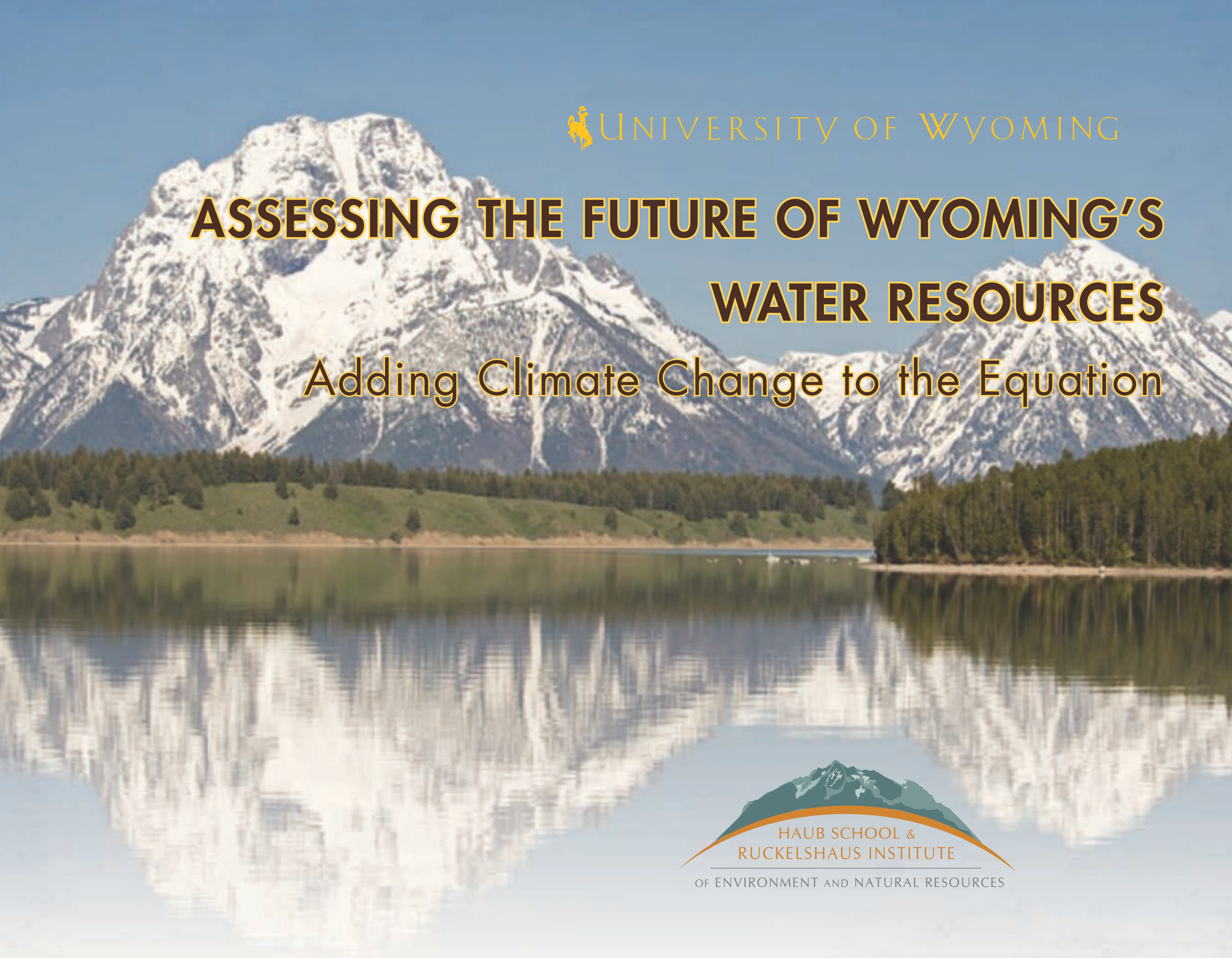
University of Wyoming

ASSESSING THE FUTURE OF WYOMING'S WATER RESOURCES

Adding Climate Change to the Equation



HAUB SCHOOL & RUCKELSHAUS INSTITUTE

OF ENVIRONMENT AND NATURAL RESOURCES

This publication is a summary of current scientific knowledge about the implications of climate change for water resources in Wyoming and the West. This project is the result of many discussions and input by the Ruckelshaus Institute Board, resource managers, stakeholders, legislators, and Governor Freudenthal's office about the need for a summary report on Western water resources, and the concerns about future availability of water. This publication is intended for a wide audience – from decision-makers to the general public – and anyone concerned about the future of our water resources. The authors hope that this report will spur further discussions on how to better manage Wyoming's water resources in the face of drought and climate change. It is also hoped that this publication will provide a foundation for further research, and support the need to better incorporate climate considerations into planning, decision support, and policy for water resources in the West.

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Photo courtesy of Tom Dietrich.

Wyoming's water resources are highly vulnerable to climate variability and climate change. Water availability in the West and the impacts of climate are two of the most important issues facing scientists and resource managers today. Even the most conservative estimates for regional temperature change would have major consequences for Wyoming's water resources, particularly as demand – from cities, agriculture, industry, and recreation – continues to grow.

There is mounting evidence that the earth is experiencing a warming trend. Climate change has resulted in a 1° F increase in average global temperature in the past century, largely in the past 30 years (IPCC 2007). The concern now is that climate change may increase the impact of droughts, just as population growth and other factors have greatly increased the West's vulnerability to water shortages. The impacts of these global changes on Wyoming's weather and river systems include altered precipitation patterns and changes to the timing of snowmelt and river flows, which together will significantly alter Wyoming's water supply.

Potential changes in climate are a key part of the water resources equation. With our changing climate in mind, we need to take an interdisciplinary approach to water analysis. Scientists and resource managers are studying the sensitivity of water resources to climate change in the state and region. They are also considering the many factors that have contributed to water scarcity and drought conditions in Wyoming and the West. The values that people place on water and the habitats and recreational opportunities it provides are also important considerations for future management. This report seeks to summarize the state of our knowledge as it relates to these issues, and to provide a starting point for collaborative processes that can help us adapt to and mitigate the impacts of climatic variability and change.

Climate change needs to be a primary focus in water management because it will continue to alter our ability to secure a safe and stable water supply.

What We Know: Wyoming's Water Resources Are Highly Vulnerable to Climate Change

Multiple factors make water resources in Wyoming highly sensitive to climate change, regardless of the cause. Three of the most important factors are the following:

Vulnerability #1 – Wyoming's "Dry" Climate

Wyoming is the fifth driest state in the United States. More than 70 percent of the state receives less than 16 inches of precipitation on average each year. Though technically speaking, much of Wyoming does not qualify as true desert, it is a "dry" state by any measure.

Vulnerability #2 – Mountain Snow is the Main Source of Wyoming's Surface Water

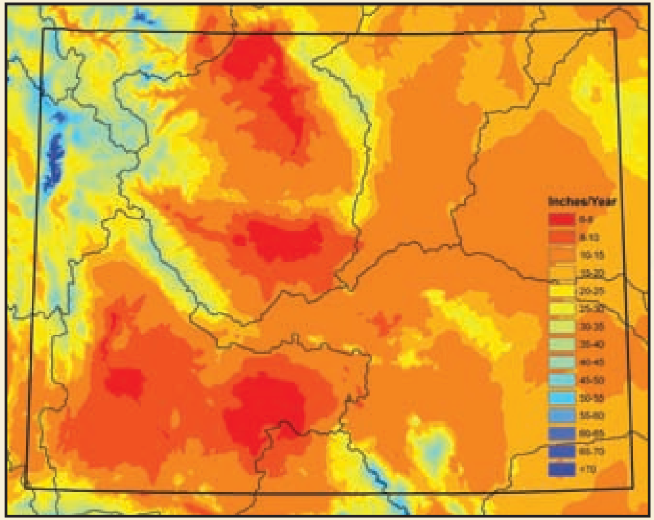
The majority of snowpack in Wyoming is concentrated in a relatively small area. This small land area is responsible for the majority of Wyoming's runoff and surface water supplies. Any events — changes in climate, vegetation change, fires, insect outbreaks — that impact these mountain watersheds will have major consequences for all of Wyoming's water users, as well as for water users far downstream.

Vulnerability #3 – The "Top of the Watershed" Problem

Wyoming is a headwaters state for some of the largest river systems in North America, including the Snake-Columbia, Green-Colorado, Yellowstone-Missouri, and Platte Rivers. While being a major headwaters state has its benefits, it also puts Wyoming at a disadvantage when faced with many scenarios for climatic, economic, and demographic change.

Top of the Watershed Problem

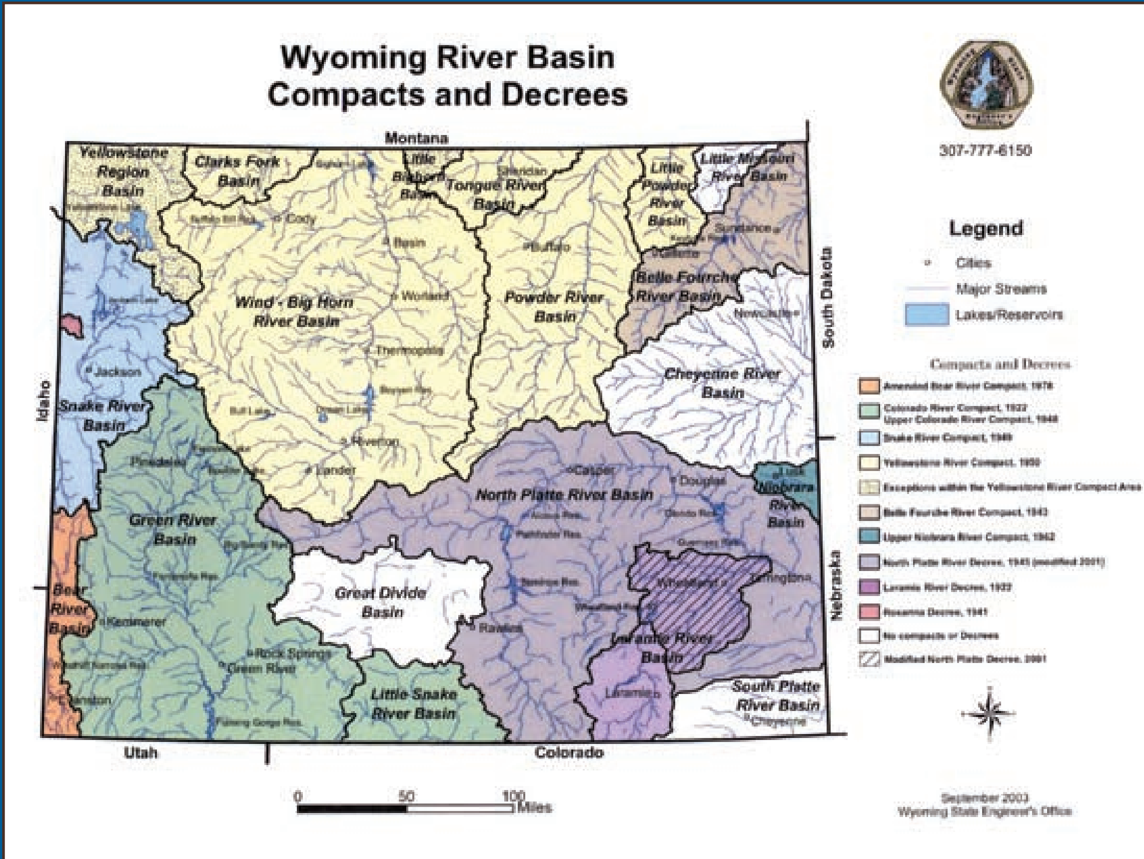
In one sense, water users farther downstream are somewhat buffered from the types of drought we see in the historical record; dryness in one upstream area will often be offset by average to wet conditions in another part of the basin. Downstream states may also benefit from a relatively large amount of storage on the river above them. But in Wyoming the water that falls as snow in nearby mountains is often the only local source of surface water for the entire year, and there may be no chance of supplementing this supply from other areas. Moreover, numerous agricultural users in Wyoming — as well as many aquatic and riparian habitats that rely on regular flows of freshwater and sediment — depend on the water that comes directly from local mountain snowpack. These ecosystems support a wealth of fish and wildlife, and are a key part of what makes Wyoming a special place to live. In many of these cases there is no tributary water to ease the impacts of drought, and the swings between wet and dry years can be very large.



Average annual precipitation over the period 1971-2000.

Climate change may amplify these problems by increasing the severity of drought years and by altering the snowpack. As a headwaters state, Wyoming is also vulnerable to an increase in human populations in downstream states. Water availability is likely to decrease with the combination of climate change and increasing development.

Climate change could amplify water resource vulnerabilities by increasing the severity and frequency of drought, and by altering snowpack and runoff dynamics.



This map shows Wyoming's major river basins and the primary compacts and decrees that govern water use in each area. These legal agreements regulate the delivery of water from Wyoming to users in downstream states.

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While obligations related to compact compliance can differ from basin to basin, Wyoming is generally bound to provide a set volume of flow or a percentage of total river flows to other states in the region. As demand in downstream areas increases, Wyoming will undoubtedly experience increased pressure to meet delivery obligations, and conflicts among user groups and the states themselves seem more likely to arise. In this context, any climatic change — natural or otherwise — that decreases river flows could have significant consequences for water users in Wyoming.

Regional Perspectives: Why Is Water In The West So Vulnerable To Climate Change?

Two factors make the western United States especially vulnerable to climate change. First, it has several large, rapidly-expanding urban populations living in very dry locations. Second, the West has a relatively small amount of surface water that must be shared by diverse user groups, and in many cases water resources must be shared across state, tribal, and international boundaries.

The Rocky Mountain West is the fastest-growing region in the country. This rapid growth is especially prominent in the persistently water limited Colorado River Basin; six of the 10 fastest growing states and many of the fastest growing U.S. cities are located within the basin (U.S. Census Bureau 2007). The Colorado River itself is already the primary water supply for 27 million people in seven U.S. states, plus two states in Mexico and dozens of Native American tribes (Pulwarty et al. 2005). Projections suggest that the Colorado River Basin may be home to almost 40 million people by 2020. Similar patterns of rapid growth can be seen in parts of the Columbia River Basin, as well as nearby in the Colorado Front Range. In all of these cases, growing populations mean increasing demand, as well as major changes to key characteristics of water use, and the infrastructure required to deliver water supplies.

Today, relatively few Western river systems have any water available for new uses. In Wyoming's North Platte Basin, for example, every drop of water has been legally allocated (WWDC 2006). Likewise, multiple factors have led to the over-allocation of Colorado River water, and several downstream states have historically used more than their legal share (Pulwarty et al. 2005; NRC 2007). As a result, water to support development in much of the West must come from alternate sources (e.g., groundwater, trans-basin diversions), or more often from existing uses. In most cases the primary existing use of water is for agriculture. At times this places population growth directly at odds with food production. Meeting tribal and international treaty obligations further complicates the situation, while demands for industrial water — especially water used in energy production — also continue to grow.

Given rapidly increasing demand and often conflicting interests, any reduction in water supplies could have major consequences for natural resources, industry, energy production, and people throughout the region.

The Colorado River Dilemma

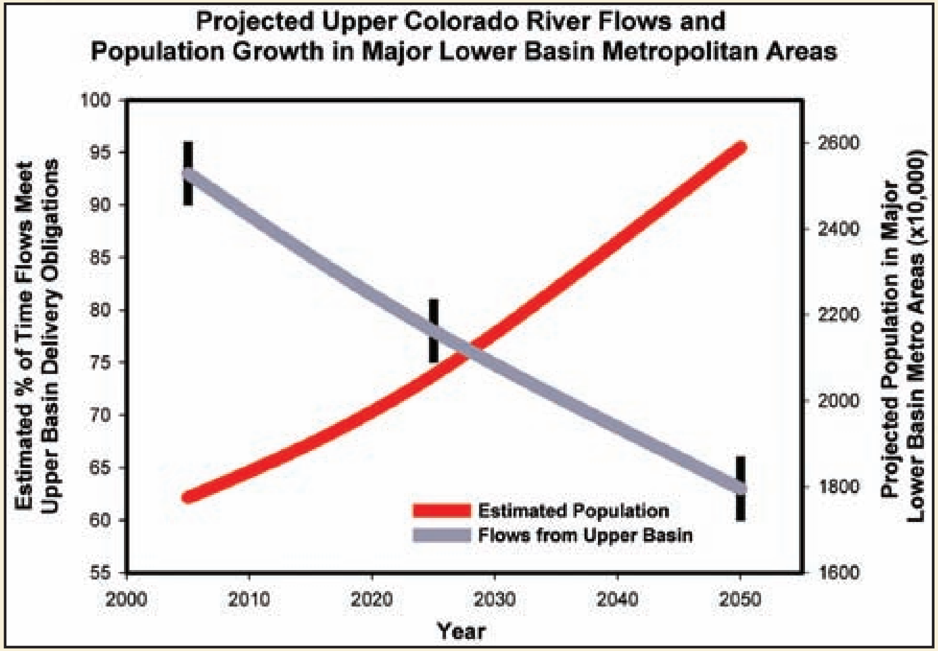
The Colorado River and its tributaries serve as a primary source of water for populations in seven Western states: Wyoming, Colorado, Utah, Nevada, Arizona, New Mexico and California. The Colorado River provides irrigation water for 3.5 million acres of farmland in these states, and together with populations in northwestern Mexico, supports 27 million people (Pulwarty et al. 2005; NRC 2007). The majority of water in the Colorado River system originates in the high mountains of Wyoming and Colorado, with smaller amounts of water coming from Utah and New Mexico. These states are collectively referred to as the "Upper Basin."

Through a series of compacts, court decisions and decrees dating back to the 1920s (earlier in some cases), the Upper Basin states must meet quotas for the delivery of water to the Lower Basin states, namely Arizona, California, and Nevada.

A growing number of studies suggest that projected climate change will make meeting these delivery obligations increasingly difficult, at the same time that human populations and subsequent demand will continue to grow in the Lower Basin (see figure on page 7). One study conducted by the U.S. Geological Survey predicts that flows from the Upper Basin will meet Lower Basin demands only 60 percent of the time by 2050 (McCabe and Wolock 2007).

Another study revealed that Lake Mead and Lake Powell, two critical Colorado River storage reservoirs, have a 50 percent chance of reaching minimum storage levels (effectively going dry) by 2021, if major management changes are not put in place (Barnett and Pierce 2008). Water augmentation projects are being proposed as a means for stretching existing supplies (e.g., SNWA 2008). These strategies may only postpone the need to make trade-offs and reductions among water-users throughout the Colorado River Basin (Pulwarty et al. 2005; NRC 2007).

"We were stunned at the magnitude of the problem and how fast it was coming at us. Make no mistake, this water problem is not a scientific abstraction, but rather one that will impact each and every one of us that live in the Southwest."
— Dr. Tim Barnett, Scripps Institution of Oceanography



Growing Scarcity Meets Growing Demand in the Colorado River Basin.

The plot above shows projections for population growth in the major metropolitan areas of the Lower Colorado River Basin (Arizona, California, and Nevada; red line) versus the percentage of time flows from the Upper Colorado River Basin states (i.e. Wyoming, Colorado, Utah, and New Mexico) are forecast to meet obligations in the 1922 Colorado River Compact (gray line). Predicted river flows are based on modeling studies (McCabe and Wolock 2007) that considered the impact of a 1.5 ° to 3.6° F temperature increase while maintaining precipitation at 20th century levels. Black vertical bars show the range between the 25th and 75th percentile of flow estimates. The major metropolitan areas represented in this graph are Greater Phoenix and Greater Tucson, Arizona, San Diego County and Los Angeles County, California, and Las Vegas, Nevada. Population projections were obtained from the U.S. Census Bureau, California Department of Finance, City of Las Vegas, and the Arizona Department of Economic Security. Although both of the estimates for future population growth and river flows include a large amount of uncertainty, these and other studies (see Barnett and Pierce 2009) point to the growing scarcity of water and the potential for serious water-related conflicts in the Colorado River Basin in the future.

What We Know: Small Warming, Big Changes

In the 2007 Fourth Assessment Report, the International Panel on Climate Change (IPCC 2007) states that the earth as a whole is becoming warmer, and the magnitude of this warming has been approximately 1° F over the past 100 years. Furthermore, the IPCC has reported that it is likely that a significant portion of this warming is caused by human activities, and this warming will likely continue for the foreseeable future. Climate models predict that Wyoming and the West will become warmer in the coming decades (Christensen et al. 2007). There is more uncertainty about future precipitation in the region (Leung et al. 2003), but most predictions are within +/- 5 percent of historical averages (Christensen et al. 2007). There is growing evidence that drought and wet events may become more extreme, and that the timing of precipitation and runoff may change (Leung et al. 2004; Diffenbaugh et al. 2005; Allan and Soden 2008; Trapp et al. 2007, 2009). On the whole, small increases in regional temperature changes as small as 1.5° F of additional warming — would have major consequences for Wyoming's water resources, even in the absence of major precipitation change.

Increasing temperatures can also decrease the amount of water available for plant growth, which would impact a wide range of habitats. Increasing temperatures will likely bring a suite of consequences for rivers in Wyoming, including earlier and faster spring runoffs, and diminished late-season flows (Barnett et al. 2004; Stewart et al. 2004). Among these

Photo courtesy of Tom Dietrich.

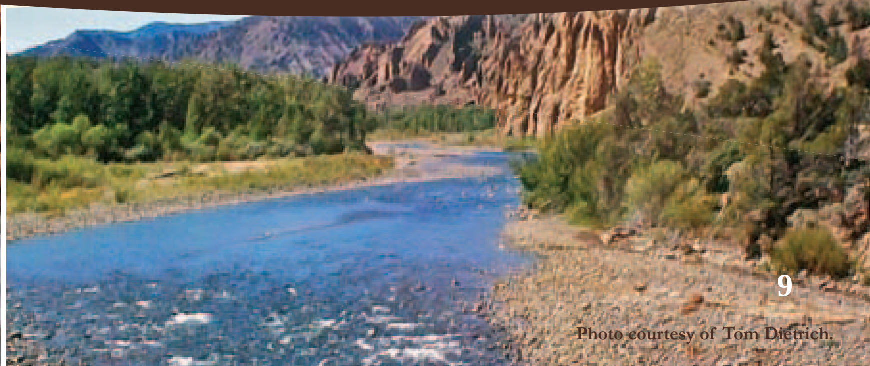
impacts, warmer temperatures could have the greatest effect on water supply vulnerability by altering the timing of snowmelt. When compared to historical averages, a clear trend toward earlier spring runoff has already been recorded in the Sierra Nevada Mountains of California, as well as the mountain ranges in western Oregon and Washington (USGS 2005; Stewart et al. 2004).

In Wyoming, recent drought years have resulted in earlier, faster runoffs in many parts of the state. If early runoff becomes commonplace in the future, storing water for Wyoming and downstream users could become more challenging. In short, a rapid or "flashy" runoff could limit the ability of reservoir managers to balance flood control and storage. Moreover, an early runoff inevitably leads to diminished late-season flows, which are crucial to a wide variety of municipal, agricultural, industrial, and environmental uses.

Increasing temperatures will bring greater evaporative losses from lakes, streams, wetlands and from terrestrial ecosystems (Arnell 1999). This aspect of climate change may be especially difficult for water managers to cope with, because it would be coupled with the need for more agricultural irrigation (Brikowski 2008). Increasing temperatures will also significantly intensify the types of dry events seen in the historical record, and might even bring about a new type of climate where conditions we previously thought of as "drought" become the norm (Hoerling and Eischeid 2007; Seager et al. 2007).

Both increasing evaporation and an earlier snowmelt would bring many additional impacts to the high mountain systems that supply our water. Under future climate change, earlier snowmelt and increasing evapotranspiration (the combined water loss from evaporation and water use by plants) would place additional drought stress on forest ecosystems. There is growing evidence that such drying increases the susceptibility of forests to insect pests and wildfires (Westerling et al. 2006). Large forest fires and mountain pine beetle outbreaks in recent years may then represent a preview of what future increases in temperature might bring. Other potential impacts of seemingly small temperature increases, such as a shift toward more precipitation as rain rather than snow and diminished groundwater recharge (Arnell 1999), are not as well understood.


Photo courtesy of Tom Dietrich.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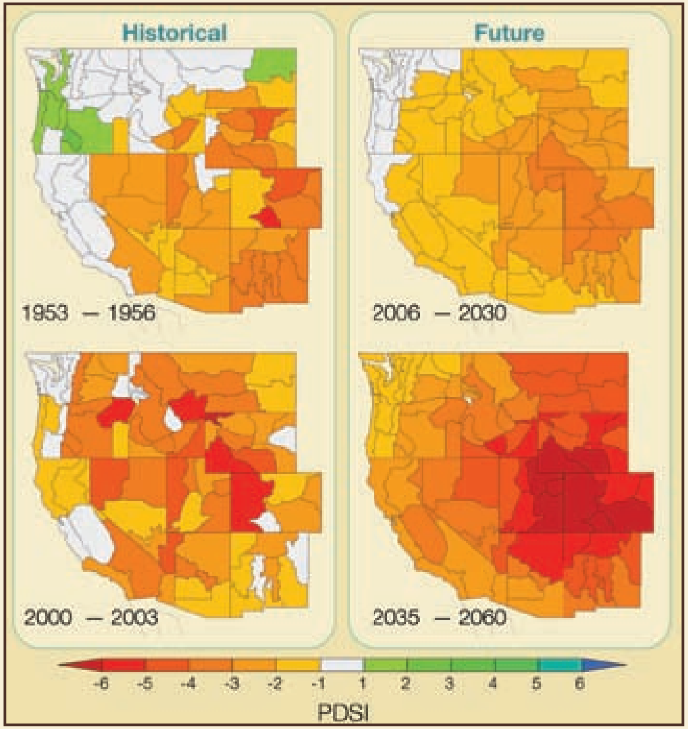

Palmer Drought Severity Index.

A growing body of research suggests that small increases in temperature alone would have major impacts on water availability in the western United States. As an example, the maps above show results from a study of how temperature increases predicted for the years 2006 to 2030 (roughly 2.5° F) and 2035 to 2060 (5° F) might affect climate in the region (Hoerling and Eischeid 2007). These maps show how changes in temperature would affect the Palmer Drought Severity Index (PDSI), which is a measure of drought intensity that accounts for variations in both temperature and precipitation over time (Palmer 1965; Alley 1984), if precipitation levels stayed at or near 20th century averages. Compared to historical PDSI values, a 2.5° F temperature increase (top right of figure) would result in average conditions on par with the driest years of the 1950s drought (top left). Likewise a 5° F temperature increase (bottom right) would result in average PDSI values that rival the driest times in recent decades (bottom left). While relating estimated PDSI to direct measures of water availability can be difficult, this study and others like it (e.g., Seager et al. 2007; Barnett and Pierce 2009) show that increasing temperatures would bring about a new "climate state" where drought becomes the norm, and dry events are magnified to levels never seen in the historical record.

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Weather Versus Climate

The difference between weather and climate is a matter of time. Weather describes atmospheric conditions that occur over short periods (minutes to days), while climate refers to atmospheric dynamics over relatively long intervals (multiple years or decades). Weather includes events such as the passing of a thunderstorm, a hurricane, blizzard, or a cold snap. Climate is the statistical average of weather, generally over multiple years or decades. One practical way to consider the difference between weather and climate is that weather helps us determine what clothes to wear from day-to-day, or if we should pack a rain jacket. Climate determines what crops we grow in a given region, and what types of plant communities we find in the areas surrounding our homes.

In many ways, understanding and predicting climate is more straightforward than understanding and predicting weather. Weather is the result of multiple processes working in concert, some of which are random, or stochastic, making weather difficult to predict. While still challenging, climate prediction focuses on longer-term patterns and averages. In a way, predicting weather is akin to predicting the first card to be drawn from a newly shuffled deck. Predicting climate is more like calculating the odds of drawing a particular hand once the game begins. Shorter-term variations and the accompanying uncertainty of weather will always persist – cool summers or heavy snow years will still occur if our climate changes. However, as predicted, climate change would increase the probability of warm days, hot and/or dry spells, and many types of extreme weather events (Bell et al. 2004; Leung et al. 2004; Diffenbaugh et al. 2005; Trapp et al. 2009).

What We Know: Climate Changes Regardless of Human Activities

Climate has changed significantly in past centuries to millennia, and these changes have occurred naturally even in the absence of human activities that can influence the climate system. Understanding this natural variability is essential because it provides the backdrop for future human-induced changes (IPCC 2007). Moreover, natural climate cycles are likely to significantly amplify (or dampen) the effects of any human-induced changes (Gray et al. 2003, 2006; McCabe et al. 2008).

The concern now is that climate change may increase the impact of droughts, just as population growth and other factors have greatly increased the vulnerability of the West to any type of drought.

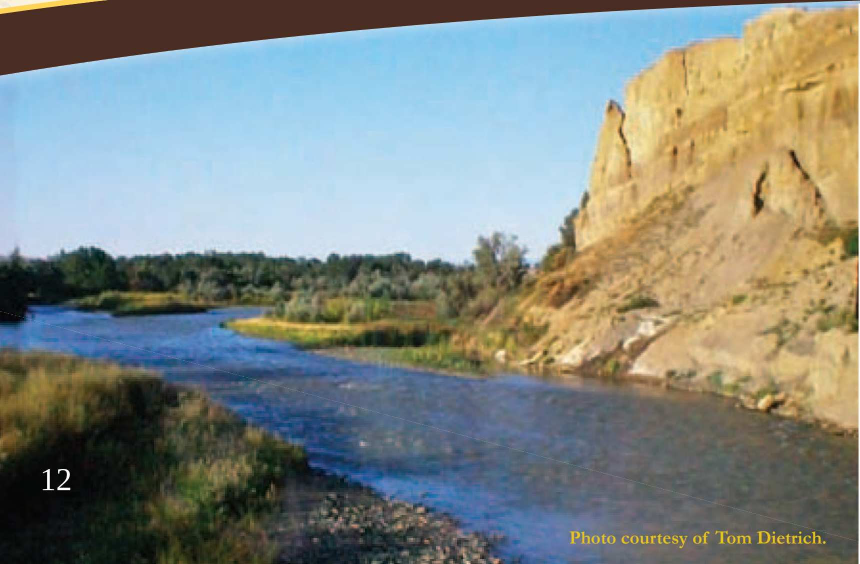
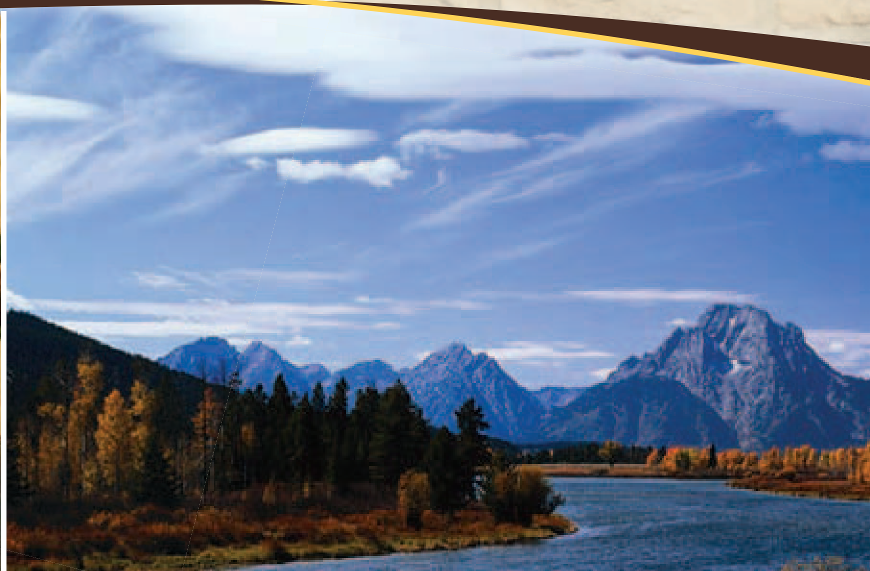


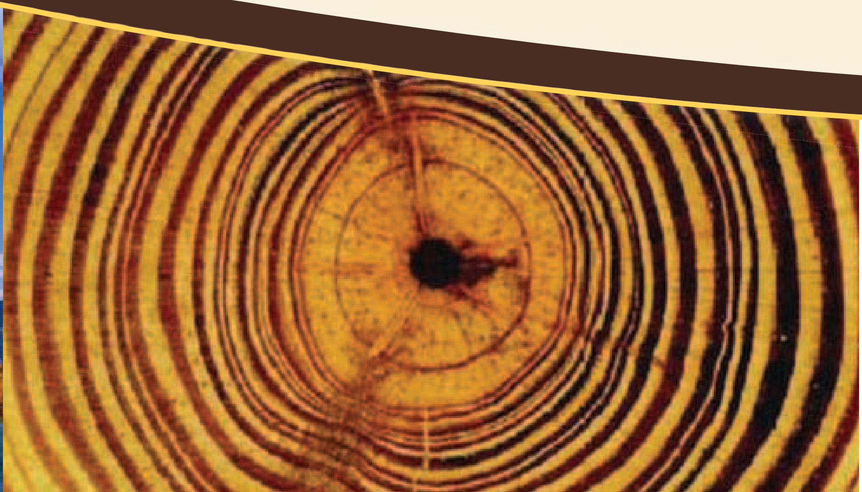
Photo courtesy of Tom Dietrich.



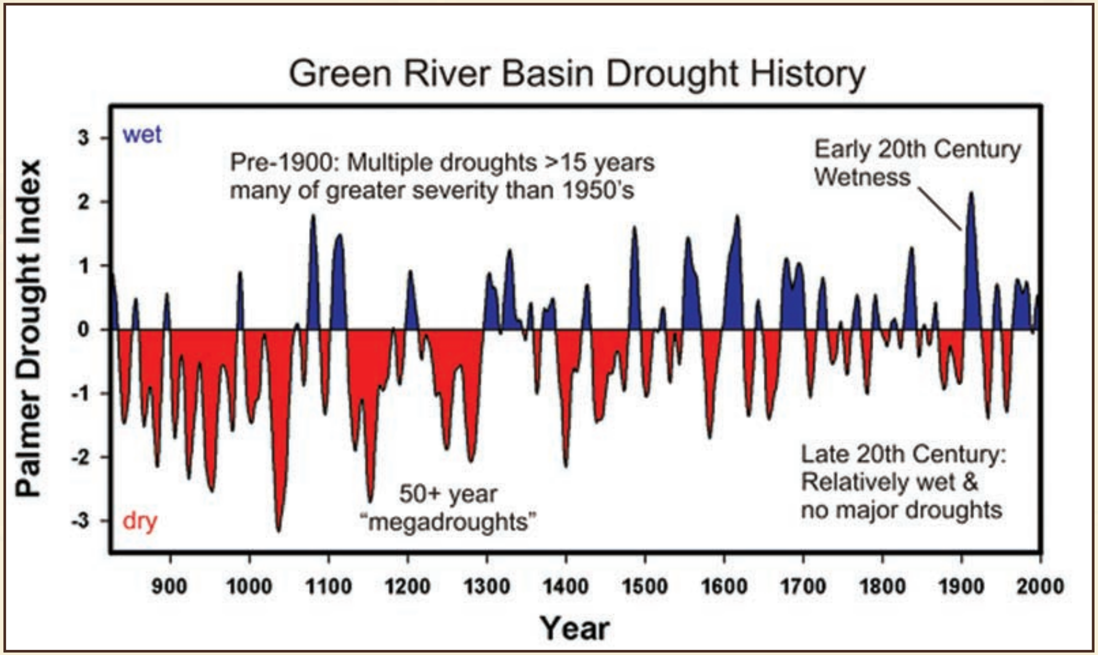
Tree Rings and Past Climates

Tree rings provide a wealth of information about past climatic conditions in Wyoming and the West. In addition to their use in estimating pre-historic precipitation and streamflow (e.g., Woodhouse et al. 2006), tree rings have been widely used to reconstruct drought indices and other integrators of hydroclimatic conditions (e.g., Cook et al. 2004). In the western United States, tree rings provide the primary means for understanding long-term variations in climate, while also revealing trends and cycles that may not be apparent in instrumental records from the last 100 years.

The study of climatic changes through tree rings (dendroclimatology) started in the 1920s. In simple terms, dendroclimatologists can determine past seasonal climates by looking at the widths of annual growth rings in trees. In certain species of trees, a ring will appear wider if the weather has been wet. During a dry season, a ring will be much narrower. A ring is established by the change in cell growth from spring to winter. During the spring, a tree adds new, large cells to the outer layer. As winter approaches, the cells are smaller in contrast, thus establishing a record of each year that has passed.



This figure shows 1,100 years of drought history in the Green River Basin region of southwest Wyoming, as reconstructed from tree rings (Cook et al. 2004). The plot shows values for the Palmer Drought Severity Index (see also PDSI figure on page 10. Positive values (blue) of the index represent wet conditions, negative values (red) indicate drought. Values are plotted so that each point on the graph represents mean conditions over a 25-year period.



Tree rings were used to develop a 1,100-year record of the Palmer Drought Severity Index — a measure of drought incorporating both precipitation and temperature trends — for Wyoming's Green River drainage basin (Cook et al. 2004). This record is typical of Wyoming and the surrounding states in that it shows high precipitation in the early 20th century (Woodhouse et al. 2006; Gray et al. 2004, 2007; Meko et al. 2007). This same period overlapped with the development of the 1922 Colorado River Compact, with these unusual climatic conditions contributing to the over-allocation of water from the Colorado River (Pulwarty et al. 2005; NRC 2007). As in many other long-term climate records from the western United States, this reconstruction also shows the potential for severe, sustained droughts far outside the range of 20th century observations. Of particular note are several 40 to 50+ year drought periods prior to 1300 A.D.

The droughts of the 1930s and 1950s were relatively minor events compared to many pre-1900 droughts. Finally, the last three to four decades of the 20th century — a time that featured high rates of population growth and development in downstream states — was relatively wet and free of any major dry events.

These long-term perspectives highlight several important characteristics of Wyoming's climate. First, drought is a defining feature of regional climate. Second, climate can change naturally from decade to decade, but not always in ways that favor water users in the state. Third, the 20th century — our customary baseline or reference standard for understanding Wyoming's climate and water resources — was unusually wet and free of severe, sustained drought when compared to many earlier centuries.

What would happen if extended dry times such as those commonly seen before 1700 A.D. were to return? Without a doubt the consequences would be substantial, and this makes climate variability and change, of any type, a key factor to consider as we plan for the future of Wyoming's water resources. These long-term records also present another key question in the face of any future climate change: how might increasing temperatures amplify the impacts of droughts seen in the tree-ring record?

Managing for the combined effects of drought and warmer temperatures will be a key challenge in the future.

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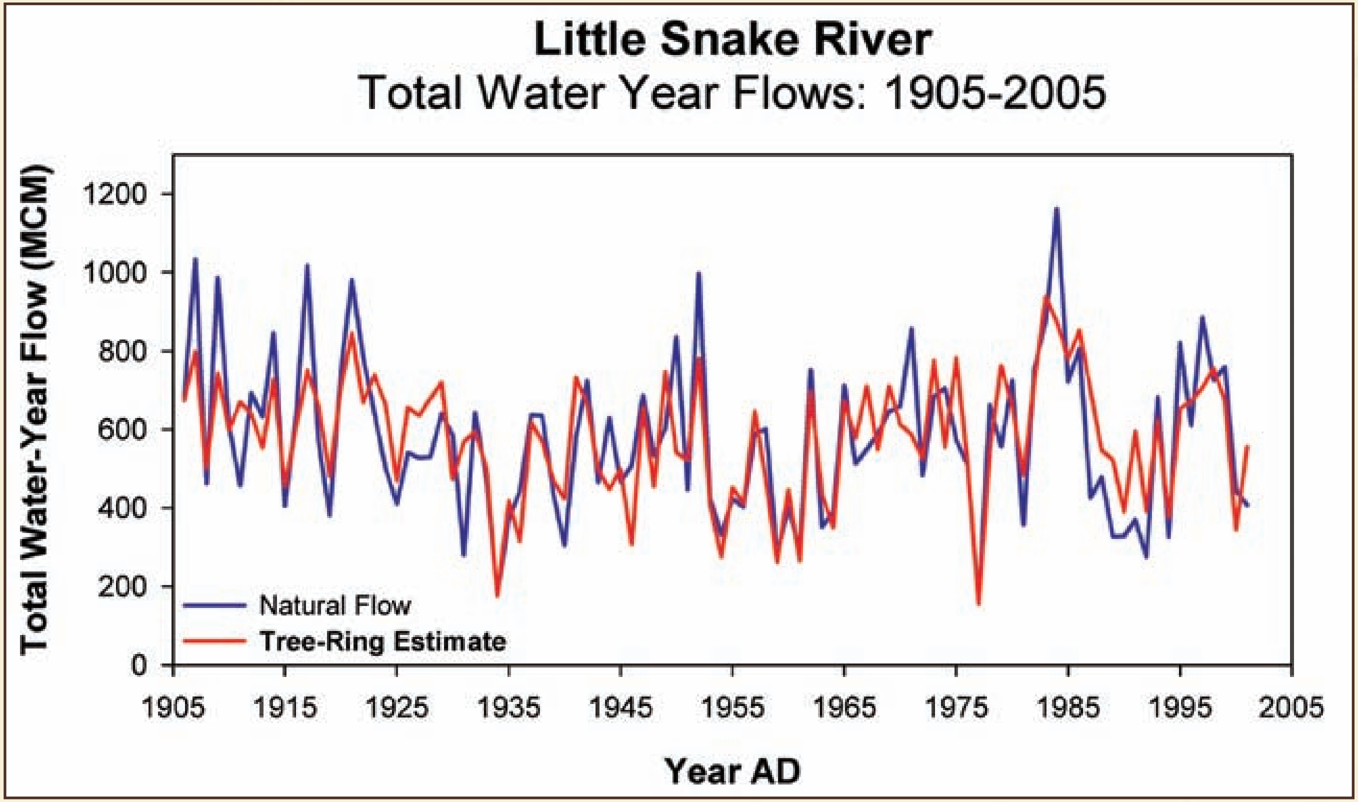
Paleo Perspectives on Climate Change

Increasing human populations, recent drought, and climate change all highlight the importance of understanding long-term water supply variability in the western United States (Woodhouse et al. 2006; Watson et al. 2009). While instrumental records — measurements from precipitation gages, stream gages, and automated snow observing sites, etc., tell us a great deal about the hydrology of the West, these records are limited in what they can say about the range of natural variability and longer-term trends. At best, instrumental records capture only a handful of extended droughts and wet events, and they may not include the full range of shorter-term extremes that may be relevant to planning (Meko and Woodhouse 2009). Even the longest instrumental records, some more than 100 years in length, may fall short as baselines for water resources planning and for understanding the potential impacts of climate change (Gray et al. 2004; Meko et al. 2007).

Tree rings and other paleo (prehistoric) archives provide insights to augment the instrumental record. In Wyoming and other parts of the western United States, tree species such as Douglas-fir, limber pine, and pinyon pine can live for hundreds of years, and their wood is often preserved long after the tree has died. Given proper site conditions (e.g., soil type, slope angle, geology), these trees will produce relatively small annual growth-rings during dry years, and relatively wide rings in wet years. By studying patterns of large and small rings in thousands of trees, scientists can use this information to develop accurate estimates of past precipitation and stream flow, and a detailed history of droughts and wet events (see figure on page 14). Multiple tree-ring records from Wyoming now extend back 750 years or more (e.g., Gray et al. 2004, 2007; Watson et al. 2009), and other records from the West date back to over 1,500 years (e.g., Meko et al. 2007).

Photo courtesy of Tom Dietrich.



Comparison of natural (i.e., unregulated) flows on the Little Snake River near the Colorado-Wyoming border, against tree-ring based estimates of flow at the same gage (Gray et al. In review).

Tree rings capture both year-to-year and longer term variations in river levels, and scientists can use these relationships to reconstruct flows going back hundreds to thousands of years. This same approach has been used to reconstruct precipitation and drought-index histories for the western United States.

Emerging Issues

The Water Energy Nexus

The links between energy production, the emission of pollutants such as CO_2, and climate change are widely recognized (IPCC 2007). However, in Wyoming and the western United States, the impact of climate change on water resources and, in turn, energy production has only recently garnered attention (DOE 2006).

The links between hydroelectric power and water are apparent, but much of Wyoming's energy industry is tied to coal and natural gas production. These extraction processes and subsequent power generation also require large quantities of water (WWDC 2007). Extractive activities often take place in areas that are already water limited, and this can present substantial problems for the municipalities that support these industries. Production of biofuels is also extremely water intensive. The growth of biomass (e.g., corn and soybeans) required to produce biofuels usually depends on irrigation, and large inputs of water are required to process biomass into a useable fuel (DOE 2006).

Given that much of the surface water in Wyoming is already allocated, and that droughts regularly cause supplies to fall short of demand, additional energy production could require the transfer of water from other applications. Relative to other Western states, Wyoming has yet to see major changes in water use. However, when combined with climate change, increasing demands for domestic energy production may hasten this shift.

In addition to the impacts of energy production on surface waters, coalbed natural gas development affects groundwater. Varying quantities of groundwater are released as a by-product of coalbed natural gas extraction, and depending on the location and geologic substrate, the produced water may have high solute concentrations. Assessing the beneficial and cost effective use of coalbed methane water relative to the benefits of energy extraction is key to future water management strategies in several of Wyoming's river basins, especially the Green and Powder River and basins where energy development is concentrated.

Davy Johnston Power Plant, near Glenrock, Wyoming. Photo courtesy of Tom Dietrich.

Water Markets and Valuation

In many parts of the West current demand for existing water supplies and the increasing costs of developing new water have led to an ever-increasing number of water transfers. Research indicates that economic forces tend to drive water toward uses with the highest economic return (Saleth and Dinar 2005). The economic value of water tends to be higher for municipal and industrial uses than for agricultural applications (Howitt and Hansen 2005), and this has resulted in a net-transfer of water away from crop and livestock production. In the Colorado Front Range, for example, thousands upon thousands of acres of farmland have been retired from cultivation and their associated water rights transferred to other uses. In many cases these transfers are permanent, and have thus contributed to a significant shift in the economic, social, and demographic character of portions of the western United States.

While the permanent sale or trading of water is likely to become more common, there are many other shorter-term options for easing shortages. What most of these alternatives have in common is the need for a market structure and legal framework that allows interested parties to attach a tangible value to water (Howitt and Hansen 2005). However, creating viable water markets and other means of short-term transfers can be exceedingly difficult (Easter et al. 1998; Howitt and Hansen 2005). This is because: 1) in most Western states the ultimate owner of the water is considered to be the state or federal government itself; 2) existing laws and regulations may limit or prohibit short-term transfers; 3) fluctuations in water supply result in "thin" markets with few participants (i.e., little competition and few buyers or sellers); and 4) water transfers often involve significant costs related to physically transporting the resource.

In Wyoming, agriculture has historically been the dominant user of water, accounting for more than 80 percent of statewide consumption (WWDC 2007). If climate change or any other factors decrease water supplies, or if demand increases in Wyoming and in downstream states, many of these agricultural users will undoubtedly experience pressure to transfer their water rights. The challenge then becomes one of ensuring that water transfers take place in a fair and equitable manner, and that water transfers are balanced against the cultural and environmental interests of Wyoming's citizens. Water markets and other economic models might assist in achieving these goals (Easter et al. 1998). Water markets may likewise provide incentives for conservation and a means for providing water to environmental, recreational, and habitat-related uses.

"Expanding population and environmental protections place additional demands on existing water supplies. Today, meeting these demands by traditional methods of supply augmentation is complicated by high environmental and fiscal costs. Excess water demand is thus increasingly met by conservation and reallocation of existing supplies."
— Dr. Kristiana Hansen, University of Wyoming

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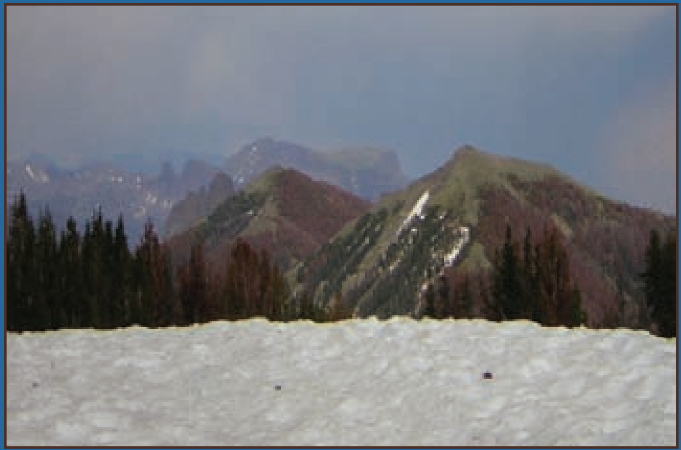
Pine Beetle Impacts

The mountain pine beetle is a native insect found in the pine-dominated forests of Wyoming and surrounding states (Romme et al. 2006). Like other bark beetles, adult mountain pine beetles bore into lodgepole pines and other related species and lay their eggs within the inner bark. The larvae feed on tissues used to conduct nutrients throughout the tree, thereby killing it. The impact of beetles is magnified by a fungus they carry. Commonly referred to as blue stain, this fungus further disrupts the movement of water and nutrients within an infested tree, and prevents the tree from using its natural defenses (e.g., resin production) against the beetle larvae. Numerous historical accounts and scientific studies tell us that mountain pine beetles are always present in lodgepole pine forests, as well as forests and woodlands made up of ponderosa and limber pines. While these insects usually persist in small numbers, they occasionally reach outbreak or epidemic levels affecting large numbers of trees.

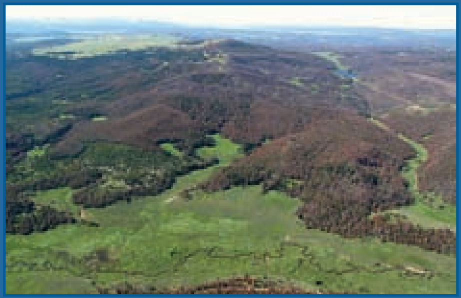
In recent years, mountain pine beetle outbreaks have become common across the western United States and large parts of Canada. In southeast Wyoming and northern Colorado alone, mountain pine beetles have already affected more than 1.5 million acres of forest (USFS 2008). Experts predict that within the next five years, mountain pine beetles will kill nearly every mature (> 5 inches diameter) lodgepole pine in southeast Wyoming. Mountain pine beetle outbreaks are also occurring throughout every major mountain range in the state. Outbreaks of this scale are unprecedented in recorded history.



Forest dieback caused by mountain pine beetle and other pathogens has the potential to fundamentally alter watersheds in Wyoming and the West for decades to come.

Pine beetle outbreaks have dramatically altered our Western landscapes. But why are these outbreaks occurring now, and why are they so prevalent in Wyoming? The leading hypothesis is that recent dry conditions and warm temperatures have made forests particularly susceptible to attack by mountain pine beetle and other insects (Hicke et al. 2006; Romme et al. 2006). Drought can weaken a tree's defenses, allowing mountain pine beetles to flourish. Years of warm temperatures have also reduced winter kill in beetle populations, and have helped facilitate the reproduction and spread of these insects. In some areas, though not all, the legacy of past forest management practices may also have set the stage for outbreak conditions. Through a combination of fire suppression and timber harvesting history, some forest stands have now reached a level of maturity that makes them highly susceptible to mountain pine beetle attack.

Given that snowmelt from lodgepole pine forests and other high mountain ecosystems is Wyoming's primary source of streamflow, mountain pine beetles will have a substantial impact on water resources in the state. Previous studies performed over relatively small areas suggest that runoff will likely increase after mountain pine beetle outbreaks (e.g., Troendle and King 1985, 1987), because of fewer live trees taking up water. However, no study has ever looked at the impact of mountain pine beetle outbreaks over such large tracts of forest.



There are three major factors that have combined to create the current beetle kill outbreak in the West:

1. Extended period of drought stress weakens trees and increases susceptibility to insect attack.

2. Increased winter survival of larvae due to fewer days of extremely low winter temperatures.

3. Abundance of suitable host trees (forest structure).

— Dr. Dan Tinker, University of Wyoming

Strategies for Addressing Change

The Western Governors' Association (WGA 2006) has made four key recommendations for managing water in the face of climate change:

- Facilitate collaborative watershed-focused planning that balances desirable growth and protection of the natural environment.
- Prepare for climate change by expanding data collection networks, and by funding research aimed at prediction and impact assessment.
- Promote down-scaling of global climate predictions to a regional level.
- Increase partnerships with existing user-support providers such as state climatologists, regional climate centers, and agricultural extension services.

Wyoming has implemented several of these recommendations in an effort to better address drought and water demands of downstream users. These same policies represent significant first steps toward meeting the challenge of managing water with climate change in mind. Watershed planning efforts represent a particularly attractive "win-win" strategy for addressing the combined challenges of drought, shifting demand, and climate change.

Watershed planning in Wyoming relies on the efforts of multiple groups, including the Wyoming Association of Conservation Districts, the University of Wyoming's Water Resources Extension Program, the Natural Resource Conservation Service, Wyoming Water Development Office, Wyoming Department of Environmental Quality, and the Wyoming Department of Agriculture. Created in 2005, this network is primarily focused on water quality, but drought assessment has become an important component to the program. Currently, the state has 27 watershed plans, with six in the development phase (NRCS 2009). These plans provide a management framework that centers on concrete responses to water-availability and water-quality issues.

Each watershed plan is crafted using data from the state's water quality and watershed monitoring programs. Watershed plans also identify critical trigger points for the initiation of management or mitigation actions. Watershed planning provides one potential foundation for addressing climate change because: 1) many of the actions taken as a part of the process will likely benefit stakeholders no matter what climate change brings to the state; 2) watershed planning brings together the key agencies and stakeholders concerned with Wyoming's water in a cooperative framework; and 3) the geographic scope of watershed plans is often well-matched with the scope of funding available for adaptation and mitigation efforts. In addition watershed assessment tools are being used in watershed planning efforts, and include hydrologic and erosion-scenario models, with multiple sources of information for each watershed linked with geographic information systems.

"Along with drought, climate change impacts on water quantity and water quality in Wyoming can be significant and highly variable in space and time. Methods to assess these uncertainties and the effects on surface water resources are being incorporated into watershed planning and assessment tools."
— Dr. Ginger Paige, University of Wyoming

What We Need To Know: Future Research

Many aspects of the relationship between warmer temperatures and water supplies are well understood. However, potential changes in consumptive water use are still highly speculative. More accurate information concerning current and future consumptive use could provide both climate scientists and policy makers with a better indication of available water resources and a better picture of where water supply vulnerabilities lie. There is also a pressing need to better understand how climatic variability and change will impact water demand. Better estimates of consumptive use could help answer key questions such as, how much water might consistently be available to support additional energy development? Or, when combined with a significant shift from agricultural to municipal use, how might predicted increases in summer temperature affect demand?

Another significant need is for the development of improved regional climate forecasts and state-of-the-art, thoroughly peer-reviewed scenarios for regional climate change. As judged by the ability of forecast models to reproduce 20th century climatic conditions and key climatic events from the past (e.g., Medieval-period warming and 19th century cooling), climate scientists have relatively high confidence in predictions for future temperatures (Leung et al. 2004; Christensen et al. 2007). Predictions for future precipitation are far less certain. This lack of predictive skill results, in large part, from the coarse resolution — often measured in degrees of longitude/latitude — of most climate models. In effect, these models fail to account for variations in local to regional topography, which is a serious shortcoming in a mountainous state like Wyoming.

In a more general sense, the coarse resolution of current climate models creates a mismatch between available forecasts and the scales at which planning and policy creation and implementation take place. Techniques for down-scaling climate predictions to a more useable scale are advancing rapidly, but to date there has been no comprehensive effort to produce such forecast products for Wyoming. Ideally such down scaling efforts would result in a set of rigorously-tested and thoroughly peer-reviewed scenarios for future climate that could then be made freely available for applications in a wide range of planning efforts.

Photo courtesy of Chris Hiemstra.

Questions to be Answered

The questions and conclusions below were generated by the Ruckelshaus Institute's Water Working Group.

- How do current management practices and policies influence our vulnerability to climate change?
- How will climate variability and change impact water demand?
- How will changing land use, land cover, and climate interact to impact regional hydrology?
- What are the potential impacts of carbon sequestration on the water cycle?
- How might climate change and energy production interact to affect water availability in Wyoming?
- How will climate change and other factors impact water quality in Wyoming?
- How and where are groundwater resources susceptible to climate change?

Addressing these questions will require better monitoring of climate and water resources in Wyoming and the surrounding region. Additional monitoring in high elevation areas that are currently undergoing major vegetation change (i.e., forests impacted by mountain pine beetle), and other areas of the state most likely to experience the impacts of climate change are sorely needed, as is more monitoring of groundwater resources. Monitoring evapotranspiration and other aspects of consumptive use are also essential.

Some Conclusions

Wyoming's water resources are vulnerable to climate change because:

1. Water supplies in Wyoming are heavily dependent on snowpack;
2. The regional climate is semi-arid to begin with;
3. Long-term records demonstrate that drought is a natural, defining feature of regional climate; and
4. Shifts in water use and growing human populations in downstream states will place an additional strain on water supplies.

Public input, consensus building, and cooperation are key components to managing water in a changing climate. As water becomes scarcer during times of increasing demand, developing policies that recognize the complex linkages among climate, water, energy, cultural values, and ecosystems will be of vital importance. Reducing uncertainties associated with regional climate forecasts, understanding consumptive use and demand, improving monitoring of climate and water supplies, and re-evaluating the strategies used to adapt to climate change — whatever the cause — will be essential for addressing impacts on Wyoming's water resources.

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