

Comment on “When Will Lake Mead Go Dry?”

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Abstract

According to Barnett and Pierce (2008, henceforth BP2008) Lake Mead has a 50% chance of “going dry” by 2021, and the lower Colorado River system is facing “a major and immediate water supply problem.” Is this an accurate assessment? Is this time scale justified by the facts? We question several assumptions in the water balance model used by BP2008 to reach these conclusions. The most serious of these is the neglect of over 800,000 acre-feet of intervening flows in the annual average between Lakes Mead and Powell. We also discuss assumptions about infiltration, evaporation, and losses downstream from Hoover Dam, all of which have a significant bearing on the water balance. Under our assumptions, we find that the 50% chance of depleting storage occurs between 2035 and 2047, at least a decade further in the future than BP2008 conclude. We agree with BP2008 that the risks to water supply on the Colorado are serious, but rather than being in a state of immediate crisis, there is a window of opportunity to craft effective policies to respond to these threats.

1. Introduction

Barnett and Pierce (2008, henceforth BP2008) make the following claims: “there is a 10% chance that live storage in Lakes Mead and Powell will be gone by 2013 and a 50% chance that it will be gone by 2021.” They also claim that “minimum power pool levels will be reached under current conditions by 2017 with 50% probability.” Interestingly, BP2008 show elevated risk of imminent drying even for their “no climate change” scenario. These latter estimates are in stark contrast to risk profiles recently calculated by the Bureau of Reclamation (Reclamation) using the more complete Colorado River System Simulation model (CRSS) under the assumption of no climate change (BOR 2007b), raising the question of whether the assumptions and simplifications used in BP2008 are realistic. We seek to understand these differences within the framework of a simple water balance model as was used in BP2008.

As we will show, the critical reason for BP2008’s alarming results is the assumption that the system is currently operating at a long-term deficit of 1.0 Maf/yr (million acre-feet; 1Maf = $1.2335 \times 10^9 \text{ m}^3$), which will only get larger in the future with increased demand and climate change depletions. *The crux of our comment is whether or not their justification for a 1Maf/yr initial deficit is valid.* For clarity, we succinctly describe their water balance model, present the problems we find in their assumptions, and show what we believe to be more realistic simulations and risk estimates, followed by some concluding remarks on metrics of system risks and management realities.

2. The Water Balance Model

We agree with BP2008 that a water balance model is adequate to characterize the gross behavior of the annual-average storage in Lakes Mead and Powell taken together. By

construction, the water balance model does not represent the risks to any individual user of water from the system. The BP2008 model is simple -- basically a leaky, evaporative bathtub:

$$S_{n+1} = S_n + Q_n - C_n - L_n \quad (1)$$

In this model, the year-to-year change in the combined live storage of Lakes Powell and Mead, S_n , is equal to natural flow at Lee's Ferry, Q_n , minus total consumptive use in the Upper and Lower Basins, C_n , minus losses, L_n , due to evaporation and "infiltration" from the reservoirs for a year n . Climate change is incorporated as a fractional decrease in the inflow that ramps up linearly from zero to $\alpha = 0.2$ (a 20 % reduction) over the period of 50 years that are simulated.

This yields the following equation¹ for inflows:

$$Q_n = \tilde{Q}_n - \alpha \frac{n}{50} Q_0 \quad (2)$$

where \tilde{Q}_n is the stochastically generated total flow in year n of the simulation *before climate change reductions are applied*. Q_0 is the initial expected value of the flow and is either specified (as in BP2008) or set equal to the long-term mean of \tilde{Q}_n (our simulations). BP2008 also considered 10% and 30% reductions due to climate change, but we will focus on the 20% scenario for this comment as those results were highlighted in their paper. Losses are assumed constant at $L_n = 1.7$ Maf/yr. Consumptive use is specified in each year according to projections of demand that start with initial value C_0 and increase according to the schedule provided by the Upper Colorado River Commission. The additional use in each year above the initial value C_0 is represented by C'_n . The water balance (Eq. 1) can be rewritten in terms of what BP2008 call the "initial net inflow", $I = Q_0 - C_0 - L$, as follows:

¹ It is unclear whether BP2008 apply their "deterministic linear runoff trend" as a fractional reduction of Q_0 or of \tilde{Q}_n . For our simulations we choose the latter formulation: $Q_n = \tilde{Q}_n (1 - \alpha \frac{n}{50})$, which leads to minor modifications of Eq. 3. This will not impact the average climate change reduction but will impact the variance of the simulated flows.

$$S_{n+1} = S_n + I - \alpha \frac{n}{50} Q_0 + Q'_n + C'_n \quad (3)$$

The initial net inflow represents the *long term* surplus or deficit of the system if there were no climate change or demand growth. The remaining terms in Eq. 3 are the “deterministic” climate change reduction, the yearly anomaly in flow due to stochastic variability ($Q'_n = \tilde{Q}_n - Q_0$), and future increases in demand beyond C_0 .

In this model, the probabilistic risks are calculated by running 10,000 realizations using stochastically generated inflows. While there are many methods to generate these stochastic inflows, we agree with BP2008 that the particular choice of method does not have a large influence on the risk estimates coming out of the model. We present results using stochastic flows generated by the non-homogeneous Markov (NHM) method of Prairie et al. (2008). This method combines the paleoclimate record with historical observations and is capable of generating longer wet and dry sequences than seen in the historical record. It is similar in spirit to the fractional Gaussian noise method used by BP2008. We have done the calculations using a first-order autoregressive (AR-1) model of inflow variability and reach similar conclusions, with the “critical dates” for system failure typically within a year or two of those determined using NHM.

3. Assumptions and Omissions in the Water Balance Model

We find two serious problems in the assumptions used by BP2008: neglect of the intervening flows between Lakes Powell and Mead, and the treatment of “bank storage” as a constant “infiltration” loss. In addition, we also believe that evaporation from the reservoirs should be treated as variable rather than constant, for reasons stated below. Under these new assumptions the “initial net inflow” in the BP2008 model would be 0.95 Maf/yr which we

believe to be an over-estimate because the BP2008 model neglects losses downstream from Hoover Dam that are effectively a part of the water budget of Lake Mead. These terms, when corrected, lead us to assess the “initial net inflow” to be in surplus of 0.4Maf/yr, not in deficit. If the existing shortage guidelines are taken into account, the “doomsday clock” is set back by another year or two. These terms are summarized in Table 1. We will consider these in order.

Intervening Flows between Lakes Powell and Mead. BP2008 entirely ignore the inflows between Lakes Mead and Powell. There are several inflows to the Colorado and Lake Mead, including the Little Colorado River, the Paria River, the Virgin River, Bright Angel and Havasu Creeks and several other spring-fed creeks that flow in the Grand Canyon. The 1906 – 2006 average for these flows add up to 862 kaf/yr (Prairie and Callejo, 2005).² Because the NHM stochastic method is based on conditional resampling of the historic flows we include the time variations in these intervening flows in the stochastic simulation as well, though we do not consider any potential future development of tributary flows.

Infiltration. The treatment of what the authors call “infiltration” is puzzling to us. The authors list values of -312 kaf/yr for Lake Powell and +5 kaf/yr for Lake Mead taken from 1971-2004 water year averages. BP2008 treat this term as a steady loss of water from the system. We believe that BP2008 are confusing “infiltration” with the “bank storage” term in the mass balance. Reclamation computes “change in bank storage” at Lake Powell as a residual term in

² Because of the lack of long-record stream gauges between Lee’s ferry and Lake Mead, this estimate is based on a water balance calculation using the assumptions detailed in Prairie and Callejo (2005). As such, it relies in part on estimates of evaporative and other losses from Lake Mead in addition to gauged flows. Subtracting out the annual average gauged flow of the Virgin River (167 Kaf; 19xx-19xx) leaves approximately 700 Kaf from other sources. We can judge the reliability of this estimate by looking at a much shorter period when streamflow was measured on the Colorado River at Diamond Creek (USGS 94042, 225 river miles below Lee’s Ferry), a gauge that was not used in the Prairie and Callejo, 2005 method. The annual average gain between Lee’s Ferry and Diamond Creek for 1990-2006 was 728 Kaf. Over this same period, Prairie and Callejo, 2005 (and supplements available online at www.usbr.gov/lc) report an annual average naturalized gain of 697 Kaf for all inflows between Lees Ferry and Hoover Dam, excluding the Virgin River.

the historical mass balance. Ideally, bank storage acts as a source of water to the reservoir when reservoir levels are falling and a sink of water from the reservoir when they are rising, so that bank storage is thought to approximately conserve water once reservoirs have reached steady-state. For example, in WY2004 the bank storage term for Lake Powell shows a source of 175 kaf to the reservoir, a result of falling reservoir levels.

The large average “infiltration” values reported by BP2008 for Lake Powell may result from the fact that during the first decade of their averaging period Lake Powell was still filling following the completion of Glen Canyon Dam in 1964. Recent years have shown both positive and negative values of change in bank storage, indicating that the reservoir has come close to a steady state. The average value since the previous low stand of Lake Powell in WY1992 is a net loss of about 75 kaf/yr – and this imbalance may not be due to infiltration, but to other losses in the system that contribute to the residual. Although there is some uncertainty in the calculation of bank storage there is no justification for interpreting the entire 1971-2004 average as a steady loss to the system. For our calculations, we assume that the infiltration loss is negligible.

Evaporation from Lakes Powell and Mead: BP2008 use the 1971-2004 average evaporation of 1.4 Maf/yr as reported by Reclamation as a constant value for evaporative losses. In reality, evaporation depends on the surface area of the reservoirs, which is a function of storage. A future that includes climate change depletions will have lower average reservoir levels, hence less average surface area and lower average evaporation. For example, our water balance with dynamically calculated evaporation also yields 1.4 Maf/yr evaporation under a forward-looking “no climate change” scenario, but when climate change is included (Scenario III, see Tables I and II), our model averages 1.1 Maf/yr evaporation. This effect will act to lower the risk of drying compared to BP2008. As noted below, the value of 1.4 Maf/yr is probably a

conservative upper bound even if there were no climate change. The reduced risk due to treating evaporation as variable may be somewhat offset by increased temperatures under climate change, but neither we, nor BP2008, investigate this effect.

Under our assumptions we calculate evaporation as a linear function of total storage plus inflow as follows (all units are acre-feet): $E_n = 5.2 * [59097 + 0.0052 * (S_n + Q_n)]$. This relationship was derived from a linear fit to surface area vs. storage assuming equipartition of storage between Powell and Mead (inside the square brackets), along with total annual evaporation of 5.2 feet/yr derived from the monthly coefficients of the CRSS model (BOR 2007a). Adding in the total inflow before calculating evaporation provides a conservative upper bound on annual cycle effects that we are not able to resolve. Note that the 50-year mean from a forward-looking “no climate change” scenario in the CRSS model yields 1.1 Maf/yr of evaporation, lower than either BP2008 or our model. Since we calculate evaporation dynamically, we use the long-term mean from a “no climate change” simulation to estimate the evaporative loss term when calculating the “initial net inflow”. While BP2008 note that they investigated the effects of variable evaporation on their results and found little difference in risk, we find otherwise. Perhaps this is because their calculations start from a large initial deficit (due to the neglect of intervening flows) that may overwhelm this particular effect.

Intervening flows and losses below Hoover Dam: BP2008 assume that the allocation of 9 Maf for the Lower Basin and Mexico represents the actual amount released and drawn from Lake Mead. In practice, a total of about 9.6 Maf is released and drawn from Lake Mead in the annual mean— the difference mainly compensates for net downstream losses. Therefore we need

to account for an additional net loss of about 600 kaf/yr in our water budget.³ This correction acts to increase the risk to the system.

Implementation of the interim shortage guidelines. BP2008 do not include the interim shortage guidelines (BOR 2007a) in their baseline water balance, though they do include a scenario with 5% reduction in water delivery when Lake Mead drops below power pool level. The actual guidelines implement a graduated schedule of shortages, up to 500kaf, that are triggered when Lake Mead reaches specified elevations. In our simulations, these shortages act to further reduce the risk of drying in the near term, though the gains are modest. To implement these guidelines, we assume equipartition of the storage and calculate the resulting shortage amounts based on the resulting reservoir levels. For the purposes of our simulations we extend these guidelines beyond the interim period. While this technique will give a gross representation of how these shortage criteria may play out in the future, clearly a more detailed model of the system such as CRSS would be needed to accurately simulate these shortages.

4. Simulations and Probabilistic Risk Estimates

We performed simulations that reproduce the results of BP2008, and compare those to simulations with the above modifications implemented in the model. As usefully identified by BP2008, the “initial net inflow” defined above is a crucial parameter that determines much of the behavior in this model – particularly the near-term risk profile. BP2008 estimate the initial net inflow from 20th century historical data to be -0.2 Maf/yr, and present the 50% chance of Lake Mead reaching power pool “in about 2017” based on this assumption. Under these conditions

³ Based on historical observations and water budgets from Reclamation (Russ Callejo, personal communication) we estimate that about 1 Maf of “loss” occurs in the United States portion of the Lower Basin below Hoover Dam. This total includes phreatophyte losses, evaporation from Lakes Mohave and Havasu, Yuma (Welton-Mohawk) return flows, and over-delivery to Mexico. We model this as a net 11.5 % loss for flows below Hoover Dam. In addition there is, in the long-term average, 455 kaf/yr of intervening flow below Hoover Dam. (Prairie and Callejo, 2005).

the 50% chance of reservoir depletion occurs in 2027. To reach the “headline” result of a 50% chance of depleting storage by 2021, BP2008 run the model with an assumed initial net inflow of -1.0 Maf/yr. The chance of depleting storage by a given year is shown in Fig 1a using the NHM method for stochastic simulation, but otherwise implementing the BP2008 model. The chance of the reservoirs dipping below the power pool even once during the simulation is shown in Fig 2a. The years in which the 50% chance for each of these metrics is reached are summarized in Table 2.

When we include intervening flows, dynamic evaporation (with no “infiltration” term), shortage guidelines, and net losses below Hoover Dam, the chance of storage depletion declines substantially (Figure 1a, blue curve). Our assumptions lead to an initial net inflow of +0.4Maf/yr and a 50% chance of depletion by 2035, a full 14 years later than BP2008.

The assumption of present-day consumptive use (13.5 Maf/yr) was taken from projections made in 1999. We perform a second analysis that starts with the actual consumptive use in 2006 (12.7 Maf) (BOR 2008), but still increases demands in the future according to the year-to-year increments in the Upper Basin depletion schedule (Figure 3). The 2006 value is similar to the average of the past decade, a period that included extended drought and therefore represents a low-end value for the initial consumptive use. These two curves represent an “envelope of risk” that illustrate one aspect of uncertainty in the evolution of consumptive use.

5. Discussion

The image of the reservoir being “depleted” or “exhausted” or “running dry” is a powerful one. It suggests a finite natural resource that has been used up for good. BP2008 calculate the cumulative risk that the reservoir was depleted at least once by a given year. This is not a typical measure of system reliability, and does not model reservoir recovery resulting from

the large natural variability in Colorado River flow. For comparison we show an alternate metric of the risk of reservoir storage being depleted in any single year in Figures 1b, 2b and 4b. This metric does take into account reservoir recovery, and also allows a clearer depiction of the increasing risk with time as demands and climate change effects become large (Rajagopalan et al., 2009 submitted). Under our Scenario III (see Table 1), the 50% risk of storage depletion occurs in 2055 and of reaching power pool in 2035. It is important to understand that “the reservoir running dry” is not the same as “the river running dry”. Even if the reservoirs were to reach “dead pool” levels, the river would continue to flow and considerable amounts of water could still be delivered downstream of Hoover Dam. A more complete view of risk is obtained by noting the frequency and magnitude of future shortages under various scenarios (Rajagopalan et al., 2008, submitted).

BP2008 criticize the measures in the Interim Guidelines (BOR 2007a) on shortages as too small. However, the Interim Guidelines allow for the development of more stringent reductions in deliveries should Lake Mead drop below 1025 feet above sea level, opening up the prospect of a powerful management tool that could be used to avert the worst consequences of a prolonged drought. The Interim Guidelines also call for all parties to reconvene *by* 2020 to start negotiation on operating guidelines following 2026.

BP2008 obtain their main results by assuming an initial net inflow of -1 Maf/yr, rather than the value based on the 20th century average of -0.2 Maf/yr. Under their modeling assumptions, this equates to a value for Lee’s Ferry naturalized flow of 14.2 Maf/yr (See Table 1). The two main factors cited for this are that the 1906-2005 Lee’s Ferry naturalized flow of about 15 Maf/yr may be too high an estimate because the 20th century was a relatively wet period compared to the paleoclimate record, and that anthropogenic climate change may already have

reduced the expected flows below 20th century averages. There is no clear agreement in the scientific literature about the magnitude of these two effects, but we agree that they represent important uncertainties in this risk analysis of the Colorado River system and deserve more study. We would like to point out that uncertainty in future demand should also be considered along with uncertainties in inflow to develop a more comprehensive envelope of risk.

But fundamentally we do not agree with their modeling assumptions. Even if we were to assume a value of 14.2 Maf/yr for Lees Ferry naturalized flow, we would calculate an initial net inflow of -0.4 Maf/yr, *not* -1.0 Maf/yr. Note that the reference in BP2008 to the Lake Mead water balance being in a deficit of 1 Maf is not adequate justification for assuming a similar deficit in the Mead+Powell system, as other factors including the terms of the Colorado River Compact and releases to compensate for losses downstream from Hoover Dam are relevant and have tended to amplify the effects at Mead compared to Powell.

The time frame matters. BP2008 present the water supply as being in immediate crisis and fear that litigation will “put off any rational decisions on this matter until serious damage has been done to the diverse users of the Colorado River.” But precipitative action also carries risk, and policies implemented in haste may be ineffective or inefficient. Alternatively, there is the risk that doomsday scenarios may lead to inaction – after all, if the risks and impacts are as imminent as BP2008 proclaims, what can one do except react? Either way, the system may fall into unnecessary litigation that may impede the effective management of projected shortages. Nonetheless, we agree with BP2008 that the risks to water supply on the Colorado are serious, and we hope that this comment serves to put the analysis on a stronger footing. In a related paper (Rajagopalan et al , 2008), we and several co-authors argue that there is a window of opportunity to allow development of management strategies to cope with the looming threats of

climate change, population growth and episodic drought to the Colorado River water supply.

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Table 1. Terms in calculating the “Initial Net Inflow” for the water balance model for different scenarios. Alternate values used in scenarios I and IV are shown in parentheses.

Scenario	Barnett and Pierce, 2008		New Water Balance Model	
	I	II	III	IV
Upper Basin Natural Flow	(14.2) ⁴	15.0	15.0	
System Demands		-13.5	-13.5	(-12.7) ⁵
Inflow Between Powell and Mead		--	0.86 ⁶	
Loss from Powell and Mead		-1.7 ⁷	-1.4 ⁸	
Net Powell and Mead Inflows		-0.2	0.95	(1.75)
Losses Below Hoover Dam		--	-1.0 ³	
Inflows below Hoover Dam		--	0.45 ³	
Initial Net Inflow	(-1.0)	-0.2	0.4	(1.2)

⁴ Implied by the assumption of -1.0 Maf/yr net inflow, keeping other parameters fixed.

⁵ 3.7 Maf Upper Basin consumptive use in 2006 (BOR 2008)) plus 9 Maf annual Lower Basin demands.

⁶ Tributary inflow (0.86 + 0.45 Maf) and lower basin losses (-1 Maf) are based on historic observations and water balances.

⁷ 1971-2004 average evaporation from Lake Powell (-0.516 Maf), Lake Mead (-0.894 Maf) and combined “infiltration” loss (-0.312 Maf).

⁸ Initial evaporative loss (-1.4 Maf) based on storage-evaporation relationship from Scenario III water balance model under the assumption of no climate change. Note that a similar calculation using the CRSS model yields 1.1 Maf/yr of evaporation.

Table 2. Year by which cumulative probability of having at least one drying event or below power pool event is 50%. Scenario parameters are shown in Table 1. All scenarios assume a 20% reduction in natural flows over the next 50 years due to anthropogenic climate change.

Drying Event	Initial Net Inflow	Barnett and Pierce, 2008	New Water Balance Model
Scenario I	-1.0	2021	2021
Scenario II	-0.2	2027	2026
Scenario III	+0.4	NA	2035
Scenario IV	+1.2	NA	2047

Below Power Pool			
Scenario II	-0.2	About 2017	2019
Scenario III	+0.4	NA	2026
Scenario IV	+1.2	NA	2037

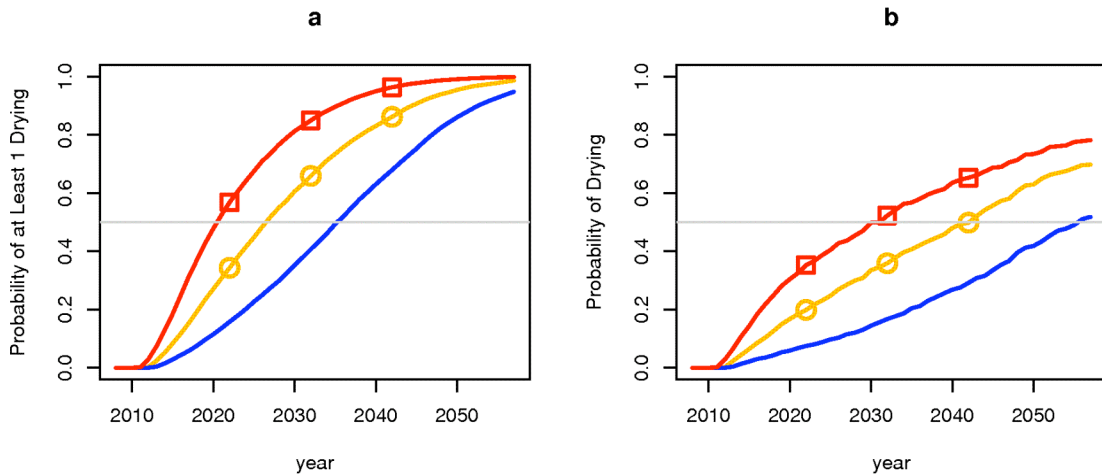


Figure 1. The probability of at least one drying (left) and drying in each year (right) are presented. Scenario I (Barnett and Pierce (2008) water balance model with -1.0 Maf net inflow) is shown in red square, Scenario II (Barnett and Pierce (2008) water balance model with -0.2 Maf net inflow) in orange circle, and Scenario III (includes all intervening flows, losses below Mead, dynamic reservoir evaporation, and shortages from the Interim Guidelines extended through 2060) in blue.

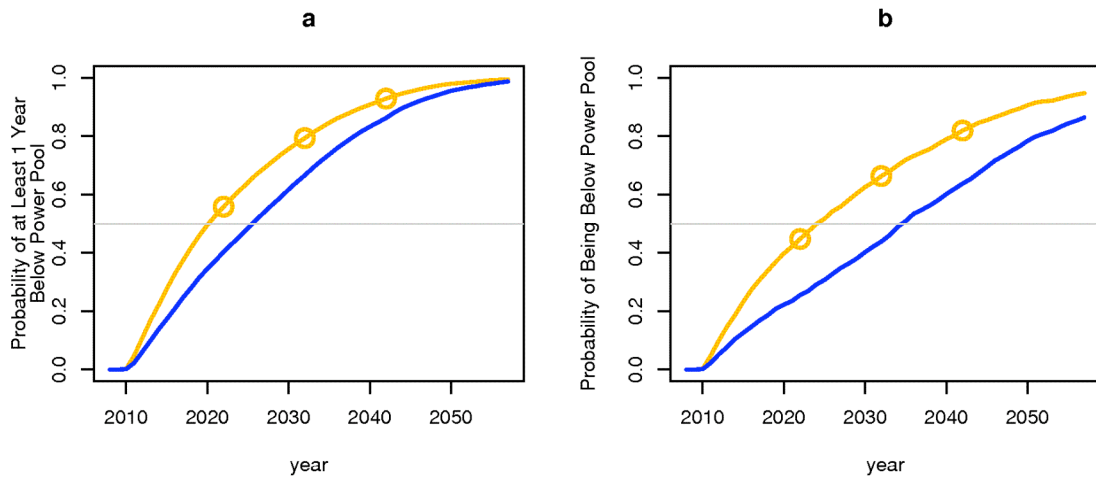


Figure 2. The probability of at least one year below power pool (left) and being below power pool in each year (right) are presented. Scenario II (Barnett and Pierce water balance model with net inflow = -0.2 Maf/yr) is shown in orange circle. Scenario III (includes all intervening flows, losses below Mead, dynamic reservoir evaporation, and shortages from the Interim Guidelines extended through 2060) is shown in blue.

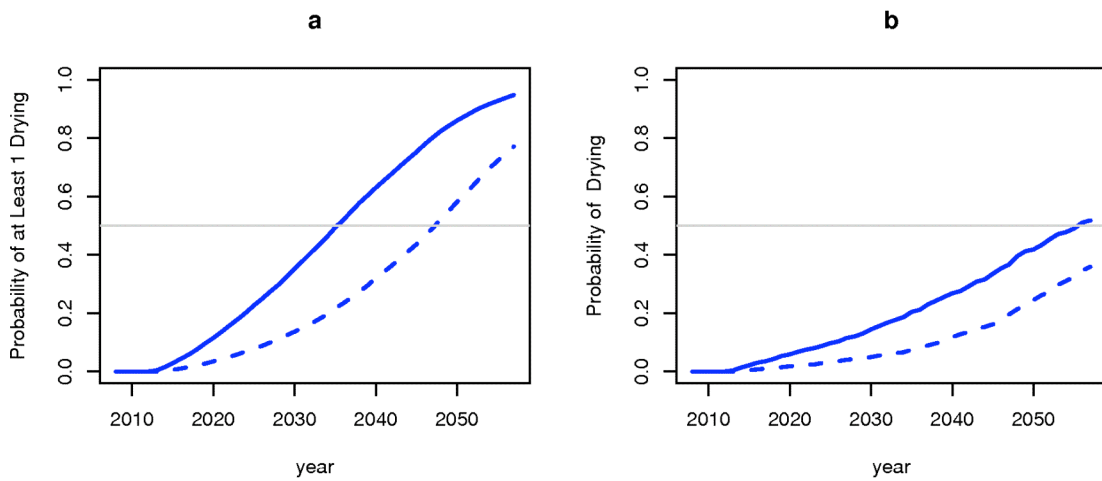


Figure 3. The probability of at least one drying (left) and drying in each year (right) are presented. Scenario III (solid line) includes projected annual demands starting at 13.5 Maf. Scenario IV (dashed line) starts with annual demand of 12.7 Maf. A 20 percent reduction in inflows over the next 50 years due to climate change is assumed. The region between the curves illustrates an envelope of risk due to uncertainty in consumptive use projections.