**What drought intensities and durations can Lake Mead sustain?**

A bottom-up vulnerability analysis

David E. Rosenberg

Colorado River Futures Project

Utah State University

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# Introduction

From 2000 to 2015, Colorado River flows averaged 13.4 million acre-feet (MAF) per year. Lake Mead’s water level fell from 1,214 feet (25.2 MAF active storage, nearly full) to 1,089 feet (10 MAF of active storage, 40% of capacity). This decline has prompted widespread interest in questions such as what drought intensities and durations can Lake Mead sustain? How do those drought events compare to droughts reconstructed from paleo stream records? And the related question: how long can reservoir storage delay the impact of droughts?

This brief analysis performs a multi-dimensional sensitivity analysis to identify the number of years that Lake Mead can sustain various scenarios of steady drought flows for different starting reservoir storage volumes. The sensitivity analysis applies the decision scaling method ([Brown et al. 2019](#_ENREF_2)) to identify system vulnerability to uncertain future drought flow and reservoir storage conditions that can only be described by scenarios of possibilities (Level 3 uncertainty). This scenario approach contrasts with [Tim Barnett and David Pierce Barnett and Pierce (2008)](#_ENREF_1) who asked in their impactful work “When will Lake Mead go dry?” what is the likelihood that a combined Lake Powell and Mead system will go dry by a certain year (Level 2 uncertainty)? [Tim Barnett and David Pierce Barnett and Pierce (2008)](#_ENREF_1) generated 10,000 realizations of river flow that were statistically consistent with historic variability from 1906-2005 and tree ring flow estimates over the prior 1250 years. They imposed a deterministic linear runoff trend over time and found that there was a 50% chance to reach dead pool by 2053 even when reducing full deliveries by 10% after Mead fell below an active storage of 7.5 MAF (~1,048 feet). Since 2007, Lake Mead’s level has continued to fall and California, Nevada, and Arizona have agreed to larger and earlier cutbacks under the Drought Contingency Plan. Below, this analysis describes the main benefits from the work, sensitivity methods used, key findings, and caveats.

# Main Benefits from this Work

* Provide context for and show impacts of Homa’s and Dave T.’s hydrologic scenarios work
* Identify the combinations of flow intensity, flow duration, and starting reservoir storage conditions that drive Lake Mead to dead pool, to fill, or to a long-term steady storage value.
* Show interaction of flow interaction and duration factors and answer questions posed in many recent Colorado River Futures meetings.
* Provide a way to show impacts of transitions from dry to wet hydrology and vice-versa.
* Use decision scaling to extend [Barnett and Pierce (2008)](#_ENREF_1) stochastic treatment of inflow uncertainty (Level 2) to scenarios (Level 3).

# Methods Used

1. Defined scenarios of steady drought inflows to Lake Mead from 5 to 12 million acre-feet per year (MAF/year) in increments of 0.5 MAF/year. Each steady inflow scenario repeats the same flow value each year (e.g., 5, 5, 5, …, 5 MAF/year). These steady flow values represent the average flow of a multi-year event and can be converted to comparable average Colorado River flows reported from the historical and paleo records (see Step #7).
2. Defined scenarios of starting active reservoir storage from 3 to 25 MAF in increments of 2 MAF. These starting reservoir storage values represent the volume of water managers have available to carry through a steady flow scenario. Multiple starting storage scenarios are considered because reservoir storage will invariable change over time; the same analysis can still be used. Current Mead active storage is 11.3 MAF (1094.9 feet). Start storages above 25.9 MAF were ignored as this space should be reserved empty to capture flood water.
3. Simulated each combination of a starting reservoir storage value and steady Lake Mead inflow. The simulation ran on an annual time step and used a well-trodden, deterministic reservoir simulation method and data:
   1. Storage in the next year equals storage in the current year plus Mead Inflow minus Mead Release minus Mead Evaporation.
   2. Mead Release is specified by the 2019 Drought Contingency Plan schedule ([Wang et al. 2020, Sidebar 3](#_ENREF_4)). Above 1,090 feet, release is the full 9.6 MAF/year (Lower Basin + Mexico + downstream evaporation losses). Below 1,090 feet, release is cutback according to the schedule of Mead water elevations.
   3. The Mead evaporation rate used is 6.2 feet/year (Moreo et al, 2015; average value from 2010 to 2015). To obtain the evaporation volume, multiply the rate by the Mead pool area. The reservoir area-volume relationship for Lake Mead specified in the Colorado River Simulation System model (CRSS; Wheeler et al, 2019) was used to interpolate a pool area each year from the storage volume.
4. Ran each simulation year by year until one of three stop conditions was reached:
   1. Reservoir storage drew down to the Dead Pool (895 feet, 0 MAF of active storage; Years to Dead Pool)
   2. The reservoir filled to 25 MAF of active storage (Years to Fill)
   3. An iteration limit of 100 years was reached. These simulations reached a steady reservoir storage (somewhere between dead pool and 25 MAF; Steady Storage).
5. Recorded the number of years to reach stop condition (a) or (b). This number of years represents the duration that the reservoir can sustain the specified hydrologic scenario with the specified starting storage volume. For stop condition (c), the steady storage volume was recorded.
6. Linearly transformed the Lake Mead steady inflow scenario values to other useful scales:
   1. A Powell Release equals the Steady Mead inflow minus 0.75 MAF/year. 0.75 MAF/year approximates the median Grand Canyon tributary and local inflows between Lake Powell and Lake Mead (Paria, Little Colorado, Virgin) over the historical record as reported in the natural flow database ([Prairie 2020](#_ENREF_3)).
   2. A Lee Ferry Natural Flow equals the Steady Mead Inflow minus 0.75 MAF/year (Grand Canyon tributary inflows) plus 4.5 MAF/year (average Upper Basin consumptive use) plus 0.46 MAF/year (Lake Powell evaporation). The evaporation volume assumes an evaporation rate of 5.7 feet/year and lake area corresponding to 9 MAF of active storage. The effects of both assumptions are discussed under Caveats.

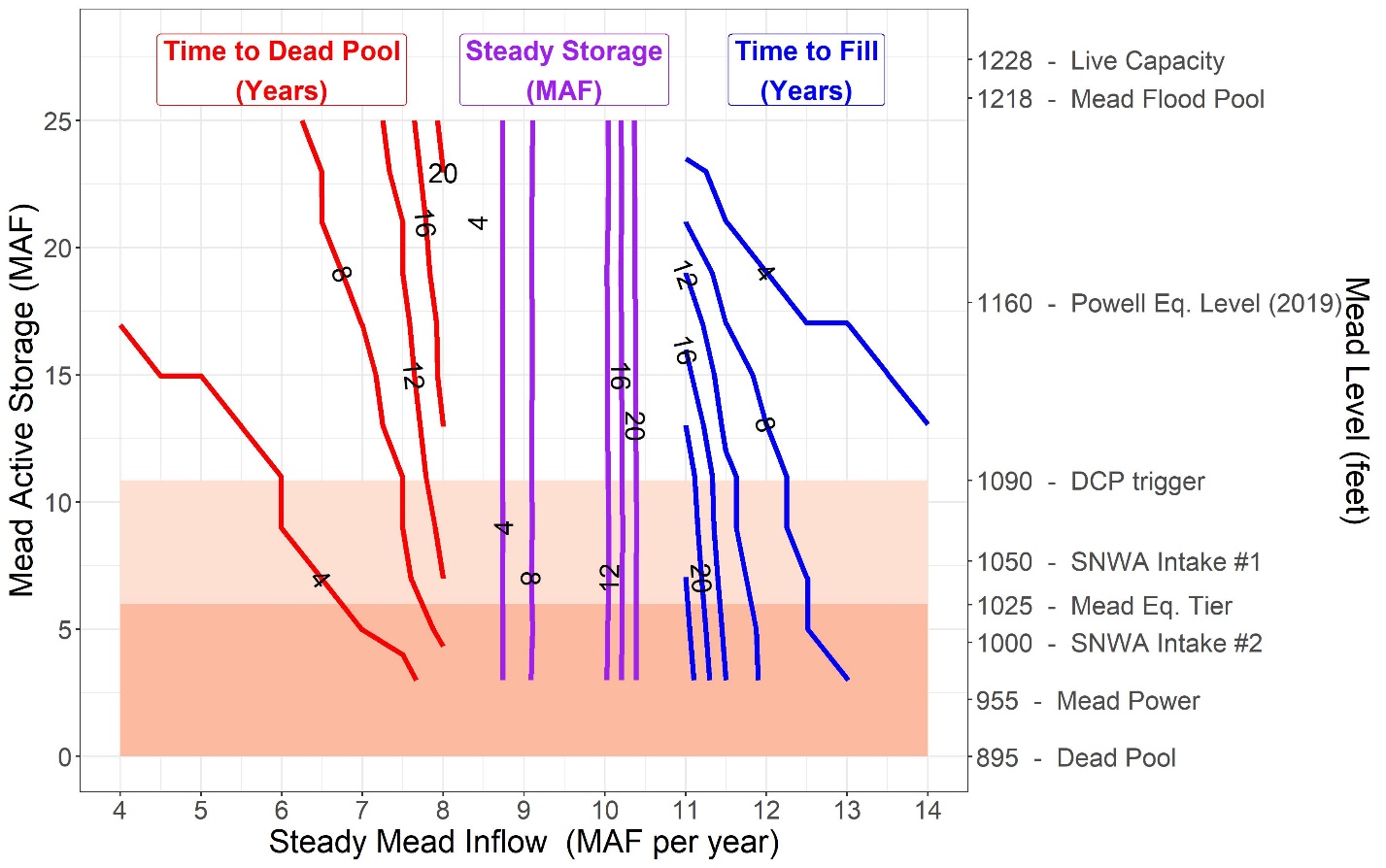
# Key Findings

System vulnerability is visualized by plotting the scenarios of Steady Mead Inflow and Mead active starting storage on the x- and y- axes (Figure 1). Within the plot, red, purple, and blue contours show years to dead pool, the steady storage volume, or years to fill. The pink filled area shows Mead elevations between 1,090 and 1,025 feet when Drought Contingency Plan cutbacks start while the red fill shows elevations below 1,025 feet when cutbacks continue at their maximum value.

At current active storage of 11.3 MAF and operations, low flow and short-duration events can draw Lake Mead down to Dead pool. For example, Mead can only sustain steady inflows of 6 MAF per year for 4 years or 7 MAF per year for 6 years.

Steady annual Mead inflow determines the reservoir end state (Dead Pool, fill, steady storage).

1. For steady Mead inflows of 8 MAF per year and less, Mead draws down to its dead pool. The time to reach dead pool depends on the starting reservoir storage. At the current active storage of 11.3 MAF, Mead can sustain annual flows of 8 MAF per year for 14 or more years before reaching dead pool. However, Mead can only sustain steady flows of 7 MAF per year for 6 years before reaching dead pool.
2. For steady Lee Ferry natural flows between 8 and 10.5 MAF per year, the Mead storage volume will equilibrate between 4 and 20 MAF of active storage. For steady flows at or below 9.5 MAF per year, Mead will equilibrate at an active storage volume below its current volume of 11.3 MAF.
3. For steady Mead inflows at or above 11 MAF per year, Lake Mead will eventually fill to 25 MAF of active storage. At the current level of 11.3 MAF this time to fill will be 22 years with 11 MAF inflow and 6 years with 13 MAF per year of steady inflow.

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**Figure 1. Years to reach dead pool (black numbers on red lines), steady storage volume (black numbers on purple lines), and years to fill (black numbers on blue lines) for combinations of steady Lee Ferry Natural flow and reservoir storage.**

A steady Mead inflow scenario can also be interpreted as a steady Lake Powell release scenario plus 0.75 MAF per year for Grand Canyon tributary inflows (Figure 2; only difference between Figures 1 and 2 is that the x-axis is shifted by 0.7 MAF per year to represent Grand Canyon tributary inflows). Thus, the problem can be reframed as: how long can Mead sustain a Powell release of 8 MAF per year? Or how long can Powell release 8 MAF per year? Two further points:

* A steady 8 MAF per year Powell release is the point when Mead transitions from maintaining a steady storage (Figure 2, purple lines) to falling to its dead pool (red lines; note, the.
* Sustained Powell releases of 7 or 7.5 MAF per year as required when Powell storage is below 6 or 9 MAF active storage (lower or mid equalization tiers) will draw Mead down to dead pool in 6 to 8 years.
* At 8.5 MAF per year of steady Powell releases, Mead storage equilibrates but to as small volume of 4 MAF of active storage that is much lower than current storage of 11 MAF.

A steady Mead inflow scenario can also be interpreted as a steady Lee Ferry natural flow scenario (Figure 3; only difference between Figures 1 and 2 is that the x-axis is shifted to represent Grand Canyon tributary inflows, Powell evaporation, and Upper Basin consumptive use). Mead goes to dead pool for steady Lee Ferry natural flows of 12 MAF per year or less.

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|  | **Figure 2. Years to reach Mead dead pool (red lines), steady storage volume (purple lines), and years to fill (blue lines) for combinations of steady Lake Powell release and Mead reservoir storage.** Figure 2 structure is identical to Figure 1 except that x-axis is shifted to account for Grand Canyon tributary inflows. |

4.5 MAF to represent Upper Basin consumptive uses, Powell evaporation, and Grand Canyon tributary inflows) or Lee Ferry Natural Flow

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**Figure 3. Years to reach dead pool (red lines), steady storage volume (purple lines), and years to fill (blue lines) for combinations of steady Lee Ferry Natural flow and reservoir storage.** Figure 3 structure is identical to Figure 1 except that x-axis is shifted to account for Grand Canyon tributary inflows, Powell evaporation, and Upper Basin consumptive use.

# Caveats

1. This analysis ignores the intentionally created surplus program. Users who intentionally create surplus voluntarily cut back their delivery from Lake Mead, keep that water in the reservoir, and can later withdraw it (when Mead level is above 1,025 feet). Additional cutbacks under the program will delay the time to reach dead pool or speed the time to fill. Conversely, if users call on their surplus water as the Mead level drops towards 1,025 feet, the time to reach dead pool will shorten. For reference, the maximum volume allowed by the intentionally created surplus program is 0.625 MAF/year and much smaller than the 1.3 MAF/year required by the DCP at 1,025 feet.
2. Sidesteps Lake Powell-Lake Mead equalization and modeling of Powell. Equalization can be considered by looking at the effects of steady Powell releases between 7 and 9 MAF per year required by equalization. This range of Powell releases, if sustained, may result in Mead going to dead pool or reaching a stable but very low active storage. At low Powell and Mead storages, sustaining Powell releases to prop up Mead will draw down Powell.
3. Converting Steady Mead Inflow to Lee Ferry Natural Flow assumes a constant Lake Mead evaporation volume. From the range of evaporation rates measured at Powell, evaporation volumes at 9 MAF of storage may vary ± 0.06 MAF/year. The evaporation volume and range both decrease as the storage volume decreases. Upper Basin consumption use may vary from year

# Next Steps

1. Annotate plots with paleoflow events (identified by Homa and Dave T.)
2. Redo for lumped, always-equalized Powell-Mead model (combined storage, Lake Mead + Lake Powell evap as function of combined storage, Alter DCP cutback points to 2 \* Mead volume.

# References

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