alternatively, locally production of high valued crops such as fruits and vegetables may persist or increase due to more intensive use of highly efficient drip irrigation systems.

A shift to earlier runoff and lower late summer streamflow might create a need for construction of more reservoir storage space for seasonal flow regulation. It could also encourage restoring storage space at existing reservoirs that may have deteriorated or enhancing existing reservoirs by raising dam heights. More dam inspectors and dam safety requirements may be necessary. The higher rate of evaporation caused by higher temperatures may result in more dams being located at higher elevations or more underground water recharge storage projects. An increase in the amount of the spring runoff that is captured in reservoirs could prove beneficial for instream flows by providing a means to redistribute streamflow from times when flows are higher than needed for stream habitat maintenance to times when streamflows would otherwise be too low to support habitat. Taking advantage of this opportunity could require changes in perspective regarding water supply projects for both habitat conservationists and water system managers.

Colorado municipalities may be in a more favorable position to handle hydrologic changes resulting from climate change than other areas because water managers in the state are used to coping with highly variable hydrology and significant uncertainty in water supply availability from one year to the next. Water supply systems in the state have typically have the capability of smoothing annual variations in water availability. Many cities already have drought response plans. In general, citizens have some sense that they live in a semi-arid area and that drought years requiring a reduction in water use will occur occasionally. Larger cities in the state tend to have well-established water conservation programs in place. Most water systems in the state have some reservoir storage capability. Given the high degree of dependence on reservoir storage caused by the existing snowmelt-driven hydrology, many state water managers may be faced with the easier problem of altering reservoir management rather than developing new reservoir systems. Given this current state, the foundation is in place for adaptation to climate changes that may bring greater hydrologic extremes and more fluctuation between wet and dry cycles.

In response to this climate study, Boulder has identified several areas in which current actions are warranted. However, given the uncertainty in study results due to limitations in resolution of current GCMs and the variety of results produced by the selected study GCMs, city decision-makers believe it is premature to dedicate significant sums of money to capital improvements for the water system that may or may not ultimately prove to be necessary. For example, one response to the study result showing an increase in occurrence of minor droughts under some of the modeled scenarios could be acquiring additional water rights and/or building additional reservoir storage to prevent more years with water use restrictions for the city. These actions would be expensive, would have environmental effects, might be unpopular with some members of the public, and could turn out to be unnecessary if the actual outcomes for the city water system prove to be different than these modeled scenarios.

Instead, the city is electing to pursue activities that will increase the reliability and flexibility of the water system and that can easily be incorporated into current projects and operations. Enhanced operational flexibility improves the ability to respond to unexpected system upsets in the present and improves the adaptability of the system to a wide range of future hydrologic changes. Pursuit of these “no regrets” actions, which are useful now and would remain useful under many future conditions, is relatively inexpensive, yet acknowledges the impacts that climate change might produce. Areas in which the city has identified items to pursue at this time are:

- Monitoring
    - Future improvements in climate science
    - Actual climate changes
- Modeling
    - Improve understanding of capabilities of existing water system
    - Identify when climate changes move outside of these capabilities
    - Complete additional water system modeling when improvements in climate modeling provide enhanced regional data
- Plan for adaptation
    - Identify cost-effective reservoir storage space increases or reservoir operations modifications in preparation for possible need
    - Have community dialogue on possibility of long-term demand reduction strategies that alter current water use expectations
    - Investigate changes to the adopted water system reliability criteria to accept more frequent minor water use restrictions
    - Improve drought recognition criteria to avoid unnecessary imposition of water use restrictions despite increase in risk

- No-regrets actions

  - Water system management changes to increase efficiency
  - More integrated use of water rights portfolio
  - Earlier initiation of the water exchanges allowed under city water rights to increase water in city's upper water system reservoirs
  - Facilities improvements that increase operational flexibility whether or not negative climate change effects occur
  - Enhancing existing water conservation programs

- Education

  - Public understanding of efficient water use measures
  - Decision-maker understanding of limits of water supply system.

Boulder's water system and water rights portfolio differ from those of other cities and water users, so some of the study results and selected actions may not be applicable elsewhere. For example, the city's high-elevation reservoirs and diversion points will create a different set of advantages and disadvantages for maintaining water yields than experienced by water users located at lower elevations. Also, the city has access to a large of amount of reservoir storage space and a mixture of source water basins on both slopes of the Rocky Mountains, which might experience differing climate change effects. The city's senior direct flow rights will provide stability for water yields during low streamflow periods. Boulder's water system may have more operational flexibility than some and less than others given the city's two water treatment plants. Finally, Boulder's water demand patterns could vary from other cities because Boulder is at about 90% of its ultimate built-out condition and delivers two-thirds of its municipal water supply for indoor use because of the compact urban form typical of older Colorado cities.

Despite the possible differences between Boulder's situation and that of other water users, some suggestions can be drawn from the climate study that may have general applicability. Most water systems can benefit from improved water system modeling to provide better understanding of system response to changing conditions. Improved modeling should include water rights data for the system and for other water users, an extended hydrologic record using paleohydrology, and modeling of synthetic hydrologic traces or reorganized historical hydrologic data to test system limits. This modeling would form a strong basis for inclusion of climate change data as it becomes available, including climate-driven changes in irrigation water right demands.

If reliability criteria have not been established for a water system, it could be useful to develop performance goals for several purposes. Water shortages are then planned for as a part of the expected performance of the water system. This helps alter the attitudes and perceptions of those served by the water system to create an understanding that water shortages during droughts does not mean that the water system has failed to perform. Educated decisions can be made about the amount of investment to be made to ensure various levels of water supply reliability. Established reliability criteria are useful in educating the public that droughts will occur at some frequency and a full water supply for all possible uses should not be expected under all conditions.

Bibliography

Barnett, T.P., D.W. Pierce, H.G. Hidalgo, C. Bonfils, B.D. Santer, T. Das, G. Bala, A.W. Wood, T. Nozawa, A.A. Mirin, D.R. Cayan, and M.D. Dettinger. 2008. Human-induced changes in the hydrology of the Western United States. *Science* 319:1080-1082.

Block, P. and B. Rajagopalan. 2008. Interannual variability and ensemble forecast of Upper Blue Nile Basin Kiremt season precipitation. *Journal of Hydrometeorology* 8(3):327-343.

Callahan, B., E. Miles, and D. Fluharty. 1999. Policy implications of climate forecasts for water resources management in the Pacific Northwest. *Policy Sciences* 32:269-293.

Christensen, N.S. and D.P. Lettenmeir. 2007. A multimodel ensemble approach to assessment of climate change impacts on the hydrology and water resources of the Colorado River Basin. *Hydrology and Earth System Sciences* 11:1417–1434.

Christensen, J.H., B. Hewitson, A. Busuioc, A. Chen, X. Gao, I. Held, R. Jones, R.K. Kolli. W.-T. Kwan, R. Laprise, V. Magaña, L. Mearns, C. Guillermo, J. Räisänen, A. Rinke, A. Sar, and P. Whetton. 2007. Regional climate projections. In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Solomon, S.D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (eds.). Cambridge University Press, New York.

City of Boulder. 1988. Raw Water Master Plan. Available: http://www.ci.boulder.co.us/files/Utilities/Projects/source_water_mp/rawwater_mp_1988.pdf. Accessed August 15, 2008.

City of Boulder. 2003. Drought Plan: Volume 2: Technical Information and Analysis. City of Boulder Public Works Department, Colorado. Available: http://www.ci.boulder.co.us/publicworks/depts/utilities/conservation/DroughtPlanVol2.pdf. Accessed May 24, 2004.

City of Boulder. 2004. Water Supply & Water Resources. City of Boulder, Utilities Division, Colorado. Available: http://www.ci.boulder.co.us/publicworks/depts/utilities/water_supply/where.htm#Boulder's%20Water%20History. Accessed May 24, 2004.

City of Boulder, 2008a. Source Water Master Plan. Draft. Boulder, Colorado.

City of Boulder, 2008b. Population. Available: http://www.bouldercolorado.gov/files/PDS/community_data_report.pdf. Accessed August 29, 2008.

Easterling, W.E., B.H. Hurd, and J.B. Smith. 2004. Coping with Climatic Change: The Role of Adaptation in the United States. Pew Center on Global Climate Change, Arlington, VA.

FAO. 1996. Crop Evapotranspiration (guidelines for computing crop water requirements) Food and Agriculture Organization Irrigation and Drainage Paper, No. 56.

Field, C.B., L.D. Mortsch, M. Brklacich, D.L. Forbes, P. Kovacs, J.A. Patz, S.W. Running, and M.J. Scott. 2007. North America. In *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Parry, M.L., O. Canziani, J.P. Palutikof, C. Hanson, P van der Linden (eds.). Cambridge University Press, New York. Available: http://www.ipcc-wg2.org/.

Gleick, P.H. 1990. Vulnerability of water systems. In *Climate Change and U.S. Water Resources*, P.E. Waggoner (ed.). John Wiley & Sons, New York.

Houghton, J.T., Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, D. Xiaosu, and K. Maskell (eds.). 2001. *Climate Change 2001: The Scientific Basis*. Cambridge University Press, New York.

Hydrosphere. 2003. Simulation of Hypothetical Climate Change Scenarios Using the Boulder Creek Watershed Model. Hydrosphere Resource Consultants, Boulder, CO.

Gupta, V.J. and S. Sorooshian. 1983. Uniqueness and observability of conceptual rainfall–runoff model parameters: the percolation process examined. *Water Resources Research* 19(1):269-276.

Gupta, V.K. and S. Sorooshian. 1985. Relationship between data and the precision of parameter estimates of hydrologic models. *Journal of Hydrology* JHYDA7 81(1/2):57-77.

Huber-Lee, A, D. Yates, D. Purkey, W. Yu, C. Young, and B. Runkie. 2005. How can we sustain agriculture and ecosystems? The Sacramento Basin (California, USA). In *Climate Change in Contrasting River Basins: Adaptation Strategies for Water, Food and Environment,* J.C.J.H. Aerts and P. Droogers (eds.). CABI Publishing.

Hurd, B.H., N. Leary, R. Jones, and J.B. Smith. 1999. Relative regional vulnerability of water resources to climate change. *Journal of the American Water Resources Association* 35(6):1399-1410.

Jones, P.D., A. Leadbetter, T.J. Osborn, and J.P. Bloomfield. 2006a. The impact of climate change on severe droughts: River-flow reconstructions and implied groundwater levels. United Kingdom Environment Agency, Bristol, England. Science Report: SC040068/SR2.

Jones, P.D., D.H. Lister, R.L. Wilby, and E. Kostopoulou. 2006b. Extended riverflow reconstructions for England and Wales, 1865-2002. *International Journal of Climatology* 26:219-231.

Kaczmarek, Z. 1993. Water balance model for climate impact analysis, *Acta Geophysical Polonica* 41(4):423-437.

Kaczmarek, Z. 1998. Human Impact on Yellow River Water Management. Interim Report IR-98-016. International Institute for Applied Systems Analysis, Austria.

Lach, D. and M. Quadrel. 1995. Decision Makers Information Needs Elicitation. Pacific Northwest National Laboratory, Richland, WA.

Lach, D., M. Mosely, S. Quadrel, S. Rayner, B. Fischhoff, and S. Jones. 1994. Decision Makers' Information Needs Elicitation. Pacific Northwest National Laboratory, Richland, WA.

Lall, U. and A. Sharma. 1996. A nearest neighbor bootstrap for resampling hydrologic time series. *Water Resources Research* 32(3):679-693.

McCabe, G. and D. Wolock. 1999. General-circulation-model simulations of future snowpack in the Western United States. *Journal of the American Water Resources Association* 35(6):1473-1484.

Mote, P.W., A.F. Hamlett, P.W. Clark, and D.P. Lettenmaier. 2005. Declining mountain snowpack in Western North America. *Bulletin of the American Meteorological Society* 86:39-49.

Nakićenovic, N., J. Alcamo, G. Davis, B. de Vries, J. Fenhann, S. Gaffin, K. Gregory, A. Grubler, T.Y. Jung, T. Kram, E.L. La Rovere, L. Michaelis, S. Mori, T. Morita, W. Pepper, H. Pitcher, L. Price, K. Raihi, A. Roehrl, H.-H. Rogner, A. Sankovski, M. Schlesinger, P. Shukla, S. Smith, R. Swart, S. van Rooijen, N. Victor, and Z. Dadi,. 2000. *Emissions Scenarios. A Special Report of Working Group III of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK and New York, 599 pp.

NOAA. 2008. U.S. Temperature and Precipitation Trends. National Oceanographic and Atmospheric Administration Climate Prediction Center. Available: http://www.cpc.ncep.noaa.gov/charts.shtml. Accessed August 16, 2008.

Prairie, J., B. Rajagopalan, T. Fulp and E. Zagona. 2005. A modified K-NN Model for Generating Stochastic Natural Streamflows. *Journal of Hydrologic Engineering* 11(4):371-378.

Rajagopalan, B. and U. Lall. 1999. A nearest neighbor bootstrap resampling scheme for resampling daily precipitation and other weather variables. *Water Resources Research* 35(1):3089-3101.

Rayner, S., D. Lach, H. Ingram, and M. Houck. 2005. Weather forecasts are for wimps: Why water resource managers don't use climate forecasts. *Climatic Change*. 69:197-227.

Smith, J.B., R. Richels, and B. Miller. 2001. Potential consequences of climate variability and change for the Western United States. In *Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change*. National Assessment Synthesis Team. Report for the US Global Change Research Program. Cambridge University Press, UK.

Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (eds.). 2007. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Intergovernmental Panel on Climate Change. Cambridge University Press, New York.

Strzepek, K., R. Balaji, H., Rajaram, and J. Strzepek. In preparation. A Water Balance Model for Climate Impact Analysis of Runoff with emphasis on Extreme Events. University of Colorado, Boulder, CO.

Strzepek, K., A. McCluskey, J. Hoogeveen, and J. van Dam. 2005. Food demand and production: A global and regional perspective. In *Climate Change in Contrasting River Basins: Adaptation Strategies for Water, Food and Environment*, J.C.J.H. Aerts and P. Droogers (eds.). CABI Publishing.

Strzepek, K, C. Rosenzweig, D. Major, A. Iglesias, D. Yates, A. Holt, and D. Hillel. 1999. New methods of modeling water availability for agriculture under climate change. *Journal of the American Water Resources Association* 35(6):1639-1655.

Tebaldi, C., L.O. Mearns, D. Nychka, and R.L. Smith. 2004. Regional probabilities of precipitation change: A Bayesian analysis of multimodel simulations. *Journal of Geophysical Research Letters* 31(L24213).

Tebaldi, C., R.L. Smith, D. Nychka, and L.O. Mearns. 2005. Quantifying uncertainty in projection of regional climate change: A Bayesian approach to analysis of multi-model ensembles. *Journal of Climate* 18:1524-1540.

Towler, E., B. Rajagopalan, S. Summers, and C. Seidel. 2006. A new technique for capturing uncertainty in source water quality. University of Colorado: Boulder, Colorado.

University of Colorado. 2008. Niwot Ridge Long Term Ecological Research Site. Available: http://culter.colorado.edu/NWT/site_info/site_info.html. Accessed August 16, 2008.

(USDA) U.S. Department of Agriculture. 1970. Irrigation Water Requirements: Technical Release 21. (Revision 2 of 1967 edition). (Available from National Technical Information Service, Springfield, VA, as NTIS Report PB 85-178390/XAB).

Wade, S.D., P.D. Jones, and T. Osborn. 2006. The impacts of climate change on severe droughts: Implications for decision making. United Kingdom Environment Agency: Bristol, England. Science Report: SC040068/SR3.

Woodhouse, C. 2003. Boulder Creek at Orodell, Colorado, Mean Annual Streamflow Reconstruction. International Tree-Ring Data Bank. IGBP PAGES/World Data Center for Paleoclimatology. NOAA/NGDC Paleoclimatology Program, Boulder, CO.

Woodhouse, C.A. 2001. A tree-ring reconstruction of streamflow for the Colorado front range. *Journal of the American Water Resources Association* 37:561-569.

Woodhouse, C. and J. Lukas. 2005. Recorded in the Rings – The Application of Tree-Ring Data to Sustainable Water Management in California and the West. DWR News, State of California, Department of Water Resources. Available: http://www.publicaffairs.water.ca.gov/dwrnewsletter/news-people/News-People-fall05.pdf. Accessed August 29, 2008.

Woodhouse, C. and J. Lukas. 2006. Streamflow Reconstructions for Boulder Creek, South Boulder Creek, and the Colorado River. Report to City of Boulder and Hydrosphere Resource Consultants, 10 pp. AMEC Consulting, Boulder, CO.

Yates, D. 1996. WatBal: An integrated water balance model for climate impact assessment of river basin runoff. *International Journal of Water Resources Development* 12(2):121-139.

Yates, D., S. Gangopadhyay, B. Rajagopalan, and K. Strzepek. 2003. A nearest neighbor bootstrap technique for generating regional climate scenarios for integrated assessments. *Water Resources Research* 39(7):1199.

A. Climate Change Scenarios Data

2030 precipitation, A1B

	Annual	DJF	MAM	JJA	SON
Wet (cccma.t63)	11.4%	20.0%	10.1%	13.1%	3.1%
Dry (gfdl0)	-5.0%	7.8%	-3.2%	-18.4%	-3.0%
Middle (gfdl1)	-3.7%	1.8%	4.1%	-10.4%	-14.0%
Other (giss.eh)	-2.4%	2.8%	-6.8%	-6.4%	5.2%

2030 temperature, A1B

	Annual	DJF	MAM	JJA	SON
Wet (cccma.t63)	1.1	0.9	1.2	1.6	1.3
Dry (gfdl0)	1.7	1.1	1.3	2.6	1.9
Middle (gfdl1)	1.5	1.8	0.6	2.5	1.6
Other (giss.eh)	1.1	0.7	0.8	1.8	1.3

2030 temperature, A2

	Annual	DJF	MAM	JJA	SON
cccma.t63	NA	NA	NA	NA	NA
gfdl0	1.4	1.4	1.1	2.3	1.4
gfdl1	1.3	0.8	0.6	2.3	1.8
giss.eh	NA	NA	NA	NA	NA

2030 temperature, B1

	Annual	DJF	MAM	JJA	SON
cccma.t63	1.1	1.2	1.4	1.5	0.6
gfdl0	1.1	0.7	1.0	1.9	1.1
gfdl1	1.4	1.5	0.8	2.2	1.3
giss.eh	NA	NA	NA	NA	NA

2070 precipitation, A1B

	Annual	DJF	MAM	JJA	SON
Wet (cccma.t63)	15.9%	23.5%	9.4%	17.7%	17.6%
Dry (gfdl0)	-6.6%	11.6%	3.5%	-26.5%	-15.9%
Middle (gfdl1)	1.8%	18.2%	13.9%	-18.7%	-8.4%
Other (giss.eh)	-4.2%	-3.7%	-10.1%	-6.4%	8.6%

2070 temperature, A1B

	Annual	DJF	MAM	JJA	SON
Wet (cccma.t63)	2.2	2.3	2.0	2.3	2.4
Dry (gfdl0)	4.2	3.6	3.0	5.9	4.9
Middle (gfdl1)	3.6	3.1	1.8	5.7	4.0
Other (giss.eh)	2.3	1.6	2.4	3.7	1.9

2070 temperature, A2

	Annual	DJF	MAM	JJA	SON
cccma.t63	NA	NA	NA	NA	NA
gfdl0	4.2	3.0	3.1	6.5	4.5
gfdl1	3.3	2.6	2.4	5.4	3.4
giss.eh	NA	NA	NA	NA	NA

2070 temperature, B1

	Annual	DJF	MAM	JJA	SON
cccma.t63	2.2	2.5	1.9	2.5	1.9
gfdl0	2.8	1.8	2.8	3.8	2.6
gfdl1	2.2	1.8	1.5	2.9	2.6
giss.eh	NA	NA	NA	NA	NA

B. K-Nearest Neighbor (K-NN)

K-Neareast Neighbor is the resampling method used to simulate the 1,000 member ensemble of possible climate scenarios (combinations of monthly T&P) over a 437-year period for which we have reconstructed streamflows.

The resampling technique used in this study may be a new concept to some readers. This appendix describes the technique. First, we provide a general overview of K-NN algorithm. Then, we provide a general description of how we utilized K-NN resampling in this study. Finally, the third section of this appendix provides a more detailed example of how the technique was applied to the data we used.

B.1 General Overview of the K-NN Algorithm

B.1.1 Development of K-NN

Lall and Sharma (1996) developed a K-NN bootstrap method for time series re-sampling and applied it to streamflow simulation. In this approach, "K" is the ***number of points*** in the set from which to re-sample, and the "nearest neighbors" are the ***actual data points*** in the set. The set of "nearest neighbors" can change from one point estimate to the next. To conduct this conditional, re-sampling technique, first, K-NN of each point of interest from the historic data are found. Then the neighbors are re-sampled via a weight function that assigns large weight to the nearest neighbors and a smaller weight to the farthest, thereby generating ensembles. This approach is similar to the more traditional approach of estimating the conditional pdf and simulating from it.

The heuristic scheme for selecting "K" (the number of "nearest neighbors") suggested by Lall and Sharma (1996) is square-root of N, where N is the number of data points from the historic record that is to be re-sampled.

The neighbors are weighted based on their proximity to the point of interest. Any weight function can be used to provide the weights because the K-NN approach is insensitive to the choice of the weight function. One possible weight function (the one used in our analysis) is the inverse distance weight method. This weight function gives more weight to the nearest neighbor and less weight to the farthest neighbor. The weights are normalized to create a probability mass function or weight metric.

Note: if K is set to N (i.e., the set of points from which to resample is set to all available observation data, and the closest neighbor is assigned a weight equal to one and all other points are assigned a weight equal to zero, this approach collapses to the “single-approach” described earlier.

B.1.2 Limitation to the K-NN approach

This approach is data driven. One limitation of this and other bootstrapping techniques is that there are no “new” data points added to the simulations. The sampling technique can only obtain values from the observed record, so it is not possible to create new extreme lows or highs.

This has been addressed by Rajagopalan and Lall (1999) who present a strategy of nearest neighbor bootstrapping with perturbations of the ensemble.

B.2 K-NN Approach Used in this Study

B.2.1 Why we used this technique

The analysis of the vulnerability of Boulder Creek’s water supply to climate change utilized a K-NN bootstrapping technique to simulate annual streamflow ensembles representative of the paleo-record. The K-NN algorithm used in the analysis utilized the observed streamflow record (the modeled natural streamflow record developed by L. Rozaklis, and others at Hydrosphere), the observed temperature and precipitation records from both Boulder and the C1 location at Niwot Ridge (maintained by Mark Losleben, INSTAAR, LTER), and the reconstructed paleo-streamflow record (developed by Connie Woodhouse).

We utilized a non-parametric re-sampling method to generate a 1,000 member ensemble of 437 ”years” that, when examined from the perspective of the annual streamflow of each year, reflects the statistical properties of the 437-year long paleo-streamflow reconstruction. Each of the 1,000 members of the ensemble is comprised of a set of 437 “years.” The “years” are those for which we had an overlap of:

- Reconstructed annual paleo-streamflow (from Woodhouse)
- Historic, annual, natural streamflow (from Hydrosphere)
- Observed monthly temperature and precipitation from both Boulder and C1-Niwot Ridge.

The time period for which there is an overlap in these data is the 53-year period between 1953 and 2005. Therefore, the “years” from which we can resample are the 53 years from 1953 to 2005.

Each member of the ensemble was generated by re-sampling from the pool of 53 years. In the K-NN approach, the data is re-sampled using a probability metric that gives more weight to the nearest neighbor and less to the farthest. Each "year" that makes up a single member (which has 437 points) is conditioned on the reconstructed paleo-streamflow record. Since there are only 53 years from which to resample and each member of the ensemble is comprised of 437 records, any given year from the 53-year pool will show up multiple times in each member of the ensemble.

The reason that we were interested in generating an ensemble of "years" is that for each year we have an estimate of:

- Annual streamflow from the paleo-reconstruction (1 value)
- Historic, natural annual streamflow (1 value)
- Average temperature for each month of that year (12 values)
- Total precipitation for each month of that year (12 values).

Each "year" is actually a vector of five variables (year, paleo SF, historic SF, T, P). Therefore, each member of the ensemble represents a simulated time series of annual streamflow, temperature and precipitation.

An advantage of the non-parametric re-sampling technique used is that each of the 1,000 members of the simulated ensemble are statistically equally likely.

B.2.2 Limitations to the K-NN approach

A limitation to our approach in particular, is that we had a limited sample size (50) to begin with, but by creating conditional groups of streamflow (low, normal and high), we created three samples that were even smaller. The consequence of this is that we limited the variety in the ensembles.

Another limitation in our study was that there simply are no ideal weather stations. We had to use C1 because it was the only one available with a long enough record, but it is far from ideal.

B.3 Detailed Example from Data used in This Study

The two key steps involved in the resampling technique we used are classification of streamflows and application of the K-NN algorithm.

Classification

First, we classified 53 years (1953-2005) of "historic" streamflows as low, normal or high (see Figure B.1):

- Low: streamflow of interest < 60,000 acre-feet (15 instances in observed record; approximately 25%)

- Normal: 60,000 acre-feet < streamflow of interest < 84,000 acre-feet (25 instances in observed record; approximately 50%)

- High: streamflow if interest > 84,000 acre-feet (13 instances in observed record; approximately 25%).

[15 years are "low" (28%); 25 years are "normal" (47%); 13 years are "high" (25%)]

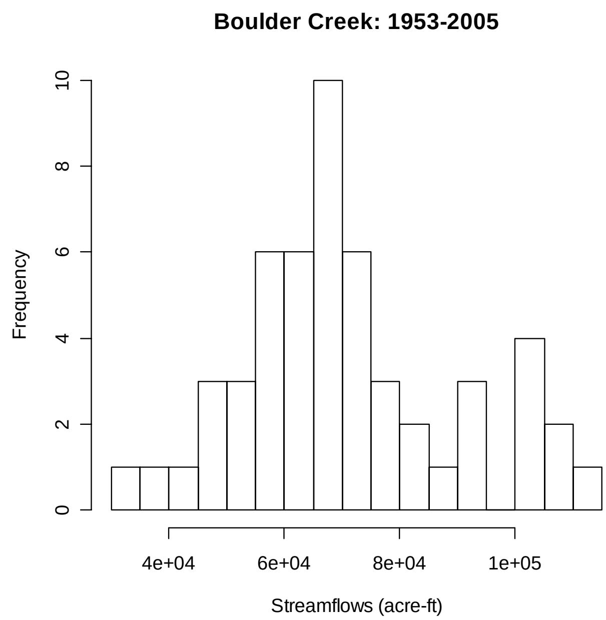

Figure B.1. Frequency of observed runoff.

Then, we examined the condition of each year in the hybrid-paleo-streamflow reconstruction. Consider the streamflows from the reconstruction (1566 to 2002; see Figure B.2). Using the same criteria, classify each year as low, normal or high. Ideally, approximately the same percentage of years would be categorized as "low," "normal," and "high." In this 437-year record, the results are: 98 years are "low" (22%), 259 years are "normal" (59%), and 82 years are "high" (18%).

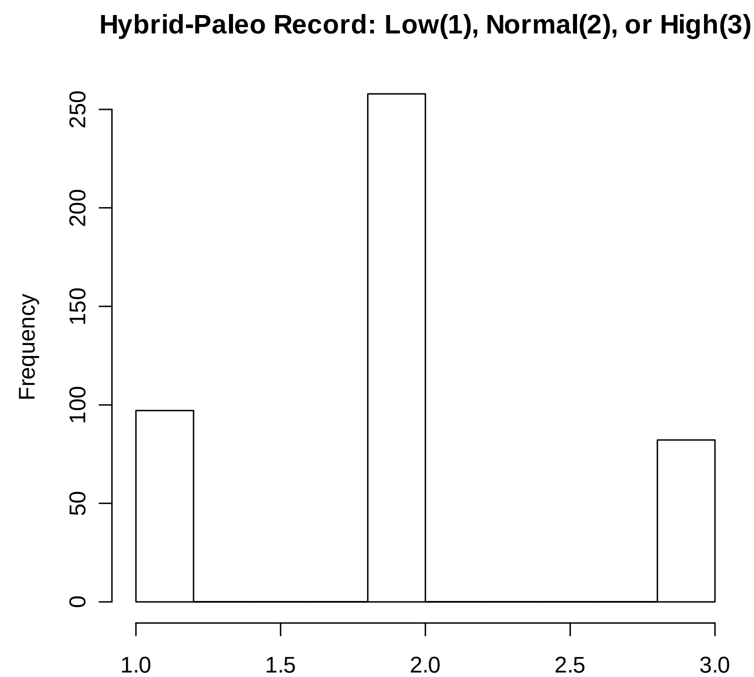

Figure B.2. Distribution of low, normal and high flows.

Apply K-NN algorithm

Once the nearest neighbors have been identified, the simulation begins. Starting with the streamflow value for year one, 1566, one of the K-NN (from the observed record) is selected according to a probability metric where the nearest neighbor has been assigned the most weight, and therefore gets picked the most frequently and the furthest neighbor has been assigned the least weight and gets picked the least frequently. The "bootstrapped" value (i.e., the streamflow value from the observed record that was selected) and the year from the observed record during which that streamflow occurred, are added to the ensemble for "year one" This continues for each year (437 years total). This is repeated for a total of 1,000 simulations in the ensemble.

1. Consider year of the hybrid-paleo-streamflow reconstruction.

   Was that year classified as low (1), normal (2) or high (3)?

   E.g., year 1 = 1566, classification = 2 (normal).

2. This classification determines from which of the three categories (low, normal or high) of the **gauged streamflow** record we can bootstrap a streamflow value to add to our simulated (or synthetic) record

   E.g. the simulated value must come from the "normal" (class = 2) subset of gauged streamflows (there are 25 possible values)

3. What was the streamflow value (from the reconstruction) for that year?

   E.g. for year 1 = 1566, SF = 67,870 acre-feet.

4. Find the "nearest neighbor" streamflow values from within the appropriate category of gauged streamflows.

   E.g. the appropriate category is "normal;" we are concerned with the 5 (K = 5) values (5 "nearest neighbors" out of 25 values) in that category that are closest to 67, 870 acre-feet.

   These are: 67,769 (1990), 68,275 (1953), 67,212 (1985), 65,359 (1991), and 64,614 (1968).

5. Weight those "nearest neighbor" values such that the closest value is weighted the most and the farthest value is weighted the least.

   E.g., 67,769 (weight = 43%,W = 0.43), 68,275 (weight 22%, W = 0.65), 67,212 (weight 15%, W = 0.80), 65,359 (weight 11%, W = 0.91), and 64,614 (weight 9%, W = 1.00).

6. Generate a random uniform number between 0 and 1, e.g., 0.696.

7. Select the "nearest neighbor" streamflow value that is weighted such that the random uniform number is ***less*** than the "W" for that streamflow value.

   E.g. 0.696 > W = 0.43, so *do not* select 67,769; 0.696 > W = 0.65, so *do not* select 68,275; **but 0.696 < W = 0.80, so we select 67,212** as the streamflow for the given year of the simulation.

8. Record the year to which this selected streamflow corresponds.

   E.g. 1985.Repeat steps 1-8 for each subsequent year (2-437) of the hybrid-paleo-reconstruction.

   E.g. repeat for years 1567-2004.

Steps 1-9 will yield a simulated annual streamflow record (synthetic streamflow time series, or 1 member of the ensemble) that is comprised of 437 pairs of values (these pairs of values are streamflow values and the corresponding year from the observed record in which the streamflow occurred). Each pair of values in the simulated record was selected from the 50-year observed/historic record, and therefore the corresponding monthly temperature and precipitation values for each year are known. Corresponding to the simulated 437-year long record is a climate record of 5,268 monthly temperature values (437 years × 12 months) and 5,268 precipitation values.

This process is repeated to create a 1,000 member ensemble of synthetic records (each is 437 ”years” long).