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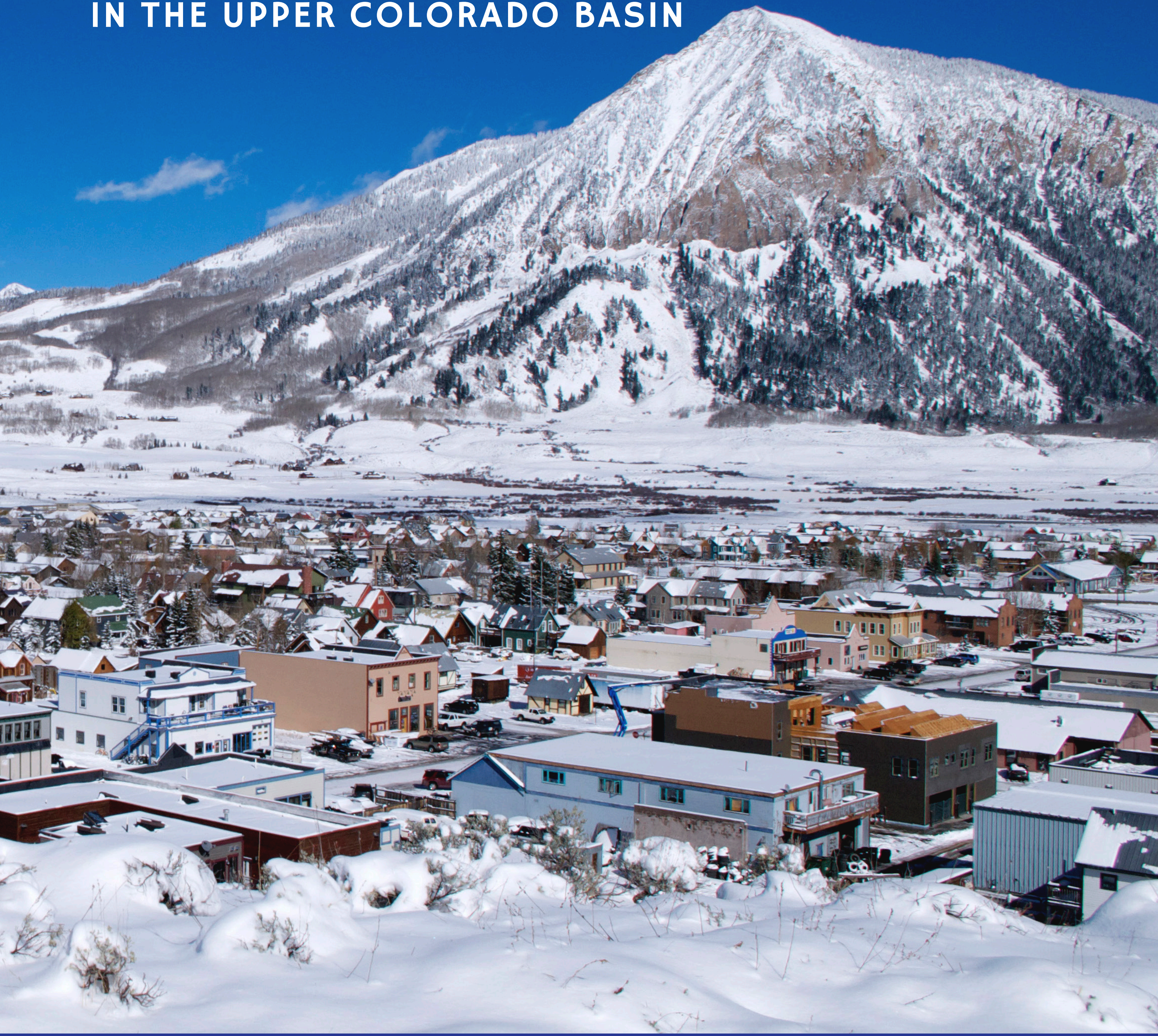
IN THE UPPER COLORADO BASIN



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AUTHOR

Ken Cousins

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ECONOMICS
107 N. Tacoma Ave
Tacoma, WA 98403
253-539-4801
www.eartheconomics.org
info@eartheconomics.org

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When snow first falls to earth, it adversely affects travel. But accumulated snowpack also supports winter recreation, aesthetic values, and regional and local climate dynamics, which in turn influence both wildlife habitat and ecosystem function. As seasons change, the pace and timing of snowmelt can cause localized flooding, affect water availability throughout the basin, and directly impact plant and animal species. As water, melted snow supports plants and animals, but is also subject to increased evaporation and transpiration, especially as it flows to lower elevations with higher average temperatures. Gravity-driven flow drives hydroelectric generation and both direct and indirect human consumption of water.

The Colorado River Basin supplies water to more than 34 million people and irrigates over four million acres of cropland. As a whole, the basin is estimated to support one-fifth of the nation's GDP.[1] Snow is a particularly important feature of the water cycle in the Basin, and affects human wellbeing and the economy in every phase, whether snowfall, snowpack, or snowmelt. The following sections describe many of the economic benefits and costs associated with snow and snowpack, with a focus on the Upper Colorado Basin (UCB). We explore some of the ecological and economic changes that can be expected from climate shifts, and discuss their significance throughout the UCB (and beyond). Finally, we point to a few policy responses that are attempting to mitigate and adapt to the risks associated with decreasing snowpack and water flows.

Falling Snow

While snowpack provides many critical benefits, there are also costs associated with snow, especially as it falls and as it melts. Even moderate snowfall can block streets, roads, and highways; snow removal costs the United States around $2.5 billion every year.[2] Snowfall also often leads to transportation delays, lost workdays, damage to buildings, infrastructure, and agriculture, as well as accidents, injuries, and the loss of life. These costs can be considerable: In 2004, the cost of snowstorm-related air and ground transportation delays across the United States were estimated at over $4 billion (2016 dollars).[1] Major storms also commonly cause injuries and death. Other storm-related costs include efforts to prepare for storm events—whether they occur or not—and insurance premiums and claims. The March 2003 blizzard (Colorado's most costly to date) resulted in $122.7 million (2016 dollars) in snow and ice damages to private vehicles and homes, with over 28,000 claims filed.[i] Most of this damage was caused when heavy snows collapsed roofs and outbuildings. There was also significant water damage from melting snow, wind damage, and temporary shelter costs.[3] Increasingly damaging natural disasters (including wildfires and hailstorms) have led to higher insurance premiums; Colorado rates are above the national average and rising.[4] See Table 1 for a summary of these costs.

Earlier snowmelt also increases the risk of larger and more frequent avalanches. Since 1950, Colorado has had the highest number of avalanche-related fatalities in the country, more than twice that of Alaska, in second place.[5] Shifts in the timing of snowmelt are also likely to impact winter tourism and aesthetic values, although this has not been closely studied.

Winter Recreation

Snow and snowpack provide the basis for the winter recreation industry, including alpine and cross-country skiing, snowboarding, snowshoeing, snowmobiling, and winter mountaineering. The industry is significant for the state of Colorado. From 2009 to 2010, winter recreation contributed over $2.4 billion (2016 dollars) and 37,800 jobs to Colorado's economy, including 20 percent of all ski visits in the country.[6] Many local communities rely on this income to sustain their economies throughout the year. Yet the industry is considered highly vulnerable to climate change. A 2006 study estimated that April snowpack in Colorado counties with ski resorts will decline 43-82 percent by the end of the century.[36,37]

In Colorado, the difference between high and low-snowfall years accounts for over 1.8 million fewer skier visits, translating to a loss of $170 million (2016 dollars).[5] For ski resorts, a common benchmark for profitability is the "100-days rule," whereby resorts can remain economically viable with 12 to 20 inches of snowpack over 100 days between December and mid-April.[8] While nearly 90 percent of winter resorts make artificial snow to extend skiing seasons, the process still requires low temperatures and sufficient water and energy.[9] Snowmaking is especially water-intensive, requiring from 64,000 to 160,000

TABLE I: THE COST OF WINTER STORMS

IMPACT	SCOPE	YEAR	[COST]	SOURCE
Snow removal	United States	1997	[$2.5 billion (annual)]	Adams et al 2004
Transportation delays (year- round)	United States	2001	[$4 billion (annual)]	
Damage to homes and vehicles	Colorado	2003	[$122.7 million (single event)]	RMIIA 2015

*all values in 2016 US dollars.

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[i] These figures do not include damage to commercial buildings and infrastructure.

gallons per acre. The necessary energy can also be quite significant—as much as 50-80 percent of a resort's annual use, upwards of $550,000 per resort (2016 dollars).[10] These benefits and costs are summarized in Table 2.

Another alternative is for the industry to shift winter recreation locations to higher altitudes or higher latitudes. While this may provide some long-term flexibility, the costs of relocating are likely to be substantial. Costs include purchasing new property, building additional lift and support facilities, and promoting those new destinations to their customers.[11] Where public infrastructure must be extended to new or expanded resort properties, additional costs to the public can be anticipated. The full cost of extending (or improving) roads, tunnels, or bridges to access more remote areas may be unknown, but it represents a substantial cost of a changing climate.

Natural Beauty and Aesthetic Value

Snowpack also contributes to human wellbeing in less direct ways. Even non-skiers enjoy the sight of snow-capped mountains. Though the economics of winter-season-sightseeing are not well-studied, properties with views of snow-capped mountains commonly fetch higher prices. A 2009 study, which assessed the impact of a warming climate on home prices near alpine skiing and snowboarding locales, revealed a very high correlation (R2 = 0.72 to 0.98) between home value and snowfall intensity (the percentage of precipitation falling as snow during winter months).[12] The effect of low snowfall can be substantial; low snowfall years were associated with declines of up to 8.8 percent of a home's value (see Table 3). While the Rockies may not face a high risk of snowpack loss in the short and medium-term, the ultimate losses to property values may be substantial.

TABLE 2: BENEFITS AND COSTS OF WINTER RECREATION

IMPACT	SCOPE	YEAR	BENEFITS [COSTS]	SOURCE
Consumer spending	Colorado	2009-2010	$2.4 billion	Burakowski and Magnusson 2012
Employment			37,800 jobs	
Snowmaking in low snowfall periods	United States		[$550,000 per resort]	

*all values in 2016 US dollars.

TABLE 3: HOME VALUE IN LOW-SNOWFALL YEARS

IMPACT	SCOPE	YEAR	BENEFITS [COSTS]	SOURCE
Home values in low-snowfall years	Western United States	2009	[≤8.8% decline in sale value]	Butsic et al 2009

*all values in 2016 US dollars.

Habitat and Biodiversity Support

Thriving ecosystems are critical to Colorado's economy. In 2006, recreational fishing, hunting, and wildlife viewing in the Colorado basin directly contributed over $1 billion (2016 dollars) to the state's economy—nearly $2.7 billion (2016 dollars) when indirect and induced spending are included.[13] The spatial extent of snowpack and timing of snowmelt impacts the viability of plant and animal species (as well as broad ecosystem health) throughout the basin, and throughout the year. The albedo of snowpack, which is higher than dry land, reflects sunlight and helps maintain cooler temperatures, both locally and globally. Snowpack can also protect new plant growth from hard frosts, by insulating new growth from the colder open air.[35]

Gradual melting, which occurs more consistently and for longer durations with higher snowpack, keeps runoff colder, maintaining and moderating seasonal temperature cycles. Fish adapted to spawning in cold waters are strongly impacted by stream temperatures; warming drives those species to higher altitudes, reducing and fragmenting habitat, and decreasing effective breeding populations.[14] Higher stream temperatures also reduce dissolved oxygen, further impacting aquatic diversity and general ecosystem health.[15,16]

Changes to local and regional climates do not impact all species equally. Conditions that weaken some species may favor others. For example, populations of mountain pine beetle and spruce beetle have recently exploded, as earlier spring temperatures have allowed them to emerge four to six weeks earlier than in the 1970s. Beyond increasing their feeding period, early warming and longer summers have allowed a second summer breeding period.[17] Where drought has weakened trees, these pests have decimated forests, leaving millions of dead trees and significantly impactinglocal ecosystems.[18,19] In turn, massive die-offs have led to campground closures, as risks of wildfire and falling trees have increased.[20] In Rocky Mountain National Park alone, beetle outbreaks have cost between $5 and $61 million in lost recreational income (2016 dollars).[21] This equates to a loss of $33.6 to $381.5 per acre (see Table 4).

TABLE 4: ECONOMIC BENEFITS OF HABITAT, COSTS OF DIMINISHED HABITAT QUALITY

IMPACTS		SCOPE	YEAR	BENEFITS [COSTS]	SOURCE
Recreational fishing, hunting, wildlife viewing	Direct Spending	Colorado Basin	2006	$1 billion	Kaval 2011
	Indirect & induced spending			$1.7 billion	
Reduced park visitation due to pine beetle infestations	Per acre losses	Rocky Mountain National Park	2009	[$33.6 to $381.5 per acre]	Rosenberger et al 2013
	25% decline in tree density due to mortality			[$5.7 million]	
	50% decline			[$5.7 million]	
	75% decline			[$65.9 million]	

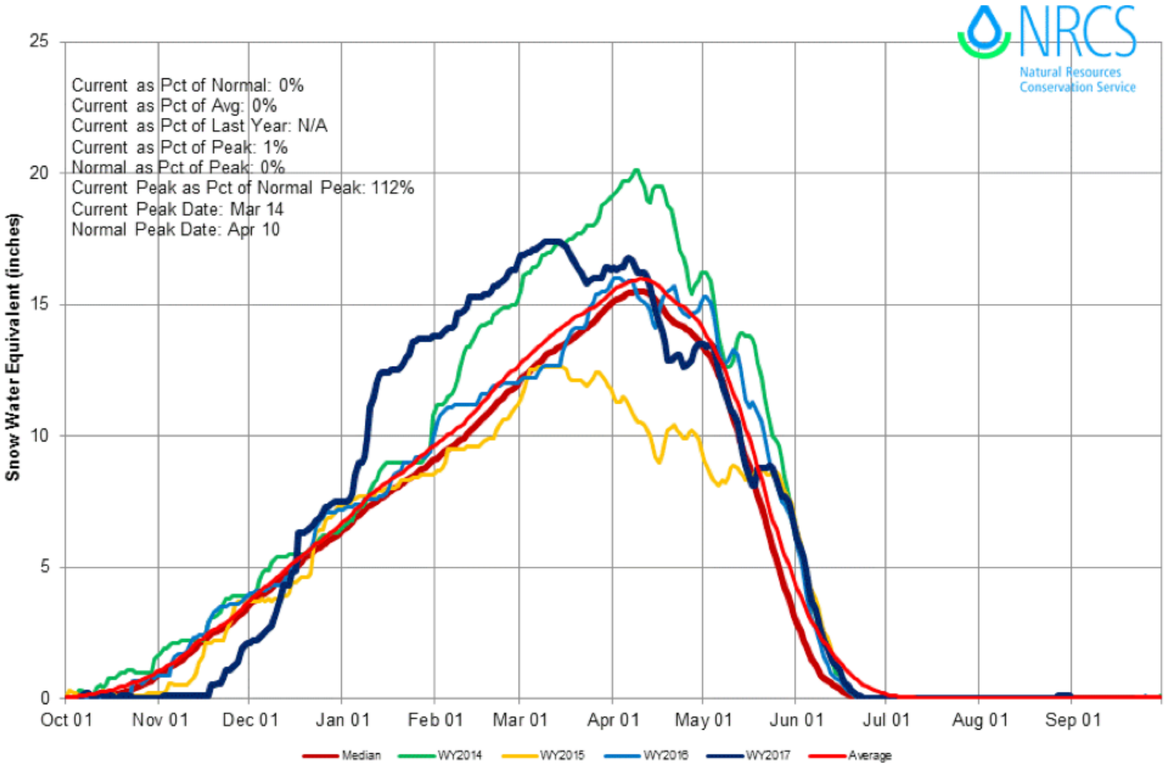
*all values in 2016 US dollars.

Water Supply and Storage

Up to 70 percent of the precipitation in the UCB falls as winter snow.[22] That snowpack serves as a form of storage, holding water at higher elevations and lower temperatures through the early spring. But by late June, most of the snowpack melts (see Figure 1), limiting water supplies throughout the basin to groundwater and upstream reservoirs.

Winter snows are well-distributed across the UCB (see Figure 2), but storage capacity is not. Lake Powell, which holds nearly 70 percent of the reservoir capacity in the UCB, lies well below the Basin's lowest population center.[23] While the whole reservoir system has the capacity to store four years of the river's full flow, the capacity to store water for human consumption effectively goes no higher than 5,700 feet, which is also quite near the midpoint of population distribution across the UCB. Because only about 30 percent of the system's capacity is available for the water needs of the Upper Basin, seasonal shortages for the Upper Basin are not uncommon.[24] The massive storage capacity of Lake Powell is only significant to the UCB for the recreational opportunities and hydroelectricity it provides, rather than its water supply potential.

FIGURE 1: UCB SNOW WATER EQUIVALENT, 2014-17 WATER YEARS [42]

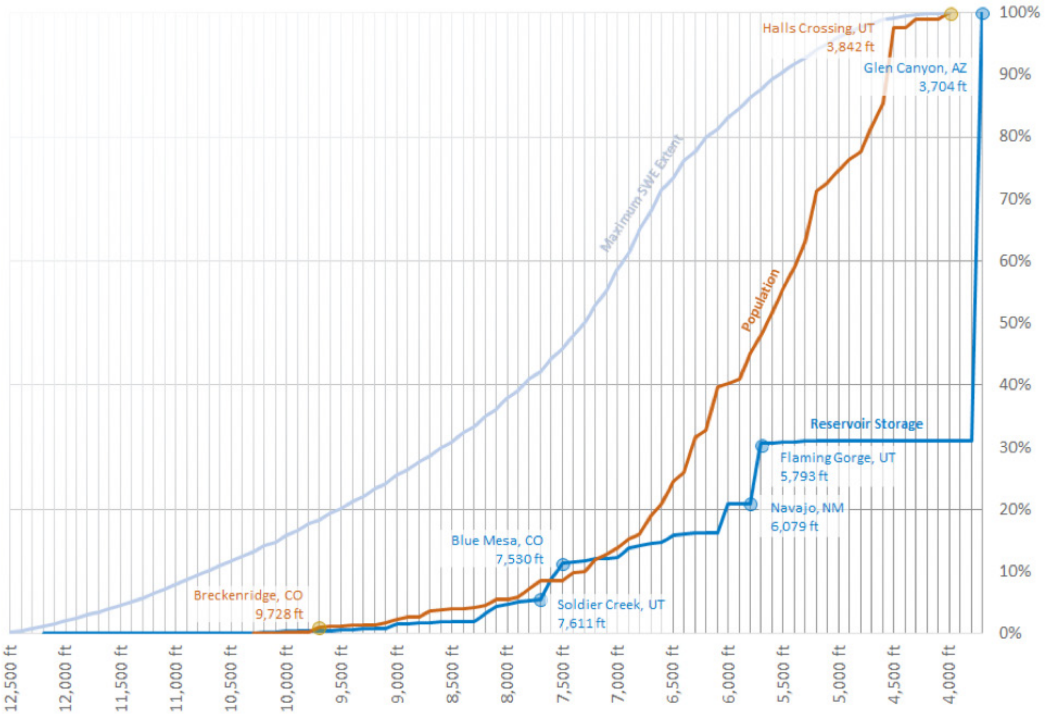


However it may be distributed, the water of the UCB is already over-allocated, putting stress on regional and international water agreements. Because agriculture accounts for nearly two-thirds of demand in the UCB, the impacts of water scarcity within the UCB are likely to extend far beyond the region itself.[27] Retaining water at higher elevations (and cooler temperatures) directly impacts water availability downstream throughout both the Upper and Lower Basins. Unless something can be done to delay snowmelt, or retain more water at higher elevations, shortages in the upper basin are likely to become both more common and more severe. Earlier snowmelt means earlier growth in vegetation, increasing transpiration (i.e., vaporized water lost through plant leaves).

Evaporation is a function of multiple factors (e.g., exposed surface area, solar aspect, air and water temperatures, cloud cover, and barometric pressure). Of these, two are especially significant: exposed surface area and air temperature. As with reservoir capacity, surface area in the UCB reservoir system is dominated by Lake Powell, which accounts for over 43 percent of all exposed reservoir surface in the Basin (see Table 5). If all other factors are held the same, evaporation scales with surface area, which means we can expect at least 43 percent of all reservoir evaporation across the basin to come from Lake Powell.

Of course, all factors do not remain the same. Air temperature is a strong predictor of evaporative losses and tends to inversely correlate with altitude—that is, both air temperature and evaporation tend to increase at lower elevations. Figure 3 shows relative evaporation rates at different altitudes and temperatures across the UCB.[28] These reflect monthly evaporation in Class A pans (National Weather Service standard)[ii], as compiled by the Western Regional Climate Center from 1889-2005 (UCB stations only). Elevation and monthly average maximum daily temperature data were also provided by WRCC. The red circles demonstrate the relative evaporation at

FIGURE 2: UCB POPULATION, SNOW WATER EQUIVALENT, AND RESERVOIR CAPACITY, BY ELEVATION [22,25,26]

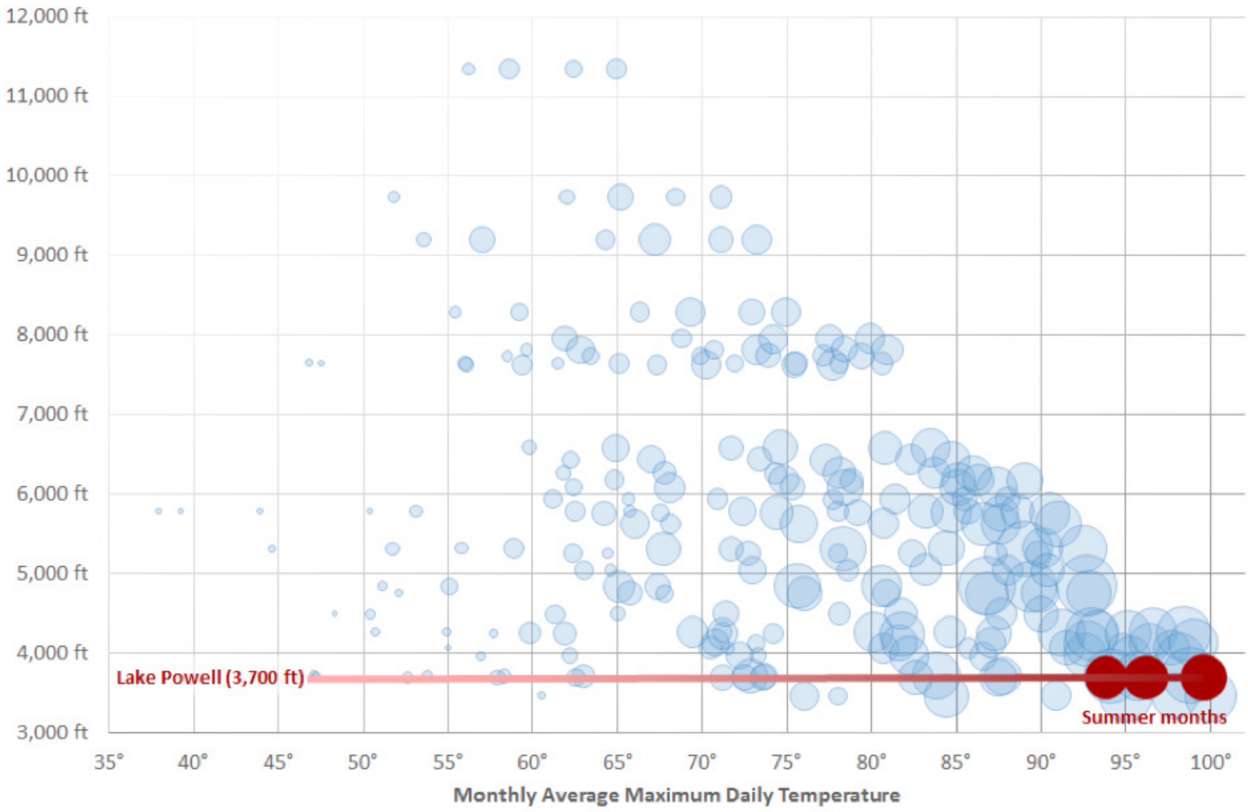


[ii] Class A pans are 48 inches in diameter, or 12.6 square feet of exposed surface area.

TABLE 5: FIVE LARGEST RESERVOIRS, UCB[22,28]

DAM	ELEVATION (FT)	STORAGE (MILLION ACRE-FT)	% OF ALL UCB	SURFACE AREA (ACRES)	% OF ALL UCB	JULY AVERAGE DAILY HIGH (°F)
Glen Canyon (AZ)	3,704	29.875	68.4%	160.8	43.4%	96.6°
Flaming Gorge (UT)	5,793	4.003	9.2%	43.8	11.8%	86.2°
Navajo (NM)	6,079	1.987	4.5%	15.6	4.2%	91.5°
Soldier Creek (UT)	7,611	1.127	2.6%	17.3	4.7%	77.5°
Blue Mesa (CO)	7,530	0.941	2.2%	9.2	2.5%	83.4°

FIGURE 3: EVAPORATION BY ELEVATION AND TEMPERATURE, UCB [22,26]



Lake Powell—without scaling by exposed surface area—during the three hottest summer months. Lake Powell's evaporative losses are likely to be far higher than any other reservoir in the UCB system; current evaporative losses in the upper basin are already equal to 59 percent of all consumptive use.[29] Together, evaporation and transpiration are estimated to reduce surface water runoff in the basin by as much as five percent.[38] Because warming temperatures cause more precipitation to fall as rain and earlier snowmelt,[30] a projected temperature increase of an average of 4.3°F across the UCB by the end of the century[33] will lead to even greater evaporative losses.

Prolonged droughts lead to longer wildfire seasons, with larger fires increasingly common.[31] What drought means for water management in the basin, however, remains unclear. In an average year, the Colorado's annual flow is over-allocated. Persistent drought has depleted both Lake Powell (the system's largest reservoir, providing over 60 percent of all storage potential in the UCB) and Lake Mead (the largest reservoir in the country, and the largest source of water for Arizona and Southern California), raising the possibility of federal intervention to re-allocate supplies. Until this year's higher-than-average snowpack, river stakeholders were negotiating substantial conservation measures to avert that possibility.[32] While the risk of re-allocation has been temporarily reduced, stakeholder groups still disagree on virtually every river-related issue, from the prudence of water conservation to whose water rights should have precedence over others.[33]

Climate Changes and Policy Responses

Across the Northern Hemisphere, spring snow cover has declined significantly since 1970.[34] The latest climate models for the UCB predict average temperatures to increase up to 4.3°F by 2070.[35] This is not only expected to shorten winters and lengthen summers, but also to shift snowlines to higher altitudes, although regions above 3,300 feet elevation may be less affected.[36,37] Over the entire basin, spring snowpack is projected to decline nearly 70 percent by 2070,[38] with one model projecting that late spring snow could disappear entirely by the end of the century.[39] The moment of peak snowmelt in the UCB is already an average of two weeks earlier than in the 1970s, reducing overall streamflow in the Colorado River system.[34] Less runoff in late spring also reduces aquifer recharge and leads to greater water scarcity. Basin-wide, runoff is projected to drop between 8.5 and 45 percent by 2050.[1]

Although climate models generally predict earlier snowmelt and decreasing snowpack, predictions of future UCB snowpack are highly uncertain. Precipitation in the Upper Colorado Basin—both winter snows and summer rains—is driven by cycles in the northern and tropical regions of the Pacific Ocean.[25] Interactions between the El Niño-Southern Oscillation and warming ocean waters are complex and not well-understood. Such gaps in knowledge make predicting snowpack difficult, even in a future of global and proactive climate policy. Given such uncertainty, policymakers, scholars and stakeholders across the Upper and Lower Basins have focused on minimizing and mitigating the risks associated with too little (and too much) snowpack and runoff, especially in the face of limited options for expanding storage capacity throughout the basin.[40]

Policy responses have addressed water conservation, energy conservation (much of the region's electricity is sourced from hydroelectric dams), and reduced environmental impacts. Perhaps the most interesting is a set of approaches known collectively as "water banking," which allows larger-scale users (e.g., municipalities, industry) to trade water efficiency gains for seasonally extended access, both reducing and spreading demand over time.[24] Other promising approaches include: water insurance and futures markets, which give municipalities a hedge against higher water prices during drought; and municipal green bonds, which finance investments in more efficient water infrastructure. A more complex solution is the creation of markets for trading ground and surface water rights, with a primary goal of strengthening incentives for conservation and responsible stewardship.[38] While markets offer the potential for efficiency gains—shifting uses from low-value (e.g., agriculture) to higher-value (e.g., direct human consumption)—the complexities of water rights and the expense of transferring water long distances has largely limited trading to the basin level. One exception, the Colorado-Big Thompson (CBT), has successfully moved water from the western to the eastern slope of the Rocky Mountains for over half a century. A complex system of underground tunnels and reservoirs, supported by water brokers and transparent pricing, has led to a stable market, gradually shifting demand to higher-value uses.[41]

Conclusions

Like most complex atmospheric phenomena, snow produces a range of benefits and costs throughout the water cycle. Blizzards snarl and delay traffic, and even moderate snowfall usually requires removal from streets, roads, and runways. Yet stable snowpack supports winter recreation and seasonal income flows that in turn sustain many rural mountain communities. As a moderating factor during seasonal transitions between winter and spring, snowpack protects many regional plant and animal species. Where snowmelt is released gradually, groundwater, river, and reservoirs are capable of absorbing and storing runoff, reducing flooding and sustaining ecosystems throughout the river system. As peak snowmelt occurs earlier and earlier, both ecosystems and built infrastructure face new and increased stresses, harming the services that downstream communities have come to rely on for survival. These stresses are diverse and widely felt. For example, earlier snowmelt may cause biodiversity loss, shortened recreation and tourism seasons, lower home prices, higher insurance premiums, seasonal drought, lower hydroelectric generation, and generally reduced water availability.

The shift in the timing of peak snowmelt has been attributed to changes in climate variability, as has the gradual trend towards more spring rains than snowfall. While the ultimate impact of these changes on the total water captured and stored in the UCB is unclear, even seasonal changes in water availability can significantly impact the communities and industries that call the Basin home, as well as the millions further downstream whose survival depends on the water captured in the UCB. The key drivers of both precipitation and seasonal temperatures are global and exist well beyond the Basin itself, placing significant limits on available regional policy responses.

However, citizens and policymakers alike must consider trade-offs between mitigating impacts and reducing exposure to risk through adaptation. Developing and applying regional policy instruments and institutions to incentivize water conservation, and shifting demand to higher-value uses (e.g., municipal consumption) will likely prove critical to mitigating the risks associated with absolute water scarcity. Decisions are complicated by the pace and magnitude of climate change. Just as ecosystems are sometimes unable to adapt quickly to changing environmental signals, both communities and industries face constraints to their abilities to respond. Reducing risk also has limits, especially as population throughout the Basin steadily increases. The degree to which snowfall and snowpack will continue to be major factors in the UCB over the long-term is an open question.

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