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What is the risk to Colorado River storage and deliveries under climate change scenarios? A review of several recent studies

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Abbreviation	Full Citation
Barnett08	Barnett, T. P., and D. W. Pierce. 2008. When will Lake Mead go dry? *Water Resources Research*, 44, W03201, doi:10.1029/2007WR006704.
Barsugli09	Barsugli, J. J., K. Nowak, B. Rajagopalan, J. R. Prairie, and B. Harding. 2009. Comment on “When will Lake Mead go dry?” by T. P. Barnett and D. W. Pierce, *Water Resources Research*, 45, W09601, doi:10.1029/2008WR007627.
Rajagopalan09	Rajagopalan, B., Nowak, K., Prairie, J., Hoerling, M., Harding, B., Barsugli, J., Ray, A., and B. Udall. 2009. Water Supply Risk on the Colorado River: Can Management Mitigate? *Water Resources Research* 45 W08201, doi:10.1029/2008WR007652.
Barnett09	Barnett, T. P., and D. W. Pierce. 2009. Sustainable water deliveries from the Colorado River in a changing climate. *Proceedings of the National Academy of Sciences (PNAS)*, 106, 7334– 7338, doi:10.1073/pnas.0812762106.

Table 1. The four studies discussed in this article. Contact wwa@noaa.gov to receive PDF copies of any of these studies.

In February 2008, the publication of a research paper with the title “When Will Lake Mead Go Dry?” made a big splash in the media, and caused much consternation among Colorado River stakeholders. The most provocative and widely reported conclusion of the paper, by Tim Barnett and David Pierce of the Scripps Institute of Oceanography, was that under climate change, Lake Mead and Lake Powell would have a 50% chance of “going dry” (depleting live storage) by 2021. Not surprisingly, the Barnett and Pierce paper (hereafter, “Barnett08”) motivated several follow-up studies (see Table 1).

The first goal of this article is to examine the similarities and differences among these studies. The second goal is to present the shared lessons from these studies about the behavior of the Colorado River system as depletions approach, and potentially exceed, average inflows—whether from climate change, increased consumptive use, or both.

What do these studies of the Colorado River Basin have in common? First, they all use a simplified water balance model to assess the future trajectory of total reservoir storage in the Colorado River Basin. The model calculates changes in storage as the net effect of inflows, consumptive use in the whole basin, and evaporation and other losses (Figure 1). When certain modeling assumptions are made, a simplified water balance model can come close to reproducing the results of the Bureau of Reclamation’s detailed Colorado River Simulation System (CRSS) model for the combined storage in Lake Powell and Lake Mead on annual and longer time scales.

Second, all of the studies attempt to represent the potential effects of climate change on reservoir storage and the reliability of water supply. To do this, they all assume reductions in average annual flow which ramp up to an overall decline of either 10% or 20% by about 2050. These two reduction scenarios are consistent with the results of hydrologic modeling studies of the Colorado River Basin done using climate change projections, but are not derived directly from those studies (see the sidebar on *Reconciling projections* on page 2). The purpose of the studies reviewed in this article was not to assess the likelihood of these scenarios occurring, but to investigate the impacts if these flow reduction scenarios were to occur.

The Barnett08 study made a number of assumptions about the gain and loss terms in their water balance model (summarized in Tables 2 and 3 and discussed in detail in Barsugli09). Barnett08 assumed that cur-

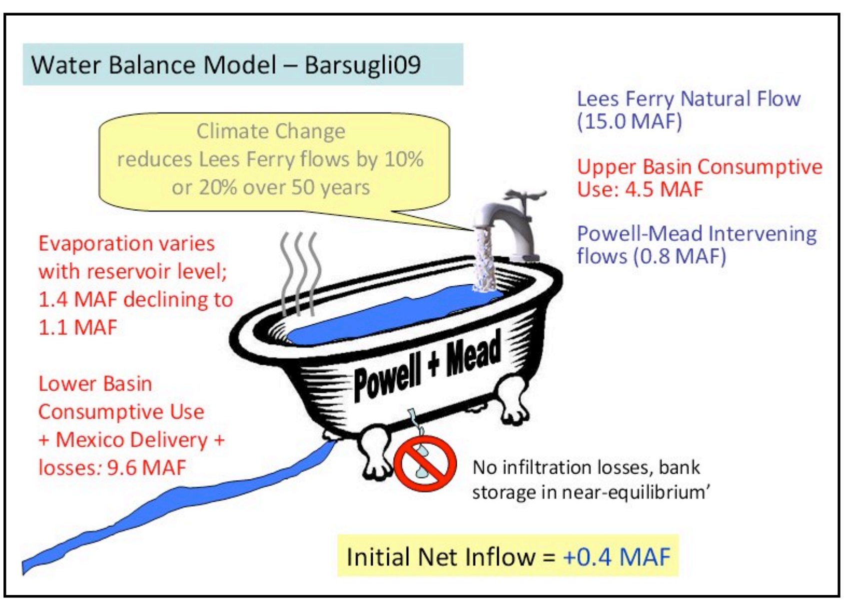

Figure 1. Schematic of simplified water balance model, and assumptions regarding inflows and depletions, used in Barsugli09. The model used in Rajagopalan09 is very similar except that the “bathtub” is larger (60 MAF vs. 50 MAF). See Tables 2 and 3 for a complete list of the model assumptions in these studies and the Barnett studies.

	Barnett08	Barsugli09	Barnett09	Rajagopalan09
Inflow to Powell	-- see Table 3--			
Current consumptive use	13.5	13.5 Alternate: 12.7	13.5	13.5 Alternate: 12.7
Inflow: Powell to Mead	0	0.86	0.86	0.86
"Infiltration"	-0.3	0 ("near equilibrium")	Function of change in storage	0
Reservoir Evaporation	-1.4	Function of area, -1.1 to -1.4	Function of area, + 7% increase	Function of area
Inflow below Mead	0	0.45	0.45	0.45
Losses below Lake Mead	0	10% of Mead releases (1.0 avg.)	0.88	10% of Mead releases (1.0 avg.)
Total Storage	50 (Mead + Powell)	50 (Mead + Powell)	50 (Mead + Powell)	60 (total system)

Table 2. Modeling assumptions in the four Colorado River studies. All values are in million acre-feet (MAF).

	Barnett08	Barsugli09	Barnett09	Barnett09 "paleo" baseline	Rajagopalan 09
Lees Ferry "baseline" 20th century	?	15.0 (1906-2005)	15.3 (1906-1984)	14.1	15.0
Lees Ferry "baseline" 2007	14.2 (implied)	15.0	14.8 (-10%) 14.3 (-20%)	13.7 (-10%) 13.2 (-20%)	15.0
20% flow reduction 2050	---	12.4	12.2	11.3	12.4
20% flow reduction 2057	11.2 (implied)	12.05	11.9 (trend continued)	11.0 (trend continued)	12.0

Table 3. Modeling assumptions regarding natural inflows to Lake Powell (i.e., at Lees Ferry) in the four Colorado River studies. All values are in million acre-feet (MAF).

rent consumptive use in the entire basin is 13.5 MAF, which is consistent with the depletion schedule adopted by Reclamation in 1999. Given these assumptions, one would calculate that the Powell-Mead system was already operating as of 2007 at a net deficit of -0.2 MAF/year, given the observed (1906–2005) average natural inflow into Lake Powell of 15.0 MAF/yr. Their modeling did not include the new reservoir operating rules finalized in the interim shortage guidelines released in fall 2007.

Barnett08 ran their model using a range of net balances and other factors, and reported a corresponding range of results in the paper. However, the result that was singled out and highlighted—that the Powell and Mead had a 50% chance of going dry by 2021—assumed that the Powell and Mead system was actually in net deficit of -1.0 MAF/yr as of 2007. Given their other modeling assumptions, this deficit would imply Powell inflows of 14.2 MAF/yr, not 15.0 MAF. In other words, the main result from Barnett08 implicitly assumes that the current "expected flows" are much less than the observed mean.

With those modeling assumptions, particularly the last assumption about the current deficit, the dire results in Barnett08 necessarily follow – drastic, near-term risk of the reservoirs running dry. As Terry Fulp, now the Deputy Director of Reclamation's Lower Colorado Region, was quoted in the Las Vegas Review Journal when the study came out, "Given [Barnett's] assumptions, I won't quibble with his conclusions. I think the real question is, 'Are these the right assumptions?'"

The Barsugli09 study argued that the Barnett08 assumptions regarding gain and loss terms were not correct. These included (1) the neglect of tributary inflows to the mainstem Colorado between Powell and Mead; (2) the neglect of gains and losses below Mead; (3) the treatment of evaporation as a constant value independent of lake surface area; and (4) and the inclusion of a loss term from bank "infiltration" from the reservoirs. They also questioned the assumption of a large current deficit and the implication of Powell inflows that were well below the observed mean. The Barsugli09 modeling, using a set of gain and loss assumptions more in line with those of Reclamation (Table 2), and Powell natural inflow of 15.0 MAF, found less near-term risk to storage from climate change. Using those assumptions, and with current consumptive use set at 13.5 MAF, Lake Mead had much lower risk of going dry by 2021 (~20%), and the 50% risk of drying would not occur until 2035 to 2047, under a 20% decrease in flow by 2057 due to climate change. Barsugli09 also performed a second analysis starting with the actual consumptive use in 2006, 12.7 MAF, which resulted in lower future risk of drying.

Barsugli09 still concluded that, if the reductions in flow caused by climate change were to occur, the inevitable clash of increasing demand and reduced inflow would begin in the late 2020s, dragging the system towards increasingly lower reservoir storage and higher risk of shortages. The analyses in Barsugli09 also confirmed that as overall depletions in the basin approach the average natural inflow, the "risk profile" is very sensitive to small

Reconciling projections of future Colorado River streamflow

A separate set of studies have all used output from global climate models (GCMs) along with hydrologic modeling to project Colorado River streamflows into the future. These studies consistently find that reductions in flow in the Colorado River basin will occur in the next half-century, mainly as a result of warmer temperatures which increase evapotranspiration, although the studies differ regarding the likely magnitude of the reductions. WWA, in conjunction with other RISA programs, has been conducting an assessment of these studies determine why the results are different, and to try to narrow the range of the flow projections so they are more useful for water planning. This assessment project, called "Reconciling projections of future Colorado River streamflow" was reported on in the May 2009 issue of Southwest Hydrology (http://www.swhydro.arizona.edu/archive/V8_N3/feature2.pdf)

Also see the WWA web page on the reconciling flows project: http://wwa.colorado.edu/current_projects/CO_River/rcn_strmflw_corvr.html

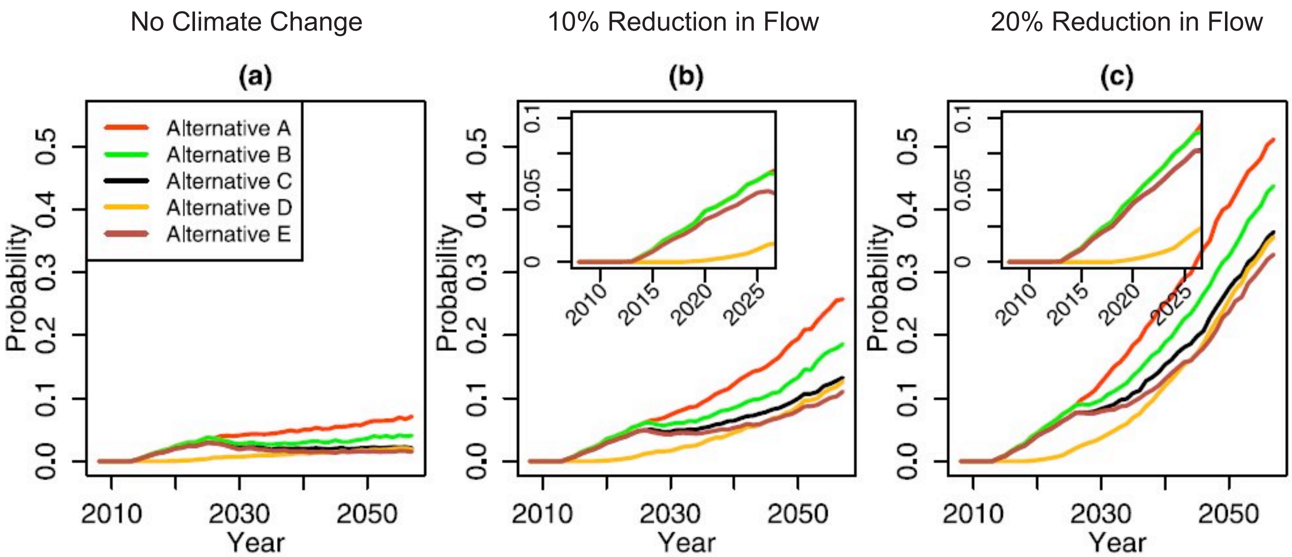

Figure 2. From Rajagopalan09: (a) Risk of drying (depleting system-wide active storage in a given year) for five management alternatives, with an initial demand of 13.5 MAF and no climate change–induced reduction in flow. (b) Same as Figure 2a but for 10% reduction in the annual average inflow over the 50-year period. Inset shows the risk in the near term for the period 2008–2026. (c) Same as Figure 2b but for 20% reduction in annual average inflow. Note: Alternative A (red line) is the current policy (2007 interim shortage guidelines). See Rajagopalan09 for descriptions of all five alternatives.

changes in the model assumptions regarding consumptive use and inflows.

The Rajagopalan09 study was a companion to the Barsugli study, with largely the same group of authors. (Both studies were supported by the Western Water Assessment and Reclamation.) It used the same water balance model as Barsugli09, with the exception that it modeled the entire 60 MAF storage on the Colorado River System rather than just the 50 MAF storage in Powell & Mead. Rajagopalan09 brought two new dimensions to the analyses: representing uncertainty in future demand as an envelope of risk; and investigating several policy scenarios that might be undertaken to mitigate risk.

Rajagopalan09 found (Figure 2) that under projected growth in consumptive use (starting with 13.5 MAF in 2007) and with no inflow reductions due to climate change, the risk of drying of system storage by 2057 was very low, under 6%, with all five policy scenarios. But with a 10% reduction in inflow, the risk of drying jumped to 9-24%, and with a 20% reduction in inflow, the risk of drying increased to 30-50%, depending on the policy scenario. But even in the 20% flow reduction scenario, the risk of drying by 2026 (the end of the interim shortage guidelines) was below 10%. The take-home messages of Rajagopalan09 were that (1) as flows are reduced in a linear manner, the risk of drying increases exponentially; (2) this increase in risk is most pronounced after ~2026; (3) the risk of drying could be partially mitigated by changes in policy management, e.g., modifications to the interim shortage guidelines.

In 2009, in response to the comments on their methods, Barnett and Pierce published a second paper, "Sustainable water deliveries from the Colorado River in a changing climate", which differed from their original study in two key respects. First, they changed their modeling assumptions regarding loss terms to nearly match those made in the CRSS model, bringing them in line with Barsugli09 and Rajagopalan09. Second, rather than expressing model outcomes in terms of storage (e.g., Mead going dry), they used Lower Basin deliveries—and shortages therein—as the metric for system risk. Their key finding was that, given a 20% reduction in flow caused by climate change, scheduled deliveries to the Lower Basin (8.23 MAF minus shared shortages per the interim guidelines) were not met 88% of the time by 2050. The average delivery shortfall by 2050 under this scenario was 2.2 MAF. Even as soon as 2021, deliveries were not met ~40% of the time—suggesting a much greater near-term system risk than found by Rajagopalan09.

One main reason for this disparity is that Barnett09 assumed that climate change-induced reductions in Powell inflows had already begun, in 1985. This means that under the 20% reduction scenario, by 2007 the modeled inflow had already decreased to ~14.3 MAF, while in the Rajagopalan09 modeling, 2007 inflow was still pegged at 15.0 MAF, the observed 1906-2005 mean. While no significant downward trend in Powell inflow has yet been detected over the entire observed natural flow record (now 1906-2009), the possibility that climate change is already reducing flows in the basin can't be dismissed. The decade that just ended (2000-2009), for example, experienced the lowest 10-year mean natural flow (12.0 MAF) in the observed flow record.

Barnett09 also pointed out something that tree-ring scientists have been trying to convey to water managers for over 30 years: that tree-ring reconstructions of streamflow for the Colorado River basin consistently indicate that the 20th century was anomalously wet compared to the past 500-1200 years. Barnett09 took the average of all 10 reconstructions published since 1976 to arrive at 14.1 MAF as a more realistic long-term mean Powell inflow, and when they re-ran their analyses using this lower

***Dead Pool* and Lake Powell**

In January 2009, the book *Dead Pool*, by geologist James Powell, was released. Like the four studies described in this article, a brief chapter in *Dead Pool* describes the results of modeling of the Colorado River system under climate change scenarios. In this case, the model is the Colorado River Open Source Simulator (CROSS), developed by Niklas Christensen at the University of Washington, and intermediate in complexity between the water balance models used in the four studies and Reclamation's CRSS model.

CROSS is available for download for anyone to run with their own preferred model input (http://www.onthecolorado.org/cross.cfm). For the analysis in *Dead Pool*, Powell specified that inflow was reduced 10% by 2050 by climate change, and that the long-term natural flow was 14.6 MAF, consistent with the latest paleo studies. CROSS does not permit Mead to fall below 1000' elevation, to protect the Southern Nevada Water Authority intakes. The result from running CROSS with these inputs was that Lake Powell falls to dead pool in the 2040s—thus the title of the book. While it's difficult to compare directly, this result seems consistent with those from Rajagopalan09 and Barnett09, and likely falls in between them regarding future risk to storage.

"paleo baseline", the risk of shortages, and size of shortages, increased even more. But some of the earlier paleo studies were likely biased low due to methodological issues and less extensive tree-ring datasets. The most recent reconstructions (Woodhouse et al. 2006, Meko et al. 2007, Gangopadhyay et al. 2009) all indicate a long-term mean of around 14.6 MAF—still lower than the observed mean.

Summary

So where does the situation with these studies stand now? The Barnett08 study has clearly been superseded by Rajagopalan09 and Barnett09. The two research teams' water balance models for the Colorado River basin now closely agree in their assumptions regarding evaporation and other losses from the two reservoirs, net losses below Lake Mead, the character of year-to-year variations of inflow to Powell and Mead, and the implementation of the interim guidelines.

Where the latest studies still differ is in how they answer these questions:

- What is the "true", pre-climate change, long-term average natural flow in the river: 15.0 MAF/yr (the observed mean)? 14.1 MAF/yr (all paleo studies)? Or 14.6 MAF/yr (the most recent paleo studies)?
- Has climate change has already begun (prior to 2007) to substantially reduce flows in the basin?
- What is the correct modeling assumption for current consumptive use (13.5 MAF? 12.7 MAF?), and what projections of future consumptive use should be used?

There may not be "right" answers to these questions. And even if there were perfect agreement on the model assumptions—and perfect knowledge of future climate—answering the question posed in Barnett08, "When will Lake Mead go dry?" would not foretell the future. The levels of Lake Mead and Lake Powell are the result of the operation of both reservoirs in accordance with the compacts, legal decisions, and agreements that form the Law of the River. It is difficult to imagine that the status quo would be stubbornly maintained in the face of future reductions in inflow and chronically depleted reservoirs. The establishment of the 2007 interim shortage guidelines provides evidence that adjustments can be made to policy and operations to respond to future trends in hydrologic conditions and system storage.

Thus, the real value of these studies is not in providing "forecasts" of system outcomes (e.g., Lake X will likely go dry by year Y); it is in providing a broad-brush picture of the vulnerability of Colorado River water supplies given a changing climate and increasing consumption, and to facilitate the process of investigating and implementing strategies to mitigate this risk. And despite the differences in details, that broad-brush picture is consistent among the studies: with consumptive use plus other depletions now approaching average annual inflow, the Colorado River system is operating on a narrow "margin of error". Any reductions in future inflow due to climate change will dramatically increase the risk of delivery shortages and/or reservoir depletion. A 20% flow reduction over the next 50 years, which is within the range suggested by runoff projections, would lead to levels of risk that would be widely regarded as unacceptable, absent major changes in policy and reservoir operations.

In the simple models considered in these studies, an increase in consumptive use has the same effect as a decrease in inflow: they both increase the risk of delivery shortages on the system as a whole. Because the use of the river has neared (or according to Barnett09, exceeded) the expected inflows, the additional risk per acre-foot of additional use is larger than it has ever been. If climate change further reduces inflows, then additional demands pose an even greater marginal increase in risk. But projected consumptive use is an assumption in these models. In the real world, the level of consumptive use depends on the physical and legal availability of the water at the locations where diversions take place, and more detailed modeling is required to determine the magnitude of these risks.

While the findings of the Barnett08 paper were poorly received by many in the the water resources community, we think that the discussion and follow-on research stimulated by that paper will ultimately benefit the Colorado River system and its users, by describing the envelope of future risk and providing a framework to evaluate changes in policy to reduce that risk.

Additional References:

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