The 21st Century Colorado River Hot Drought and Implications for the Future

Glen Canyon Dam Adaptive Management Program
Technical Workgoup Meeting
April 24, 2018

The twenty-first century Colorado River hot drought and implications for the future

Bradley Udall\textsuperscript{1,2} and Jonathan Overpeck\textsuperscript{2,3}

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Coauthor: Jonathan Overpeck
Ave. Temperature dep from Ave (deg F) 10/1/2017 - 4/21/2018

Generated 4/22/2018 at WRCC using provisional data.
NOAA Regional Climate Centers
Westwide SNOTEL Current Snow Water Equivalent (SWE) % of Normal

April 23, 2018

Notice: We anticipate this map will not be available next year due to staffing constraints. Alternate maps: https://go.usa.gov/xnzzk

The snow water equivalent percent of normal represents the current snow water equivalent found at selected SNOTEL sites in or near the basin compared to the average value for those sites on this day. Data based on the first reading of the day (typically 00:00).

Prepared by: USDA/NRCS National Water and Climate Center
Portland, Oregon
http://www.wcc.nrcs.usda.gov
National Weather Service, Colorado Basin River Forecast Center, SLC, Utah

April mid-month Forecast

"product_issuance=mid-month"

Reservoir Unregulated Inflow Forecasts

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<th>ID</th>
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<th>Most Probable</th>
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<tr>
<td>GRNU1</td>
<td>Flaming Gorge</td>
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Other Reservoir Unregulated Inflow Forecasts

<table>
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<th>Outlook</th>
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<td>Ridgway</td>
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</table>
It’s official: 2018 has been the driest winter ever for Arizona’s mountain watersheds

Published: April 6, 2018
Statewide Average Temperature Ranks
March 2017
Period: 1895–2017
Upper Colorado River Basin Time Series Snowpack Summary
Based on Provisional SNOTEL data as of Jun 16, 2017

State of Colorado Colorado River Basin Snowpack

Current as Pct of Normal: 300%
Current as Pct of Avg: 67%
Current as Pct of Last Year: 150%
Current as Pct of Peak: 6%
Normal as Pct of Peak: 2%
Current Peak as Pct of Normal Peak: 112%
Current Peak Date: Mar 14
Normal Peak Date: Apr 10

Snow Water Equivalent (inches)

Oct 01  Nov 01  Dec 01  Jan 01  Feb 01  Mar 01  Apr 01  May 01  Jun 01  Jul 01  Aug 01  Sep 01

Median  WY2014  WY2015  WY2016  WY2017  Average
State of Colorado Colorado River Basin Snowpack

June 15, 2017 CBRFC
Forecast April – July runoff at 116%

Past Forecasts:
3/1  = 145% =10.4 maf
3/15 = 138%  = 9.9 maf
4/1  = 130%  = 9.3 maf
4/18 = 123%  = 8.8 maf
5/03 = 123%  = 8.8 maf
6/05 = 116%  = 8.3 maf
6/15 = 116%  = 8.3 maf

2.1 maf reduction 3/1 to 6/15

March was warmest Colorado March in 123 years of records.
8.8 F warmer than normal
Source: NOAA
May 2015 was the country’s wettest May since records began 121 years ago.

In fact, it was the wettest month ever recorded!

https://www.climate.gov/news-features/featured-images/may-2015-was-wettest-month-ever-recorded-us
The twenty-first century Colorado River hot drought and implications for the future
Bradley Udall\textsuperscript{1,2} and Jonathan Overpeck\textsuperscript{2,3}

\textsuperscript{1}AGU Water Resources Research

Key Points:
- Record Colorado River flow reductions averaged 19.3\% per year during 2000–2014. One-third or more of the decline was likely due to warming.
- Unabated greenhouse gas emissions will lead to continued substantial warming, translating to twenty-first century flow reductions of 35\% or more.
- More precipitation can reduce the flow loss, but lack of increase to date and large megadrought threat, reinforce risk of large flow loss.
The Unusual 21st Century Colorado River Hydrology

• 2 5–Year Periods below average flow
• Only 4 Years with above average flow
• ~ 19% Flow Loss Relative to 20th Century
Most Severe Colorado River Low Flow Sequences

Length of Low Flow Sequence − Years

% of mean flow

Ending Decade

21st Century Run

20th Century Run

% Mean Flow

Most Severe Colorado River N-Year Flow Sequences

Length of Flow Sequence in Years

- 21st Century Run
- 20th Century Run
Most Severe Colorado River Low Flow Sequences

Length of Low Flow Sequence − Years
% of mean flow
Ending Decade
21st Century Run
20th Century Run

Most Severe Colorado River N-Year Flow Sequences

Length of Flow Sequence in Years
% Mean Flow

Ending Decade
21st Century Run
20th Century Run
### Most Severe Colorado River Low Flow Sequences

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<th>% of mean flow</th>
<th>Ending Decade</th>
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<tr>
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<td></td>
<td>21st Century Run</td>
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#### Length of Flow Sequence in Years

- **% Mean Flow**
- **Ending Decade**
- **21st Century Run**
- **20th Century Run**

![Graph showing the distribution of flow sequences.](image-url)
Most Severe Colorado River Low Flow Sequences

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<tbody>
<tr>
<td>Ending Decade</td>
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<tr>
<td>1920s</td>
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<td>2000s</td>
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<tr>
<td>2010s</td>
<td></td>
</tr>
</tbody>
</table>

2000-2018 severity much worse than 20th century

2000-2018 – frequency of low flow sequences overrepresented in these 10-worst flow sequences
Contents of the Two Largest Reservoirs in the United States

2000 = 90%
2015 = ~ 40%

Most Serious Drought since records kept

Causes...
Lake Powell: Drought
Lake Mead: Structural Deficit (“overuse”)

[Graph showing the contents of Lake Powell and Lake Mead from 1900 to 2010, highlighting different periods and events affecting their contents.]
Calculated Temperature Sensitivity and Precipitation Elasticity with 6 different runoff models

Temperature Sensitivity: Change in Flow per Degree Increase in Temperature. Is a Negative Percent

Precipitation Elasticity: Percent Change in Flow per 1% Change in Precipitation. Is a unit-less number

Temperature Sensitivity and Precipitation Elasticity are roughly additive
Warming alone will drive Colorado River flow declines of -6.5% +/- 3.5% per °C.

An interdisciplinary team reconciled the future of the Colorado River.

Vano et al., 2014

Bulletin of the American Meteorological Society, January 2014 issue
Two Droughts – Two Different Causes

1953-1967 Drought
- 18% Flow Decline
- 6.1% Precipitation

2000-2014 Drought
- 19% Flow Reduction
- 4.6% Precipitation

Note:
2000s Drought is only 75% of the Precipitation Decline in the 1950s Drought

Source: Udall & Overpeck, 2017; flow data from Reclamation, PRISM Precipitation
Temperatures Key to 2000s Decline

2000-14 Temperatures are 1.6°F above 1906-99 Average

Temperature Sensitivity Explains 1/6 to ½ of the current runoff reduction. 1/3 is mid point of 1/6 and 1/2

Source: Udall & Overpeck 2017, PRISM Temperatures
• Why less water?
  – Longer Growing Season
  – More Warmth on Any Given Day
  – At some point, possibly more plants and growth upslope
  – More Evaporation from Soils
  – More opportunity for sublimation
  – More atmospheric demand

Linear Trends in Vapor pressure Deficit
mb/53 years

Seager et al, 2015
The Upper Colorado River Basin is Megadrought Country – 1200 years of Colorado River flow thanks to tree rings

Meko et al., (Geophysical Research Letters, 2007)
In both Central Plains and Southwest, Multi-decadal Drought Risk* exceeds 80% in 21st Century

* Defined as Drought lasting 35 or more years
Relative impacts of mitigation, temperature, and precipitation on 21st-century megadrought risk in the American Southwest

Toby R. Ault, Justin S. Mankin, Benjamin I. Cook, Jason E. Smerdon
The Complete Picture...

You have to invoke higher temperatures to explain the current drought.

AND....

This does not bode well for the future...
Colorado River Future Flow Losses

Climate Change a combination of ...

1. For-Sure Temperature Rise -> Flow Losses

2. Not-Sure Precipitation Change -> Flow Gains or Losses
Key Additional Points

Our results are generally comparable to Reclamation’s most recent results when considering the full range of our analysis when both precipitation and temperatures are included. However, our focus and emphasis is on the large near-certain temperature-induced flow declines with a separate analysis of precipitation. Reclamation, by contrast, has a focused on climate multimodel-ensemble median declines, including medians calculated across emission scenarios [Reclamation, 2013, 2012]. Decision makers often treat these median outcomes as a proxy for risk despite the fact that the median obscures the wide range of results and lumps wet and dry, warm and hot, large and small emission increases and, most critically, near certain temperature increases and very uncertain precipitation changes.

We assert that the large precipitation increases necessary to offset substantial temperature-induced flow decreases appear unlikely to occur for a number of reasons. These reasons include the potential for storm tracks to go north of the basin due to Hadley Cell expansion, the high potential for megadrought to increase evaporation while reducing precipitation and runoff for extended periods, the large size of the needed precipitation increases, especially when compared to decadal historical increases, the consistent identification by global assessments of the Southwest as an area likely to dry, and finally the lack of any trend over the last century or last 16 years (Figure 2c). Hence, we choose to focus on highly likely temperature-induced declines with separate analysis of the precipitation needed to offset these declines.
Increasing influence of air temperature on upper Colorado River streamflow

Connie A. Woodhouse¹,², Gregory T. Pederson³, Kiyomi Morino², Stephanie A. McAfee⁴, and Gregory J. McCabe⁵

Key Points:
• When UCRB flow departs from precipitation, temperature is a major forcing
• Since 1988, flows have often been less than expected given winter precipitation
• Warm temperatures exacerbated modest precipitation deficits in the 2000s drought
Declining Runoff Efficiency

Most of the year-to-year variability explained by precipitation

Since the late 1980s increases in temperature have caused a substantial reduction in runoff efficiency

Over the last 3 decades temperature has reduced the flow by 7%

McCabe et al, 2017
Mountain runoff vulnerability to increased evapotranspiration with vegetation expansion

Michael L. Goulden and Roger C. Bales

Kings River basin ET currently peaks at midelevation and declines at higher elevation, creating a cold-limited zone above 2,400 m that is disproportionately important for runoff generation. Climate projections for 2085–2100 indicate as much as 4.1 °C warming in California’s Sierra Nevada, which would expand high rates of ET 700-m upslope if vegetation maintains its current correlation with temperature.
If you believe the climate models, north is wet, and south is dry.

Wet: Wind Rivers + Unita
Dry: All of Colorado
Concluding Thoughts

• Temperature is impacting Colorado River Flows
• We’ve lost ~7% already
• We could lose 20% by 2050, 35% by 2100
• Increases in precipitation could reduce these temperature-induced losses
  – But many reasons to doubt this will occur
• We need to deal with greenhouse gases
  – Must all go away
  – The sooner the better
  – This is everyone’s responsibility
Climate Basics:
1. It’s warming
2. It’s us
3. Experts agree
4. It’s bad
5. We can fix it
End
Perspectives on the causes of exceptionally low 2015 snowpack in the western United States

Philip W. Mote¹, David E. Rupp¹, Sihan Li¹, Darrin J. Sharp¹, Friederike Otto², Peter F. Dennis P. Lettenmaier⁴, Heidi Cullen⁵, and Myles R. Allen²,⁶

Key Points:
- In the 2012-2015 west coast drought, unusually high temperatures played a prominent role in reducing snow accumulation and causing drought.
- In much of the westernmost U.S., April snowpack was at its lowest ever in 2015.
- Crowd-sourced climate modeling shows that greenhouse gases and SST patterns did more to cause drought in the Northwest than in California.

Figure 1. Locations of snow courses with data back to at least 1976 indicating the rank of 2015 against all available years, for 1 April SWE. Symbols and color indicate rank (including ties); filled circle indicates lowest ever.
The Colorado snowpack is off to its worst start in more than 30 years, said Brian Domonkos, who supervises the U.S. Department of Agriculture snow survey in the state.

Heavy snowfall on Colorado’s Western Slope and Utah’s Wasatch Range in December and January boosted snowpack in the five-state Upper Colorado River Basin to 157 percent of average.
Drought Contingency Proposal

Potential Shortage Sharing and Protection Actions, by Lake Mead Elevation and State/Country

Current

Proposed

Shortage Reductions (x 1,000 AF)
“The improved hydrology has changed the landscape and given us a reprieve,” said Suzanne Ticknor, CAP’s water-policy director.

Other water users disagree with this position, including the Arizona Department of Water Resources (DWR), the Tucson and Phoenix water utilities and the Gila River Indian Community, which controls the largest share of CAP water.
Lake Mead to get above-average flow of Colorado River water

By Dan Elliott The Associated Press
April 18, 2017 - 8:51 am

The federal government plans to release an above-average amount of Colorado River water into Lake Mead this year, but it’s less than many hoped after a healthy snow season across much of the West.

The Bureau of Reclamation, which manages dams and reservoirs on the Colorado River, said Monday that it will release 9 million acre-feet (enough water to cover an acre of land one foot deep) from Lake Powell, sending it down the Colorado to Lake Mead, where it will be tapped by Arizona, California and Nevada.

Last month, the agency projected it could release 11.1 million acre-feet from Lake Powell, but a dry early March reduced the amount of snow in the mountains that feed the river.
• 2°F Warming since 1900
• Snowpack Reductions and Changes in Runoff Timing Already Present
• Most Severe Drought since records kept
• Powell and Mead at 50% of capacity now, full 2000
• Tree Mortality Rates High
• Increase in Wildfire Frequency
• Drought may be natural, but exacerbated by higher temperatures
• Snowpack Reductions and Runoff Timing attributed to climate change
• Continued drying likely as temperatures increase and storm tracks shift
• Megadroughts independent of climate change a possibility with severe consequences if combined with warming
Running dry: The U.S. Southwest's drift into a drier climate state

Weather Patterns that provide winter precipitation are becoming less frequent due to Hadley Cell Expansion. Southwest Precipitation has declined by 25%.

Prein et al, 2016
Anthropogenic warming has increased drought risk in California

Noah S. Diffenbaugh, Daniel L. Swain, and Danielle Touma

Department of Environmental Earth System Science and Woods Institute for the Environment, Stanford University, Stanford, CA 94305

Edited by Jane Lubchenco, Oregon State University, Corvallis, OR, and approved January 30, 2015 (received for review November 22, 2014)

• No change in precipitation over last few decades

• But the occurrence of drought has increased in last two decades over previous century

• The probability that precipitation deficits occur with warm temperatures has increased