

The Colorado River Basin and Climate: Perfect Storm for the Twenty-First Century?

By Carson McMurray

Key Findings:

- The effects of climate change are already being felt within the Colorado River Basin.
- Over the next century, flows of the river are projected to decrease by 6% to 20%.
- Releases of water to the Lower Basin will meet Compact obligations less than 70% of the time.
- Adaptation will require an adaptive management plan to adjust for new data and technology.

The 2012 Colorado College State of the Rockies Report Card
The Colorado River Basin:
Agenda for Use, Restoration, and Sustainability for the Next Generation

About the Author:

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“The more we can think about innovations and solutions from science, from policy, and from practice, the more we open up the debate right now and allow ourselves to consider new ways of doing business; better when that crisis eventually faces us that we’ll be able to adapt and move forward.”

-Beth Conover, editor of *How the West Was Warmed* speaking at the Colorado College, December 5th, 2011 as part of the

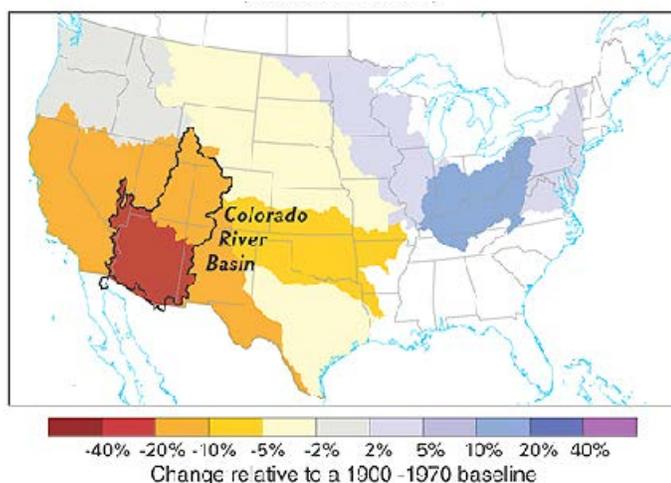
State of the Rockies Project Speakers Series

Introduction

The Colorado River Basin was once one of the most rugged and vast regions of the United States. From the bitterly cold headwaters to the maze of canyons, the Colorado River was in control. The thought of humans impacting or influencing the raging river was unimaginable 100 years ago. Today, the Colorado River is managed by seven states and two federal government agencies for uses ranging from agriculture to municipalities. With the construction of dams, irrigation canals and vast cities, the once wild Colorado River has largely been tamed by massive dams such as Hoover and Glen Canyon Dams. As humans move into the future, we must now deal with global warming, which threatens all aspects of the lifeline of the Southwest.

As climate change effects begin to surface after years of unsustainable greenhouse gas emissions, the southwestern United States, specifically its hydrology, will be drastically affected. In a review of 19 global climate models by the Intergovernmental Panel on Climate Change (IPCC), the group noted “there is a broad consensus amongst climate models that this region will dry significantly in the 21st century and that the transition to a more arid climate should already be underway.”¹ The Bureau of Reclamation has also found consensus among federal climate models that predict a significant decrease in water availability by the end of the twenty-first century.² The predicted reduction in annual runoff between 2041-2060 for the Colorado River Basin is between 6% and 20%, depending on the location within the basin. This is by far the largest reduction in the continental United States (see **Figure 1**).³ This diverse region ranges from 14,000 foot

Figure 1: Average Projected Changes in Annual Runoff, 2041-2060 (selected river basins)



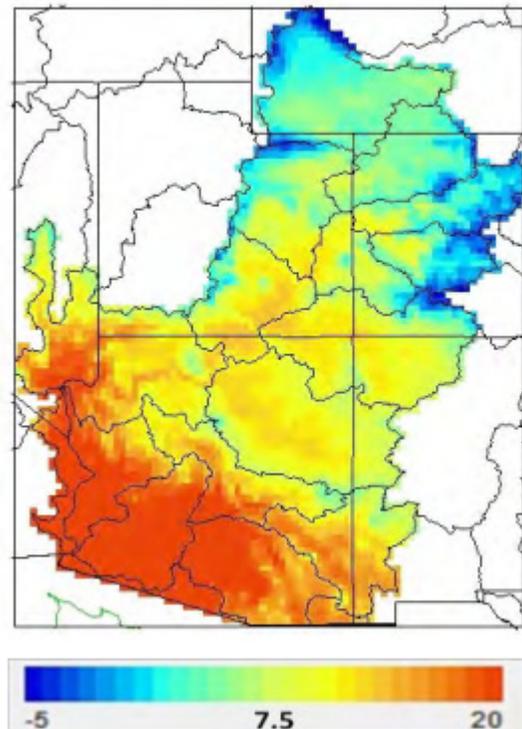
Source: National Geographic

snowcapped mountains to some of the driest deserts in the United States, making the projected impacts of climate change even more difficult to discern. However, there is consensus that temperatures will rise and precipitation patterns will change, increasing the difficulty of managing a river that is already over allocated.

Historical Climate Data: A Story of Variability

The temperature profile shown in **Figure 2** exemplifies the diversity of the Colorado River Basin. The high elevation headwaters’ annual average temperature is -5°C compared to the lowlands where temperatures annual average is nearly 20°C . The annual temperatures only tell half the story as both the high elevation headwaters and lowlands experience extreme hot and cold depending on the season due to the large differences in altitude and mid-continent latitude range.

Figure 2: Average Annual Temperature ($^{\circ}\text{C}$), 1971-2000

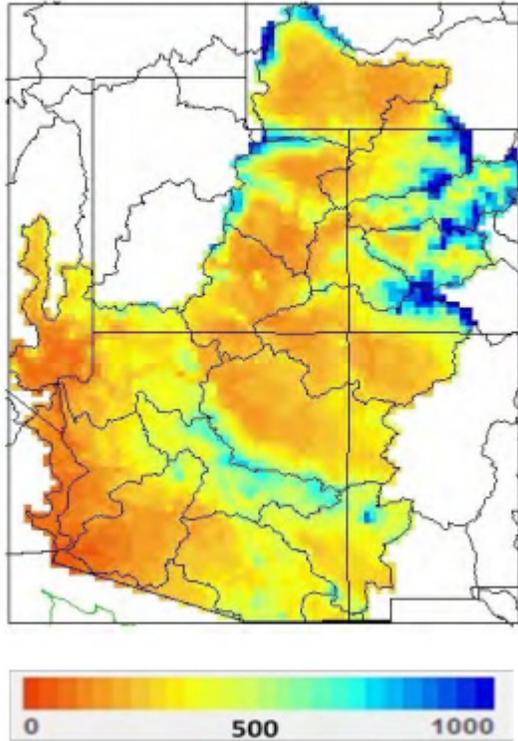


Source: U.S. Bureau of Reclamation Colorado River Basin Water Supply and Demand Study Study Team, “Technical Report B - Water Supply Assessment,” *Interim Report No. 1 - Colorado River Basin Water Supply and Demand Study*, June 2011.

Annual precipitation patterns mimic the temperature variability as certain areas of the headwaters receive 1,000 millimeters (39 inches) of precipitation annually and the lowlands receive under 5 mm (.2 inches) in some areas (see **Figure 3**). The entire basin averages 354 mm of precipitation annually,⁴ which is the definition of a semiarid desert (250 mm

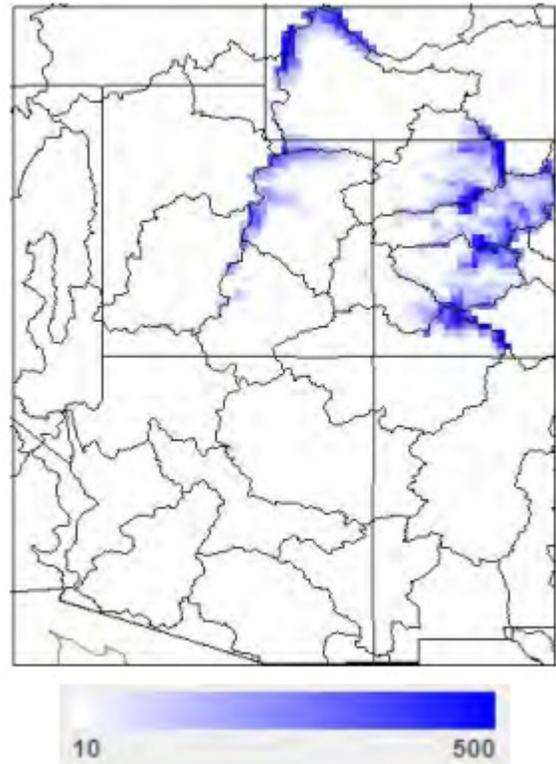
and 500 mm annually).⁵ The headwaters, which are 15% of the land mass of the Colorado River Basin, receive 85% of the total water, the majority falling as snow during the winter and spring months.⁶ The snow water equivalent (SWE) illustrates the dependence of the river flow on snowfall (see **Figure 4**). Peak runoff occurs between April and July, depending

Figure 3: Average Annual Precipitation (mm), 1971-2000



Source: U.S. Bureau of Reclamation Colorado River Basin Water Supply and Demand Study Study Team, "Technical Report B - Water Supply Assessment," *Interim Report No. 1 - Colorado River Basin Water Supply and Demand Study*, June 2011.

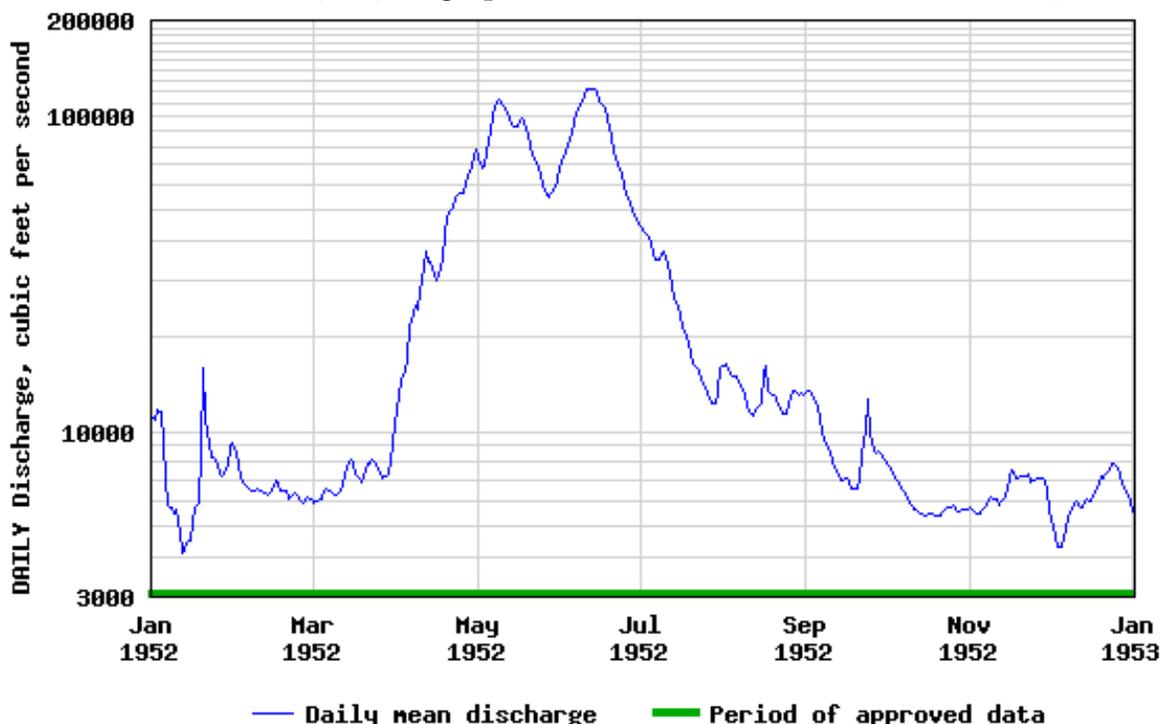
Figure 4: Average Annual March SWE (mm), 1971-2000



Source: U.S. Bureau of Reclamation Colorado River Basin Water Supply and Demand Study Study Team, "Technical Report B - Water Supply Assessment," *Interim Report No. 1 - Colorado River Basin Water Supply and Demand Study*, June 2011.

on snowpack and temperature, and fuels the classic mountain flow regime of the Colorado River.⁷ The hydrograph for Lee's Ferry, before creation of Glen Canyon Dam, also shows that snowpack melting is the primary source of Colorado River water when the peak discharge is during the prime snow melting months of May, June, and July (see **Figure 5**).

Figure 5: USGS Lee's Ferry Hydrograph of 1952 before creation of Glen Canyon Dam



Source: U.S. Geological Survey, "Effects of Climate Change and Land Use on Water Resources in the Upper Colorado River Basin," *Fact Sheet 2010-3123*, January 2011.

Another aspect of the Colorado River flow regime is the variability of the basin. Located in an interior region, away from the consistency of maritime climates, the existence of generally arid climates makes the Colorado River Basin particularly susceptible to climate variability. Tree ring data dating back to the year 400 A.D. shows the extreme precipitation variations that can last for extended periods, notably the extended droughts that occurred during the Medieval Warm Period (see **Figure 6**).⁸ The potential natural 40% annual difference in precipitation in the headwaters causes concern for a river system that is dependent on snowmelt for the majority of its water.

Temperature and precipitation affect the runoff, evaporation, runoff efficiency, and the percentage of precipitation that leaves the watershed as runoff, all of which combine to determine stream flow (see **Figures 7, 8, 9**).

The average runoff is 45 mm/yr, which equates to a runoff efficiency of 13%, a low efficiency due to the arid climate and soils, which hold the water before it evaporates.⁹ For comparison the average runoff efficiency for a temperate climate that receives 900 mm of precipitation annually is 45%.¹⁰ The Colorado River Basin headwaters, with high precipitation and lower temperatures, provide a runoff efficiency of 20%, compared to the region's lowland's runoff efficiency of 0% to 5%. This once again highlights the importance of the headwaters on the entire Colorado River Basin, with most of the annual runoff contributed by headwater streams in Colorado, Wyoming, and Utah.¹¹

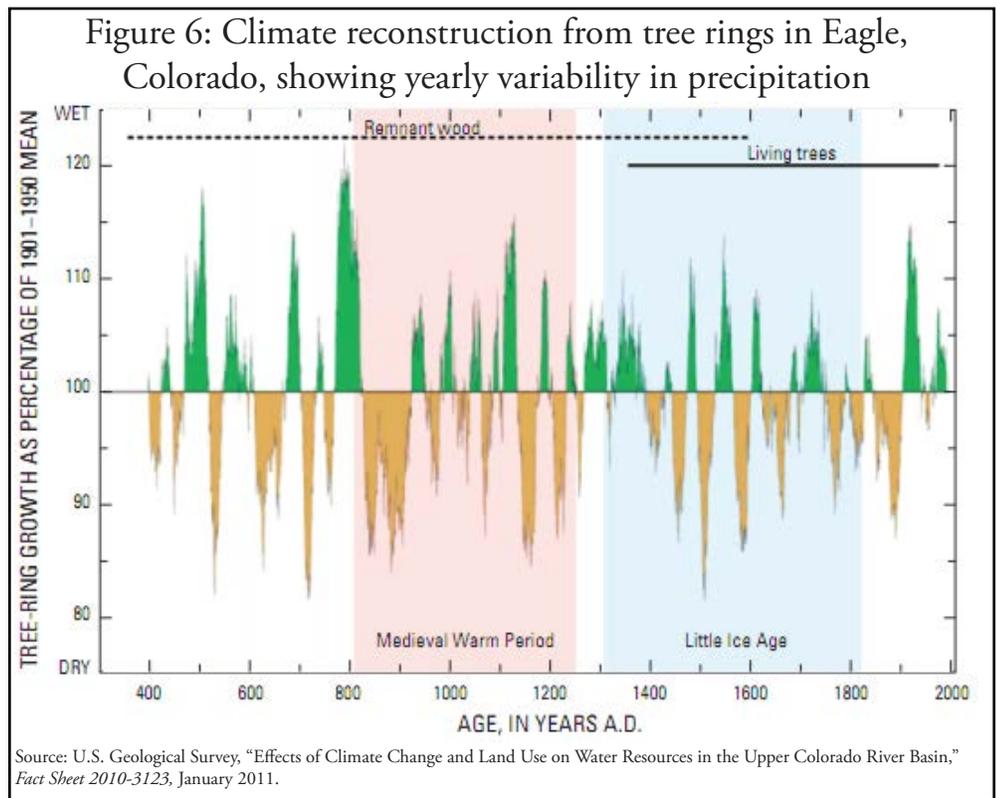


Figure 7: Average Runoff Efficiency, 1971-2000

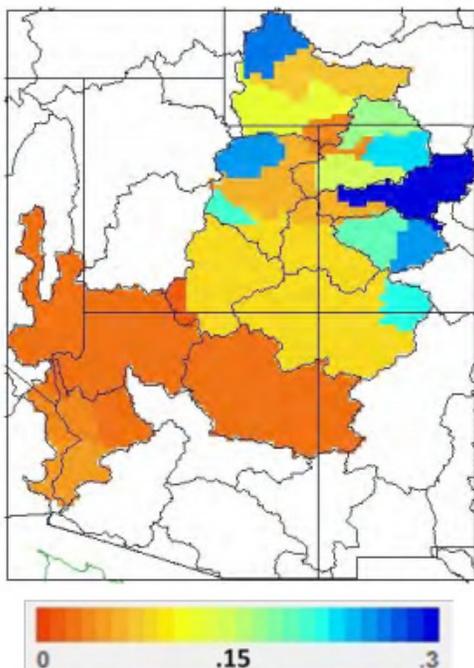


Figure 8: Average Annual Evapotranspiration (mm), 1971-2000

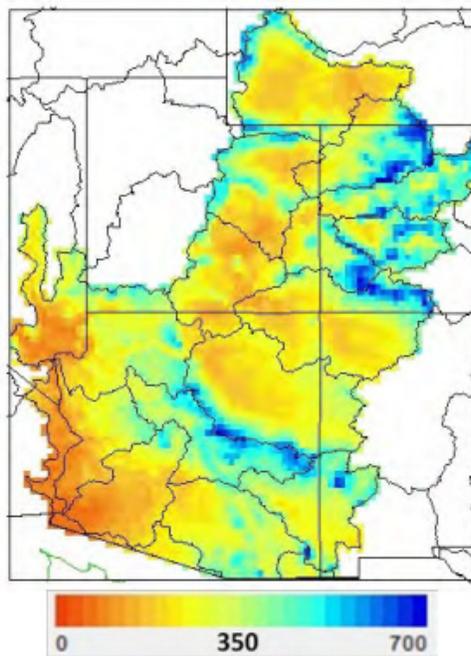
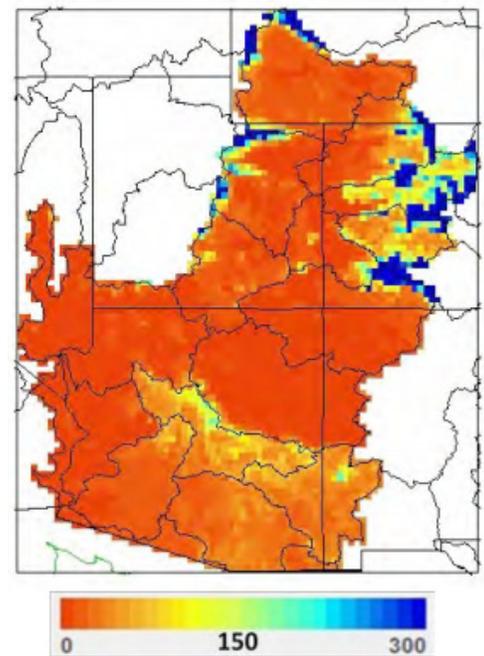
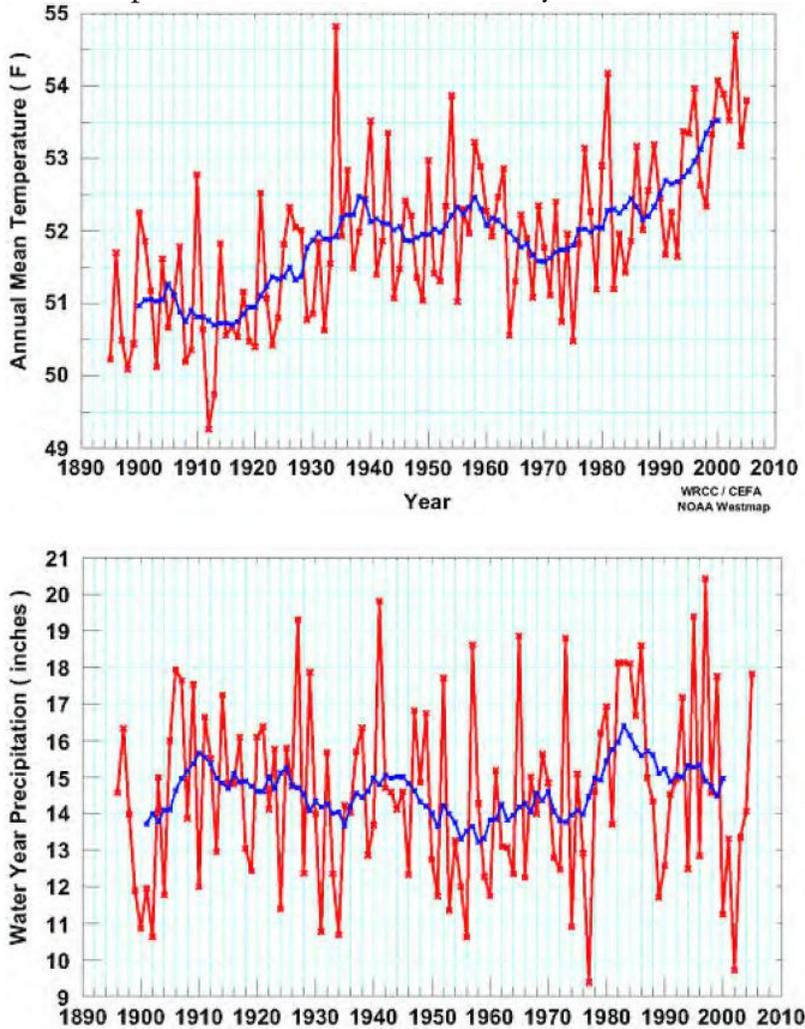


Figure 9: Average Annual Runoff (mm), 1971-2000



Source: U.S. Bureau of Reclamation Colorado River Basin Water Supply and Demand Study Study Team, "Technical Report B - Water Supply Assessment," Interim Report No. 1 - Colorado River Basin Water Supply and Demand Study, June 2011.

Figure 10: Average Annual Air Temperature (F) and Precipitation (inches) at Lees Ferry, 1895-2005

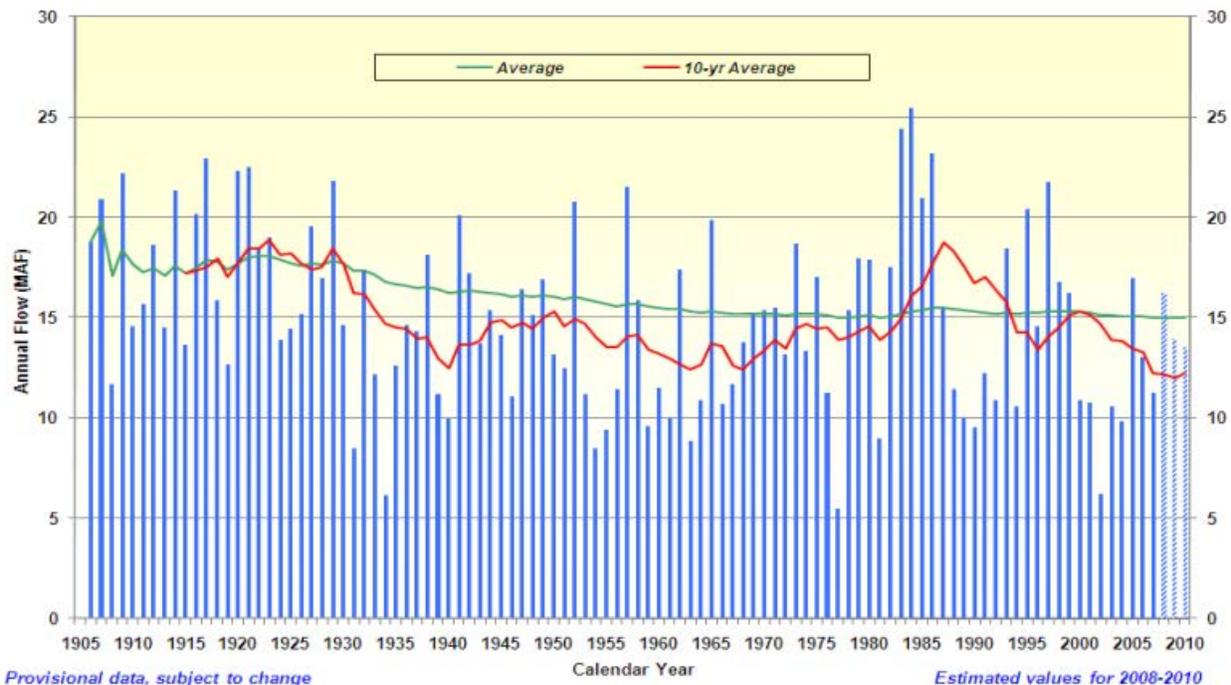


Source: U.S. Bureau of Reclamation Colorado River Basin Water Supply and Demand Study Study Team, "Technical Report B - Water Supply Assessment," *Interim Report No. 1 - Colorado River Basin Water Supply and Demand Study*, June 2011.

Whether anthropogenic or natural, climate change has already begun in the Colorado River Basin. Since the late nineteenth century, temperatures have risen nearly 1.4° Celsius, which exceeds levels of natural climate change with very high statistical confidence.¹² The annual average temperature has increased nearly 2°C at Lee’s Ferry, the dividing point between the Upper and Lower basin, since recording started in 1906 (see **Figure 10**). While temperature has shown marked increase, year-to-year precipitation has not changed significantly, but extreme annual variation is evident (see **Figure 10**). This small rise in temperature and the presence of droughts made the 2000-2010 the lowest runoff period in recorded history.¹³

The natural stream flow of the Colorado River varies significantly annually, but in recent years has been extremely low. Whether this is attributable to anthropogenic climate change is debatable, but the average natural flow, measured at Lee’s Ferry, was 15.1 million acre-feet (maf) annually from 1906-2005 with a maximum of 25.5 maf and minimum of 5.5 maf.¹⁴ Compare this data to the period of 2000 to 2008 when the average natural flow was 11.7 maf and the severity of the situation becomes apparent. The steady decline in average natural stream flow at Lee’s Ferry is beginning to threaten the Colorado River Compact and stress the already tenuous relations among managers of the basin (see **Figure 11**).

Figure 11: Natural Flow of the Colorado River Calculated at Lees Ferry, 1905-2005

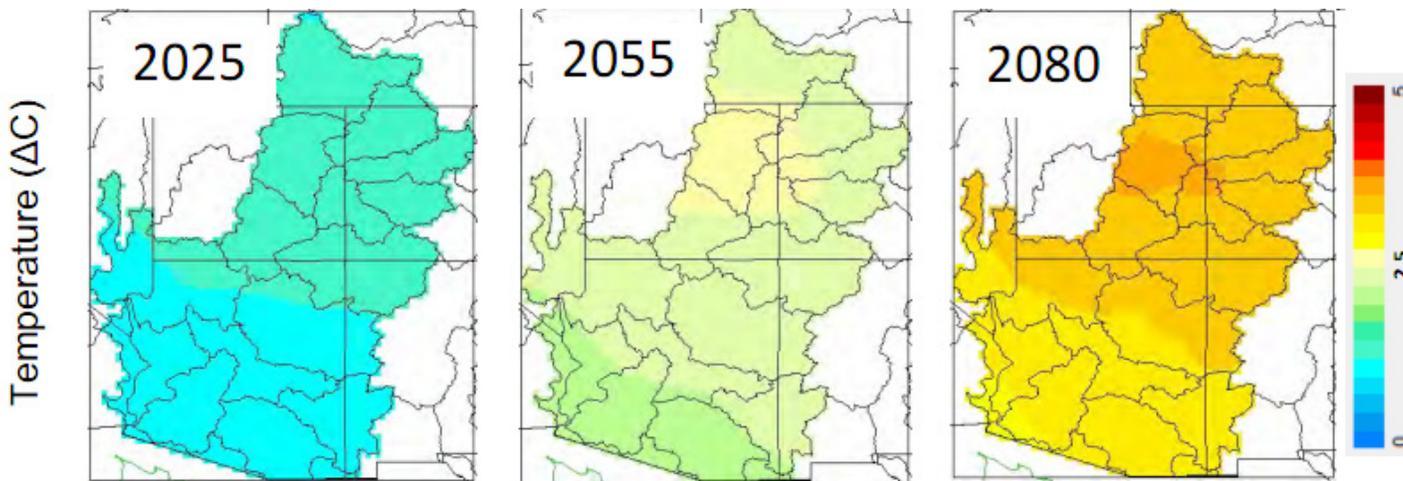


Source: U.S. Bureau of Reclamation, "Planning Hydrology based on Blends of Instrumental Records, Paleoclimate, and Projected Climate Information," A presentation from: *Workshop on Nonstationarity, Hydrologic Frequency Analysis, and Water Management*, Boulder, CO, January 13-15, 2010.

What is Climate Change in the Colorado River Basin?

As atmospheric greenhouse gas concentrations continue to increase, the effects of climate change on the Colorado River Basin will also respond to climate forcing. Current predictions from downscaled global climate models with a “business as usual” rate of greenhouse gas emissions predict a temperature increase of 1°C by 2025, 1.7°C by 2055, and 2.4°C by 2085¹⁵ (see **Figure 12**). The temperature increase will be the largest in the Upper Basin, where the majority of the precipitation falls. This is potentially dangerous because the high alpine areas, which are the largest contributor of water to the basin, are particularly vulnerable to climate change, although the vulnerability is partly due to the uncertainty of climate change on these high elevation areas.¹⁶

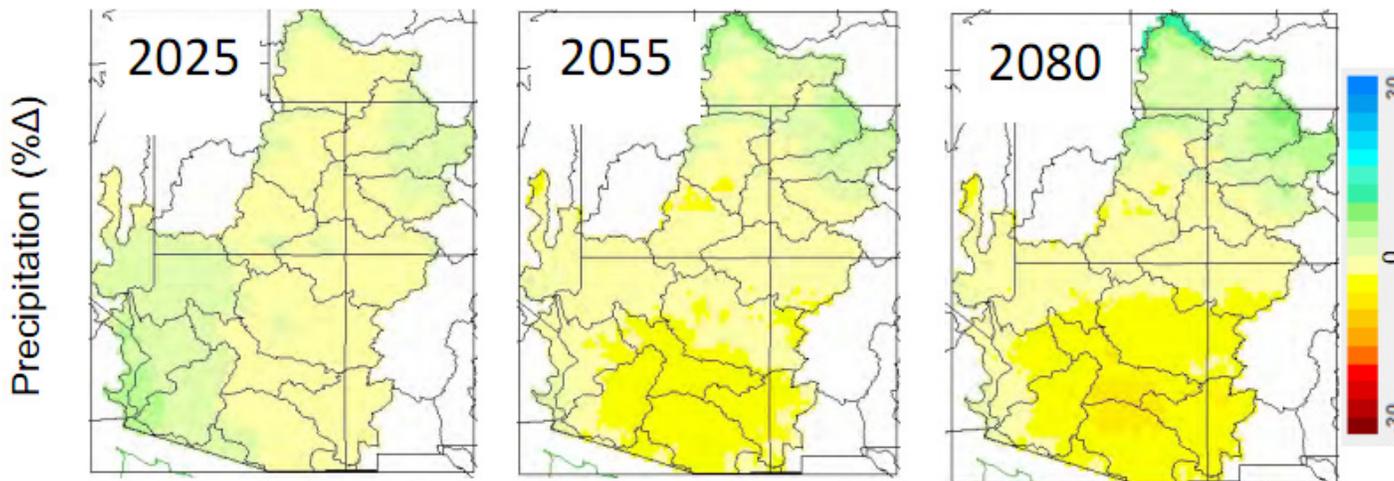
Figure 12: Mean Predicted Change in Temperature (°C)



Source: U.S. Bureau of Reclamation Colorado River Basin Water Supply and Demand Study Study Team, “Technical Report B - Water Supply Assessment,” *Interim Report No. 1 - Colorado River Basin Water Supply and Demand Study*, June 2011.

Climate change effects on precipitation will not be as noticeable as its effect on temperature because of the complex systems that govern precipitation. The predicted decrease in precipitation is 10 mm/yr (3%) by 2025, 20 mm/yr (6%) by 2055, and 10 mm/yr (3%) by 2085¹⁷ (see **Figure 13**). The location of precipitation will undergo a more drastic change than the amount, as the Lower Basin will become more arid with northern Arizona receiving 15% less water, and the headwaters area receiving more water, an increase of up to 10%.¹⁸

Figure 13: Mean Predicted Change in Precipitation

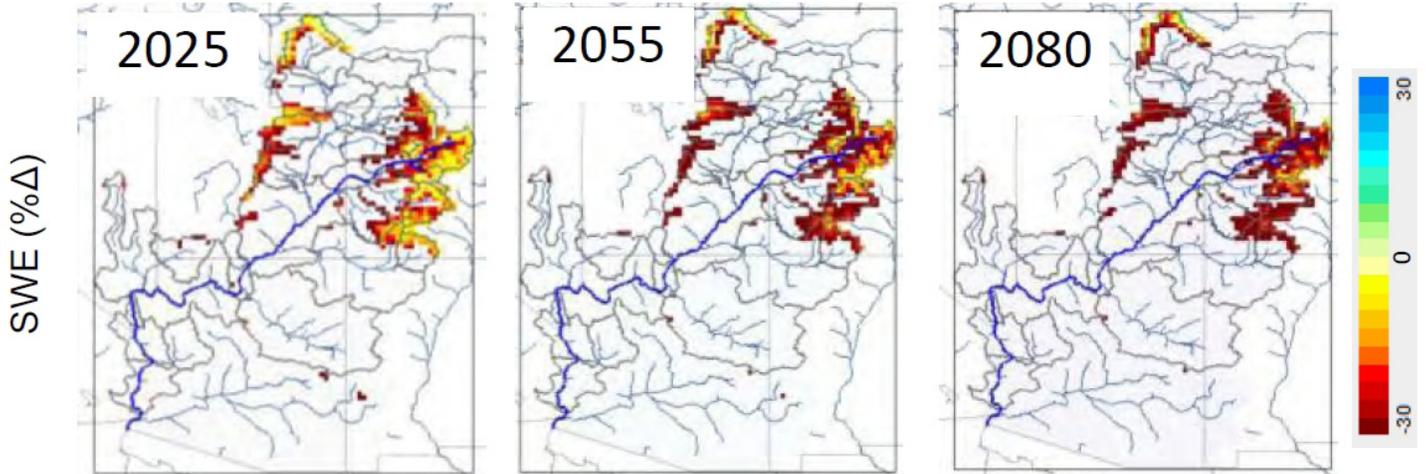


Source: U.S. Bureau of Reclamation Colorado River Basin Water Supply and Demand Study Study Team, “Technical Report B - Water Supply Assessment,” *Interim Report No. 1 - Colorado River Basin Water Supply and Demand Study*, June 2011.



Will Stauffer-Norris, Bald eagle on Lake Powell with the Navajo coal plant

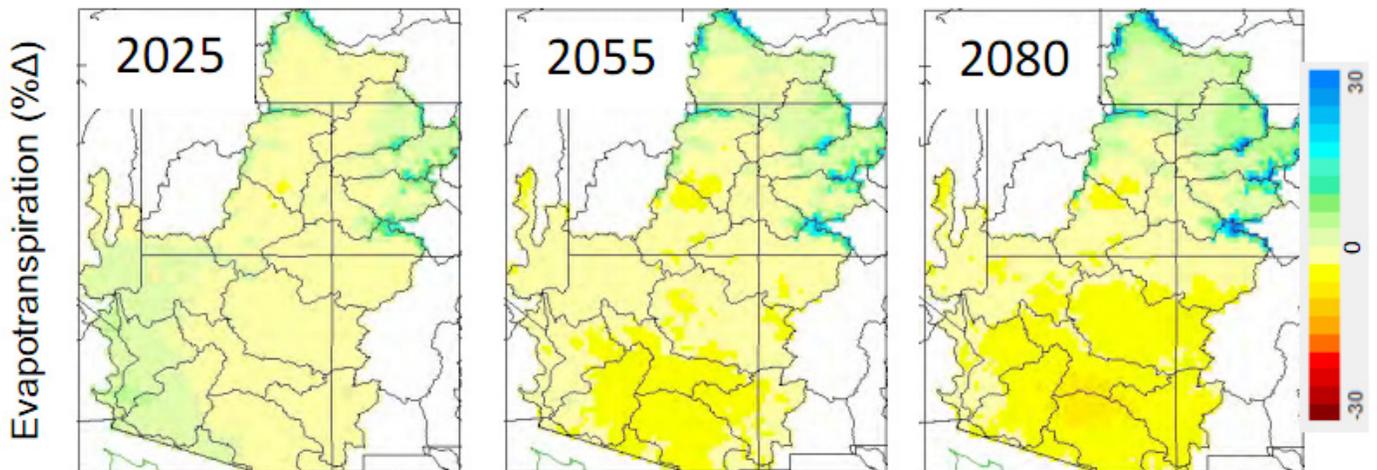
Figure 14: Mean Predicted Snow Water Equivalent (April 1st)



Source: U.S. Bureau of Reclamation Colorado River Basin Water Supply and Demand Study Study Team, "Technical Report B - Water Supply Assessment," *Interim Report No. 1 - Colorado River Basin Water Supply and Demand Study*, June 2011.

The main source of water, snowpack, will be impacted greatly by the increase in temperature and change in precipitation. Although the headwaters will receive slightly more precipitation, the increased temperature will result in a drastic decrease in the snow water equivalent, as shown in **Figure 14**. April 1st snow water equivalent, normally the largest amount of snow during the hydrologic year, from October 1st to September 30th, will decrease by 24% by 2025, 29% by 2055, and 30% by 2085.¹⁹ The reason for this drastic decrease in snow water equivalent is the increase in temperature, leading to more precipitation falling as rain rather than snow, and a potential decrease in winter and spring precipitation^{20,21} (see **Figure 15**). The area hit hardest by these changes will be the lower elevation alpine areas because of their natural proximity to the boundary between snow and rain and the greater chance of the ground being exposed by snowmelt.²²

Figure 15: Mean Predicted Change in Evapotranspiration

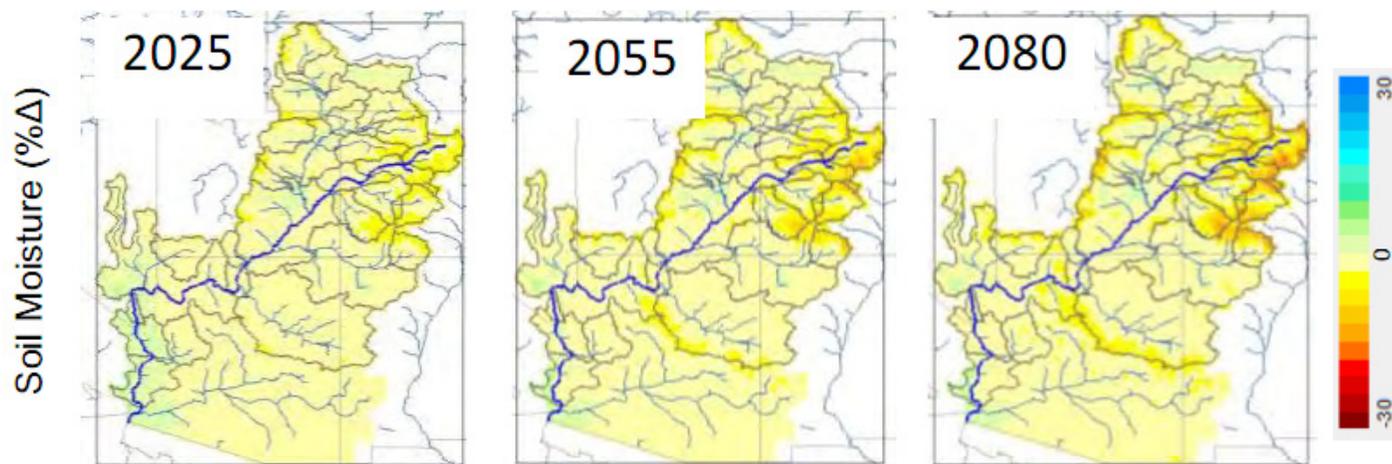


Source: U.S. Bureau of Reclamation Colorado River Basin Water Supply and Demand Study Study Team, "Technical Report B - Water Supply Assessment," *Interim Report No. 1 - Colorado River Basin Water Supply and Demand Study*, June 2011.



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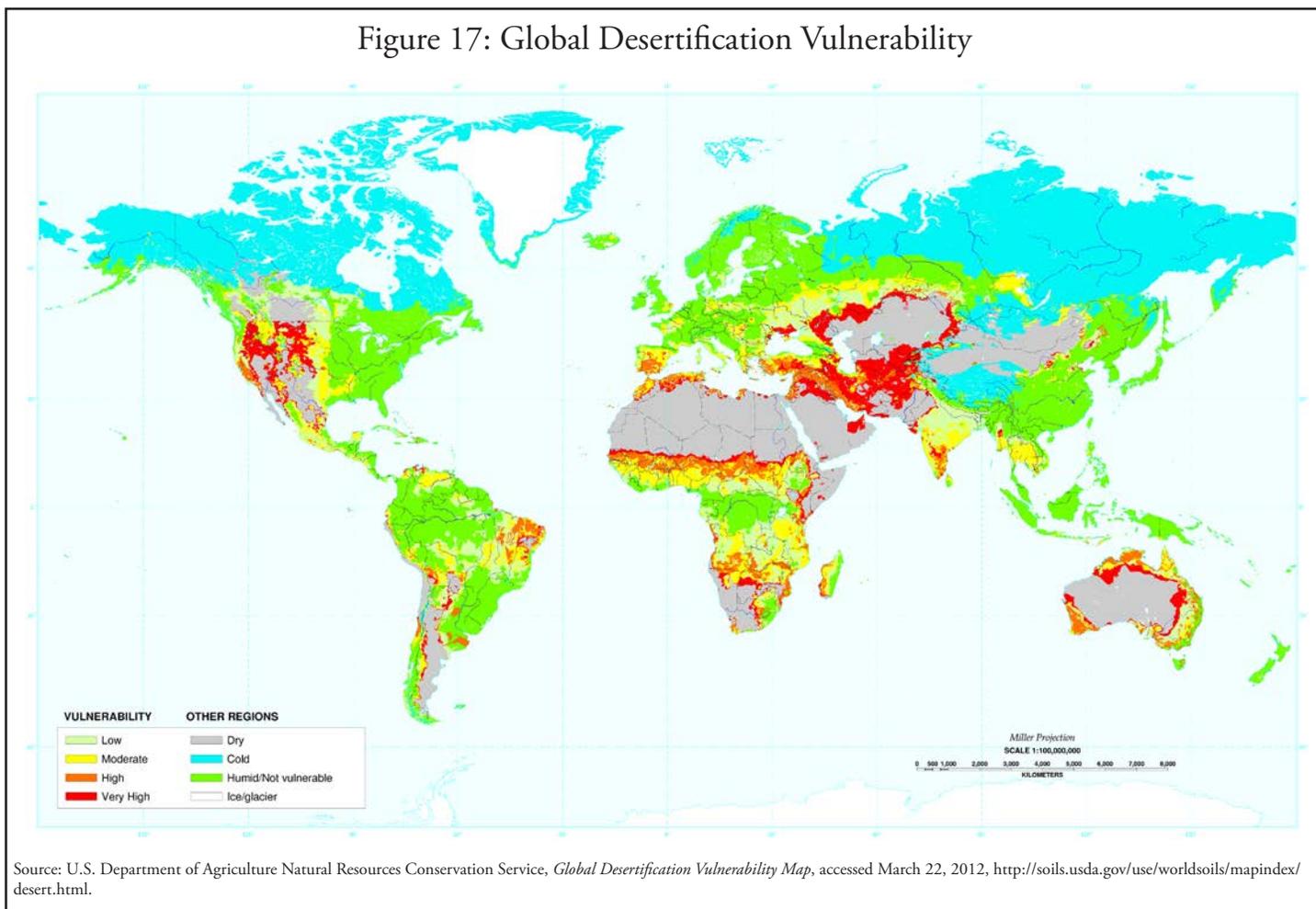
Figure 16: Mean Predicted Change in Soil Moisture (June 30th)



Source: U.S. Bureau of Reclamation Colorado River Basin Water Supply and Demand Study Study Team, "Technical Report B - Water Supply Assessment," *Interim Report No. 1 - Colorado River Basin Water Supply and Demand Study*, June 2011.

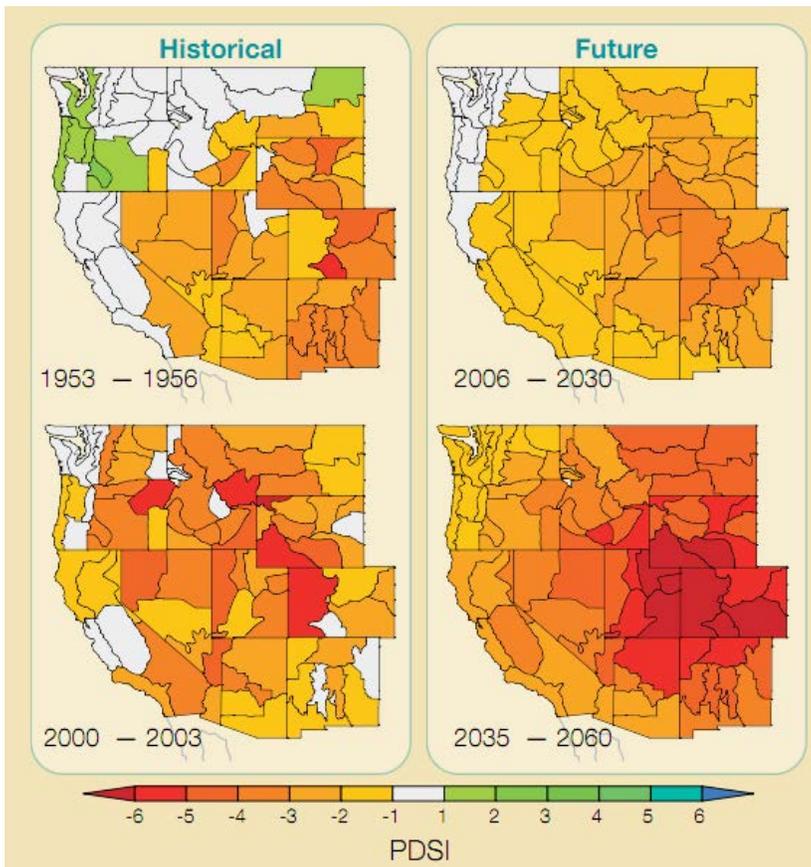
The increased projected temperature will also affect the soil moisture, which is an important factor in runoff. Already arid soils of the Colorado River Basin, especially the Lower Basin, are not predicted to dry significantly but the more moist soils of the Upper Basin will see a significant decrease in soil moisture (see **Figure 16**). The drier Upper Basin soils are predicted to result in reduced runoff due to greater percolation into the groundwater and absorption into the surface soils. The result is a predicted increase in desertification of the Upper and Lower Basins (see **Figure 17**).

Figure 17: Global Desertification Vulnerability



Source: U.S. Department of Agriculture Natural Resources Conservation Service, *Global Desertification Vulnerability Map*, accessed March 22, 2012, <http://soils.usda.gov/use/worldsoils/mapindex/desert.html>.

Figure 18: Palmer Drought Severity Index (PDSI)



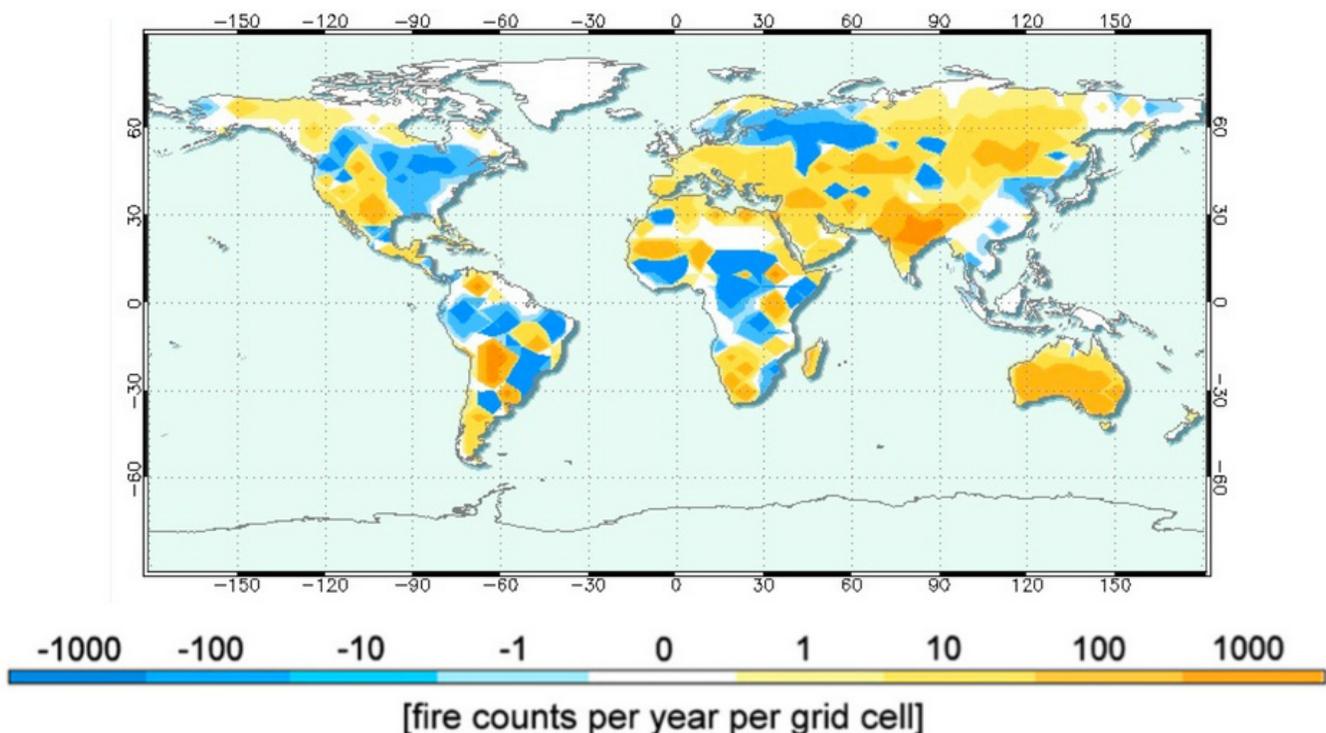
Note: Values less than -3 denote severe drought conditions

Source: Martin Hoerling and Jon Eischeid, "Past Peak Water in the Southwest," accessed March 22, 2012, http://wwa.colorado.edu/climate_change/docs/hoerling%20past%20peak%20water%20in%20press.pdf.

The lower precipitation, higher temperature, and desertification will create basin-wide drought conditions. The Palmer Drought Severity Index (PDSI), created by Walter Palmer in the 1960s, determines dryness using temperature and precipitation data. Between the years 2035 and 2060, the Upper Basin's moisture balance is predicted to be similar to the worst drought on record (see Figure 18). This expected desertification is potentially dangerous due to the feedback cycles that could result due to a drier climate. As Auden Schendler, the vice president of sustainability at Aspen Skiing Company, stated "It isn't the warmer temperature or lower precipitation that scare us; the potential feedback loops of climate change are what keep us up at night."²³

One of the most concerning feedbacks is the increased number and severity of fires. Under current greenhouse emission rates over coming decades, the fire risk in the West is predicted to increase by 30% to 60% by the end of the twenty-first century; even with reductions in emissions, the Southwest is extremely vulnerable to wildfires (see Figure 19).²⁴ Wildfires have the potential to create a feedback loop of their own due to the decrease in albedo, the reflectivity of a surface, and the reduction in vegetation. Reduced albedo would lead to land surfaces absorbing additional incoming solar radiation, therefore increasing basin temperatures, and leading to greater fire risk. Larger or more frequent fires could also lead to extremely unstable soils, which can easily lead to sedimentation or airborne dust.

Figure 19: Regional Projected fire activity changes under maximum emission scenario



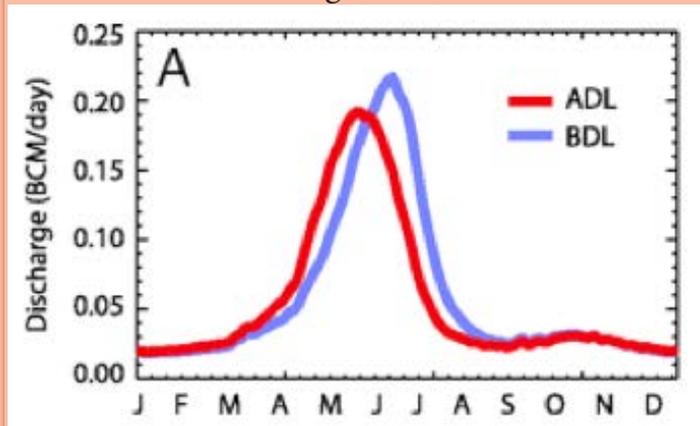
Source: U.S. National Aeronautics and Space Administration, accessed March 22, 2012, http://www.nasa.gov/images/content/492951main_Figure-3-Wildfires.jpg.

Case Study: Dust on Snow

The measureable temperature effects of climate change could produce significant runoff effects on the Colorado River Basin, but the feedback cycles are what frighten the experts. As Auden Schendler, the Vice President of Sustainability at Aspen Skiing Company stated “the potential feedback loops of climate change are what keep us up at night.”²⁵ One of the most dangerous feedbacks for the Colorado River Basin is desertification and the resulting dispersion of dust on snow. Water in the Colorado River Basin is largely dependent on snowpack from winter months melting slowly into spring and summer. It represents over 80% of the total water supply in the basin, and variability of high alpine zones to climate change make dust on snow a potentially devastating feedback loop.^{26,27} The dust increases the absorption of solar energy due to its lower albedo, the reflectiveness of a surface, therefore decreasing runoff and an earlier peak runoff.²⁸

The source of the dust that falls on the Colorado River headwaters comes from the Colorado Plateau and Basin areas due to agricultural uses that disturb the sensitive soils.²⁹ This has resulted in a increase of solar energy absorbed by 25-50 watts per square

Figure 20: Differences in runoff timing and volume between After Dust Loading (ADL) and Before Dust Loading (BDL) dust scenarios.



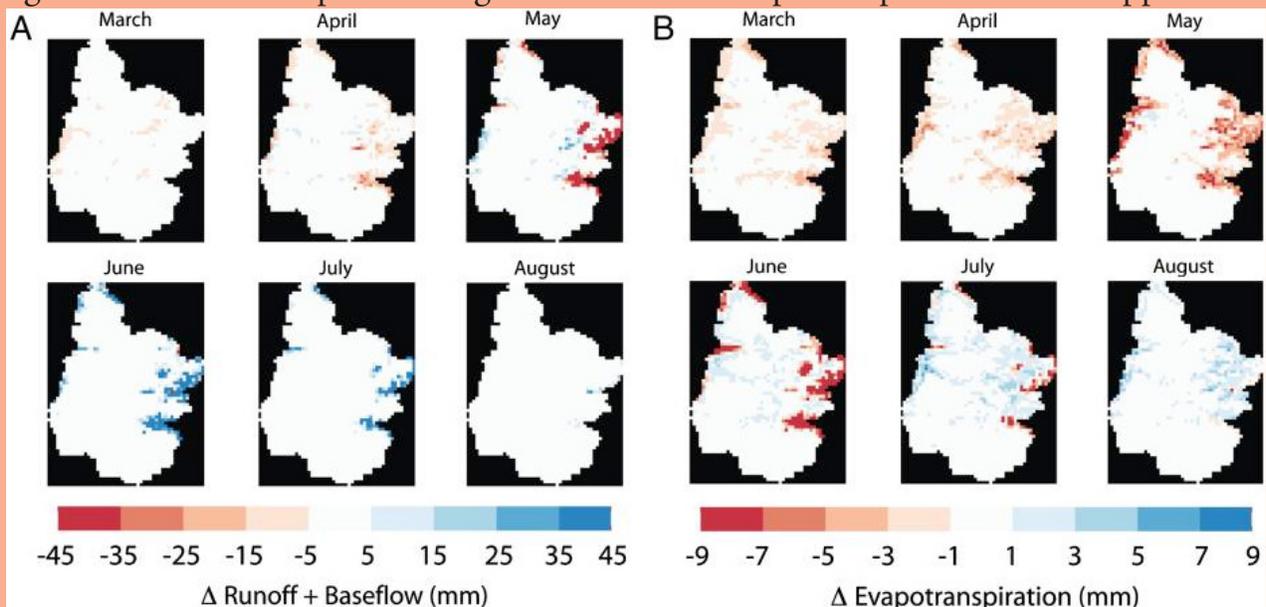
meter (W/m^2) in the eastern central Colorado River Basin, which when compared to the increase of energy due to greenhouse gases ($2 W/m^2$), illustrates the impact of dust on snow.³⁰ This influx of energy has resulted in a 27-35 day reduction in snow coverage compared to snow without dust in the Colorado headwaters.³¹ Extrapolated to the entire Upper Basin, the predicted flows at Lee’s Ferry show significant decreases in timing, on average three weeks earlier, and amount of runoff, one billion cubic meter or approximately 5% of the yearly average (see Figure 20).³²

These decreases in amount of runoff and changes in timing have the potential to cripple the Upper and Lower Basins of the Colorado River. The lower amount of runoff will stress an already over-allocated watershed and as loss of vegetative cover increase so will the desertification of the basin. The earlier snow-melt will also have feedback impacts in the basin by increasing the amount of evaporation of the water in streams and reservoirs and increasing evapotranspiration in the headwater areas due to sublimation,

water transforming from snow to water vapor and evaporating, and liquid water in the snowpack reaching plant life therefore being respired (see Figure 21).³³ Dust on snow is also vulnerable to changes in vegetation density throughout the basin, as the widespread existence of plants provides much needed stability to soils.

Although the role of dust on snow is well documented, research is needed on the effects of lower melt water runoff in the basin. This potential feedback loop will threaten the basin’s main water supply and cause disastrous results downstream. Current research initiatives, such as the Colorado Dust on Snow Program, are trying to discover the complex relations between snow, dust, and the Colorado River water.

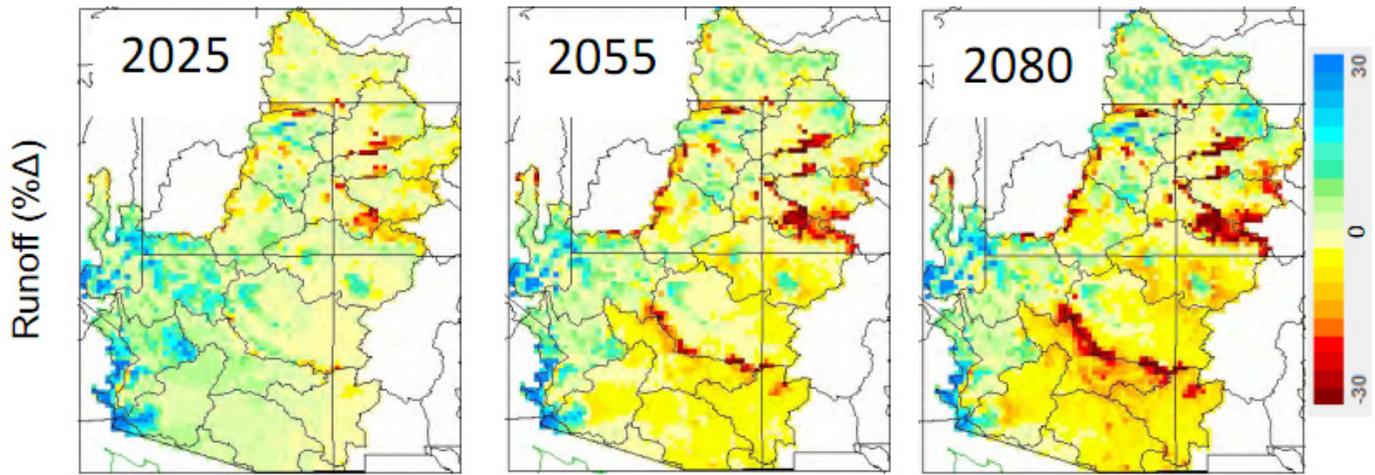
Figure 21: Simulated spatial changes in runoff and evapotranspiration in the Upper Basin



Note: (A) Spatial change in monthly average runoff (BDL–ADL) for March–August. (B) Spatial change in monthly average ET (BDL–ADL) for March–August. Note the difference in scales. Representation of runoff and ET in terms of depth (mm) is traditional for these studies and can be thought of as the depth of water across the entire grid cell. Each cell’s volume of runoff or ET comes from multiplying this depth by the area of the cell.

Source: Figures from Thomas Painter, “Response of Colorado River Runoff to Dust Radiative Forcing in Snow,” Proceedings of National Academy of Sciences 107, no. 40 (2010): <http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2951423/>.

Figure 22: Mean Predicted Runoff Change



Source: U.S. Bureau of Reclamation Colorado River Basin Water Supply and Demand Study Study Team, "Technical Report B - Water Supply Assessment," *Interim Report No. 1 - Colorado River Basin Water Supply and Demand Study*, June 2011.

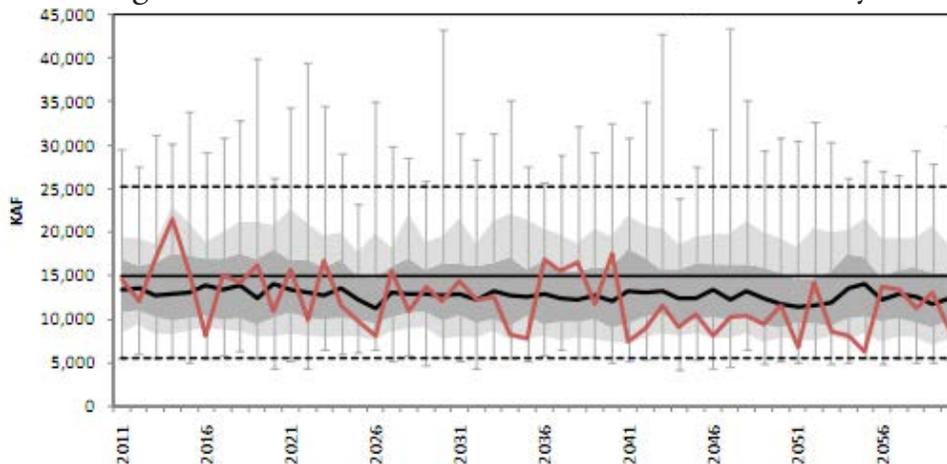
All of these results of climate change will combine to reduce runoff basin wide by a projected 6 mm/yr (14%) in 2025, 8 mm/yr (18%) in 2055, and 8 mm/yr (18%)³⁴ (see **Figure 22**). The hardest hit areas will be the headwaters and the mountains in central Arizona due to higher temperatures and reduced precipitation in this area. The lower runoff will drastically reduce stream flows through the basin as runoff represents the majority of water that constitutes stream flows in the Colorado River Basin.

Figure 23: Project changes in Colorado River Basin stream flow by mid-21st Century

Study	Global circulation models (runs)	Spatial scale	Temperature	Precipitation	Year	Runoff (flow)	Risk estimate
Christensen and others (2004)	1 (3)	VIC model grid (-8 mi)	+3.1°F	-6%	2040-69	-18%	Yes
Milly (2005) replotted by P.C.D. Milly	12 (24) (-100-300 mi)	CGM grids --	--	--	2041-60	-10% to -20% 96% model agreement	No
Hoerling and Eischeid (2007)	18 (42)	NCDC Climate Division	+5.0°F	-0%	2035-60	-45%	No
Christensen and Lettenmaier (2007)	11 (22)	VIC model grid (-8 mi)	+4.5°F (+1.8 to +5.0)	-1% (-21% to +13%)	2040-69	-6% (-40% to +18%)	Yes
Seager and others (2007)	19 (49)	CGM grids (-100-300 mi)	--	--	2050	-16% (-8% to -25%)	No
McCabe and Wolock (2007)	--	USGS HUC8 units (-25-65 mi)	Assumed +3.6°F	0%	--	-17%	Yes
Barnett and Pierce (2008)	--	--	--	--	2057	Assumed -10% to -30%	Yes

Source: U.S. Geological Survey, "Effects of Climate Change and Land Use on Water Resources in the Upper Colorado River Basin," Fact Sheet 2010-3123, January 2011.

Figure 24: Predicted annual natural flow at Lees Ferry



Note: Predicted annual natural flow at Lees Ferry. Median (line) 25th-75th percentile band (dark shading) 10th-90th percentile band (light shading) maximum (whiskers) selected individual realization (red line) and 1906-2007 observed mean, min, max (dashed lines)
Source: Christensen, Niklas S. "The Effects of Climate Change on the Hydrology and Water Resources of the Colorado River Basin." *Climate Change* 62, no. (2004): 337-363.

Many climatologists have modeled the expected changes in the Colorado River Basin with consensus on reduced flows, but the magnitude of the change is still being debated. These projections range from a 6% to 45% reduction in flow, with a consensus on a 15% to 20% decline by 2050 (see **Figure 23**).³⁵ The projected annual natural flow at Lee's Ferry shows that the variation of yearly flows will also be a factor that needs to be incorporated into future management (see **Figure 24**).

The Future of Climate Change in the Colorado River Basin: What do the Projections Mean?

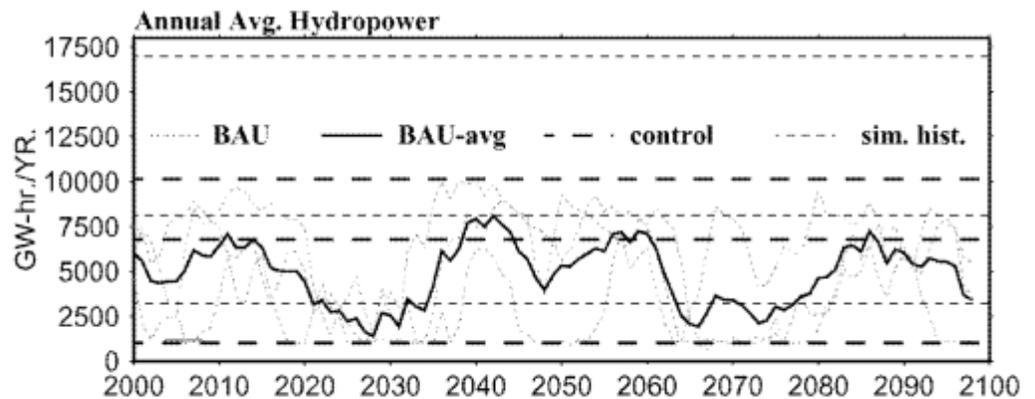
The effects of a modified climate will drastically change the way the Southwest uses Colorado River water. As a primarily rural, agricultural area, 78% of water is used for agriculture. Expected increased temperatures and decreased water availability have the potential to negatively affect the agricultural economy by raising the price of water high enough for lower value crops to become unprofitable.³⁵ The main culprit will be higher evapotranspiration and lower soil moisture due to increased temperatures, particularly for water-intensive crops. The effects on agriculture are disputed, but most agree that crops will require more water than they currently need to grow; however, there is a possibility of shorter time required for crops to mature due to the higher concentrations of carbon dioxide in the atmosphere.³⁶ Whether the predicted beneficial aspects of climate change occur or not, the agricultural sector is facing an uphill battle because of the reduced water availability and the increase in water needed for growing crops due to higher temperatures.

Just as the average annual temperature will rise, the yearly variation will increase. Coupled with lower water availability, these variables have the possibility to affect agriculture. The low flow years could potentially result in farmers having to fallow their fields or abandon crops due to insufficient water. This will only become more prevalent as the Southwest's population continues to grow and water storage becomes scarcer. In southern California, one of the largest consumers of Colorado River water for agriculture, there is a predicted 29% decrease in water deliveries due to projected climate change.³⁷ The other primary agricultural activity is ranching, which is just as susceptible to climate change as farming due to the necessity of water to grow feed, as well as provide water for livestock.³⁸

With the increased demand and decreased supply of water in the West, the cost of water will most likely increase. This increase is particularly dangerous to the agricultural sector for multiple reasons, including the large volume of water utilized by crops and the decreased irrigation efficiency association with increased evapotranspiration. Experts predict a loss of \$300 million per year in California's agricultural districts that rely on Colorado River water by midcentury, related directly to the effects of climate change.³⁹

Another major economic sector of the Colorado River Basin is hydropower electricity generation by basin dams. Currently the major dams of the Colorado River and its tributaries, primarily Glen Canyon and Hoover Dams, have the ability to produce over nine billion kilowatt hours per year (kWhr/yr).⁴⁰ Due to increased evapotranspiration and sedimentation behind dams, there is a predicted 53% decrease in hydropower production by the year 2080 (see Figure 25).⁴¹ This decrease in power, combined with the probable increase in energy prices, will have a significant economic effect on the Southwest. Many industries and municipalities are reliant on relatively cheap hydropower to provide services. An example of this is the Wellton Mohawk Irrigation District, a 65,000-acre agricultural zone in western Arizona. The agricultural operations only remain profitable due to the cheap power provided by Parker Dam, which allows them to pump water uphill to their fields.⁴²

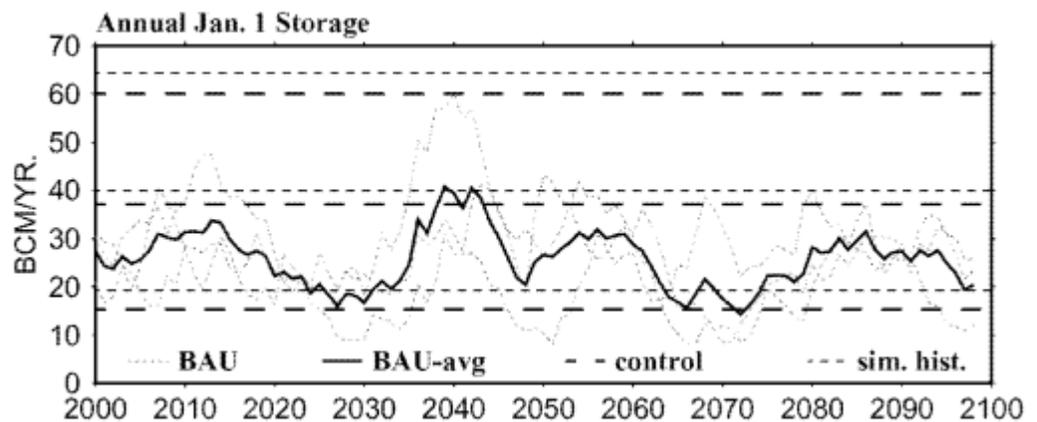
Figure 25: Predicted total annual hydropower production



Source: Christensen, Niklas S. "The Effects of Climate Change on the Hydrology and Water Resources of the Colorado River Basin." *Climate Change* 62, no. (2004): 337-363.

Storage capacity is another aspect of the Colorado River Basin that is vulnerable to climate change. A 10% to 20% reduction in annual flow has a predicted 30% to 60% reduction in annual storage.⁴³ Currently the maximum storage of all the dams in the Colorado River Basin is 60 maf since Lake Powell filled in 1983.⁴⁴ The predicted average annual storage for the years 2010-2039 is 20.08 maf (33% of potential storage), 2040-2069 is 21.91 maf (36%), and 18.99 maf (32%) for 2070-2099 (see Figure 26).⁴⁵

Figure 26: Predicted January 1st storage



Source: Christensen, Niklas S. "The Effects of Climate Change on the Hydrology and Water Resources of the Colorado River Basin." *Climate Change* 62, no. (2004): 337-363.

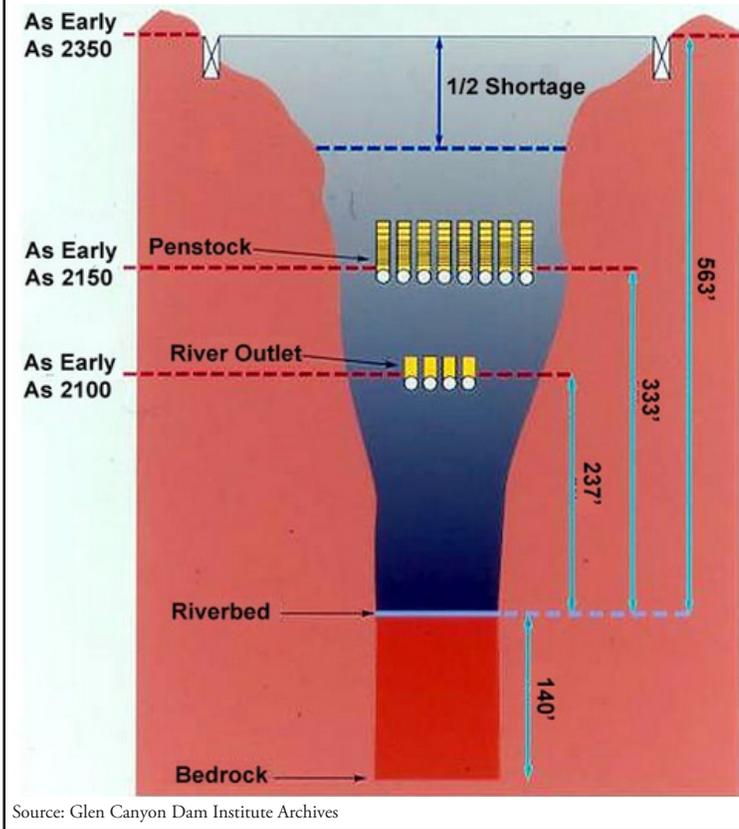
The cause for this large decline in average storage is mainly due to increased evaporation with higher temperatures. Due to the arid climate and large surface areas of the reservoirs, evaporation currently accounts for a 1.4 maf/yr loss from the large dams on the Colorado River, more than four times the consumptive water usage of Nevada.⁴⁶ As temperature increases the evaporative loss will continue to grow, further depleting the storage capabilities of the Colorado River. Another effect of rising temperatures is peak runoff

occurring earlier in the year, therefore allowing more time for the water to evaporate. The increased temperatures are responsible for an increase of 2 watts per square meter (W/m²) that has the potential to significantly alter the timing of peak runoff.⁴⁷ The increased exposure of snowmelt to the desert climate will result in an increase in evaporative losses.

The other element affecting the reservoirs on the Colorado River is sedimentation. Natural sediment loads once were carried all the way to the Gulf of California, creating the Colorado River Delta. As dams were installed in the basin, sediment began settling to the bottom of reservoirs, a process that slowly reduces storage capacity of the reservoirs from the bottom up. The largest recipient of sediment on the Colorado River is Lake Powell behind Glen Canyon Dam. Receiving over 100 million tons of sediment annually, the equivalent of nearly 30,000 dump trucks per day, the Glen Canyon Dam could be unable to produce power by 2150 and completely filled by 2350 (see Figure 27).⁴⁸

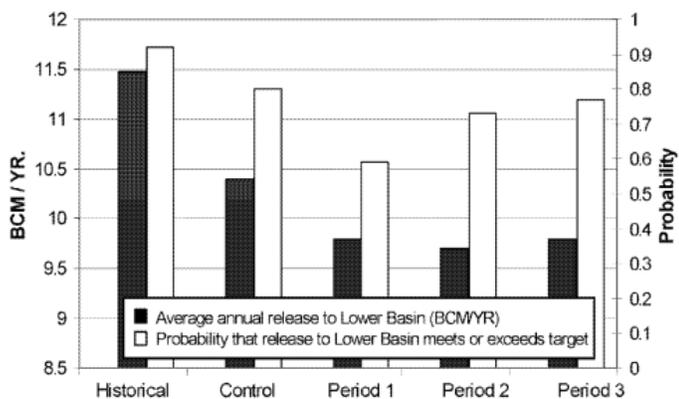
Ultimately the effects of climate change will result in difficulties to meet Colorado River Basin Compact requirements. The anticipated chance of releasing 8.23 maf annually at Lee's Ferry, the required amount from the Upper to Lower Basin, will only be met 59% of the time from 2010-2039, 72% of the time in 2040-2069, and 79% of the time in 2070-2099 (see Figure 28).⁴⁹ The average release is predicted to drop from 9.5 maf/yr to 7.9 maf/yr during the twenty-first century.^{50,51} The water delivery agreement with Mexico will also be tested, as the average release will drop to 0.9 maf/yr, well under the 1.5 maf/yr they are allocated.⁵² The chance of fulfilling 1.5maf is predicted to decline to 24% of the time from 2010-2039, 46% chance in 2040-2069, and 25% chance in 2070-2099 (see Figure 29).⁵³

Figure 27: Potential Sedimentation in Lake Powell behind Glen Canyon Dam



Source: Glen Canyon Dam Institute Archives

Figure 28: Simulated average annual release from Glen Canyon Dam to the Lower Basin and probability that release targets are met for simulated historical, control, BAU Periods 1-3



Source: Christensen, Niklas S. "The Effects of Climate Change on the Hydrology and Water Resources of the Colorado River Basin." Climate Change 62, no. (2004): 337-363.

Figure 29: Simulate average annual release from Imperial Dam to Mexico and probability that release targets are met for simulated historical, control, BAU Periods 1-3

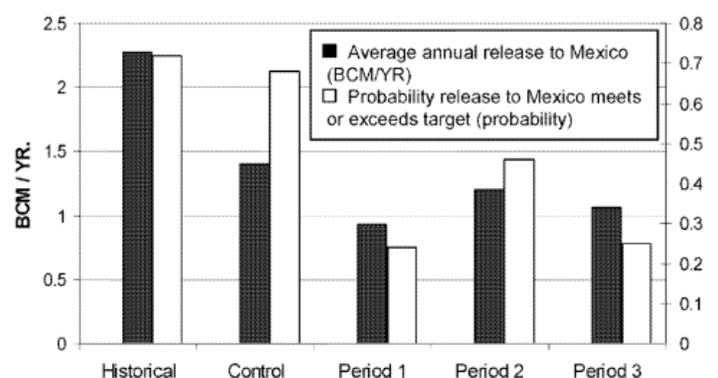
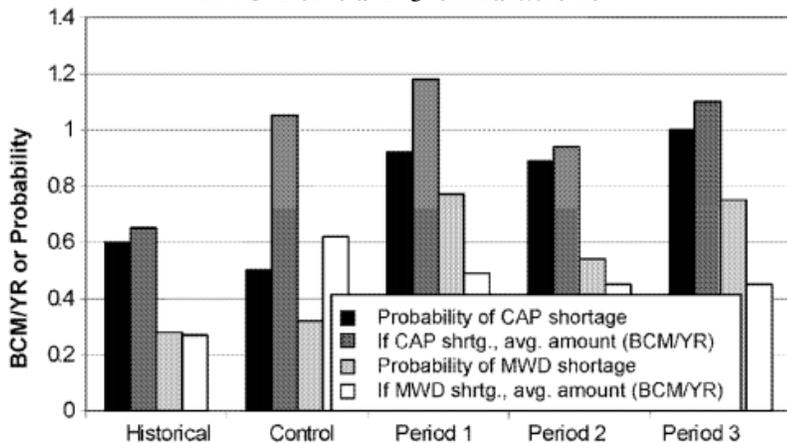


Figure 30: Probability of a delivery shortage to Central Arizona Project and metropolitan Water District; and average amount of shortages for simulated historical, control, and BAU Period 1-3 simulations



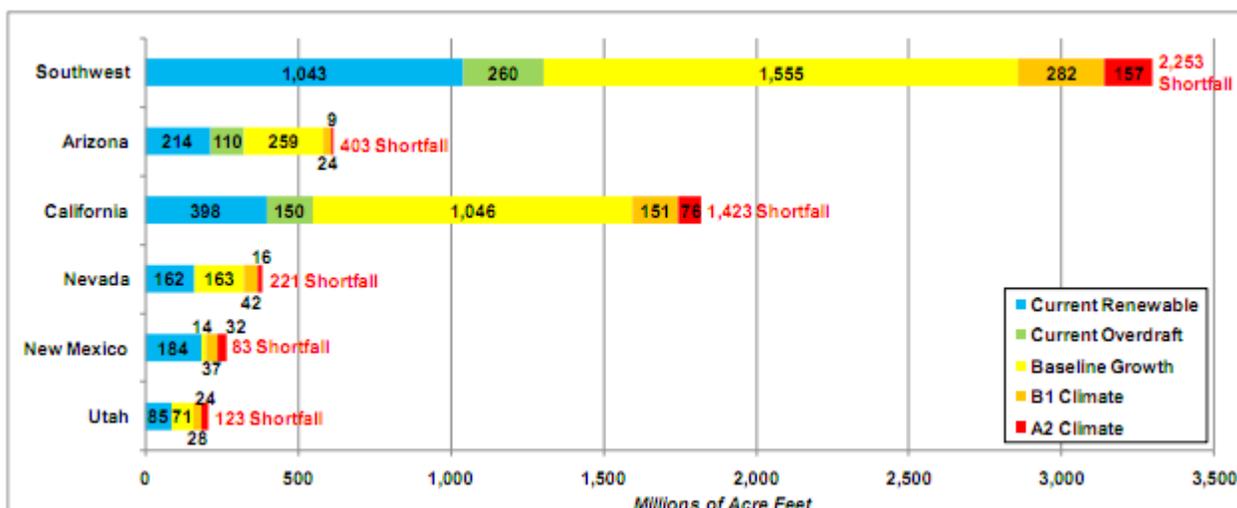
Source: Christensen, Niklas S. "The Effects of Climate Change on the Hydrology and Water Resources of the Colorado River Basin." *Climate Change* 62, no. (2004): 337-363.

Along with stressing the Compact, lower water availability will stress the metropolitan areas of Los Angeles, Las Vegas, and Phoenix. These water districts have restrictions that are based upon the level of the large reservoirs, mainly Lake Mead. Level 1 shortages, which entails the diversifying of water sources through ground water exploration and Central Arizona Project receiving 288,000 less acre feet per year, are expected to occur 92% of the time during 2010-2039, 89% of the time during 2040-2069, and 100% of the time during 2070-2099 (see Figure 30).^{54 55 56} The more restrictive Level 2 shortages, which include a Central Arizona Project receiving 360,000 less acre feet per year and basin-wide discussion on water conservation action, will need to be implemented 77% of the time during 2010-2039, 54% of the time during 2040-2069, and 75% of the time during 2070-2099.^{57 58 59}

potential effect of climate change on other sources of water? The largest alternative source of water is fresh groundwater, replenishment of which is extremely vulnerable to the increase in temperature and other aspects of climate change. The expected fresh groundwater use for the Southwest shows the unsustainable predicted increase in withdrawals and how climate change will affect the fresh groundwater reserves (see Figure 31).⁶²

The other potential source of water for the Colorado River Basin is the importation of water from nearby watersheds suggested by many decision makers within the basin.⁶³ This idea is limited by a few factors, as most of the surrounding area is extremely arid and has little water to offer, population is growing in the western U.S., climate change will likely adversely affect these sources, as well as the huge costs associated with transferring water.

Figure 31: Predicted Southwestern states groundwater use under a 'baseline' scenario of current climate change conditions combined with expected population and income growth; and under two climate change scenarios, comparing a mild (B1) and more severe (A2) climate forecast.



Source: Frank Ackerman and Elizabeth A. Stanton "The Last Drop: Climate Change and the Southwest Water Crisis." Stockholm Environment Institute, February 2011.

Adaptation to Climate Change in the Colorado River Basin

Projected climate change will have a significant effect on the Colorado River Basin. The question is how will the Southwest adapt to these changes? The rising temperatures, increased water variability, and desertification will stress an already fragile basin to new levels. The most important change for the basin is to install a fully adaptive management system, a structure process of decision making in the face of uncertainty by using knowledge gained to develop better management practices, which can cope with the drastic changes of climate change and the constant influx of better information (see Figure 32). This circular approach will ensure the inclusion of the most current data and stakeholders that will be essential in combating an extremely complex and changing problem.

Figure 32: Adaptive Management Cycle



Source: Conservation Measures Partnership, *Open Standards for the Practice of Conservation, Version 2.0*, October 2007, accessed March 27, 2012, http://www.conservationmeasures.org/wp-content/uploads/2010/04/CMP_Open_Standards_Version_2.0.pdf.

In addition to a new management plan, new technologies to offset the increased temperature and evaporation are needed. As the primary water user, agriculture's involvement in implementing new water efficient practices is essential. Some progress has been made in the last few years that can be extrapolated to the entire basin. For example, lining irrigation canals can prevent water from seeping into the groundwater. The largest canal-lining project was the lining of 23 miles of the All-American Canal. This project saves over 70,000 acre feet annually from entering the groundwater table and similar projects have potential to save valuable surface water.⁶⁴ This prevention of surface water entering the groundwater table

can also be seen as restricting the replenishment of groundwater reserves.

Another way to offset the increased evaporation is storing water underground. Artificially replenishing aquifers is currently being done by a number of water districts. Southern Nevada Water Authority's artificial aquifer replenishment program stores water during the wet months and extracts it during the dry; annual average artificial replenishment is 13 to 18 feet.⁶⁵ A similar project has been operating in central Arizona for nearly 15 years now and represents the largest artificial aquifer replenishment with a potential 376,000 acre-feet per year of water being replenished.⁶⁶ There are many large, mainly depleted aquifers in the Lower Basin that could be refilled during extreme high water years or by undesirable water such as water from a grey or brown system.⁶⁷ Underground storage is attractive because it eliminates evaporative loss, which is responsible for 3% to 5% loss of water stored annually in Lake Mead.⁶⁸ The drawback of underground storage is the amount of energy required to pump water into the ground.

Some of the proposed new sources of water are controversial and none are more debated than cloud seeding, the practice of introducing silver iodine or dry ice into the atmosphere to condense gaseous water into liquid. Some American states have been cloud seeding for years to offset the effects of droughts and increase agricultural production or decrease the intensity of storms.⁶⁹ In 2006, the state of Wyoming started a pilot project of cloud seeding over the Medicine Bow, Sierra Madre, and Wind River mountain ranges to evaluate the effectiveness of cloud seeding.⁷⁰ The economic analysis of the potential revealed that a 10% increase in snowpack as a result of cloud seeding would equate to \$2.4 to \$4.9 million of water.⁷¹ Comparing the price of water, purchased from the High Savery Dam at \$158.93 per acre foot versus cloud seeding costs of \$6.60 to \$13.00 per acre foot, shows the massive potential for cloud seeding in the West.

Importing water from outside the Colorado River Basin occurs rarely, but currently the prospects of increased precipitation in other regions have sparked the idea. Certain areas, especially flood-prone ones like the Mississippi, would benefit in transferring some of their water west to the Front Range of Colorado, which currently relies heavily on Colorado River water through trans-mountain diversion.⁷² The obstacle is the cost of infrastructure to deliver the water nearly 1,500 miles away. The energy required to move water up nearly 5,000 feet would also be extremely expensive and currently impractical. Other ideas including piping water south from the Northwest, but the large mountain ranges in between make this an unlikely solution as well.

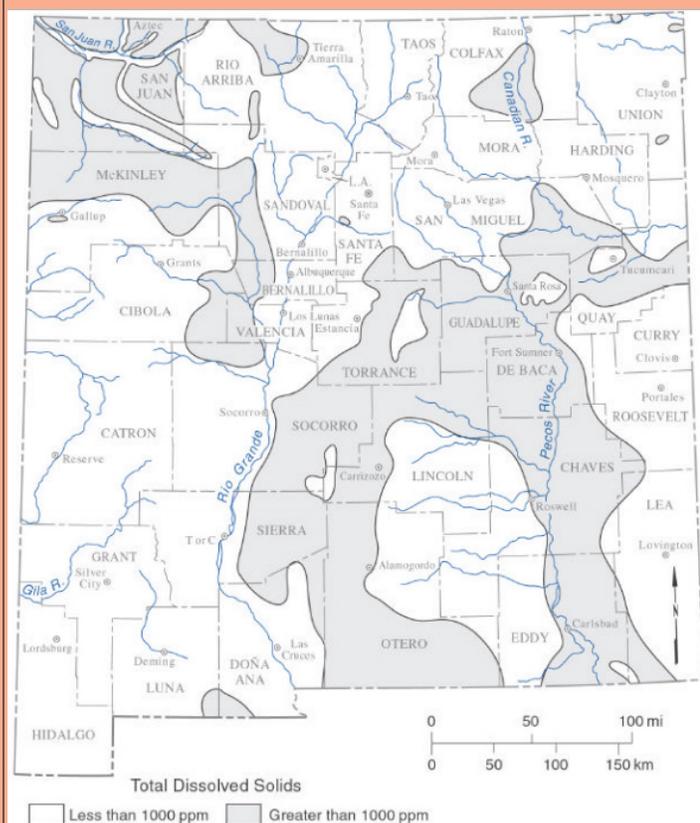
Case Study: Desalination

As the need for new sources of water increases, due to depletion of fresh water, desalination of brackish groundwater has potential to provide the Lower Colorado River Basin with a viable and extensive source of water. There are over 1.5 billion acre-feet of brackish groundwater, defined as containing 1,000 to 10,000 milligrams per liter (mg/L) of dissolved solids, in Arizona and New Mexico alone (see Figure 33, 34).^{73 74} This vast amount of brackish water could provide the entire Lower Basin with 200 years of its apportionment, 7.5 million acre-feet. The groundwater is also being replenished by agricultural runoff, which accounts for 78% of water use throughout the basin, making desalination of brackish groundwater a potentially sustainable water supply. The major obstacle for desalination is the energy required for treatment and large infrastructure required to supply a substantial amount. Recent developments in new desalination technologies have reduced the cost of desalinating low salt concentration water, 1,000 to 5,000 mg/L of total dissolved solids, to \$325.85 to \$977.55 per acre foot of water, compared to the average of \$700.00 per acre foot now paid for municipal water in parts of the Lower Basin or as low as \$15 for agricultural water.^{75 76 77}

Figure 34: Map of brackish water reserves in Arizona



Figure 33: Map of brackish water reserves in New Mexico



Source: Edwin McGavock, "Desalination of Brackish Groundwater in Arizona," Errol L. Montgomery & Associates Inc. (2008): 1.

The potential uses of desalinated brackish water are numerous and the water can be treated to precise concentrations of dissolved solids to reduce cost when water quality is not as important, for example, in mining or energy production water use. Increasing and diversifying domestic water supplies is particularly attractive to metropolitan areas within the Colorado River Basin, due to their water rights being junior to agricultural water rights and recent population growth. Currently, Las Vegas, Phoenix, and Tucson are evaluating groundwater desalination opportunities and smaller cities such as Scottsdale and Abilene have already built desalination plants for groundwater.⁷⁸ The plants can range from 10 million gallons per day (30 acre-feet per day) to 30 million gallons per day (90 acre-feet per day), which would provide a significant portion of municipal uses.⁷⁹

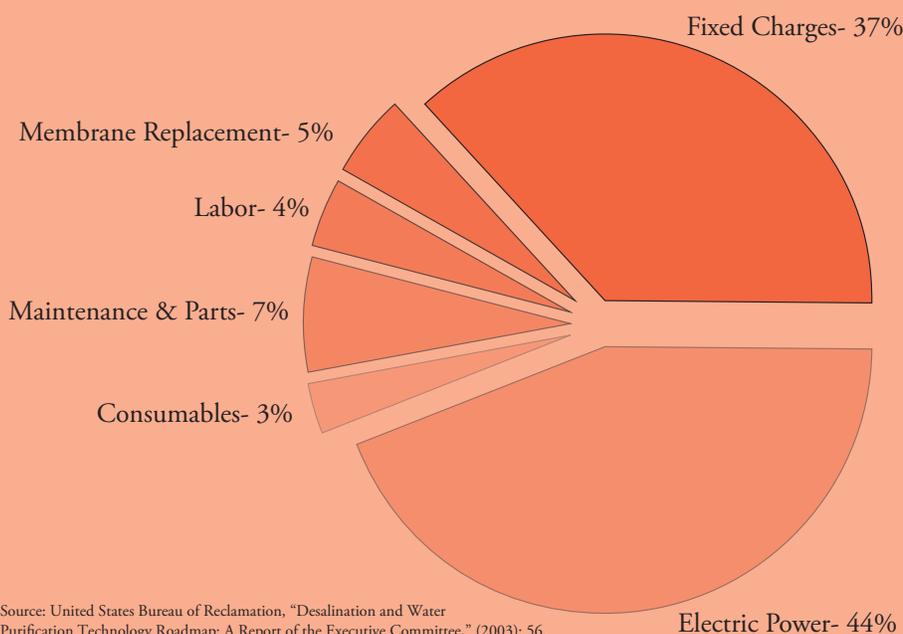
Another potential benefit of building desalination plants is the possibility of having to desalinate Colorado River water to comply with Total Maximum Daily Load (TMDL), a subsection of the Clean Water Act that designates the maximum total dissolved solids for wastewater treatment or industrial uses.⁸⁰ Although not currently being implemented in the Colorado River Basin, there is that possibility due to the impacts of possible future oil shale production and present agricultural runoff, which both influence water quality.

Source: Peggy Johnson, "Hydrogeological Mapping and Assessment of Saline Aquifers," New Mexico Groundwater Assessment Program Workshop (2004): 11, <http://web.archive.org/web/20100604122806/http://wrii.nmsu.edu/conf/brackishworkshop/presentations/johnson.pdf>.

While desalination of groundwater has promise to provide a large enough water source to adapt to reduced water runoff due to climate change, it still has its flaws. The major flaw is the energy use and cost (nearly seven to eight times the cost of fresh water treatment) needed to pump the brackish water through reverse osmosis membranes (see **Figure 35**).⁸¹ This large energy need is likely to be met by fossil fuels, which will only increase the concentration of greenhouse gases, exacerbating the climate change issue, or by large solar plants, which are currently extremely expensive. Disposal of the waste product, an extremely salty slurry, which is between 25% and 40% of the input, provides another expense and environmental issue.⁸²

Treatment cost for fresh water from a conventional water treatment plant	\$0.30-0.40/1000 gallons
Reclaimed water for industry in Southern California	\$2.22/1000 gallons
Treatment cost for desalinated brackish water for residential use	\$1-3/1000 gallons
Treatment cost desalinated seawater	
Santa Barbara, CA (1992)	\$5.50/1000 gallons
Cyprus-2 (1999)	\$3/1000 gallons
Tampa Bay (2001)	\$2.08/1000 gallons
Source: United States Bureau of Reclamation, "Desalination and Water Purification Technology Roadmap: A Report of the Executive Committee," (2003): 52.	

Figure 36: Potential reductions in desalination process



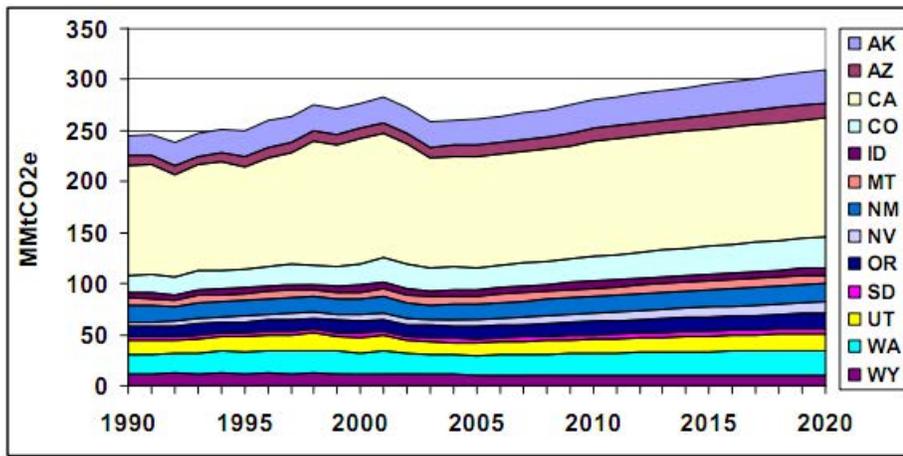
In 2003, the Bureau of Reclamation, along with consultants, released the *Desalination and Water Purification Technology Roadmap*, with the aim to increase technology development and awareness of desalination opportunities. The report details the cost breakdown of desalination and the possible reductions in energy use and maintenance cost that could make desalination a viable alternative to Colorado River water (see **Figure 36**).⁸³ The extensive report illustrates the belief, despite the current issues of desalination, that brackish groundwater is a promising future water source in the Southwest.

Source: United States Bureau of Reclamation, "Desalination and Water Purification Technology Roadmap: A Report of the Executive Committee," (2003): 56.



Zach Yates

Figure 37: Current and predicted carbon dioxide emissions in the Western United States



Source: Center for Climate Strategies and Western Regional Air Partnership "Greenhouse Gas Emission Inventories and Forecasts for Nine Western States," accessed March 22, 2012, <http://www.epa.gov/ttnchie1/conference/ei16/session3/roe.pdf>.

Mitigation of Climate Change: What can the Next Generation Do?

Adaptation presents the most achievable approach due to the uncertainty of climate change, but mitigation by reducing greenhouse gas concentrations in the atmosphere is the only true solution. Currently the western United States emits 250 million metric tons of carbon dioxide and this figure is expected to grow (see Figure 37).⁸⁴ Although the Rockies region has vast reserves of traditional fossil fuel energy sources, including coal, natural gas and oil, use of these fossil fuels will only continue to contribute to climate change.

In order to slow the rate of emissions, the Colorado River Basin, in particular, and the United States, in general, need to maximize use of renewable energy resources. The potential for renewable energy sources such as wind, solar, and biomass is vast (see Figure 38). Capitalizing on these resources in the Rockies region alone could potentially reduce carbon dioxide emission by 87 million metric tons per year or nearly 34% of America's carbon dioxide emissions.^{85 86 87}

Carbon sequestration of emissions from continued use of fossil fuels has recently gained steam due to the limitations of renewable energy and sequestration's effectiveness in combating climate change. The relatively arid climate of the Colorado River Basin limits the potential for sequestration through biomass, but the large underground petroleum fields and saline aquifers provide ample space for possible underground sequestration. Geo-sequestration, the process of injecting carbon dioxide into old oil wells or aquifers, has proven to be effective and plausible on a large scale in the United States, with over 6,000 square miles of rock formations having been mapped for sequestration purposes.⁸⁸ There are potentially dangerous side effects of carbon sequestration, primary the risk of release during an earthquake or seismic event and the destabilization of geology by the pressure of inputting gases.⁸⁹

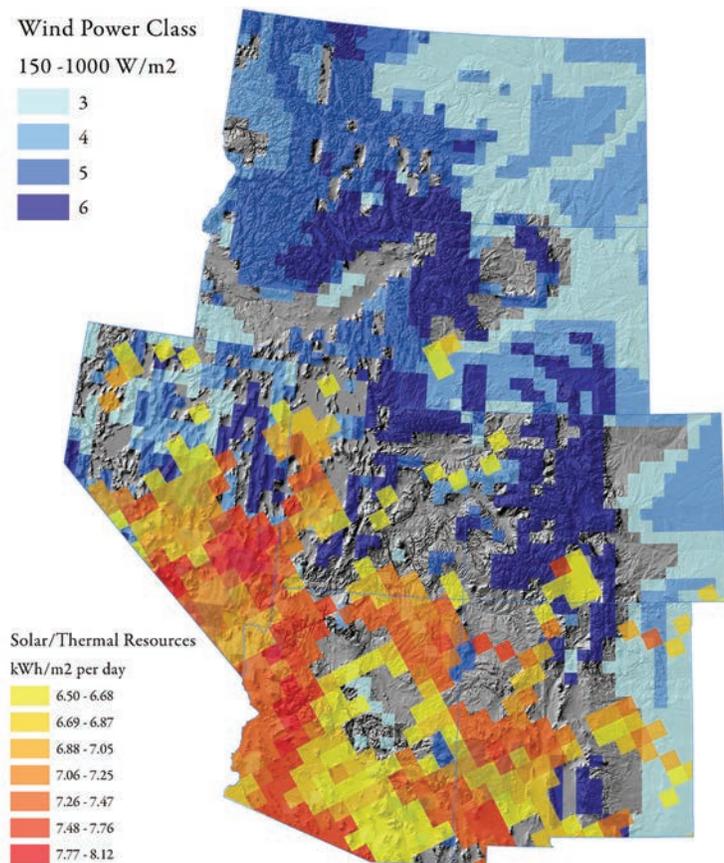
Mitigation of climate change is a daunting task for a multitude of reasons, but none are bigger than the

global scale of reductions in carbon discharge into the atmosphere required to reduce its impacts. As the ultimate "tragedy of the commons," global climate change will require the cooperation of all countries, and ultimately all people. A bottom-up approach is unlikely to be successful because the near-term effects of climate change will not be significant enough to impact the lives of humans until the globe is beyond the tipping point of climate change, meaning feedback cycles have begun that are extremely difficult to stop.⁹⁰ This dilemma puts the burden on governments to foresee the effects of climate change and take the necessary steps to mitigate climate change.⁹¹

Conclusion: Will the Twenty-First Century be Nasty?

The Colorado River Basin stands at a crossroad today. Water demand has recently exceeded supply, deliveries to Native Americans and Mexico are problematic, and infrastructure is slowly becoming outdated and inefficient. As these evident problems persist, the looming threat of climate change must be added to discussions and basin-wide management. Without careful planning for climate change adaption and lobbying for mitigation, the decrease in stream flow due to climate change will overwhelm all other issues. The

Figure 38: Renewable energy potential in the Western United States



Source: Department of Energy, National Renewable Energy Lab

conservative estimate for stream flow decrease by mid-century of 6% would still threaten the entire basin, from agriculture to municipalities.

Offsetting such a formidable challenge cannot be done in years, decades, or even centuries, but will take constant adaptation to changes in climate and water needs. This flexible adaptive management approach will continually challenge the current Law of the River, and the necessary changes cannot be enacted overnight. While the shortsighted problems of water supply for this year's crops or cities are necessary issues, without a long-term management plan that includes adapting to and mitigating climate change, the basin will inexorably move towards crises. The Colorado River represents the lifeline of the Southwest to over 30 million people. Without consideration of climate change and its effect on water availability, the once productive Southwest will return to its desert roots.

What can today's youth do in the face of such challenges? Traditional approaches to water management in the Colorado River Basin must become more flexible at a minimum, and may even need to be replaced by new management guidelines and legal constructs. The section of this *Report Card*: "Laws of the Colorado River Basin: Obsolete or Flexible for a Sustainable Future?" faces this conundrum head-on. In addition, the results of the Rockies Project's survey of college-age youth opinions about Colorado River Basin issues and management bring fresh perspectives to the debate. In the end, it is vital that today's youth become engaged and involved in how our precious natural resources in the basin are managed, for they will soon inherit the results!

¹Richard Seager, "Model Projections of an Imminent Transition to a More Arid Climate in Southwestern North America," *Science*, no. 316 (2007): 1181 <http://www.sciencemag.org/content/316/5828/1181.short>.

²United States Bureau of Reclamation. *SECURE Water Act Section 9503(3): Reclamation Climate Change and Water Report to Congress*. 2011, 7.

³Jonathan Waterman, *Colorado River Basin: Balancing a Limited Supply with an Increasing Demand*. Accessed June 20th, 2011, <http://www.environment.nationalgeographic.com/environment/freshwater/colorado-river-zoomifier/>.

⁴Niklas Christensen, "The Effects of Climate Change on the Hydrology and Water Resources of the Colorado River Basin," *Climatic Change* 62, no. 1-3 (2004): 350, <http://www.springerlink.com/content/t66120x0hw672395/>.

⁵USGS Publication "What is a Desert." Accessed August 3, 2011, <http://pubs.usgs.gov/gip/deserts/what/>.

⁶United States Bureau of Reclamation. *SECURE Water Act Section 9503(3): Reclamation Climate Change and Water Report to Congress*. 2011, 18.

⁷*Ibid.*, 23.

⁸*Ibid.*, 24.

⁹Niklas Christensen, *Climatic Change*, 350.

¹⁰*The Times Atlas of the World*. London: Times Books in collaboration with John Bartholomew & Son, 1985.

¹¹Niklas Christensen, *Climatic Change*, 338.

¹²Martin Hoerling, "Past Peak Water in the West," *Southwest Hydrology* 6, no. 1 (2007): 2, http://www.colorado.edu/climate_change/docs/hoerling%20past%20peak%20water%20in%20press.pdf.

¹³United States Bureau of Reclamation. *SECURE Water Act Section 9503(3): Reclamation Climate Change and Water Report to Congress*. 2011, 23.

¹⁴*Ibid.*, 18.

¹⁵Niklas Christensen, *Climatic Change*, 337.

¹⁶Philip Mote, "Declining Mountain Snowpack in Western North America," *American Meteorological Society* 86, no. 1 (2005): 42, <http://www.livingrivers.org/pdfs/LRlibrary/ClimateDocs/MoteHamletClarkLettenmaier.pdf>.

¹⁷Niklas Christensen, *Climatic Change*, 347.

¹⁸*Ibid.*

¹⁹*Ibid.*

²⁰*Ibid.*

²¹Arumugam Sankarasubramanian, "Climate Elasticity of Streamflow in the United States," *Water Resources Research* 37, no. 6 (2001): 1771, <http://engineering.tufts.edu/cee/people/vogel/publications/climate-elasticity.pdf>.

²²Ross Brown "Northern Hemisphere Snow Cover Variability and Change 1915-97," *American Meteorological Society* 13, no. 1 (2000): 2339, <http://journals.ametsoc.org/doi/pdf/10.1175/1520-0442%282000%29013%3C2339%3ANHSCVA%3E2.0.CO%2F>.

²³Auden Schendler. Interview by Author, Carson McMurray, Aspen, Colorado, July 11, 2011.

²⁴Olga Pechony, "Driving Forces of Global Wildfires over the Past Millennium and the Forthcoming Century," *Proceedings of National Academy of Sciences* 107, no. 45 (2010): 19169, <http://www.pnas.org/content/107/45/19167.full.pdf+html>.



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- ²⁵Auden Schender. Interview by Author, Carson McMurray, Aspen, Colorado, July 11, 2011.
- ²⁶United States Bureau of Reclamation, *SECURE Water Act Section 9503(3): Reclamation Climate Change and Water Report to Congress*. 2011, 18.
- ²⁷Philip Mote, "Declining Mountain Snowpack in Western North America," *American Meteorological Society* 86, no. 1 (2005): <http://www.livingrivers.org/pdfs/LRlibrary/ClimateDocs/MoteHamletClarkLettenmaier.pdf>.
- ²⁸Thomas Painter, "Response of Colorado River Runoff to Dust Radiative Forcing in Snow," *Proceedings of National Academy of Sciences* 107, no. 40 (2010): <http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2951423/>.
- ²⁹Thomas Painter, "Impact of Disturbed Desert Soils on Duration of Mountain Snow," *Geophysical Research Letters*, 34, no. 6 (2007): <http://www.agu.org/pubs/crossref/2007/2007GL030284.shtml>.
- ³⁰Ibid.
- ³¹Ibid.
- ³²Thomas Painter, "Response of Colorado River Runoff to Dust Radiative Forcing in Snow," *Proceedings of National Academy of Sciences* 107, no. 40 (2010): <http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2951423/>.
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- ³⁴Niklas Christensen, *Climatic Change*, 350.
- ³⁵Douglas Kenney, "Rethinking the Future of the Colorado River: Draft Interim Report of the Colorado River Governance Initiative," Western Water Policy Program, (2010): 109, <http://www.rlch.org/archive/wp-content/uploads/2010/12/CRGI-Interim-Report.pdf>.
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- ⁴⁹Niklas Christensen, *Climatic Change*, 354.
- ⁵⁰*Lake Powell Daily Averages Since 1980*, accessed November 11, 2011, <http://lakepowell.water-data.com/index2.php>.
- ⁵¹Niklas Christensen, *Climatic Change*, 354.
- ⁵²Ibid., 355.
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