How Will the Colorado Run?
The Colorado River in a Warmer World

The Future of the Colorado River
October 13, 2018

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Lake Creek, Colorado
September 8, 2018
Climate Basics:
1. It’s warming
2. It’s us
3. Experts agree
4. It’s bad
5. We can fix it
Key Points

- Climate Change already impacting the basin
  - Temps for sure, maybe precipitation
- Impacts will get Worse
  - “New Normal” inadequate to convey challenges
  - Aridification underway – not a drought
- Plan on...
  - Hotter Everywhere
  - Shifting runoff patterns
    - South (Dry) and North (Less Dry to Perhaps Wet)
    - Earlier within-year runoff
  - More WX Variability
    - year to year, within-year
  - Substantial Flow Reduction Risk
  - Flood Risks
    - Localized – Likely
    - Basin-wide - ??
  - Higher Water Temperatures
  - Fires
- Opportunity for Change
Lowest Precipitation on Record
4 Corners Area

Warmest Temps on Record
Large Parts of the Basin
Lake Powell Unregulated Inflow
Water Year 2019 Forecast (issued September 1)
Comparison with History

**Water Year 2019 Forecast**
- Sep Most Prob: 7.90 maf (73%)
- Aug Min Prob: 4.80 maf (44%)
- Aug Max Prob: 15.60 maf (144%)
- Average: 10.83 maf (1981-2010)

**Observed Apr-July:** 2.60 (36%)
**Projected WY 2018:** 4.76 (44%)
Denver Water Forecast Inflow vs Runoff 2018

• Colorado River snowpack peaked at 107% of normal

• South Platte River snowpack peaked at 85% of normal

<table>
<thead>
<tr>
<th></th>
<th>South Platte at South Platte</th>
<th>Blue River at Dillon</th>
<th>Williams Fork</th>
<th>Fraser at Winter Park</th>
</tr>
</thead>
<tbody>
<tr>
<td>May 1 NRCS Forecast</td>
<td>48%</td>
<td>99%</td>
<td>81%</td>
<td>99%</td>
</tr>
<tr>
<td>Actual Natural Volume</td>
<td>38%</td>
<td>71%</td>
<td>71%</td>
<td>77%</td>
</tr>
</tbody>
</table>

Source: Denver Water
Denver Water Forecast Inflow vs Runoff 2018

Dillon Reservoir April through July
Natural inflow 71% of normal
13th lowest since 1916

Cheesman Reservoir April through July
Natural inflow 42% of normal
11th lowest since 1916

Source: Denver Water
The 2000-18 Millennium Drought is very, very different from previous droughts in the historic record...
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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
  - Thirstier Atmosphere

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

Udall and Overpeck, WRR, 2017
New Normal?

Dave Pierce, Scripps
New Normal?

Dave Pierce, Scripps
New Normal?

Dave Pierce, Scripps
New Normal?

It clearly will get hotter

Expansion of the Wet/Dry Axis  = more variability

Hint of more occurrences of extreme wet than extreme dry

Note: precipitation is not runoff...

Dave Pierce, Scripps
Aridification – not a drought

- Declining Snowpack and earlier runoff
- Higher Temperatures
- Drying Soil
- Thirsty Atmosphere
- Moving storm tracks
- Shorter Winter/Longer Fall
- Greening?
- Megadrought?

Aridity Index (P/PET) Changes

2041-2060

Seager et al., 2018
Increasing influence of air temperature on upper Colorado River streamflow

Connie A. Woodhouse\textsuperscript{1,2}, Gregory T. Pederson\textsuperscript{3}, Kiyomi Morino\textsuperscript{2}, Stephanie A. McAfee\textsuperscript{4}, and Gregory J. McCabe\textsuperscript{5}

- Temperature can be a major flow driver
- Since 1988 flows have been less than expected given winter precipitation
- Warm temperatures exacerbated modest precipitation deficits in the Millennium Drought

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure}
\caption{Percentile comparison of WY Flow and Oct-Apr Precipitation.}
\end{figure}
Changing Precipitation Patterns: Dry South, Less Dry North

Climate models: north is wetter, and south is drier

Wet: Wind Rivers + Unita Mountains
Dry: Most of Colorado

Key: Where is the ‘hinge’ point?
CRB Mainstem critical
Other Supporting Studies

- Response of Colorado River runoff to dust radiative forcing in snow
  - Painter, et al., 2010

- Hydrologic Sensitivities of Colorado River Runoff to changes in Precipitation and Temperature
  - Vano et al., 2014

- Climatology, Variability, and Trends in the U.S. Vapor Pressure Deficit, an Important Fire-Related Meteorological Quantity
  - Seager et al, 2015

- Running Dry: The US Southwest’s Shift to a drier climate
  - Prein et al., 2016

- Relative impacts of mitigation, temperature, and precipitation on 21st-century megadrought risk in the American Southwest
  - Ault et al., 2016

- Evidence that Recent Warming is Reducing Upper Colorado River Flows
  - McCabe et al., 2017

- The Curious Case of Projected Twenty-First-Century Drying but Greening in the American West
  - Mankin et al., 2017

- Dramatic declines in snowpack in the western US
  - Mote et al., 2018

- The More Extreme Nature of North American Monsoon Precipitation in the Southwestern United States as Revealed by a Historical Climatology of Simulated Severe Weather Events
  - Luong, et al., 2018
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• Opportunity for Change
Most Severe Colorado River Low Flow Sequences
10 Worst Sequences

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<th>Length of Low Flow Sequence (Years)</th>
<th>% of 20th century mean Lee Ferry flow</th>
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<tbody>
<tr>
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Ending Decade of Flow Sequence
- 1920s
- 1930s
- 1940s
- 1950s
- 1960s
- 1970s
- 1980s
- 1990s
- 2000s
- 2010s

Length of Low Flow Sequence – Years

% of 20th century mean Lee Ferry flow

Ending Decade of Flow Sequence
- 1920s
- 1930s
- 1940s
- 1950s
- 1960s
- 1970s
- 1980s
- 1990s
- 2000s
- 2010s
Two Droughts Findings

- Similar to Long Term Findings
- 2000s have half of the UCRB precipitation reduction of the 1950s
  - -6.1 km³ vs -3.2 km³
- 2000s have higher Winter ET
  - 0.4 km³ vs 1.8 km³
- 2000s have higher Winter Flows
- ~50% due to higher UCRB temps
  - 0.1 °C vs 1.0 °C
  - T-detrend run provides comparison
- ~50% due to changing precipitation locations

Xiao, et al., 2018
Evapotranspiration Increases in Natural Systems

In the future, plants move up slope, increasing evapotranspiration.

By 2100 ET increases by 28% and Kings River flows decline by 26%.
Model-based Study using Historical Data

- Long-term Trend Analysis (-16.5% Decline)
- Temperature De-trend Model Experiment
- 1950s vs 2000s Drought Analysis
- 2017 Forecast Analysis

Findings

- ~50% of Decline due to Higher Temperatures
- ~50% of Decline due to Changing Precipitation Patterns

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