Assessing Implications of Operating the Colorado River Water Resource System WITH and WITHOUT Glen Canyon Dam

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To best assess how well the water resource needs of the Colorado River Basin can be met in a system that does not include Glen Canyon Dam and Lake Powell, we created two computer reservoir models. These models represent two scenarios: 1) Hoover Dam WITH Glen Canyon Dam and Lake Powell (called WITH Powell), and 2) Hoover Dam WITHOUT Glen Canyon Dam and Lake Powell (called WITHOUT Powell). We then compared the results for a number of metrics. Specific operating policies of the reservoir models can be found in the appendix; however, both models are simplifications of the real physical system (no reservoir storage volume or reservoir operating procedures outside of Hoover or Glen Canyon Dam are represented). 85% of basin storage capacity lies with Lake Powell and Lake Mead, so one can effectively argue for comparison purposes (WITH compared to WITHOUT Powell) the models sufficiently represent the system although simplifications do exist.

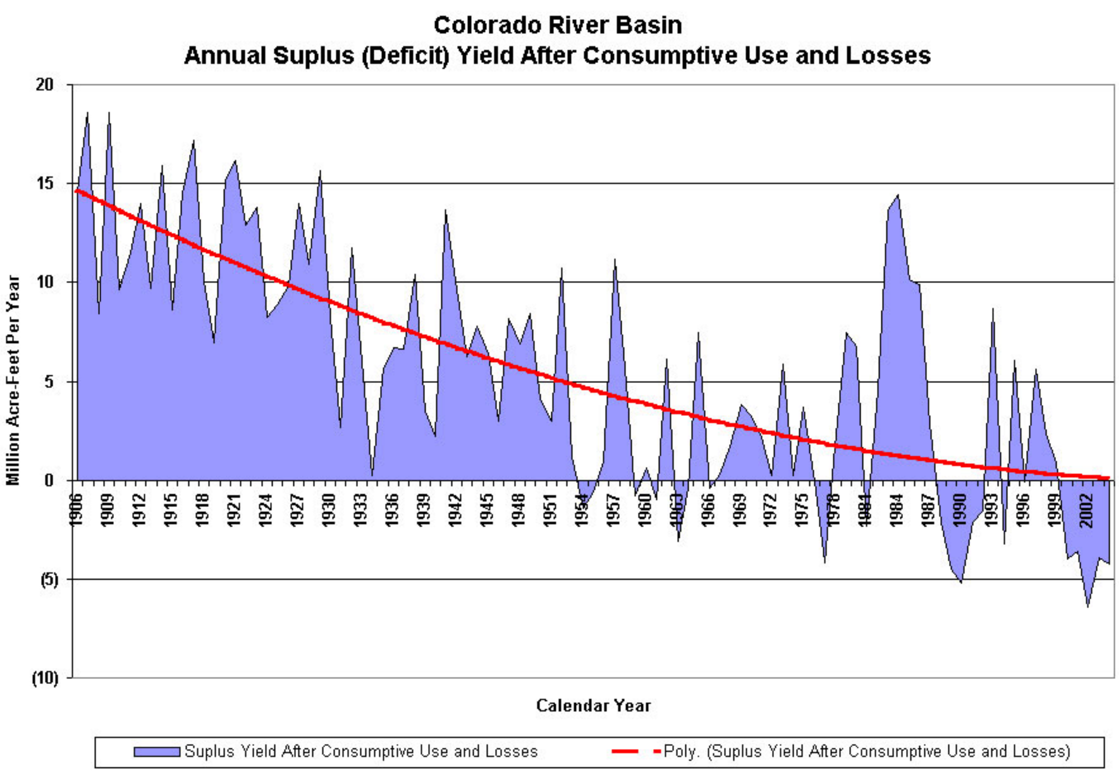
The Colorado River is balancing precipitously near equilibrium where current system demand is equal to the amount of water available. Because of this, we analyzed two Upper Basin demand scenarios. The USBR lists 4.1 MAF (million acre-feet) as the current 2005 annual Upper Basin demand, which for this study is considered as the low end. The USBR predicts Upper Basin demand will grow to 5.4 MAF per year by 2060, which is used as the upper end. Additionally, the Department of Interior provided testimony before Congress in 1989 asserting through a revised Hydrologic Determination that the Upper Basin could rationally develop consumptive use equal to 6.0 MAF/Yr. Each of the Upper Division States has incorporated its respective allocation for 6.0 MAF into state water plans for future development.

Average annual natural flow of the Colorado River above Lee's Ferry from 1895-2004 was 14.6 MAF. Upper Basin use is currently 4.1 MAF and projected to rise beyond 5.4 MAF. Lake Powell evaporates between 0.4 and 0.84 MAF per year depending upon reservoir levels (we'll take an average of .6 MAF). Given that, there is simply not enough surplus water for replenishing storage in Lake Powell. The system is obviously over-allocated and very near its threshold at current levels of consumptive use, so that any increase in demand will make it more difficult to meet compact requirements at Lee's Ferry and will aggravate shortage deliveries from Lake Mead.

A simple water balance calculation illustrates the problem. Values expressed as MAF/Yr.

Upper Basin Consumptive Use:	**4.1**	**5.4**	**6.0**
Natural Flow Above Lee's Ferry	14.6	14.6	14.6
Upper Basin Use	-4.1	-5.4	-6.0
Powell Evaporation	-0.6	-0.5	-0.4
Sideflow Between Lee's Ferry and Lake Mead	+0.6	+0.6	+0.6
Mead Evaporation	-0.8	-0.7	-0.7
Mead Release	-9.5	-9.5	-9.5
SURPLUS / DEFICIT	**+0.2**	**-0.9**	**-1.4**

The following chart illustrates how available surplus water has diminished over the past 110 years. Important: "Year" (on the x-axis of the following graphs) should not be taken as the year that actual events happen. Simulations were preformed by using the historical stream flow record (1895-2004) and running it through the model starting in what we dubbed 'year 1.'



Results from this study are presented for the following alternative scenarios:

1. 4.1 MAF Upper Basin Demand, WITH Powell
2. 4.1 MAF Upper Basin Demand, WITHOUT Powell
3. 5.4 MAF Upper Basin Demand, WITH Powell
4. 5.4 MAF Upper Basin Demand, WITHOUT Powell

In our work, we evaluated how well the WITH and WITHOUT systems met certain operating criteria. Of interest were;

1. Reliability of Meeting Lower Basin Demands
2. Ability of Upper Basin to Meet Compact Required Delivery of 75 MAF on a 10-Year Running Average
3. Comparison of Evaporation between Alternative Scenarios
4. Comparison of Flood Releases at Hoover Dam between Alternative Scenarios
5. Probable Future Levels of Lake Powell
6. Impact on Energy Production
7. Effects of Climate Change

Results for the 4.1 MAF Upper Basin demand scenarios should be considered as 110 years of 2005 like conditions. Likewise, results for Upper Basin demands of 5.4 MAF should be looked at as 110 years of 2060 (when consumptive use reaches that amount). Furthermore, we are unable to predict future streamflow sequences, nor will historical ones repeat themselves, but by using the historical record as the probable future inflow, we preserve the mean, standard deviation, and skew inherent to it.

Results:

1. Reliability of Meeting Lower Basin Demands

Glen Canyon Dam was built to ensure Lower Basin users would reliably receive water volumes promised under the 1922 Colorado River Compact. To meet full Lower Basin demands, Hoover Dam has an annual minimum objective release of 9.5 MAF (7.5 MAF for Lower Basin states, 1.5 MAF for Mexico, and 0.5 MAF for channel losses and evaporation). As Lake Mead is draw down, shortage deliveries are made to ensure Lake Mead does not fall below the elevation at which it can produce power.

The following tables show the amount of times Hoover Dam will make full and shortage releases. One table is presented for both Upper Basin annual demand scenarios of 4.1 and 5.4 MAF. Within each table are results for the reservoir model WITH Powell and the reservoir model WITHOUT Powell.

Assuming Upper Basin Consumptive Use = **4.1 MAF** per year
No. Years When Mead Release is:

MAF:	Full	< 9.5	< 8.75	< 8.0	< 7.5	< 4.5
WITH Powell	**101**	**9**	**8**	**6**	**6**	**0**
%	92%	8%	7%	5%	5%	0%
WITHOUT Powell	**95**	**15**	**10**	**8**	**6**	**0**
%	86%	14%	9%	7%	5%	0%

Assuming Upper Basin Consumptive Use = **5.4 MAF** per year

No. Years When Mead Release is:

MAF:	Full	< 9.5	< 8.75	< 8.0	< 7.5	< 4.5
WITH Powell	**84**	**26**	**22**	**20**	**18**	**8**
%	76%	24%	20%	18%	16%	7%
WITHOUT Powell	**76**	**34**	**30**	**21**	**19**	**7**
%	69%	31%	27%	19%	17%	6%

For both Upper Basin demand scenarios, the model demonstrates somewhat higher reliability for meeting Lower Basin demand requirements WITH Lake Powell represented. Lower Basin shortages WITHOUT Powell occur 70% more often than WITH Powell assuming current Upper Basin demand of 4.1MAF; and 10% more often with 5.4 MAF demand. This is a result of more frequent flood releases from Lake Mead if Lake Powell storage is not available.

Reliability comparisons were also made based on cumulative Lower Basin shortfalls over the 110-streamflow record. The numbers in bold are the total amount of water that was below the objective Lower Basin release of 9.5 MAF/year for Upper Basin demands of 4.1, 5.4, 6.0, and 7.5 MAF. .

Amount of Shortage below Minimum Objective Release, Cumulative MAF

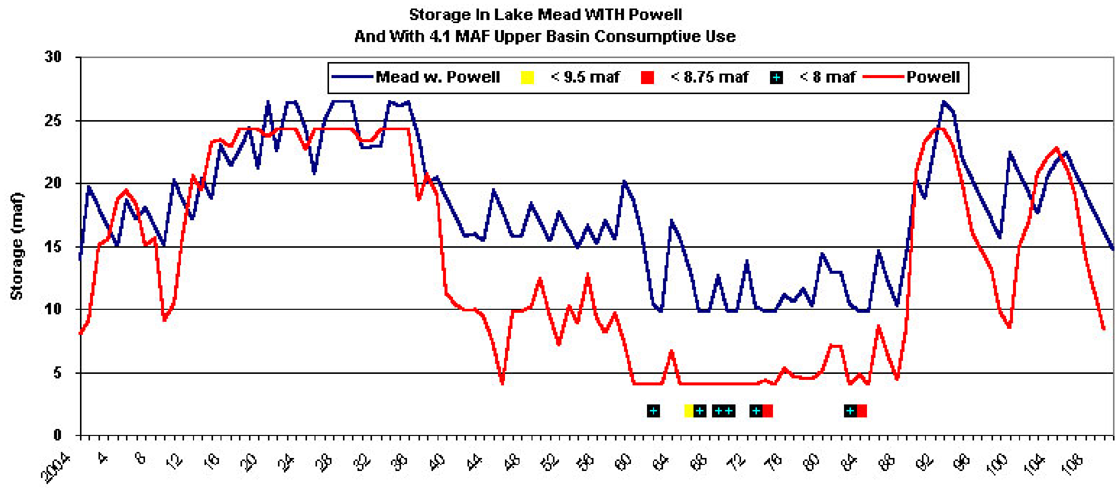
Upper Basin Use, MAF:	4.1	5.4	6.0	7.5
WITH Powell	**23**	**89**	**140**	**282**
Reliability %	98%	91%	87%	73%
WITHOUT Powell	**28**	**99**	**145**	**260**
Reliability %	97%	90%	86%	75%

Expressing reliability as a percentage of total cumulative release relative to the objective release suggests little difference between the WITH Powell and WITHOUT Powell scenarios. This is attributable to greater flood releases under the WITHOUT Powell scenario offset by greater evaporation under the WITH Powell scenario.

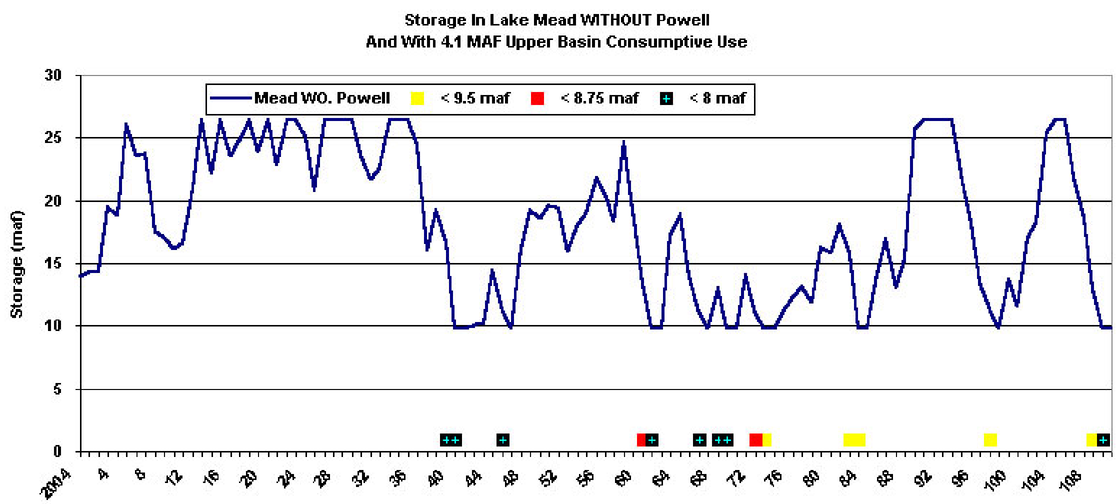
The following four plots are graphical representation of the data from the first two tables above (UB demand of 4.1 and 5.4 MAF). Dots near the x-axis indicate years when shortages were imposed. Graphs should be compared 1 vs. 2 and 3 vs. 4.

For Upper Basin demands of 4.1 MAF;

1. **WITH** Powell, UB Demands at **4.1** MAF

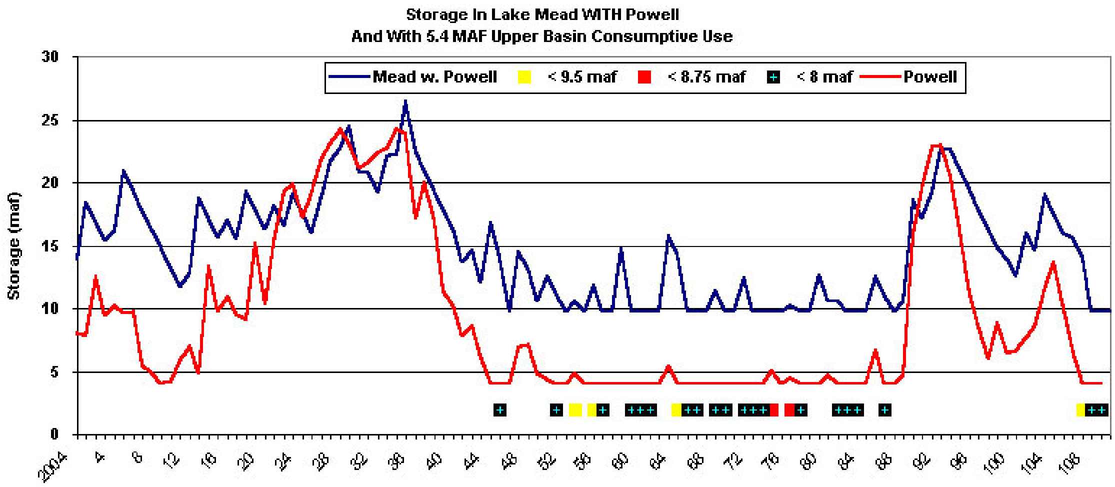


2. **WITHOUT** Powell, UB Demands at **4.1** MAF

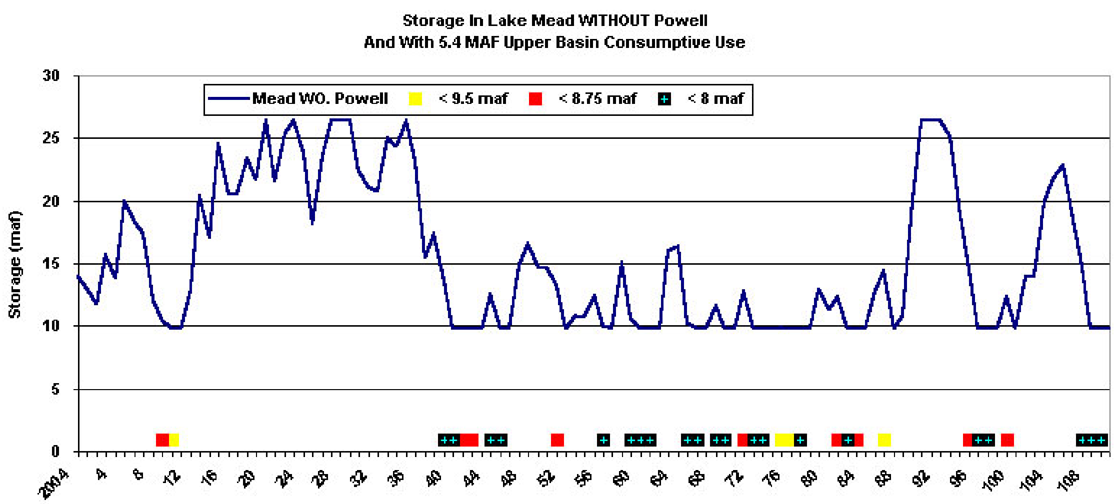


For Upper Basin demands of 5.4 MAF;

3. **WITH** Powell, UB Demands at **5.4** MAF

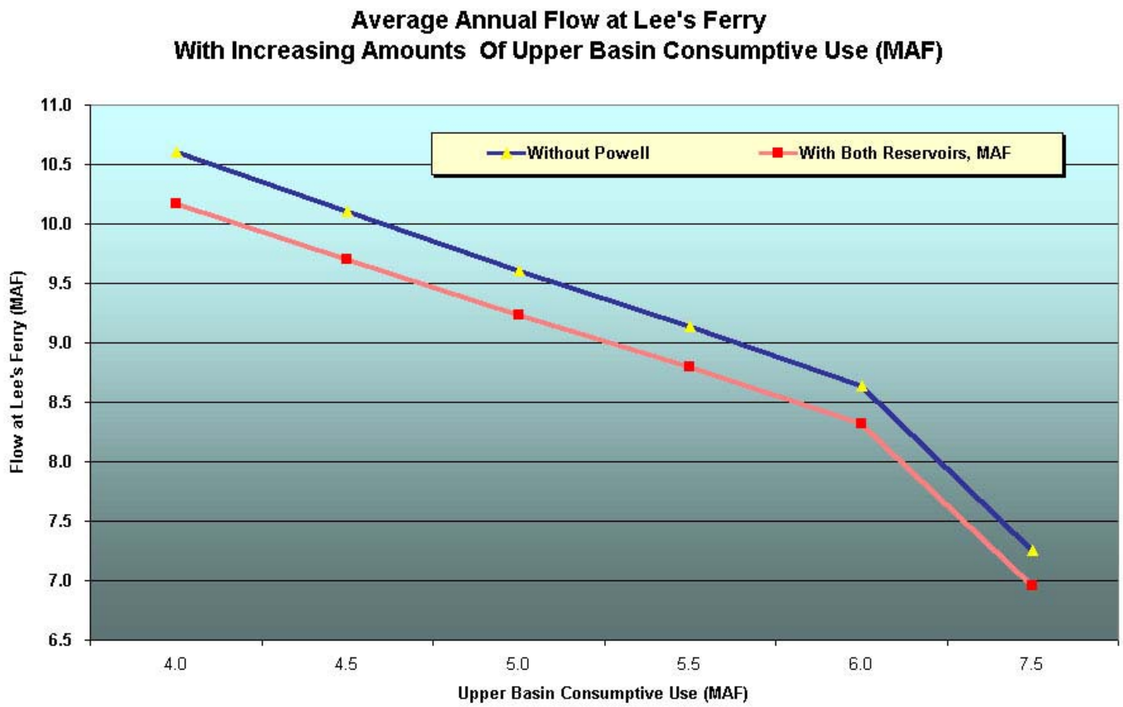


4\. **WITHOUT** Powell, UB Demands at **5.4** MAF



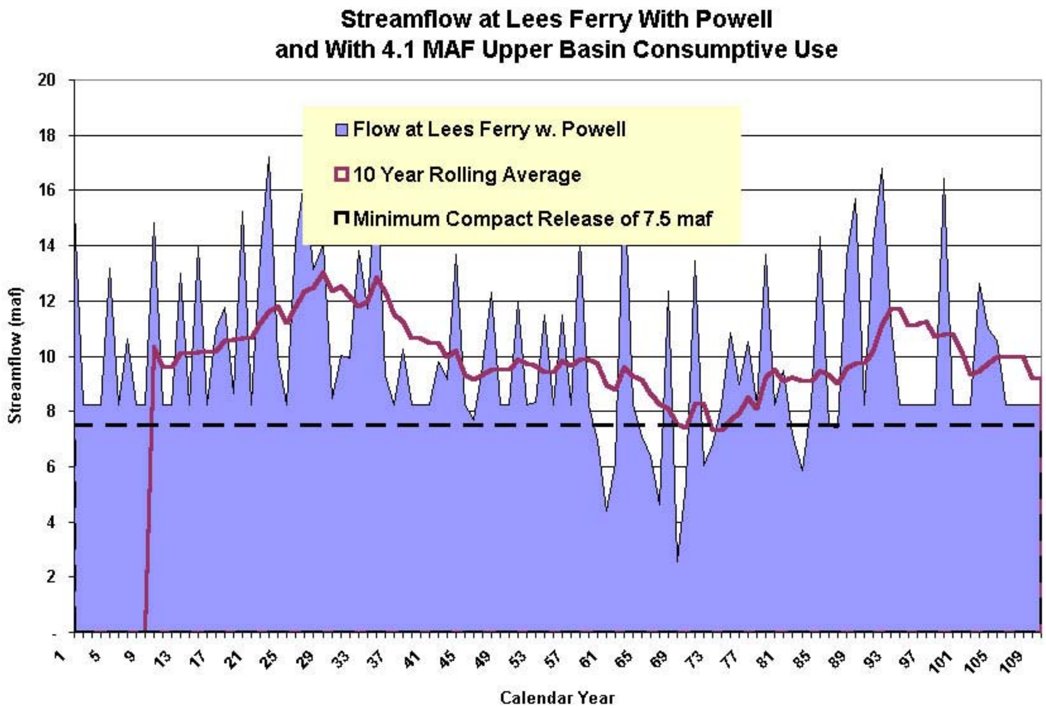
2. Ability of Upper Basin to Meet Compact Required 75 MAF on a 10-Year Running Average at Lee's Ferry

The 1922 Colorado River Compact requires the Upper Basin to deliver 75 MAF on a 10-year average. That requirement has always been met in the past. However, with Upper Basin demands increasing, it will become progressively more difficult in the future. The following chart shows a comparison of average annual flow that will pass Lee's Ferry for both scenarios.

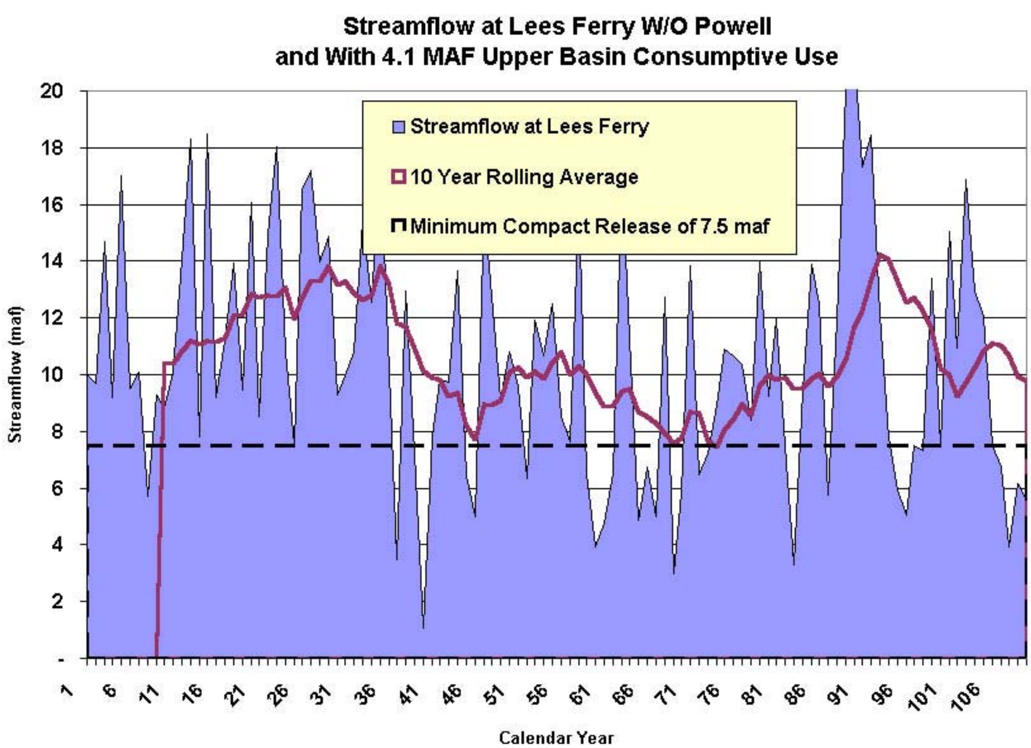


The following four plots show annual streamflow at Lee's Ferry (blue), 10 year rolling average (maroon) and the compact required annual 7.5 MAF release (black). The first two plots are for Upper Basin demands of 4.1 MAF and the second two are for Upper Basin demands of 5.4 MAF. For both demand scenarios, the Upper Basin is more likely to meet its requirement at Lee's Ferry WITHOUT Powell. This is somewhat contrary to the above water balance calculation and plot and is a function of the coefficient of variation of stream flow (95% flow / 5% flow). Annual historical (1895 – 2004) flow has fluctuated between 5 MAF to 25 MAF, while running 10-year average flow has ranged from 11 MAF to 18 MAF. Annual average flow will be higher WITHOUT Lake Powell due to avoiding evaporation loses.

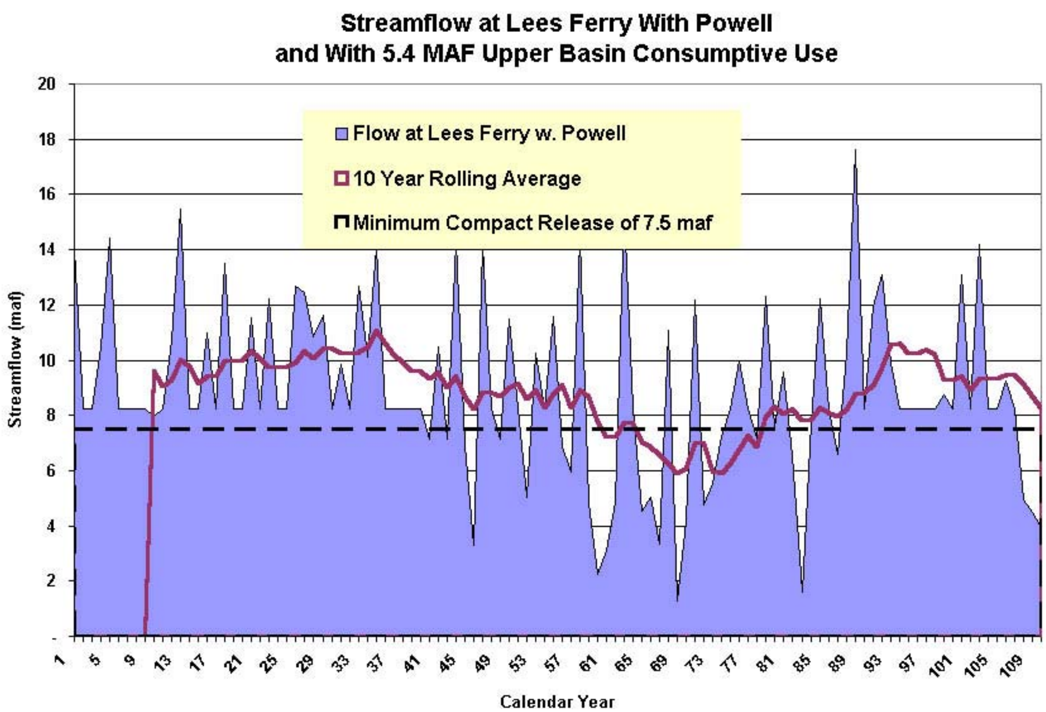
6. Stream flow at Lee's Ferry (MAF) **WITH** Powell, UB Demands at **4.1** MAF



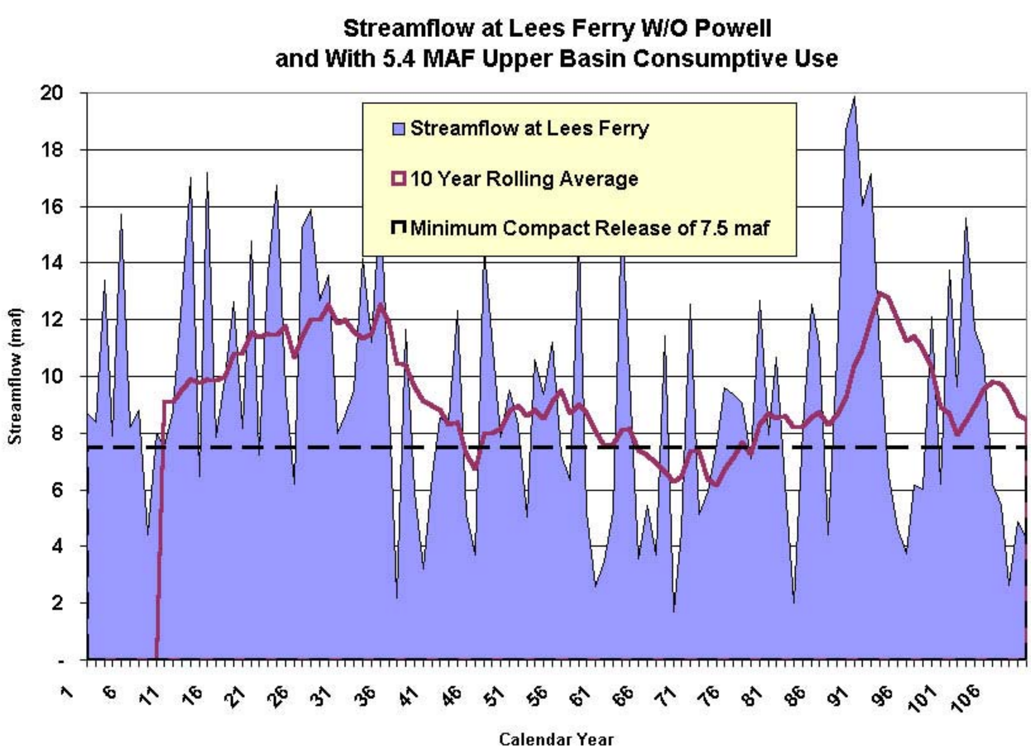
7. Stream flow at Lees Ferry (MAF) **WITHOUT** Powell, UB Demands at **4.1** MAF



8. Stream flow at Lees Ferry (MAF) **WITH** Powell, UB Demands at **5.4** MAF



9. Stream flow at Lees Ferry (MAF) **WITHOUT** Powell, UB Demands at **5.4** MAF



In addition to the Compact requirement for releasing 75 MAF over a 10-Year period, coordinated long-range operating criteria for the Colorado River System impose an additional 0.73 MAF/Yr release to supply Mexico, bringing the total minimum objective release to 8.23 MAF from Lake Powell. This minimum objective release has not always been met in past years and future projections suggest that it will not be met with increasing frequency as Upper Basin use rises. The following table lists the percentage of time that flow past Lee's Ferry will fall short of meeting the Minimum Objective Release of 8.23 MAF.

Percent of Time Below Minimum Objective Release

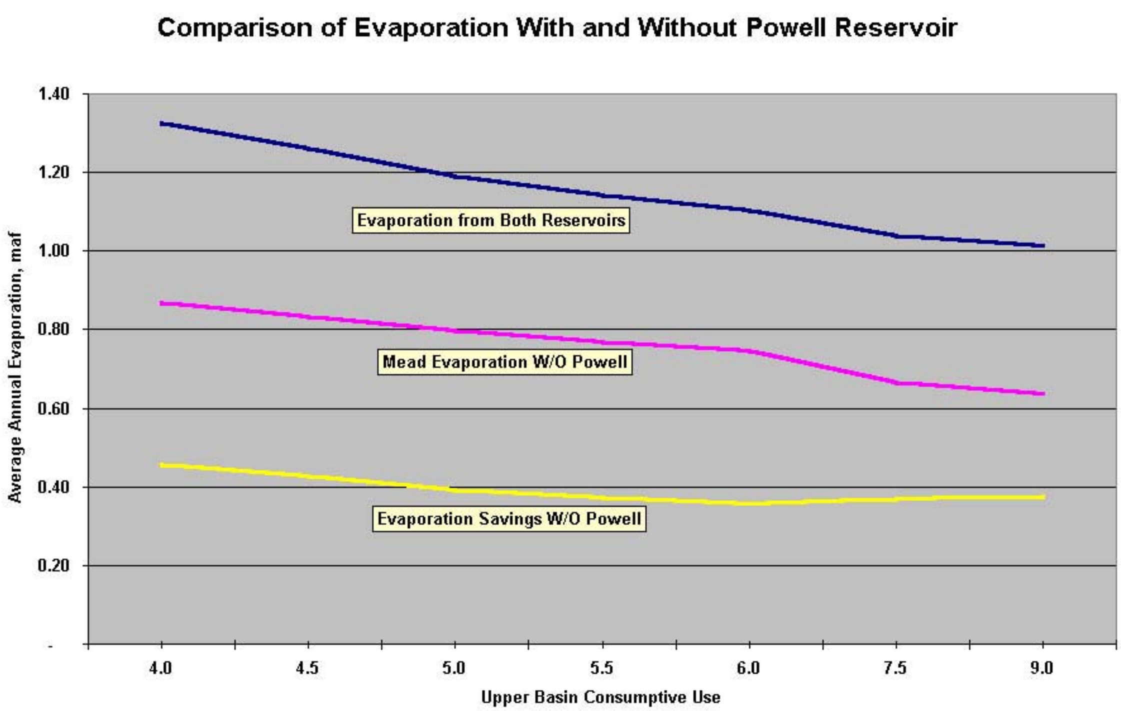
Upper Basin Use, MAF:	**4.1**	**5.4**	**6.0**	**7.5**
WITH Powell	7%	24%	40%	66%
WITHOUT Powell	7%	24%	40%	65%

3. Comparison of Evaporation between Alternative Scenarios

Evaporation losses from Lake Powell make it more difficult for the Upper Basin to meet its Colorado River Compact flow requirements. Lake Powell evaporates between 0.38 MAF (at dead pool) and 0.83 MAF (at full pool) per year. This is water that cannot be used for hydropower at Glen Canyon and Hoover dams, or for Lower Basin consumptive uses.

Lake Powell will evaporate around 60 MAF over the 110 year historical stream flow record with Upper Basin demands at 4.1 MAF/Yr. Average loss of 0.57 MAF/Yr has not been significant in the past as consumptive uses were lower and on average there was more water in the river than demand. However, as demand grows beyond 4.1 MAF/Yr, water lost to evaporation will significantly decrease reliability.

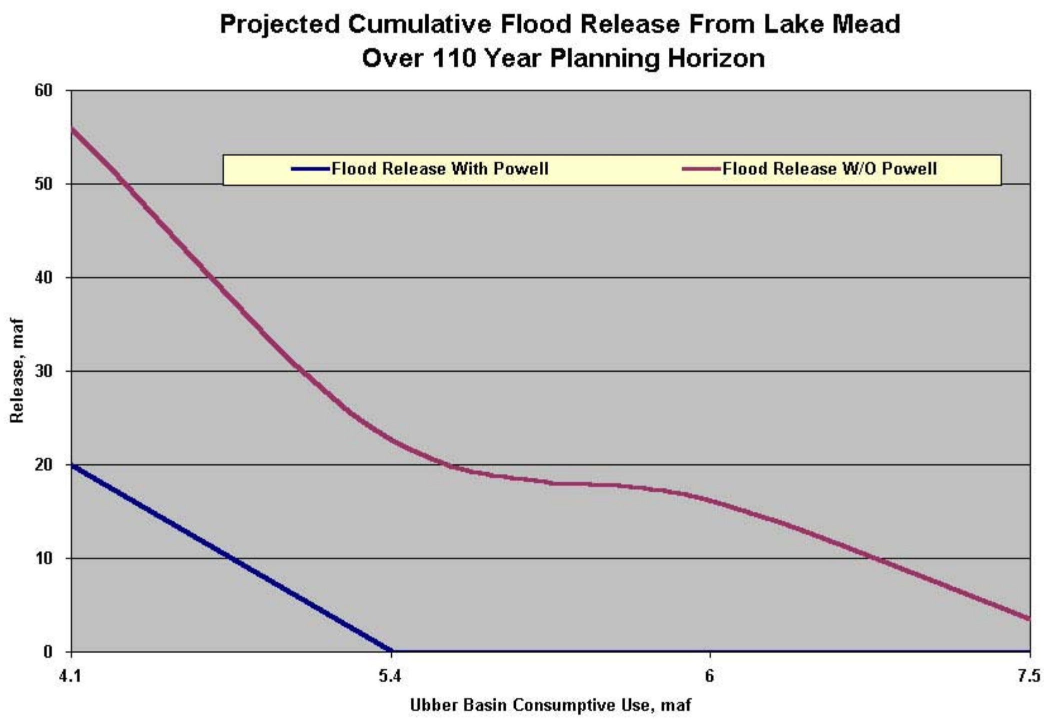
The following graph compares annual average evaporation between WITH Powell and WITHOUT Powell scenarios as a function of consumptive use. Also shown is savings from evaporation that would be achieved under the WITHOUT Powell case



4. Comparison of Flood Releases at Hoover Dam between Alternative Scenarios

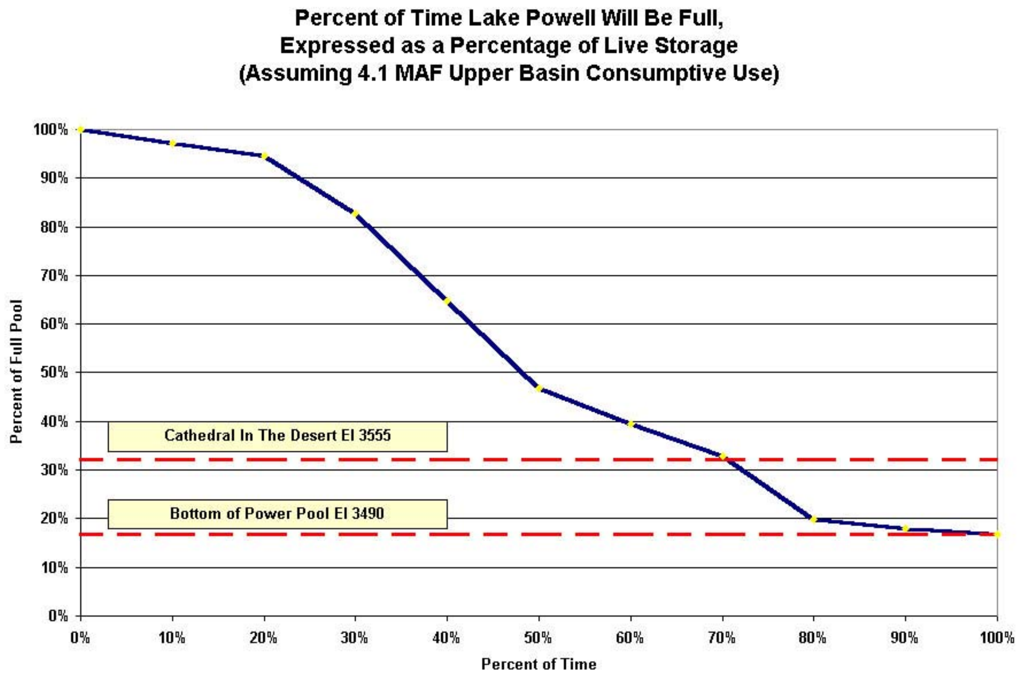
Flood Releases are releases from a full reservoir that are unable to pass through the turbines and therefore do not generate hydropower. They are generally considered 'wasted' water; however, some amount of flood release can be considered beneficial to riparian ecosystems along the reach of river between Hoover Dam and Imperial Dam as well as to wetlands in the river delta downstream. Furthermore, an opportunity exists to capture occasional flood release into underground storage facilities that would augment overdraft conditions in subsurface aquifers.

Flood Releases are significantly larger without the benefit of storage at Lake Powell if Upper Basin consumptive use remains at 4.1 MAF. However, as Upper Basin demand increases, the value of Lake Powell's storage to reduce flood releases diminishes. The following graph illustrates comparative flood release as a function of demand.

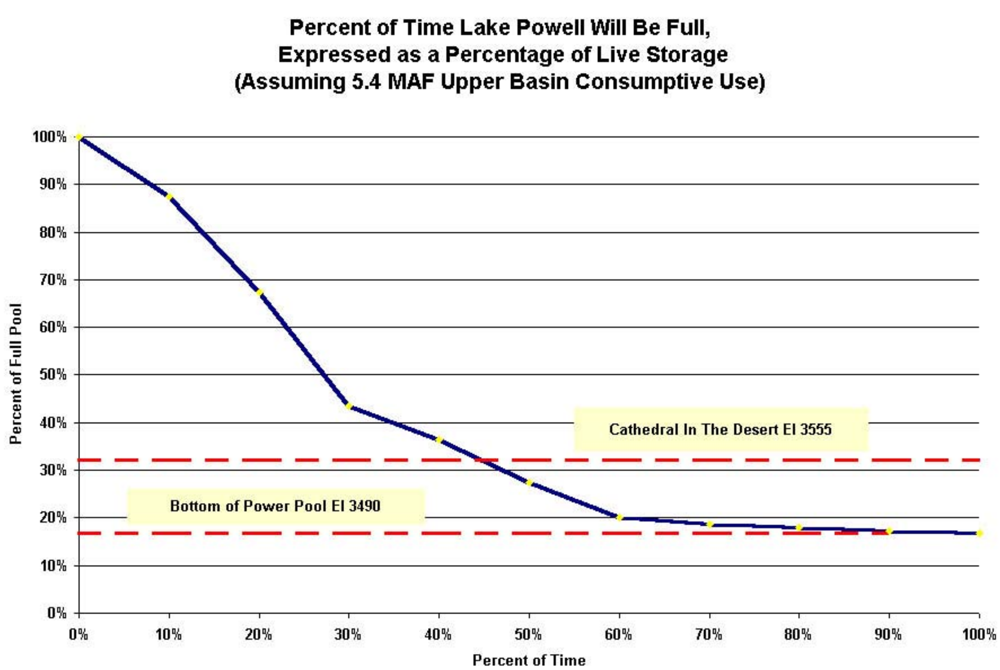


5. Probable Future Levels of Lake Powell

Assuming Upper Basin consumptive use remains constant at 4.1 MAF, Lake Powell will be less than 50% of its total storage capacity more than half of the time.

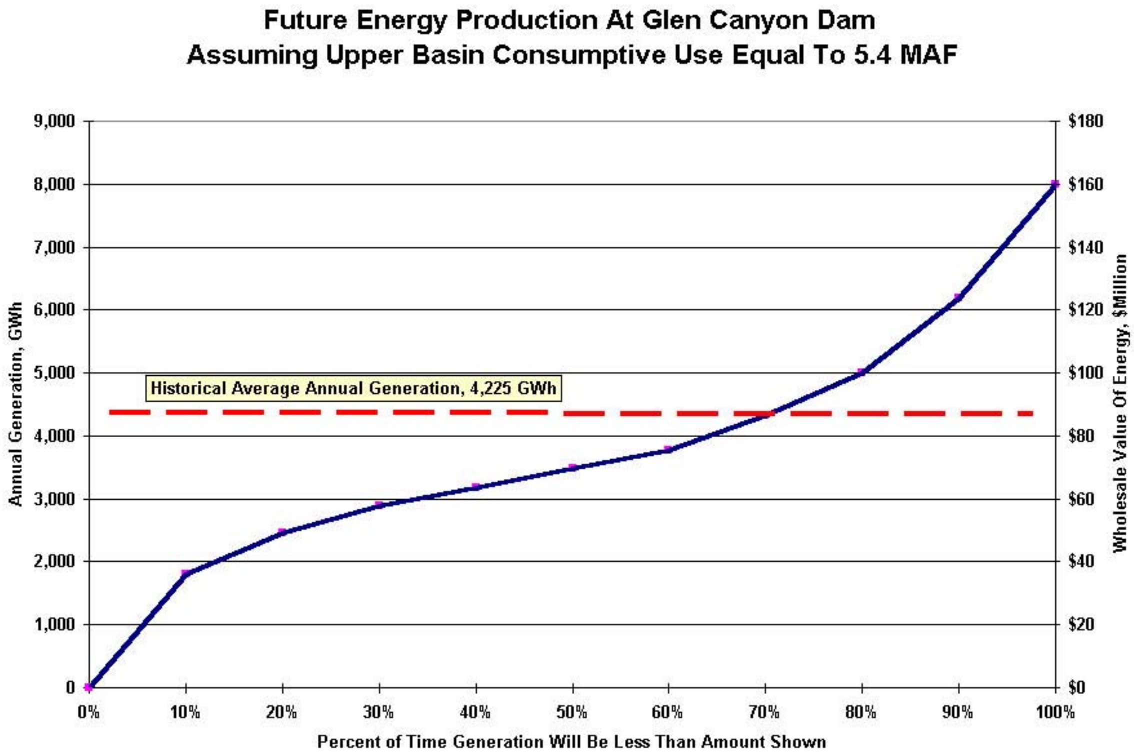


If Upper Basin consumptive use increases to 5.4 MAF, storage will be at 25% or less of total reservoir capacity half of the time. The following chart expresses percent of storage that will exist as a percent of time over the 110-year period.



6. Impact on Energy Production

Hydropower output capability will be less than 62% of maximum capacity, 50% of the time, while the pool fluctuates between El 3490 and 3510. If the pool is drawn below El 3490 (bottom of the power pool), no generation will be possible. As shown on the following chart, energy production will be below historical average production more than 70% of the time.



7. Effects of Climate Change on Hydrology and Water Resources

The Colorado River and its water resources are particularly susceptible to the effects of climate change. The basin lies on average in a semi-arid region and has a very low runoff ratio (runoff / precipitation). This results in small changes in evapotranspiration being magnified into large changes in runoff. The basin also has an almost complete allocation of its streamflow to consumptive uses. This means that almost any streamflow reduction will have significant implications on system reliability.

Climate models generate a whole suite of projected future meteorological parameters, however most applicable to generating probable future streamflow scenarios are changes in temperature and precipitation. The most recent scientific studies utilizing output from numerous Global Circulation Models suggest that the Colorado River Basin will experience warming on the order of 2.5 °C by the end of the century. Of the three biggest global modeling centers, 2 project basin average reductions in precipitation (Max Planck Institute and National Center for Atmospheric Research) while one projects precipitation increases (Hadley Center).

For our analysis here, we use streamflow projections from the latest climate change study of the Colorado River (published in the Journal of Climatic Change in February 2004). Streamflow scenarios in this paper are based on a climate 1.0 – 2.4°C warmer than historical and precipitation decreases on the order of 3%. These climate conditions are within the accepted range of 1.0 – 5.8°C and can even be considered quite modest. Likewise with the slight precipitation decrease; Gleick of the Pacific Institute published a study that showed a prescribed 10% increase in precipitation was offset by only a 2°C increase in temperature and resulted in a net reduction in streamflow. Streamflow projections in the Journal of Climatic Change paper based on the modest warming and relatively negligible precipitation decreases have an annual average streamflow 14 – 18% lower throughout the next century.

We applied this 'future climate' to our two reservoir models by reducing uniformly all streamflow to Lake Powell by 15% while keeping operating procedures the same. The results show convincingly that under reduced streamflow scenarios the reliability of the system is better without Glen Canyon Dam and Lake Powell. With reduced streamflow and mid-century demands there will simply not be enough water to fill the two reservoirs. While Lake Powell does not provide any usable or necessary additional basin storage, it does continue to evaporate .4 MAF/Yr. while it sits at dead pool. This water is simply wasted to evaporation in a system whose average streamflow is around 12 MAF/Yr. while demands are greater than 15 MAF/Yr.

The results below show that although full releases are made in a comparable amount of years (62% of the time), deliveries less that 8.75 and 8.0 MAF/Yr occur 5% more often in the system WITH Lake Powell. Also notable is that the cumulative shortfall for the WITH Powell scenario is 299 MAF while the cumulative shortfall for the WITHOUT Powell scenario is only 271 MAF. The 28 MAF (299-271) difference is water that would have been used for hydropower generation at both Glen Canyon and Hoover as well as delivered to Lower Basin users.

Assuming Upper Basin Consumptive Use = **5.4 MAF** per year

No. Years When Mead Release is:

MAF:	**FULL**	**<8.75**	**<8**	**<7.5**	**<4.5**
WITH Powell	69	67	60	54	29
%	63%	61%	55%	49%	26%
WITHOUT Powell	68	62	56	55	28
%	62%	56%	51%	50%	25%

Assumptions Used for Modeling Response to Variable Consumptive Use With and Without Powell Reservoir

VARIABLES

Future Consumptive Use	4.1	maf/yr		
Min Inflow to Powell		2.0	maf/yr	
Beginning storage in Powell	14	maf/yr		
Protect Powell El	3490	ft, msl	4.116	maf storage
Protect Mead El	1083	ft, msl	9.89	maf storage
Runoff Reduction from Climate Change	15%			

CONSTANTS AND RESULTS

1 Historical natural flow (runoff) from the Upper Basin is the sum of Upper Basin Consumptive Use plus Inflow to Powell

2 Historical UB Consumptive Use:

1895-1905	assumed equal to 1.0 maf per year
1906-2000	as reported by USBOR
2001-2004	assumed equal to 4.1 maf as reported by USGS

3 Inflow to Lake Powell:

1895-1921	estimates made by E.C. LaRue
1922-1962	USGS gage at Lee's Ferry
1963-2004	regulated inflow reported by USBOR

4 Relationship between pool elevation, storage capacity and surface area for both Lake Powell and Lake Mead obtained from historical daily operations provided by USBOR from initial filling to current

5 Evaporation assumed equal to surface area multiplied by:

Lake Powell, 61.8 inches per year as reported by USGS for 1990

Lake Mead, 87.8 inches per year

6 Forecast of future Upper Basin Consumptive Use is a variable for the models that is changed by input into cell "E45" within the Worksheet tab "Assumptions." Range of values is 4.1 - 7.5 maf per year.

7 Forecast of future Upper Basin Natural Flow is assumed to equal historical trace from 1895-2004. See Worksheet tab "UB Yield"

8 Minimum Objective Release from Powell equal to 8.23 maf

9 Supplemental Release from Powell equal to difference between Preliminary Release from Mead and 8.23 maf, if storage is available in Powell

10 Equalization Release from Powell equal to one-half the difference between storage existing in Mead and Powell when storage in Powell is greater than storage in Mead

11 Final Release from Powell is reduced from Preliminary amounts to protect against drawdown of pool below El 3490 corresponding to bottom of power pool and 4.1 maf storage

12 Sideflow between Lee's Ferry and Lake Powell assumed equal to 0.60 maf

13 Minimum Objective Release from Mead is 9.5 maf providing 7.5 maf to Lower Basin States, 1.5 maf to Mexico and 0.5 maf evaporation and channel losses downstream from Hoover Dam

14 Preliminary Release from Mead is extracted from Lookup Table for Interim Surplus Guidelines based on Mead Pool Elevation at end of prior year. See Worksheet tab "Interim Surplus Guidelines"

15 Supplemental Release from Mead is attempted to achieve Minimum Objective Release of 9.5 maf by drawing down Powell when surplus storage is available

16 Flood Release from Mead is made in attempt to draw pool down to El 1204 corresponding to the Elevation for determining Flood Control Surplus under the Interim Surplus Guidelines

17 Final Release from Mead is reduced from Preliminary amounts to protect against drawdown of pool below El 1083 corresponding to bottom of power pool and 9.89 maf storage

18 Count of Shortage Years is the sum of years during the 110 year record when either model produces Release from Mead less than the Minimum Objective Release of 9.5 maf