The Colorado River Millennium Drought: the relative impacts of higher temperatures vs. other causes

When the Rain Stops: Drought on Subseasonal and Longer Timescales
Aspen, CO
September 13, 2018

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Colorado River

- 7 States, 2 Nations
- 8% of area of the Lower 48
- Annual Flow 16.4 MAF = Hudson River
- 40 M People
- All of the Major Cities in Southwest
- 4.5m Irrigated Acres
- Fully Allocated in 1922
- Withdrawals equaled Supplies ~2000
- Large New Projects still contemplated
- No longer reaches the ocean
Most Severe Colorado River Low Flow Sequences

Worst Sequence from each century

Length of Low Flow Sequence

- Years

% of 20th century mean Lee Ferry flow

Lowest 21st Century Sequence
Lowest 20th Century Sequence

2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18

% of 20th century mean Lee Ferry flow

Length of Low Flow Sequence – Years

- Lowest 21st Century Sequence
- Lowest 20th Century Sequence
Month of Maximum Precipitation

Udall, 2017 - PRISM 30-Year Normals
Millennium Drought 2000—2018

- 2000-2017 is the worst drought in the gaged record
- ~ 20%/yr decline
- Long-term trend, too

Udall and Overpeck, WRR, 2017
Millennium Drought 2000—2018

- 2000-2017 is the worst drought in the gaged record
- ~ 20%/yr decline
- Long-term trend, too

- Lakes Powell and Mead have lost 50% of their volume

Udall and Overpeck, WRR, 2017
Millennium Drought 2000—2018

- Precipitation declines only partially explain
- ~66% of the loss

Udall and Overpeck, WRR, 2017
Millennium Drought 2000—2018

- Precipitation declines only partially explain
  - ~ 66% of the loss

- Temperature increases explain the remainder
  - ~ 33% of the loss

- Why?
  - More Evaporation

- Temperature-Induced Losses
  - Now = ~6%
  - 2050 = ~20%
  - 2100 = ~35%

Udall and Overpeck, WRR, 2017
On the causes of declining Colorado River streamflows

Mu Xiao, Bradley Udall, Dennis P. Lettenmaier

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Water Resources Research
AN AGU JOURNAL
Research Article

Model-based Study using Historical Data
- Long-term Trend Analysis
- 1950s vs 2000s Drought Analysis
- 2017 Forecast Analysis

- VIC Model Experiments
  - Daily Model at 1/16 Degree
  - Different Dataset from U&O, 2017
  - Temperature Detrend Run
    - Fixed Precipitation Run
VIC Percent of Annual Runoff at Imperial Dam

4 Key Basins (Green + Blue) produce ~55% of all runoff

All located primarily in Colorado
VIC Forcing Data / Calibration

UCRB Precipitation
1.4% Increase

Temperature
1.4 °C input data
1.8 °C output data

"Full Energy Balance" Mode

Natural Flows vs VIC
$R^2 = 0.75$
Long Term Trend Findings

- 16.5% decline over 99 years
- 53% of the decline due to warming temperatures
- Remainder due to changing precipitation patterns
- Winter ET Increases reduce SWE leading to reductions in Apr-Sept streamflow
Two Droughts – 1950s vs 2000s

Longterm Average Runoff = 18.9 km$^3$

2000s slightly worse annually
16.5 km$^3$ vs 16.3 km$^3$

2000s Slight Increase in Winter
4.1 km$^3$ vs 4.5 km$^3$

2000s Decrease in Summer
12.4 km$^3$ vs 11.8 km$^3$
Two Droughts: P, T & SWE
Anomalies relative to mean
Two Droughts: ET and Runoff
Anomalies relative to mean

1953-1967
ET declines almost everywhere evenly

2000-2014
ET spatially heterogenous

Runoff
Declines uniformly everywhere

- Increases in Utah
- Decreases in Colorado
Two Droughts Findings

- Similar to Long Term Findings
- 2000s have half of the UCRB precipitation reduction of the 1950s
  - $-6.1\text{ km}^3$ vs $-3.2\text{ km}^3$
- 2000s have higher Winter ET
  - $0.4\text{ km}^3$ vs $1.8\text{ km}^3$
- 2000s have higher Winter Flows
- ~50% due to higher UCRB temps
  - $0.1^\circ\text{C}$ vs $1.0^\circ\text{C}$
  - T-detrend run provides comparison
- ~50% due to changing precipitation locations
Other Studies

- Hydrologic Sensitivities of Colorado River Runoff to changes in Precipitation and Temperature
  - Vano et al., 2014
- Increasing Influence of air temperature on Colorado River Streamflow
  - Woodhouse et al., 2016
- Mountain Runoff Vulnerability to increased evapotranspiration with vegetation expansion
  - Goulden and Bales, 2014
- Running Dry: The US Southwest’s Shift to a drier climate
  - Prein et al., 2016
- Climatology, Variability, and Trends in the U.S. Vapor Pressure Deficit, an Important Fire-Related Meteorological Quantity
  - Seager et al, 2015
- Evidence that Recent Warming is Reducing Upper Colorado River Flows
  - McCabe et al., 2017
- Comparison of CMIP3 and CMIP5 Projected hydrologic conditions over the Upper Colorado River Basin
  - Ayers et al., 2016
Concluding Thoughts

Hot Drought has been a factor in the last 19 years in the CRB. Precipitation reductions can not explain flow loss.

Temperature is an known, significant and forecastable driver of river flows.

Precipitation is hard to forecast on almost all meaningful time scales for water managers. This is especially true in the Colorado River Basin.
Most Severe Colorado River Low Flow Sequences
10 Worst Sequences

<table>
<thead>
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<th>Length of Low Flow Sequence (Years)</th>
<th>% of mean 20th century Lee Ferry flow</th>
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Ending Decade of Flow Sequence
- 21st Century Flow Sequence
- 20th Century Flow Sequence

Length of Low Flow Sequence – Years

% of mean 20th century Lee Ferry flow
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Ending Decade of Flow Sequence
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<th>Length of Low Flow Sequence</th>
<th>Cumulative Flow Loss in Years of LFerry Mean Flow</th>
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