Recent Research on the Effects of Climate Change on the Colorado River

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Water managers in the seven Colorado River Basin states cannot adequately plan for a future of increased climate variability and change unless they can anticipate how future climate will affect streamflows in the Colorado River. Since 1979, there have been six major studies on how changes in temperature and precipitation might affect annual runoff[1] in the Colorado River (see Table 1a) along with several minor studies. This article compares both the methodology and the results of six major studies, focusing on the projected changes in runoff due to climate change. The article begins with an overview of the study methods, and then reviews each study. It ends with a discussion on study limitations and general conclusions.

Overview of Study Methods

The six studies differ in three key ways: (1) sources of future climate information, (2) techniques used to generate runoff from climate, and (3) uses of 'operations models' used to predict reservoir impacts. (See Figure 1a for the progression of data through models in these studies.) Each difference in method is described below.

The first key difference in the studies is how future changes in temperature and precipitation were derived for use as inputs to runoff models. To generate climate variables, the studies used either arbitrary **scenarios** (e.g. +/- 2ºC and +/- 10% of average precipitation), or the output of General Circulation Models (**GCM**s), which use increases in concentrations of greenhouse gases to predict changes to temperature and precipitation. The GCMs used in these studies vary from the relatively crude models used in the 1991 Nash and Gleick study to the state of the art models used by Hoerling and Eischeid (2006) and Christensen and Lettenmaier (2006).

The second key difference in the study methodologies is how they model changes in streamflow from changes in climate. Some studies **used empirical or statistical (regression)** relationships based on the observed associations between climate factors (i.e. temperature, precipitation, or drought) and past streamflows. Other studies use a **hydrologic model** run on a daily or sub-daily timestep which mimics natural processes such as snow accumulation and melt, evapotranspiration, groundwater recharge, and surface runoff using water balance (i.e., conservation of mass) and energy constraints. Hydrologic models are significantly more complicated than the regression approach, but such precision does not necessarily lead to higher accuracy.

Finally, three out of six studies use streamflow projections in an **operations model**, which considers the effects of changes in runoff on water resources system variables like reservoir storage. Note that results of the operations models strongly depend on initial conditions and should not be interpreted as predictions but used instead to find system sensitivities to changes in future runoff.

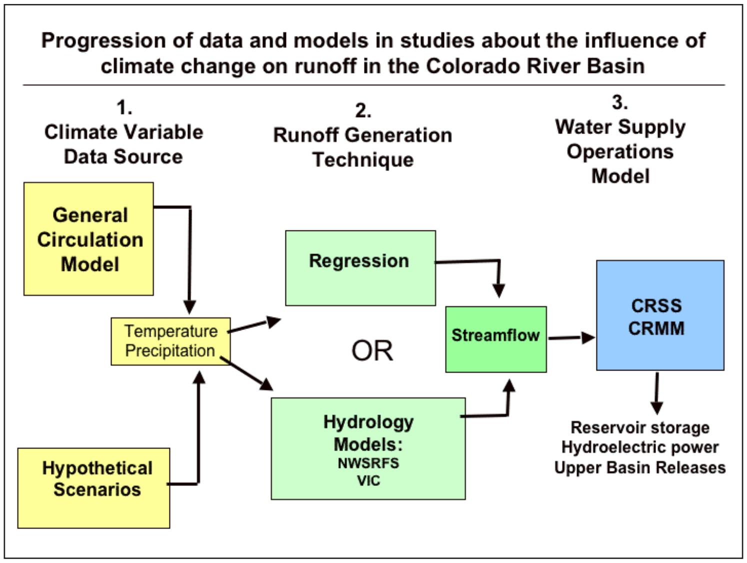

Figure 1a: Progression of data through the models used in recent research on the influence of climate change on the runoff of the Colorado River. All the studies used either a GCM or scenarios to generate future climate variables and either a regression equation or hydrology model to generate changes in runoff, but only three studies then use a water supply operations model (See Table 1a).

Geohydrological Implications of Climate Change on Water Resource Development (Stockton and Boggess, 1979)

Charles Stockton[2] of the University of Arizona (U of A) tree-ring Laboratory, and William Boggess wrote a report prepared for the U.S. Army Corps Engineering Research Center. The authors investigated how four different climate change scenarios could impact the water supplies of the United States.

The scenarios were the four combinations of +/- 2ºC and +/- 10% change in precipitation, and were generically called *warmer and drier, cooler and wetter, cooler and drier*, and *warmer and wetter.* At the time of this report, scientists were discussing both the potential for a new ice age, (global temperature records indicated a cooling from 1940 to 1970) as well as future warming due to increased carbon dioxide. Hence, the study considered all possible future climates. Stockton and Boggess utilized empirical relationships developed by Walter Langbein (Langbein, 1949) of the USGS in the 1940s showing the observed relationship between precipitation, temperature, and runoff across the United States to predict future runoff.

In all parts of the U.S. except the Upper Colorado basin, they determined that the *warmer and drier* and *cooler and wetter* scenarios set the lower and upper bounds on runoff changes since the changes in temperature and precipitation in *warmer and wetter* and *cooler and drier* scenarios usually offset each other. For the Upper Colorado River, Stockton and Boggess calculated that annual runoff would decrease by about one-third to approximately 10 maf under the warmer and drier, and, surprisingly, under the warmer and wetter scenarios. Under cooler and wetter, annual flow doubled to 30 maf, while under the cooler and drier scenario runoff was effectively unchanged.

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[1] This article uses streamflows and runoff interchangeably.
[2] This is the same Stockton of the 1976 Stockton and Jacoby Colorado River tree-ring reconstruction.

Study	*Climate Variable Source* ***(Scenario/GCM)***	*Runoff Generation Technique* ***(Empirical-Statistical/Hydrologic model)***	*Selected Runoff Results*	*Operations Model Used*	*Notes*
Stockton and Boggess, 1979	Scenario	**Empirical**: Langbein's 1949 US Historical Runoff- Temperature-Precipitation Relationships	+2C and -10% Precip = ~ -33% reduction in Lees Ferry Flow		Results are for the warmer/drier and warmer/wetter scenarios.
Revelle and Waggoner, 1983	Scenario	**Statistical Regression** on Upper Basin Historical Temperature and Precipitation	+2C and -10% Precip= -40% reduction in Lee Ferry Flow		+2C only = -29% runoff, -10% Precip only = -11% runoff.
Nash and Gleick, 1991 and 1993	Scenario and GCM	**NWSRFS Hydrology model** runoff derived from 5 temperature & precipitation Scenarios and 3 GCMs using doubled CO2 equilibrium runs.	+2C and -10% Precip = ~ -20% reduction in Lee Ferry Flow	Used USBR CRSS Model for operations impacts.	Many runoff results from different scenarios and sub-basins ranging from decreases of 33% to increases of 19%.
Christensen et al., 2004	GCM	UW **VIC Hydrology model** runoff derived from temperature & precipitation from NCAR GCM using Business as Usual Emissions.	+2C and -3% Precip at 2100 = -17% reduction in total basin runoff	Created and used operations model, CRMM.	Used single GCM known not to be very temperature sensitive to CO2 increases.
Hoerling and Eischeid, 2006	GCM	**Statistical Regression** on PDSI developed from 18 AR4 GCMs and 42 runs using Business as Usual Emissions.	+2.8C and ~0% Precip change at 2035-2060 = -45% reduction in Lee Fee Flow		
Christensen and Lettenmaier, 2006	GCM	UW **VIC Hydrology Model** runoff using temperature & precipitation from 11 AR4 GCMs with 2 emissions scenarios.	+4.35C and -2% Precip at 2070-2099 = -11% reduction in total basin runoff with a high emissions scenario	Also used CRMM operations model.	Other results available, increased winter precipitation buffers reduction in runoff.

Table 1a. Summary of models and results for changes to runoff in the Colorado River. This table is an overview of the major differences in the methods and results of the six studies in this article.

Effects of a Carbon Dioxide-induced Climatic Change on Water Supplies in the Western United States (Revelle and Waggoner, 1983)

Roger Revelle, of the Scripps Institution of Oceanography, and Paul Waggoner, of the Connecticut Agricultural Experiment Station, wrote a chapter in a report published by the National Academy of Sciences. The authors investigated how future warming and drying in the Colorado River might affect runoff. The key part of the article was the generation of a multiple linear regression between temperature and precipitation in the Upper Basin and unimpaired flow at Lee Ferry. Using data from the period 1931 to 1976 they established the following relationship[3]:

Lee Ferry Flows (in cubic meters) = 9274 + 52 (**Precipitation** in mm) – 2400 (**Temperature** in Celsius)

The equation shows that a 2ºC increase would lead to a decline in runoff of by 4800 million cubic meters (mcm) (3.9 maf or -29%) and a 10% decrease in precipitation would reduce flow by 1730 mcm (1.4 maf or -11%)[4]. With both a 2ºC increase and 10% precipitation decrease, total annual flow would decline by 40%. They note that the regression shows that a 28% increase in precipitation is necessary to balance a 2ºC increase. The equation explains 73% of the variance in streamflow during the 1931-1976 calibration period.

Sensitivity of Streamflow in the Colorado River basin to Climatic Changes (Nash and Gleick, 1991) and The Colorado River basin and Climatic Change (Nash and Gleick, 1993)

Linda Nash and Peter Gleick of the Pacific Institute for Studies in Development, Environment, and Security wrote two similar articles on future Colorado River flows under varying assumptions of a changing climate. The 1993 article is an expanded version of the 1991 study and includes results of modeling simulated future flows with the Bureau of Reclamation's (USBR) Colorado River Simulation System (CRSS) operations model.

In the 1991 study, the authors considered a total of 15 different scenarios for temperature and precipitation conditions, 10 from assumed futures (all combinations of 2ºC and 4ºC temperature increases, and changes in precipitation of -20%, -10%, 0%, +10% and +20%) and five based on GCM simulations from NASA (+4.8ºC, +15% Precip change), NOAA (+4.7ºC, 0% Precip change) and the UK Met Office (+6.8ºC, +20% Precip change). These scenarios generated meteorological inputs for use in the National Weather Service River Forecasting System (NWSRFS) hydrologic model[5]. The authors used the NWSRFS model to generate runoff projections for three relatively unimpaired sub-basins of the Colorado River basin above Lake Powell and for Lake Powell itself.

In all, fifty-two different scenarios were evaluated. The results follow expectations that higher temperatures and lower precipitation should generate less runoff. Thirty-seven scenarios (71%) resulted in flow decreases and fifteen scenarios (29%) resulted in flow increases. Projections of changes in annual runoff varied from a 33% decrease to a 19% increase. A 2ºC increase was roughly offset by a 10% increase in precipitation and a 4ºC increase was roughly offset by 15 - 20% increase in precipitation. A 2ºC increase with no change in precipitation caused runoff declines of 4 -12%, a 2ºC increase with 10% less precipitation caused runoff to decline by about 20%, and a 4ºC increase with no change in precipitation caused runoff declines of 9 - 21%. Temperature increases also caused the peak flow to shift earlier in the year.

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[3] Another version of the equation is: Lee Ferry Flows (in maf) = 42.1 + 1.07(Precip in inches) -1.08(Temp in Fahrenheit)

[4] 1931-1976 Upper Basin average temperature was 4.18ºC and basin average precipitation was 333 mm.

[5] NWSRFS is the operational model used by the NOAA National Weather Service River Forecast Centers, and specifically the Colorado Basin River Forecast Center (CBRFC), to predict annual and seasonal streamflows.

In the 1993 study, Nash and Gleick added some minor enhancements to the study and used USBR's CRSS model to investigate how changes in inflows would affect reservoir operations and system reliability. Like many other studies such as the Severe and Sustained Drought study (1995), the 1993 study showed that system storage and hydropower production are very susceptible to reduced flows. For example, 20% less runoff caused a 60 – 70% reduction in mean annual storage and a 60% reduction in power generation. These results were very dependent on assumptions made about shortage allocation, reservoir starting conditions, and other operational factors. For example, CRSS did not properly address with required Upper Basin compact deliveries.

The Effects of Climate Change on the Hydrology and Water Resources of the Colorado River basin (Christensen, et al., 2004)

This study was part of the Accelerated Climate Prediction Initiative funded by the Department of Energy. Niklas Christensen, Andrew Wood, Nathalie Voisin, Dennis Lettenmaier and Richard Palmer, all at the University of Washington, used the National Center for Atmospheric Research (NCAR) Parallel Climate Model (PCM) to generate temperature and precipitation changes from greenhouse gas emissions during three future 21st century periods, 2010-2039 (Period 1), 2040-2069 (Period 2), and 2070-2098 (Period 3). They used the output of PCM in a hydrology model to create runoff projections, which they then used in an operations model.

PCM was run using the 'Business as Usual' future emissions scenario, which results in CO_2 levels of approximately 710ppm by 2100[6]. By starting PCM from slightly different initial conditions, the authors created three future climate runs for each period. The results for Periods 1, 2 and 3 were reported as an average of the three runs. A 50-year "control run" starting in 1995 with no additional greenhouse gas emissions was also completed. Due to lags in the climate system, the control run showed warming of about 0.5ºC which is in rough agreement with what many believe to be 'committed warming' should greenhouse gas emissions stop immediately.

Monthly temperature and precipitation output from PCM was downscaled to 1/8 degree (approximately 8 mile grid boxes) daily data for use by a daily hydrological simulation model, the Variable Infiltration Capacity (VIC) model. VIC simulates snow accumulation and melt, soil moisture, evapotranspiration, runoff and baseflow. VIC was calibrated using climate and natural flow data from 1950 to 1989. Calibration runs indicated a flow match at Imperial Dam near Yuma, Arizona, within 1% of calculated natural flow at the site. Temperatures increased from 0.5 – 2.4ºC, precipitation decreased by 1- 6%, and runoff was reduced by 10 – 18% in the four runs (See Table 1b). A spatial analysis of these reductions indicated that a considerable enhancement of evapotranspiration increases occurred in the high elevation areas where a large portion of runoff occurs. Peak runoff advanced from June in the historical data to May in the latter parts of the control and 21st century runs.

Period	Temperature	Precipitation	Runoff
Control (1995)	+0.5ºC	-1%	-10%
Per. 1: 2010-2039	+1.0ºC	-3%	-14%
Per. 2: 2040-2069	+1.7ºC	-6%	-18%
Per. 3: 2070-2098	+2.4ºC	-3%	-17%

Table 1b. Model results: changes in temperature and precipitation provided by NCAR PCM, and runoff results from VIC hydrology model. (Data from Christensen et al., 2004).

VIC output was used in a monthly operations model, Colorado River Reservoir Model (CRRM), based roughly on USBR's CRSS model. Most of the modeling held 2000 Upper Basin demands constant at 2000 levels to simplify analysis. As expected from similar studies, the CRRM model found that reservoir reliability is extremely sensitive to inflow reductions, due to a nearly full allocation of the Colorado River. Average reservoir levels drop significantly even with small reductions in runoff. For example, required deliveries from Lake Powell were met 92% of the time in the historical data, and 72% in the control run and 59%, 73%, and 77% in periods 1-3, respectively.

Past Peak Water in the Southwest (Hoerling and Eischeid, 2006)

Martin Hoerling and Jon Eischeid of the NOAA Earth System Research Laboratory in Boulder published their findings 2006 in Southwest Hydrology, a publication (not peer-reviewed) published by a National Science Foundation-funded effort at U of A. They predicted future Colorado River flows based on the Palmer Drought Severity Index (PDSI) calculated for the Upper Colorado River basin[7]. Note that the PDSI was developed for use in the Great Plains states, not areas with snow-driven hydrology.
Using historical data from 1895 to 1989, they first created a simple linear regression for the Upper Colorado basin:

Lee Ferry Flows (in MAF) = 14.5 + 1.69*(**PDSI**)

This regression explains 63% of the variance at Lees Ferry over the 105-year calibration period. Using a verification period from 1990 to 2005, the equation explains 85% of the variance in the flows. The authors caution that it is unclear if this relationship between flows and PDSI is strictly applicable to the substantial changes anticipated in future climate.

Hoerling and Eischeid then calculated the PDSI using data from 42 different climate simulations using 'Business As Usual'[8] greenhouse gas emissions from 18 different coupled atmosphere-land-ocean GCMs completed for the recent IPCC Fourth Assessment Report (2007). The models in the study project an average temperature increase of 1.4ºC during 2006-2030 and 2.8ºC during 2035-2060, compared to 1895-2005. The climate models show little net change in precipitation over the next century, yet drought as determined by the modeled PDSI would be a very common occurrence in the future. Average PDSI is projected to be the same as during the 2000-2003 drought (<-3). Twentieth century droughts were driven by precipitation decreases with enhancement by increasing temperatures but the authors propose

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[6] Current CO_2 levels are approximately 380 ppm and are increasing at about 1.5 – 2.0 ppm/year. The Business as Usual emissions scenario means that greenhouse gas emissions will continue increasing at the current rate.
[7] PDSI is a frequently used metric of drought conditions and is calculated by combining temperature, precipitation, evapotranspiration and soil moisture. The index can vary from -4 (extreme drought) to +4 (extreme wetness).
[8] The Business as Usual emissions scenario is called A1B in the IPCC Fourth Assessment Report (2007).

that a "near perpetual state of drought will materialize in the coming decades as a consequence of increasing temperature."

With the above changes in temperature and no changes in precipitation, the authors found that streamflows in the river over the next twenty-five years would average 10 maf, approximately the same as during the recent 1999-2004 drought. From 2035 to 2060, the flows would drop to 7 maf on average. The modeled individual years vary considerably from these averages with some close to the historical mean of 15 maf in the next twenty years (see Figure 1b).

A Multimodel Ensemble Approach to Assessment of Climate Change Impacts on the Hydrology and Water Resources of the Colorado River basin (Christensen and Lettenmaier, 2006)

Niklas Christensen and Dennis Lettenmaier, submitted another study for publication in 2006[9]. Like the Hoerling and Eischeid study, this study is based on GCM model results prepared for the 2007 IPCC Fourth Assessment Report. The authors used the same approach as the 2004 Christensen paper with downscaled GCM data feeding the VIC hydrology model and the resultant streamflows then used in CRMM. The same reporting periods (Periods 1-3) were used but the authors used 11 major climate models, rather than using only the NCAR PCM. The GCMs used two different future emissions scenarios, A2, a relatively high scenario with 2100 CO2 levels of 850 ppm, and B1, a relatively low scenario with 2100 CO2 levels of 550 ppm[10].

Runoff changed by 0%, -7% and -8% in the B1 for periods 1-3, respectively, and by 0%,-6% and -11% in A2 for the same periods (See Table 1c). These reductions are larger than the precipitation declines and are believed to be driven by increasing temperatures.

For the operations models (CRRM), Upper Basin demands were fixed at year 2000 levels to ease analysis. In general, CRMM reservoir levels are higher than that reported in the 2004 study, although the authors claim that the results are within the same range of sensitivity. During 2070-2099, as compared to the 1950-99 base case, runoff declines of 11% average cause storage to decline by 13%, under the A2 scenario.

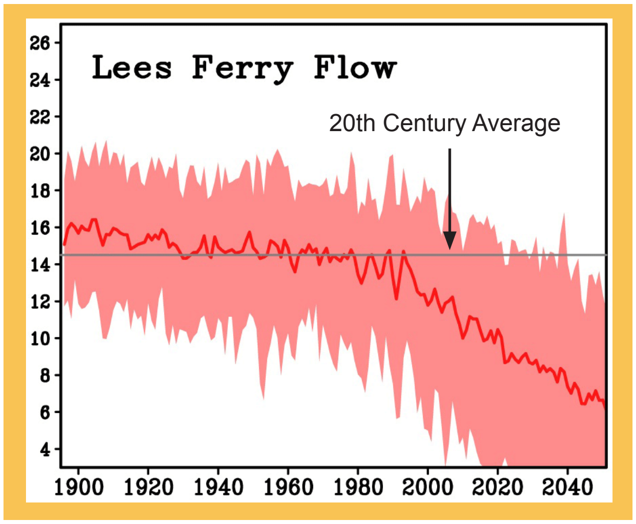

Figure 1b. Projected Lee Ferry future flows. Solid line is average of 42 runs, and red cloud shows 10% to 90% range of individual simulations (from Hoerling and Eischeid, 2006).

Emissions Scenario	Period	Temperature	Precipitation	Runoff
A2	Per.1: 2010-2039	+1.2 °C	-1%	0%
	Per.2: 2040-2069	+2.6 °C	-2%	-6%
	Per.3: 2070-2099	+4.4 °C	-2%	-11%
B1	Per.1: 2010-2039	+1.3°C	+1%	0%
	Per.2: 2040-2069	+2.1°C	-1%	-7%
	Per.3: 2070-2099	+2.7°C	-1%	-8%

Table 1c. Model results: changes in temperature and precipitation provided by 11 GCMs from the IPCC Fourth Assessment Report, and runoff results from VIC hydrology model. (Data from Christensen and Lettenmaier, 2006).

Study Limitations

All studies discussed herein suffer from limitations relating to GCMs, future applicability of statistical and empirical relationships based on historical data, hydrology model assumptions, and/or operational model assumptions. Each of these areas is discussed below.

These studies utilize three different generations of GCMs, dating from the early 1990s, late 1990s and mid 2000s. As our computational capabilities have increased, so has our understanding and ability to model climate and thus it should be expected that the GCM-derived climate inputs for the most recent studies (Hoerling and Eischeid, 2006, Christensen and Lettenmaier, 2006) are significantly more robust than older results (Nash and Gleick, 1991, 1993). In general, temperature projections are considered much more reliable than precipitation, even in the latest models. As noted by the IPCC, even with many advances over the years, global climate models still do not adequately resolve precipitation in mountainous areas. It is noteworthy, however, that the most recent GCM results for precipitation in the Colorado River basin show consistent results across models with very little change in projected precipitation relative to historical conditions.

Studies which use empirical/statistical relationships between temperature, precipitation and runoff (Stockton and Boggess, 1979, Revelle and Waggoner, 1983, Hoerling and Eischeid, 2006) have been criticized for failing to consider how these relationships might change in a future climate due to evapotranspiration and vegetation changes, and changes in seasonality of runoff. Such changes might substantially alter the relationships between temperature, precipitation, and runoff, which could invalidate the findings.

Hydrology models can potentially overcome many of the limitations inherent in the statistical approach by modeling many of the physical processes which control runoff such as snow accumulation and melt, groundwater recharge, and evapotranspiration from plants. In theory as the climate changes, these models should correctly handle new physical conditions. Unfortunately,

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[9] This summary is based on the paper submitted for publication and hence the results reported here are subject to change.

[10] A2 and B1 refer to specific emissions scenarios used in GCMs in the IPCC reports. For more information see the IPCC Special Report on Emissions Scenarios (http://www.grida.no/climate/ipcc/emission/index.htm).

these models require large amounts of data, much of which is imprecisely known. Furthermore, in order to resolve very complex and sometimes poorly known relationships, the models may overly simplify important physical processes. For example, the VIC model uses a two-meter subsurface layer to model all interactions with soil moisture and groundwater, despite the fact that surface water/groundwater interactions frequently involve various forms of aquifers with significant storage capacity.

Three of the studies use an operations model, Nash and Gleick (1993), Christensen et al. (2004) and Christensen and Lettenmaier (2006). Nash and Gleick utilize an older version of USBR's CRSS model and the Christensen studies utilize a model (CRRM) created at the University of Washington. While the results of these two models are intriguing, assumptions about reservoir starting contents and system operating policies can significantly alter results. In particular, numerous critical policy-laden decisions about how to operate the system under low flow conditions have never been resolved and these implementations either ignore these issues, or implement a solution that has no standing in the Law of the River.

Conclusions

The first studies of the potential impacts of climate change on the Colorado River basin were completed almost thirty years ago. As the years have progressed, scientific studies have relied less and less on arbitrary assumptions about future temperature and precipitation and more and more on the results from GCMs. For many years, most GCMs agreed that temperatures would increase in the Colorado River Basin over the next century, but there was no consensus on changes in precipitation. Scientists believed that reduction in runoff from increased temperatures might be offset by increased precipitation as recently as the 2001 IPCC Third Assessment and the 2000 National Assessment of the Potential Consequences of Climate Variability and Change. However, starting with Christensen in 2004 and continuing through the most recent IPCC Fourth Assessment Report (2007), the likelihood of significantly increased precipitation counterbalancing increased warming appears to be reduced. The most recent GCMs now suggest that precipitation will remain approximately the same in the basin, and current GCM temperature projections by 2100 are in rough agreement with most of the scenarios and GCM results used over the years. ***Under these conditions, all past studies indicated that runoff would be reduced.***

What remains uncertain is exactly how much reduction in runoff will occur if current precipitation projections hold. In the most recent Colorado River studies, runoff reductions range from the -11% projected by Christensen and Lettenmaier (2006) in 2100, to the -45% projected by Hoerling and Eischeid (2006) in about 2050[11]. Notably, these two numbers roughly bracket the range of all past studies that do not contain large precipitation increases. While both of these studies utilize the latest temperature and precipitation results from IPCC GCMs, they use very different techniques to generate flow. Hoerling and Eischeid's method implicitly emphasizes how higher temperatures will increase atmospheric demand for water and reduce runoff. Christensen and Lettenmaier imply that snowmelt runoff during the relatively cool spring will still be reasonably efficient in generating streamflow. Which method is more correct? Research is on-going to discover their strengths and weaknesses.

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[11] Three other recent generalized studies on future runoff projections for the U. S. Southwest not referenced in this article all support a reduction of flow in the Colorado River basin in the future: Milly et al. 2005, Seager, Ting et al, 2007, and the recent IPCC AR4, 2007 regional projections. See Sources for citations.