WATER RESOURCES RESEARCH, VOL. 44, W03201, doi:10.1029/2007WR006704, 2008

When will Lake Mead go dry?

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Received 27 November 2007; revised 22 January 2008; accepted 5 February 2008; published 29 March 2008.

[1] A water budget analysis shows that under current conditions there is a 10% chance that live storage in Lakes Mead and Powell will be gone by about 2013 and a 50% chance that it will be gone by 2021 if no changes in water allocation from the Colorado River system are made. This startling result is driven by climate change associated with global warming, the effects of natural climate variability, and the current operating status of the reservoir system. Minimum power pool levels in both Lake Mead and Lake Powell will be reached under current conditions by 2017 with 50% probability. While these dates are subject to some uncertainty, they all point to a major and immediate water supply problem on the Colorado system. The solutions to this water shortage problem must be time-dependent to match the time-varying, human-induced decreases in future river flow.

Citation: Barnett, T. P., and D. W. Pierce (2008), When will Lake Mead go dry?, *Water Resour. Res.*, *44*, W03201, doi:10.1029/2007WR006704.

1. Introduction

[2] A number of studies over the last 20 years have suggested that there will be a decrease in runoff over the Southwestern United States because of global warming. The decrease will be caused by increasing temperatures and evapotranspiration and decreasing precipitation. The statistical/empirical studies [*Revelle and Waggoner*, 1983; *Nash and Gleick*, 1991, 1993; *Hoerling and Eischeid*, 2007], as well as climate model studies of the last few years [e.g., *Milly et al.*, 2005; *Christensen et al.*, 2004, *Christensen and Lettenmaier*, 2006; *Seager et al.*, 2007] all show a decrease in runoff to the Colorado River (see caveats on climate models below). The estimates of runoff reduction from these studies are remarkably similar, and range between 10% and 30% over the next 30–50 years. The IPCC Working Group II concludes there will be a 10–30% run off reduction over some dry regions at midlatitudes during the next 50 years with very high confidence [*Intergovernmental Panel on Climate Change*, 2008]. Current naturalized flow in the Colorado River is on the order of 15 million acre feet (MAF, 1.233×10^9 m^3) per year measured at Lees Ferry (Figure 1), so these decreases will ultimately result in a runoff reduction of 1.5–4.5 MAF/a from current levels, which we assume leads to similar reductions in Colorado River flow.

[3] The Colorado River is quite literally the life's blood of today's modern southwest society and economy. Given the agreement about both size and timing of runoff reduction, it is important to examine what it will mean to the people of the southwest and, especially, when they might expect water shortage problems to appear. In its recent report on Colorado River Basin water management, the National Academy of Sciences [*Committee on the Scientific Bases of Colorado River Basin Water Management*, 2007] notes future potential problems with availability of water in the region. It calls for a comprehensive analysis of water needs and uses in the region, but provides no analysis of the timing or magnitude of potential problems. *Hoerling and Eischeid* [2007] suggest water availability could soon fall below critical levels but offer no temporal details. *McCabe and Wolock* [2007] estimate climate changes will increase chances of failure to meet water allocation requirements of the Colorado Covenant, but their methods preclude estimates of just when this might happen.

[4] Our intent is to make a first estimate of when and how the human-induced reduced runoff will impact people. We simplistically state the question as "when will Lake Mead go dry?" assuming there are no changes in water management strategies and sector-specific consumptive use. By "going dry," we mean when the live storage (the reservoir space from which water can be evacuated by gravity) in Lakes Mead and Powell becomes exhausted (Figure 2 summarizes the various storage levels in the Lakes). As we shall see below, the answer is both startling and alarming.

[5] It is obvious that once long-term outflow exceeds inflow the system is doomed to run dry. One of our purposes in this work is to point out that currently scheduled depletions (loss of water from consumptive use), along with water losses due to evaporation/infiltration and reduction in runoff due to climate change, have pushed the system into a negative net inflow regime that is not sustainable. Another purpose is to demonstrate how natural variability, i.e., the chance of getting strings of dry years consistent with the historical record, makes the system likely to run dry even with positive net inflow. When expected changes due to global warming are included as well, currently scheduled depletions are simply not sustainable.

2. Methods

2.1. Water Balance Model

[6] The method is a simple water balance approach that keeps track of water going into and out of the major

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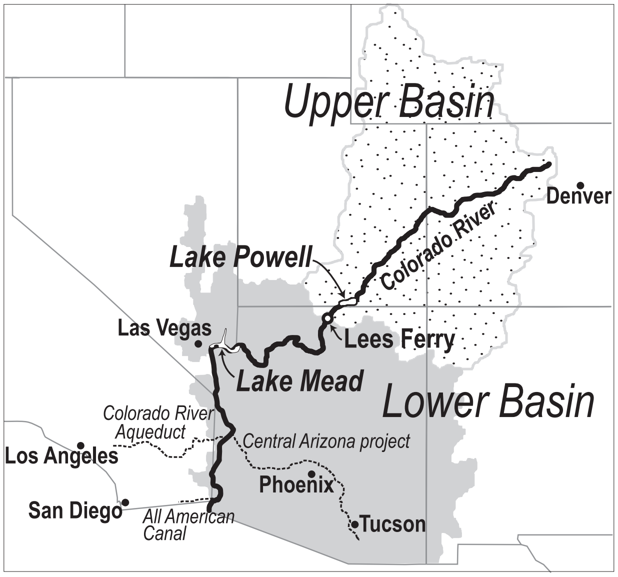

Figure 1. Overview of the region of interest (31.2°–43.7°N, 104.0°–120.3°W), which is historically separated into the "upper basin" (dots) and "lower basin" (gray). Colorado River flow from the upper to lower basins is measured at Lees Ferry.

reservoirs in the Colorado River system. The initial condition for our study (Figure 2) is the amount of water currently in live storage in the Lake Mead/Lake Powell system (25.7 MAF above the dead pool as of June 2007; U.S. Bureau of Reclamation Web page). We consider the two reservoirs as a single storage unit, consistent with the U.S. Bureau of Reclamation (USBR) plan to manage them jointly [*U.S. Bureau of Reclamation*, 2007]. We assume "perfect" management so that the amount of storage in each reservoir above dead pool is manipulated to keep the storage levels approximately the same in both reservoirs (see caveats). The naturalized flow of the Colorado River at Lees Ferry is 15 MAF/a over the period 1906–2005 (USBR Web page, http://www.usbr.gov/lc/region/g4000/NaturalFlow/current.html, accessed 10 January 2008), so we use this as a working number, although on the basis of tree ring reconstructions it is probably too high [*Committee on the Scientific Bases of Colorado River Basin Water Management*, 2007], and does not reflect the drought of the last 7 years (see caveats).

[7] Today the Colorado system is, for all intents and purposes, fully subscribed (see below) so any additional consumptive use in the upper basin as now contemplated (Figure 3), or reduced runoff into the river due to climate change, must be covered by existing storage. We consider human-induced reductions in runoff of 10 to 30%, in accordance with estimates from global climate models and statistical analysis, and take these reductions to be linear in time over the next 50 years (i.e., runoff slowly decreases until it reaches a total reduction of, say, 10% below current levels in 2057). We first do a simple deterministic analysis that does not include the complicating factors of runoff variability, evaporation, and infiltration, in order to more clearly isolate the effect of human-induced climate change on the reservoirs. We then do a probabilistic analysis of the likelihood of the reservoir storage becoming exhausted, using Monte Carlo simulations with a water budget model, and allowing for evaporation and infiltration as well as the stochastic nature of the river flow itself.

[8] We tested the water budget model by comparing it to the results obtained by *Harding et al.* [1995], who modeled a "severe sustained drought" episode on the Colorado River using a sophisticated river network model based on an enhanced version of USBR's Colorado River model, CRSS. The results (Figure 4) show the simulated, combined storage from *Harding et al.* [1995] versus that from the water

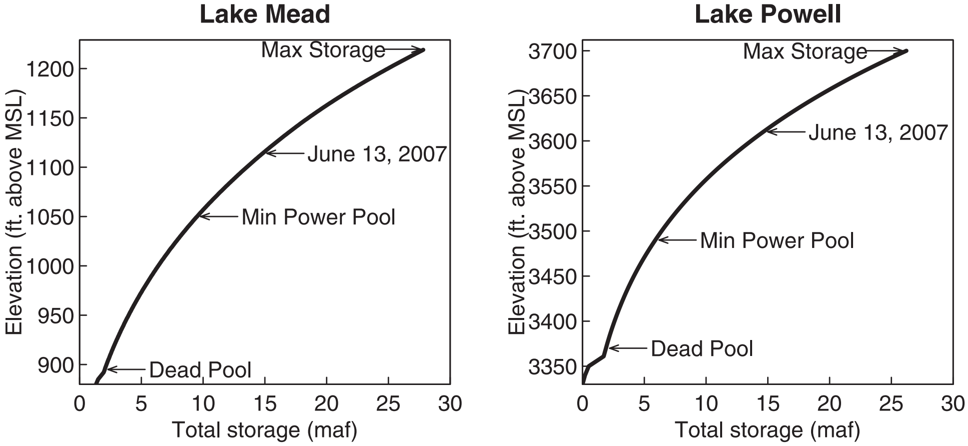

Figure 2. Total reservoir storage in Lakes Mead and Powell (million acre feet) as a function of lake surface elevation above mean sea level (feet). (We retain the units commonly used in the operation of these reservoirs; data are from Colorado River Open Source Simulator, release 1.0, 2007, http://www.onthecolorado.org/cross.cfm). Arrows indicate the maximum storage possible in each lake, the amount present on 13 June 2007, the minimum needed to enable hydroelectric power generation, and the minimum below which no more water can be extracted from the reservoir by gravity ("dead pool"). "Live storage" is all current storage above the dead pool elevation.

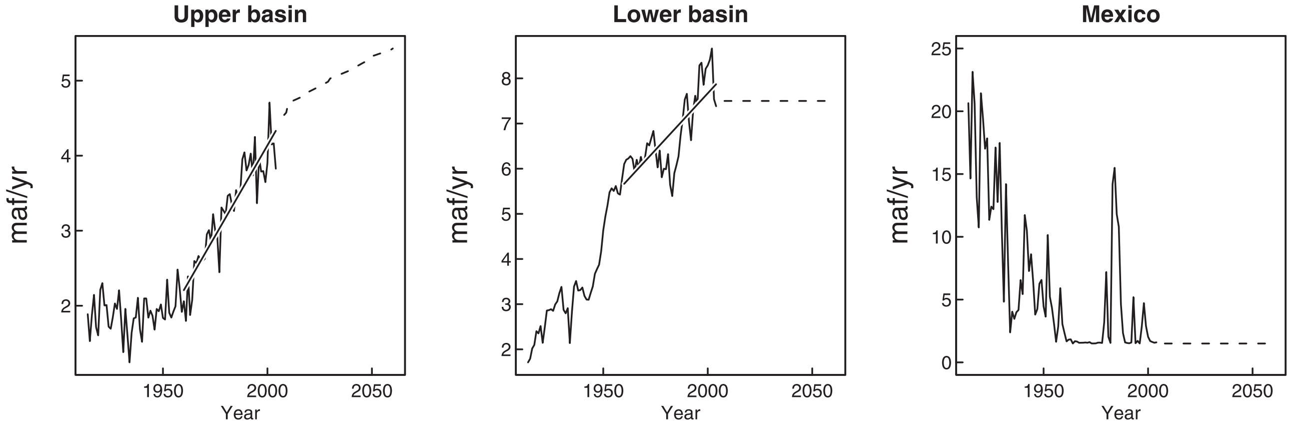

Figure 3. Historical water use (solid line) and scheduled future depletions (dashed line, 2008–2060) of the Colorado River system. Superposed lines for the upper and lower basins show the best fit least squares linear trend over the period 1960–2004. Note the abrupt change in water availability for the lower basin states.

budget analysis used here. The differences are due principally to our neglect of smaller storage units within the Colorado system. At any rate, the agreement suggests the method is adequate to address the large-scale water budget issues considered here.

[9] We tried three different methods to generate synthetic time series of Colorado River flow consistent with the historical record (Appendix A), including a simple first-order autoregressive (AR-1) approximation, fractional Gaussian noise (fGn), and a new Fourier-based technique described in Appendix A. Overall, our results are robust with respect to the method used, as the water budget effects are large compared to differences in detail of the synthetic flows. The plots shown here are made using fGn, since the more familiar index sequential method (ISM) does not correctly sample variability consistent with the historical record (see Appendix A). Synthetic time series generated with fGn also exhibit long-term persistence, which has been shown to be important for correctly simulating the statistics of hydrological processes [e.g., *Phatarfod*, 1989; *Pelletier and Turcotte*, 1997; *Wang et al.*, 2007; *Koutsoyiannis and Montanari*, 2007].

2.2. Future Depletions

[10] Future depletions are taken from published USBR schedules (appendices C and D of *U.S. Bureau of Reclamation* [2007]) over the period 2008–2060. In Figure 3 these are compared to historical water use (obtained from http://www.usbr.gov/lc/region/g4000/uses.html, accessed 14 November 2007). Total scheduled depletions rise from 13.5 MAF/a in 2008 to 14.1 MAF/a by 2030. We also include in the Monte Carlo results water loss due to evaporation and changes due to infiltration (the 1971–2004 average evaporation was 0.894 and 0.516 MAF/a for lakes Mead and Powell, respectively, while infiltration was +0.005 and −0.312 MAF/a (N. Yoder, USBR, personal communication, 2007)). Although the amount of evaporation and infiltration change with lake level, possibly providing a negative feedback as the lake area shrinks, evaporation is also likely to increase in the future as temperatures warm, and infiltration is a second-order quantity compared to the other mechanisms included here. Accordingly, in this work we have simply kept the value of evaporation/infiltration constant at −1.7 MAF/a. As a sensitivity test, we tried scaling evaporation with Lake surface area, and found it made little difference to our results; human-induced reductions in runoff overwhelm the Lake surface area-dependent changes in evaporation.

3. Results

[11] In section 3.1 we begin with deterministic estimates of when the live storage will be depleted by global warming–driven runoff reductions alone, without the outside impacts of evaporation and natural variability in the river flow. This approach is simplistic but gives an immediate feel for the scope of the climate change problem and how it relates to reservoir storage. In section 3.2 we then extend the analysis to more realistic, probabilistic estimates of the same quantities but allowing for the additional impacts of natural climate variability on runoff, as well as the effects of evaporation and infiltration. A summary of the factors included in each calculation is shown in Table 1.

3.1. Deterministic Estimates

[12] The above noted climate models and statistical studies projected decreases in runoff that can be used to compute the future decline in river flow in MAF, year by year. We start by assuming a current steady state where

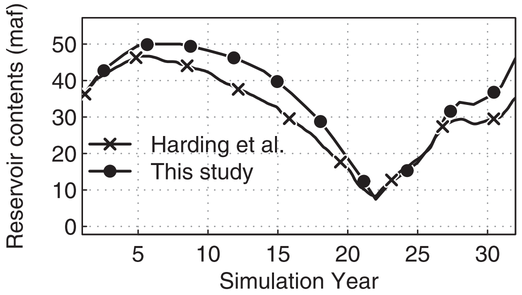

Figure 4. Reconstruction of combined Lakes Powell and Mead storage (MAF) during the "sustained severe drought" episode of the late 1500s from *Harding et al.* [1995] (crosses) and this study (circles).

Table 1. Summary of Factors Included in the Various Calculations[a]

Probabilistic Estimates?	Evaporation and Infiltration Included?	Given in Terms of Net Inflow?	Climate Change Included?	Management Strategies Considered?	Deplete to Power Pool or Dead Pool	Location of Results	10% Chance to Deplete by Year	50% Chance to Deplete by Year
No	no	no	yes	no	dead	section 3.1 (start)	NA[b]	2036
No	no	no	yes	no	power	section 3.1 (end)	NA	2021
Yes	yes	no	yes	no	dead	Figure 5	2014	2028
Yes	yes	no	yes	no	power	Figure 6	2010	2017
Yes	yes	yes	no	no	dead	Figure 7	2014[c]	2028[c]
Yes	yes	yes	yes	no	dead	Figure 8	2013[c]	2021[c]
Yes	yes	no	yes	yes	dead	Figure 9	2025[d]	2048[d]

[a] For simulations that include climate change, the quoted years are for a 20% reduction in runoff over the next 50 years.
[b] NA means not applicable.
[c] For a net inflow of −1.0 MAF/a.
[d] For a cut in requested water deliveries by 25%.

inflow to the reservoirs is equal to their discharge. In reality the Lake Mead is currently being overdrafted by about 1 MAF (T. Labonde and J. Shields, Update for Green River Basin Advisory Group, 2004, available at http://waterplan.state.wy.us/BAG/green/briefbook), so our assumption of steady state is highly conservative. We simply integrate the annual reductions in runoff in time, assuming the changes are temporally linear and levels of consumption are constant, to determine how many years until the existing live storage is gone. We find live storage will be depleted completely 23–40 years from now, or sometime in the span 2030 to 2047, for runoff reductions of 30–10% over 50 years, respectively.

[13] For further discussion, we take the median runoff reduction, from the above studies, as −0.06 MAF per year. This corresponds to a 20% decrease in runoff (3.0 MAF) 50 years from now, and yields approximately 29 years left, or calendar year 2036, before the combined Mead and Powell system is at dead pool elevation. Sensitivity studies showed the dates vary by roughly 10 years around 2036 by assuming larger/smaller 50 year runoff reduction rates or that the 20% runoff reduction will happen soon/later than 2050. The time to dead pool elevation is not very sensitive to the details and assumptions of the runoff estimates. One can also vary the date depending on when one assumes the warming impacts to set in. Recent studies show the global warming impacts have been operative in the Southwest for some decades [*Barnett et al.* 2008], but we make the conservative assumption they start in 2007. Perhaps most important are the initial conditions at the reservoirs for start of the calculations; we used the current state as of June 2007. At this time the system had about 50% of its total possible storage.

[14] In addition to water, both reservoirs are important sources of hydroelectric power. Together the two reservoirs can produce about 10,000 gW h. What do the runoff reductions mean to the availability of that latter resource? As of June 2007 there was a total, between both reservoirs, of approximately 15 MAF of water above the minimum power pool level, which is the reservoir elevation below which the power generation turbines cannot safely operate (Figure 2). Carrying through the same type of analysis as above showed that there is a 50% chance the minimum power pool elevation would be reached in around 2021; only 14 years into the future. At that point (or before), there would be an abrupt drop in the abilities of the reservoirs to generate hydroelectric power.

3.2. Probabilistic Estimates

[15] The previous results neglected the natural variability in river flow associated with weather (wet/dry years) and short-term climate variability (e.g., El Niño/La Niña). Using ten thousand realizations of river flow (statistically consistent with historic variability from 1906–2005 and tree ring flow estimates over approximately the last 1250 years), coupled with the deterministic linear runoff trend described above, allowed us to construct cumulative distribution functions (CDFs) for the depletion of the current live storage. Future depletions were taken from the USBR schedules shown in Figure 3, while evaporation plus infiltration was taken fixed at −1.7 MAF/a, as noted previously.

[16] The results are given in Figure 5 (left). The solid curve shows the likelihood of reservoir storage levels falling to the dead pool elevation with no runoff reduction. In the absence of curtailed water delivery, there is a 50% chance the system will go dry by 2037. This is driven by the sum of depletions (∼14 MAF/a by 2030) plus evaporation/infiltration (1.7 MAF/a) being larger than runoff into the system (15.05 MAF/a, the average over the period 1906–2005).

[17] Included also in Figure 5 (left) are the cases where climate change decreases runoff into the river by 10% (crosses) and 20% (circles). The probability of depleting both reservoirs' live storage is 50% by 2028, if we account for natural variability and a 20% decrease in runoff (which would be fully realized in 2057). The results are rather insensitive to changes in runoff reduction. The different methods of modeling the natural variability all give essentially the same results (Figure 5, right).

[18] All of these numbers are somewhat more pessimistic than the deterministic analysis because they include evaporation/infiltration as well as allowing for natural variability in the river flow. The answers, being expressed in probabilistic format, allow the user to determine the risk levels in any decision process they undertake.

[19] The probabilistic analysis for minimum power pool levels is shown in Figure 6. There is a 50% chance the minimum power pool levels will be realized by about 2017, in the absence of management responses. This result is rather insensitive to changes in runoff, at least in the near term. At any rate, the associated drops in power production would be precipitous in time as turbine intakes went dry. It

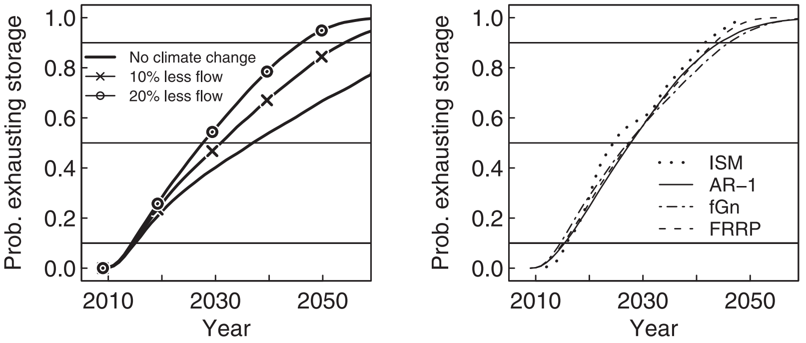

Figure 5. Cumulative distribution function (CDF) showing the probability of Lakes Mead and Powell reservoir levels falling to dead pool elevation by the indicated year. (left) Case where only natural variability is affecting river flow (solid curve) and cases where climate change produces a decrease in runoff of 10% (curve with crosses) and 20% (curve with circles). (right) CDFs obtained with four different methods of simulating natural runoff variability for the case with a 20% reduction in runoff. ISM, index sequential method; AR-1, first-order autoregressive process; fGn, fractional Gaussian noise; FRRP, Fourier reconstruction and randomized phase. See Appendix A for details.

seems clear that the threat to power production on the Colorado is both real and more imminent than most might expect.

3.3. Sensitivity to Net Inflow

[20] Are the results presented here inconsistent with previous results, modeling the severe late 1500s drought, that imply a more resilient water delivery system [*Harding et al.*, 1995]? In that work, even a severe historical drought had only a slight impact on water deliveries to lower basin states. Setting aside climate change for the moment, random weather noise provides a variable amount of water input to the system, which can vary greatly year to year. Water managers strive to deliver a near constant quantity of water every year, using reservoir storage capacity to smooth out these short-term variations. In this section we analyze the system in terms of the *net inflow*, defined as long-term mean flow into the combined Lakes Mead and Powell system minus the long-term mean of consumption plus evaporation/infiltration.

[21] If one considers the system as a whole, the net inflow is negative. The USBR scheduled delivery (Figure 3) starts at 13.5 MAF/a in 2008, which together with evaporation/infiltration of 1.7 MAF/a and a mean Colorado River flow of 15.05 MAF/a (average over 1906–2005) gives a net inflow of −0.15 MAF/a in 2008, dropping to −1.15 MAF/a by 2060 in the absence of climate change. A reduction in runoff by 10 and 20% from human-induced climate change would give net inflow of −2.6 and −4.1 MAF/a, respectively, by 2057. The reservoirs would be dry long before these levels were realized, assuming present consumption continues unchanged. Arguably more realistic would be to use the average mean Colorado River flow over the last 50 years, which would put the current net inflow even more negative, about −0.7 MAF/a, near the current overdraft of 1.0 MAF/a estimated for Lake Mead (see http://waterplan.state.wy.us/BAG/green/briefbook).

[22] Figure 7 (left) shows the CDFs of the system running dry as a function of fixed net inflow (i.e., neglecting any time-evolving contribution from climate change). It is clear that negative net inflow mandates the system running dry, but one might wonder how the system can go dry with zero or positive net inflow. Natural variability generates long periods of wet/dry years, so the system can go dry at one extreme and spill under wet conditions. These situations are equally likely from a statistical point of view when only natural variability is operating. In the absence of a management response to shortages, the system undergoes a random walk constrained only by the limits of maximum reservoir capacity (on the wet side) and completely exhausted storage (on the dry side). The middle plot of Figure 7 shows the probability of filling or going dry by year 2027 (20 years from now) as a function of net inflow. With initial reservoir storage approximately half the capacity, the curves are nearly symmetric.

[23] The CDFs shown in Figure 7 (left) have a strong sensitivity to net inflow; the system becomes rapidly prone to exhausting storage as net inflow drops from +2 MAF/a (which virtually guarantees reliable delivery) to −1 MAF/a, which has a 50% chance of running dry by 2027. So part of the reason our results seem to show a system more sensitive to climate fluctuations than earlier workers is that the

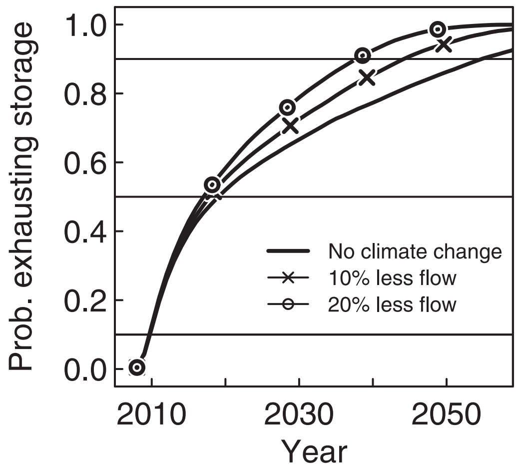

Figure 6. As in Figure 5 (left) but for reservoir storage dropping below the minimum necessary for hydropower generation.

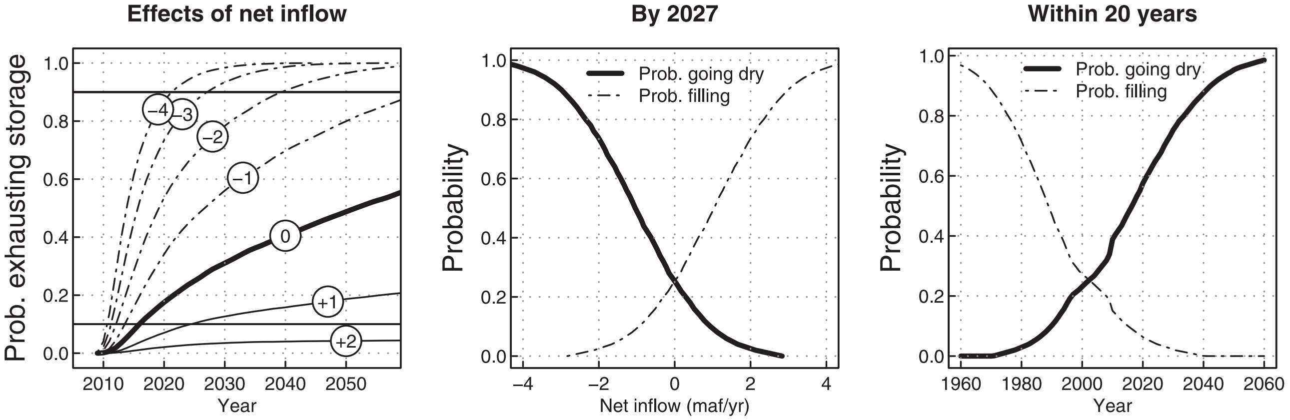

Figure 7. (left) CDFs of Lakes Mead and Powell running dry as a function of net inflow into the system, as indicated on the curves (in MAF/a). Climate change is not explicitly included. (middle) Probability of the system going dry (solid line) or filling up (dash-dotted line) by 2027, for the given net inflow (MAF/a). Climate change is not explicitly included. (right) Probability of the system going dry or filling up within 20 years of the indicated start year, given historical and future depletions and a 20% reduction in runoff due to climate change.

system becomes more unstable as the net inflow approaches zero, i.e., as the river becomes fully subscribed. Yearly depletions to the upper and lower basins have risen steadily since the 1940s (Figure 3), resulting in an increasingly unstable system.

[24] Furthermore, Figure 7 shows that the rate of increase in sensitivity of the system becomes much more rapid as the net inflow approaches zero. For example, consider the probability of the system running dry by 2027 (middle plot, thick line). The chance is negligible for a net inflow of +2 MAF/a or more, which was the case before about 1985. If the net inflow is reduced to +1 MAF/a (approximately the inflow for the late 1980s and early 1990s) the probability only rises to 9%. However, if the net inflow is further reduced to 0 MAF/a, the probability jumps to 25%; and as the net inflow drops to today's value of nearly −1 MAF/a, the probability of the system running dry by 2027 increases to 50%.

[25] We now add reductions in runoff due to climate change to the increasing sensitivity as net inflow approaches zero. The combination acts in a particularly unfortunate way. Even if current net inflow were at a somewhat safe value, such as +1 MAF/a, future reductions in runoff combined with increasing depletions (Figure 3) yield net inflows that drop to levels that render the system highly vulnerable in just a few decades. This is shown in Figure 8, where the left plot illustrates the case with initial (year 2007) net inflow of +1 MAF/a. In the absence of climate change, there is a 20% chance the system would run dry by 2040. However, a human-induced reduction in runoff by 20%, a medium value from the global model estimates, has a strong effect on the probability curve, such that there is then a 45% chance of the system going dry by 2040.

[26] In reality, we likely have a current net inflow between −0.2 and −1 MAF/a depending what base time period one wants to use for estimating mean Colorado River flow. The middle and right plots of Figure 8 show that in this regime, any reduction in river flow due to climate change has a strong effect on an already marginally reliable system, e.g., for a net inflow of −1 MAF, the probability

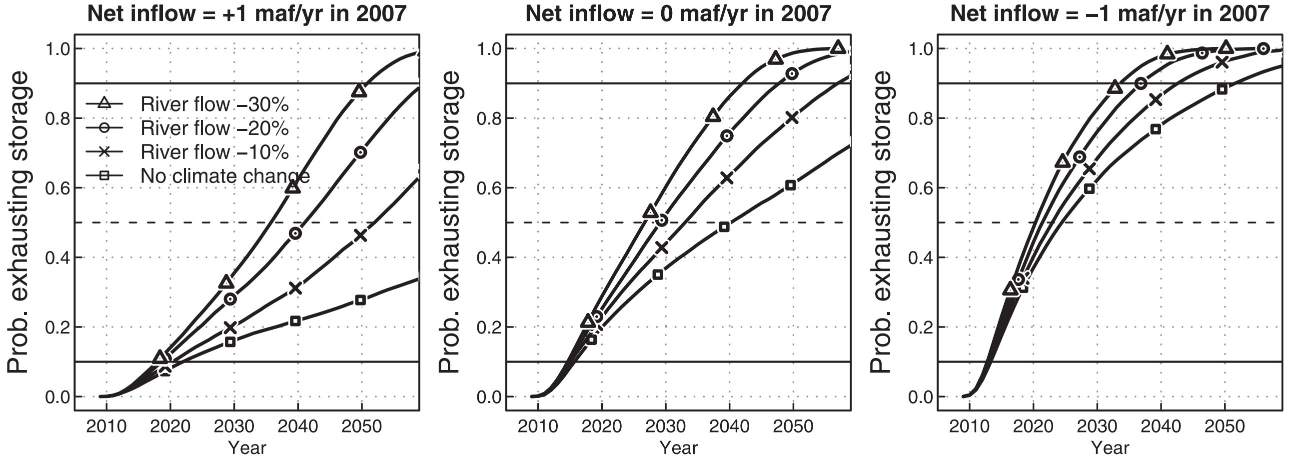

Figure 8. Effect of climate change on chances of Lakes Mead and Powell running dry, for a net inflow of (left) +1, (middle) 0, and (right) −1 MAF/a.

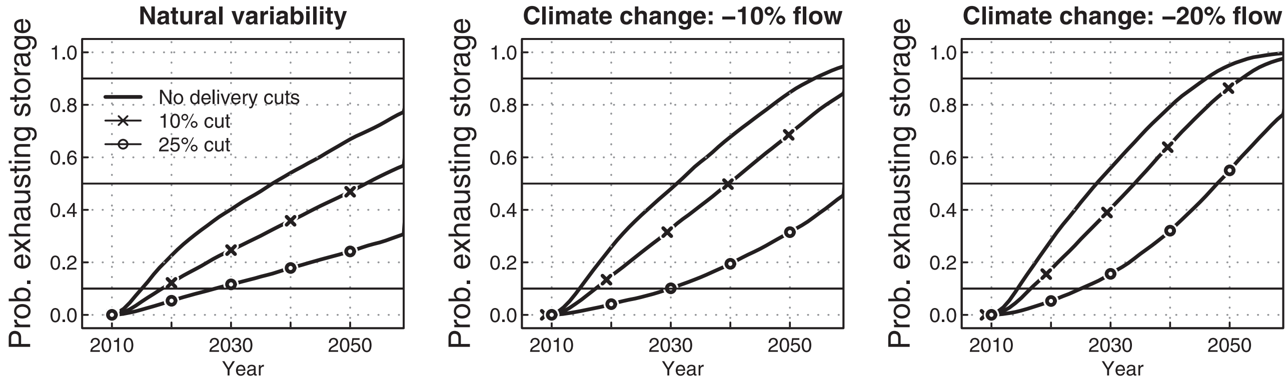

Figure 9. Effects of management strategies on likelihood of the Lakes Powell and Mead system dropping to deal pool elevations (left) for current conditions and when runoff in the Colorado River system drops (middle) 10% and (right) 20% because of climate change. Solid curve, when all requested water deliveries are supplied; curves with crosses and circles, when deliveries are cut 10 and 25%, respectively, when total storage drops below 15 MAF.

that reservoirs are at dead pool by 2021 is 50% (assuming a 20% reduction in runoff).

[27] To further illustrate the evolving reliability of the system, we combine historical and projected future depletions (Figure 3) with the reduction in runoff expected because of climate change to estimate net inflow from 1960 to 2060. Since net inflow is not intended to reflect interannual variability, we have calculated the depletions over the historical era (1960–2004) from the least squares best fit linear trends shown for the upper and lower basins in Figure 3, and taken water releases to Mexico constant at 1.5 MAF/a. Future depletions are taken from the USBR schedules. Using this net inflow, we compute the probability the system will go dry (or fill) within 20 years from the start date, including a 20% reduction in runoff over 2007–2057 due to climate change and (for consistency) a constant starting reservoir level of 25 MAF. The results are shown in the right plot of Figure 7. From 1960 to 1980, there was virtually no chance of the system running dry within 20 years; by 2000, this chance rises to 20%, and to almost 60% by 2020. In contrast, the chances of the lakes refilling drop to under 20% by 2007 and are essentially nil by 2030. At any rate, the early 2000s were marked by a significant transition, when, for the first time, the chance of the system running dry exceeded the chance of the system filling up.

4. Water Shortage Options

[28] Of course, water managers and other decision makers will do everything in their power to see that Lakes Mead and Powell do not go dry. Can the devastating scenarios laid out above be ameliorated, at least for some years, and if so how might this be done? Curtailing consumptive use is one obvious answer. The current USBR strategy for the most severe reservoir elevation reduction they consider, Lake Mead level at 1025 feet (see Figure 2), is to withhold 0.6 MAF of water per year, about 5% of Lake Mead annual releases (including evaporation) (see USBR lower Colorado Shortages Web page). Will this be enough of a reduction to solve the problem?

[29] The magnitude of the problem is illustrated in Figure 9, which shows the CDFs of Lakes Mead and Powell reaching dead pool elevation under two simplified management schemes and three runoff scenarios. The management schemes are not intended to be correct in the complicated details of how water delivery is altered under shortage conditions. Instead, they illustrate the overall sensitivities of system reliability. The curves with crosses and circles show the CDFs for when the system goes dry when water deliveries are reduced by 10% and 25% of current demand, respectively. These consumption reductions are assumed to start when combined reservoir storage falls below 15 MAF. This is equivalent to withholding 1.35 and 3.38 MAF/a on the basis of current demand. The 15 MAF cutoff was chosen as the point in time where the deliveries are to be curtailed because it corresponds to the time minimum power pool levels will be reached in the combined system (see caveats). In the presence of no runoff reduction, the chances are 50% that the dead pool volumes will be reached in 2037, 2053 and some time after 2070 for 0, 10 and 25% reduction in consumptive water delivery, respectively. If the human-induced runoff reduction is 20% then the comparable set of years to reach dead pool are 2028, 2034 and 2048, respectively.

[30] The 10% reduction in water delivery delays for about 6 years the reservoirs reaching dead pool elevations in the case of a 20% reduction in runoff, and about 10 years in the case of a 10% in runoff reduction. So a 10% reduction in consumptive delivery buys some time but does not solve the problem. Inspection of Figure 9 shows the 25% reduction in water deliveries makes a real difference in the sustainability of the reservoir storage. If we now compare the above results to the 5% delivery reduction in the USBR water shortage plan, it is clear the 5% reduction will have little impact on the sustainability of the Colorado reservoir system in a shortage situation.

5. Caveats

[31] There are a number of issues that potentially impact the results obtained above. We point these out here, although going into detail is beyond the scope of the present paper.

[32] 1. The upper basin of the Colorado has water allocations equal to those of the lower basin (7.5 MAF/a). However, they are now using something over 4 MAF/a of

water associated with those rights. Growth in that part of the West suggests this situation is changing and the upper basin is using more of this right (Figure 3). Indeed, the combined water use currently in both basins is roughly 14–15 MAF/a (USBR water accounting Web site, http://www.usbr.gov/lc/region/g4000/wtracct.html), including evaporation and infiltration. This is approximately the currently assumed average flow of the river. Is there water to satisfy increased use in the upper basin and if so, what will its use do to the net water balance of the system?

[33] 2. We implicitly assumed there would be annual releases from Lake Powell tuned to maintain storage parity between it and Lake Mead, e.g., the perfect management scenario noted above. The law of the river only requires a delivery of 75 MAF over a 10 year interval, so in principle, releases from Lake Powell could be curtailed for several years running, as long as they are made up in subsequent years. The impact on Lake Mead of such action would be devastating and, if maintained for even 2 years in the current situation, would preclude meeting consumptive allocations in the lower basin. Our methods, essentially assuming a single large reservoir, will not handle such a situation. We are interested here in longer-term, larger-scale changes and so events like Powell release or no release, which are events of a few years duration, are not considered explicitly. A more sophisticated model would be required to explore this issue.

[34] 3. Tree ring data suggest the long-term flow of the Colorado experiences more variability than has been observed over the last century [*Committee on the Scientific Bases of Colorado River Basin Water Management*, 2007]. These data also suggest prolonged droughts far worse and more extensive than seen in the last 100 years of flow record on the river are possible. Our attempt to estimate natural variability from the last 100 years alone might miss such situations, unless they are included in the methods we use to generate synthetic flows. The results given in Appendix A suggests the methods are robust to inclusion of the entire paleo tree ring record, so lack of representativeness in our model of natural variability does not seem to be a major problem. Note also, the flow reductions we have been seeing over the last 7–8 years are surprisingly close to the global warming–driven reductions in flow estimated by *Hoerling and Eischied* [2007]. They also are likely to occur by chance 10% of the time according to our FRRP statistical model of river flow (Appendix A).

[35] 4. We have assumed that 1.5 MAF will continue to go to Mexico annually per existing treaty.

[36] 5. The average annual river flow we used (15 MAF) is estimated from the 1906–2005 record of naturalized flow. However, this masks the long-term decreasing trend in flow. It might be more realistic to use the average flow over, say, the last 50 years, 14.48 MAF, or over the last 500 years, 13.7 MAF. Introduction of these lower flow estimates into our analysis would considerably speed up all of the dead pool dates cited above [*Weisheit and Harrington*, 2007].

[37] 6. We assumed that the climate model predicted changes in net moisture flux convergence would all end up in river flow. But if a significant fraction of that moisture change were, say, sequestered in the soils, then our estimates of runoff to the river would be too high [cf. *Troch et al.*, 2007]. This would allow more pessimistic estimation of future water shortages.

[38] 7. The climate models which have produced estimates of decreasing runoff have a host of problems of their own in handling the water budget from coarse resolution (little in the way of Rocky Mountains) to the variety of ways they handle soil processes and vegetation representations. However, a recent study of changes in hydrology of the western U.S. over that last 50 years shows several of the models, when run with observed anthropogenic forcings, reproduce extremely well the observed changes in river flow timing, snowpack decline and increasing air temperatures in the western United States [*Barnett et al.*, 2008]. So these models, while not perfect, have a message to tell; a message supported by their ability to reproduce well the last 50 years of multivariate hydrological observations.

[39] 8. The results shown above are based on initial conditions corresponding to the current storage levels of Lakes Mead and Powell, currently about 50% of capacity. If we rerun the simulations from full pool initial conditions, we find the CDFs are shifted to latter times, as one would expect. As a rule of thumb the dates noted above for realization of dead pool levels are pushed 15–20 years into the future.

[40] 9. We also note that the claim that the Colorado is a resilient system that can quickly recover from drought seems to depend on two factors. The *Harding et al.* [1995] simulation of the severe sustained drought of the late 1500s started with a pseudoreservoir level of about 35 MAF. Had that study been started with initial conditions from today, 10 MAF less water, the answer might have been different. Secondly, not only does the system become less reliable as net inflow approaches zero, but the rate of change of system reliability increases strongly as well. This means the system can quickly transition from a resilient to a fragile system as consumptive use of the river increases. This is exactly the regime we are in today.

6. Conclusions

[41] Twenty years of scientific research have shown the flow of the Colorado River is likely to decline 10–30% over the next 30–50 years. It is declining now and has been for some years. We have shown that reduction in runoff into the Colorado River will, within a handful of years, reduce the live storage of water in the Colorado system to nothing and seriously curtail the system's hydropower production, if no consumptive use changes are made. For example, there is a 10% chance that live storage in Lakes Mead and Powell will be gone by about 2013, and a 50% chance by 2021, if current water allocations are maintained. There is a 50% chance that minimum power pool elevations will be reached by 2017.

[42] It seems clear there are a number of management options that can forestall this disaster. Many of these problems and potential solutions were foreseen by Gleick and associates at the Pacific Institute 1–2 decades ago [*Morrison et al.*, 1996; *Gleick et al.*, 2003], and others before them. The new feature of the problem is that the Colorado River will continue to lose water in the future, if the global climate models are correct. Solutions to today's problems might not be applicable into the future [e.g., *Milly*

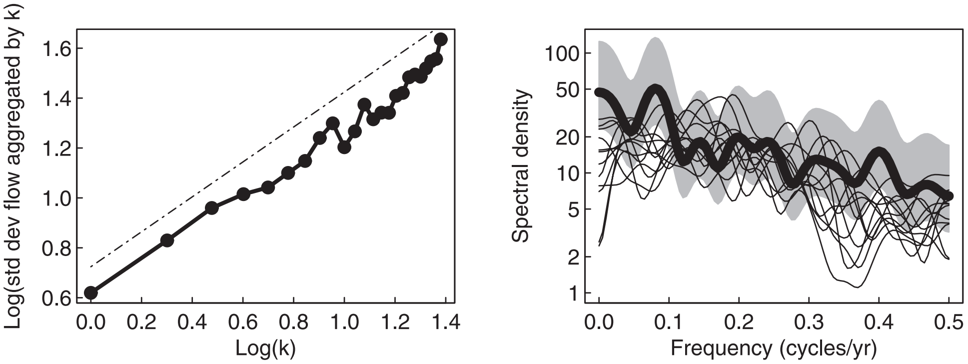

Figure A1. (left) Log of the standard deviation of Colorado River flow (1906–2005) aggregated into *k*-year blocks, as a function of log(*k*); the slope of this relationship should equal the Hurst coefficient *H*. The dash-dotted line has slope 0.7, for reference. (right) Spectrum of independent 100-year chunks of the paleoreconstructed Colorado River flow from *Meko et al.* [2007] (thin black lines) compared to spectrum of the synthetically constructed flow using the Fourier method (thick black line, with gray area showing the 95% confidence interval).

et al., 2008]. The challenge is to determine what combination of agricultural, environmental uses, and personal consumption is achievable in the future, when 10–30% less water must serve substantially more people.

[43] In the future we can count on some flow in the Colorado, albeit 10–30% less in (say) 50 years than the current rate. We need to determine now how that reduced supply of water will be used: Who will get some and who will not? Our call for action now goes beyond the additional study called for by the *Committee on the Scientific Bases of Colorado River Basin Water Management* [2007] because of the magnitude and immediacy of the problem. There is danger that litigation, associated with water right claims and environmental issues, will compound and put off any rational decisions on this matter until serious damage has been done to the diverse users of the Colorado River. Much of this litigation might be avoided if time-dependent water solutions are crafted to reflect today's and tomorrow's water realities. It is laudable that efforts in this direction are now being made. We hope this work will spur solutions, as time is short. The alternative to reasoned solutions to the coming water crisis is a major societal and economic disruption in the desert southwest.

Appendix A: Generation of Synthetic River Flow Time Series

[44] We construct pdfs of the likelihood of the Lake Powell/Mead system going dry using thousands of synthetic time series of Colorado River flow. We explored three different methods for generating these time series. The first method was simply a standard first-order autoregressive (AR-1) model, with the lag-1 correlation taken from the observations.

[45] The second method was fractional Gaussian noise (fGn) (see *Koutsoyiannis* [2002] for an overview), which captures the low-frequency variability of river flow and tendency for strings of wet or dry years better than the AR-1 method. We used the R statistics package "fArma" for this purpose (version 260.72, downloaded from http://cran.r-project.org on 23 November 2007). Various estimation methods reported a Hurst coefficient H between 0.6 and 0.8 for observed naturalized Colorado River flow, 1906–2005; we used $H = 0.7$ to generate the synthetic flows (Figure A1, left). Every century-long synthetic time series was set to have the same mean and standard deviation as the observed flow, which likely underestimates the true variability in runoff.

[46] The third method we used was one of our own devising that we term the "Fourier reconstruction and randomized phase" (FRRP) method. It is similar to the fGn method, but uses the observed power spectrum as the basis for a synthetic reconstruction rather than a fit to a theoretically derived power spectrum. We start with the historical time series of water year total Colorado River flow, *c(t)*. We then transform the time series to frequency space using a Fourier transform:

$$C(f) = \int_{-\infty}^{\infty} c(t) e^{2\pi i f t} dt$$

where C is a (complex-valued) amplitude in the frequency domain, and the frequency, f, is in cycles per water year.

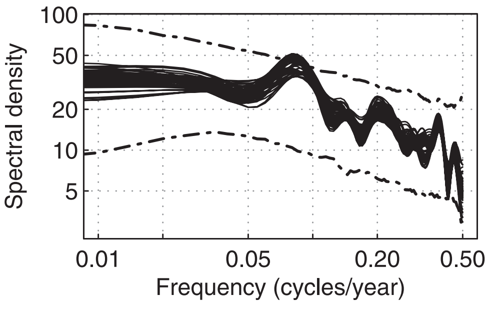

Figure A2. Spectra of 99 simulations of Colorado River flow generated with the ISM method applied to the historically observed time series (solid black lines) and 95% confidence interval of 1000 simulations of Colorado River flow generated with fractional Gaussian noise (dash-dotted line).

Since $c(t)$ is real, the properties of the Fourier transform guarantee that $C(-f) = C(f)^*$, where the asterisk denotes complex conjugate. Since we use a discrete fast Fourier transform (FFT) to calculate the $C(f)$, we have a limited number of $[C(f), C(-f)]$ conjugate pairs in frequency space. For each pair, we choose a random phase θ between $-\pi$ and π. We then calculate a new amplitude $C'(f) = C(f)e^{i\theta}$, which has the same modulus as the original amplitude but a different phase. To preserve the property that the transform of C' back to the time domain result in a real-valued function, we set $C'(-f) = C'(f)^*$. The final synthetic time series is then the inverse transform of the C' amplitudes back to the time domain. Every synthetic time series has, by construction, the same power spectrum as the original time series, and is consistent with spectra of 100 year segments of the historical flow of the Colorado River reconstructed from tree rings over the period 762–2005 [*Meko et al.*, 2007] (Figure A1, right plot).

[47] The three methods of estimating natural variability of the flow are compared in Figure 5 (right) amongst themselves and with the index sequential method (ISM) currently in use by the USBR [*Ouarda et al.*, 1997] for a runoff reduction of 20%. The three methods are essentially equivalent, and more conservative than the ISM approach. It is clear that the water balance, or lack thereof, is driving our results, not the nature of the model used to generate natural variability.

[48] As a final note, we deliberately chose not to use the ISM approach, even though it is familiar to many and widely used in USBR simulations. By continually sampling the historical record in sequence, ISM always includes any outliers than may be in the historical record, yet fails to sample all the variability that is consistent with the observed record but did not chance to occur in the past 100 years. This is illustrated in Figure A2; the spectra of 99 ISM realizations of Colorado River flow (solid black lines) show simultaneously a far narrower range of variability than spectra generated with fGn (95% confidence interval shown by the dash-dotted lines), and yet show consistently more power than would be expected at a frequency of ~0.07 cycles/a because of repeated sampling of the same particular historical sequence. This results in a statistical bias in the estimates of natural variability. Both the fGN and FRRP can produce natural climate variability outside the historical record, and simulate extreme events in ensembles of many thousands of simulations in a consistent way.

[49] **Acknowledgments.** This work was supported under a joint program between the University of California San Diego and Lawrence Livermore Research Lab called LUSCid. At UCSD, the program was run out of the San Diego Supercomputing Center, and work was done at the Scripps Institution of Oceanography. We wish to especially thank Dennis Lettenmaier for his comments and patience and also Mike Dettinger and P. Gleick for suggestions on early drafts of the manuscript. D.W.P. received partial salary support from the California Energy Commission.

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