

Analyzing the Effects of Stochastic Hydrology in the Operations of the Colorado River System

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Problem

The Colorado River is one of the most important rivers in United States. The water supply provided by the Colorado is critical for a wide range of water users in seven western states. Over 25 million people in the western states depend upon the Colorado River. However, the Colorado water resources are under great stress due to the increasing population growth, climate variability, and climate change. Understanding the variability of the river flows and its effects is important to water planners and managers of the system. The historical streamflow records of the Colorado are useful because they document the flow variability that has occurred in the past. But, the historical record is only one snapshot of an infinite number of streamflow sequences that could occur in the future. The full picture is not revealed in the single sequence. In fact, it is very unlikely that an identical sequence will ever occur again in the future. This study evaluates two alternative approaches which improve the understanding of the behavior of the Colorado River system beyond that provided by the historical record. Recently, the inability of the Colorado River's historical record to capture the system's variability has become apparent. The four-year period from 2000 to 2003 is the driest of the 98-year historical record. Prior to 2003, this drought was not included in long term planning analyses because it had not yet occurred. This drought reemphasized that the historical record is not robust enough to simulate the possible range of future conditions.

Approach

This lack of robustness is a perpetual problem. However, further insight to possible future flows can be obtained using alternative approaches that are trained by the historical record. One approach is to use tree-ring reconstructed streamflows. Tree-ring indices can be used from the present back to the end of the 15th century in order to reconstruct flows in the Colorado River system. This process creates a record that is more than five times as long as the historical record. Another approach is to generate synthetic streamflow using a statistical model based on the historical streamflows. Once a model is developed, any number of synthetic streamflow traces of any length can be created. These two approaches are compared to the historical records by running the traces through a computer model that simulates Colorado River physical processes and operational procedures. The output of the model, in the form of reservoir releases and reservoir levels, are analyzed for comparison.

Streamflows

Three different streamflow datasets are compared: the historical streamflow, the tree-ring reconstructed streamflow, and the synthetically generated streamflow. The historical records are naturalized streamflows at 29 stations throughout the Colorado River basin (Figure1). The naturalized dataset spans the period 1906-2003 on a monthly timescale and was developed by the U.S. Bureau of Reclamation (Reclamation) and Colorado State University (CSU).

Tree ring indices were obtained from the Paleoclimatology Branch of NOAA, Boulder, Colorado. The tree-ring reconstructed streamflows were developed by CSU in collaboration with Reclamation (Tarawneh and Salas, 2006). Appropriate tree ring indices from a collection of trees sampled in and around the river basin were used to reconstruct streamflows back to 1490 at four stations: the Colorado River above Imperial Dam, AZ; the Colorado River at Lees Ferry, AZ (Lees Ferry); the Green River at Green River, UT; and the Colorado River above Cisco, UT. Then, spatial disaggregation models were used to obtain the reconstructed streamflows at other sites for the entire basin. Finally, the stations were grouped and temporally disaggregated to create monthly streamflow for each station.

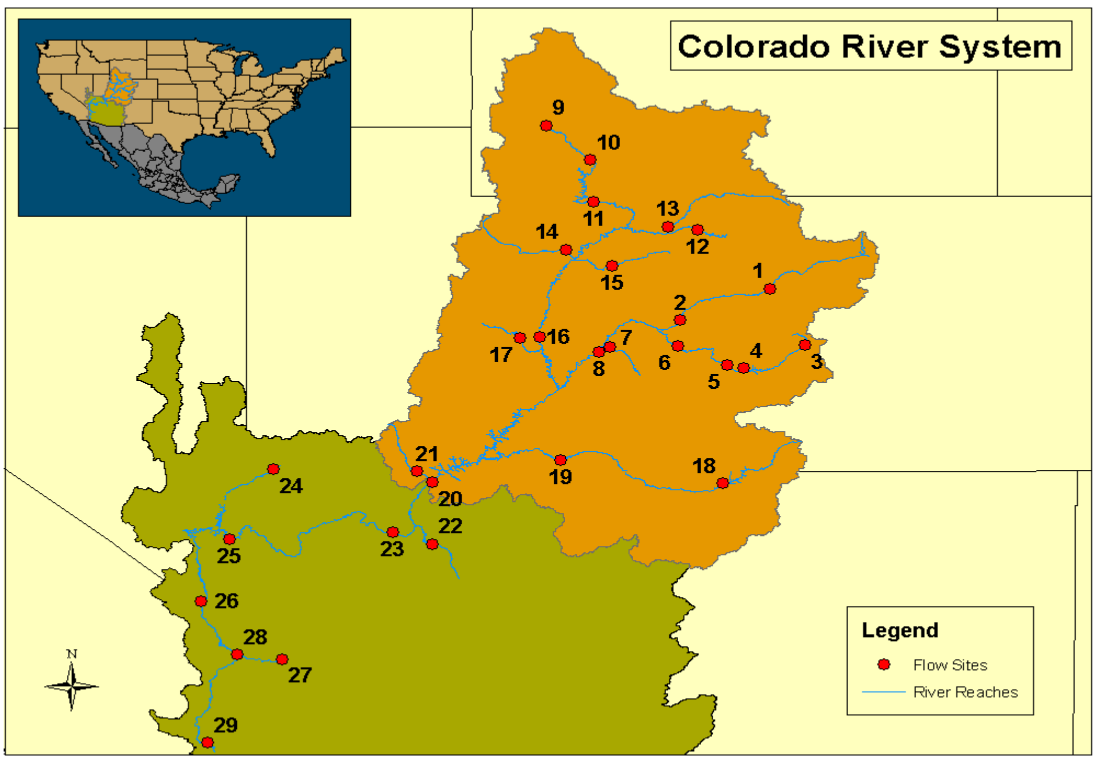

Figure 1. Colorado River system showing the location of 29 inflow sites. Site 20 corresponds to the Lees Ferry station, Lake Powell is near site 20, and Lake Mead is near site 25.

The synthetic streamflows were generated using a stochastic model implemented in the statistical software package SAMS developed by CSU (Lee et al., 2006). A bivariate autoregressive order-1 model was fit to the historical annual streamflows of two key stations: Lees Ferry and an index station comprising the sum of the intervening flows in the Lower Basin and the Paria River at Lees Ferry, AZ. These two stations were chosen because Lees Ferry streamflows are important for policy decisions involving lakes Powell and Mead, and the Lower Basin and Paria River streamflows contain the remainder of the system inflows. The model scheme included the disaggregation of the key stations into their upstream stations. Two spatial disaggregation steps were used to disaggregate the flows at the Lees Ferry station into 20 upstream intervening stations, and one disaggregation model was use to split the Lower Basin sum into the corresponding 9 intervening stations. Finally, the stations were placed into appropriate groups in order to disaggregate the annual streamflows into monthly streamflows. After the complete model was defined, 100 traces, each 71 years long, were simulated resulting in 7,100 years of synthetic flow records for each of the 29 stations.

A comparison of these three sets of streamflow was made in order to determine their statistical characteristics. The analysis is based on the flow at Lees Ferry because the station comprises the majority of flow in the system and is commonly used for reference and comparison. Determining the basic statistics of each approach gives a basis for comparison. Figure 2 illustrates the historical and tree-ring reconstructed streamflows at Lees Ferry. The thin line is the annual streamflow volume, and the thick line is the five-year running average of the annual volume. The tree-ring reconstructed streamflow has the same general pattern as the historical streamflows, only with several more extreme single-year and five-year streamflow sequences.

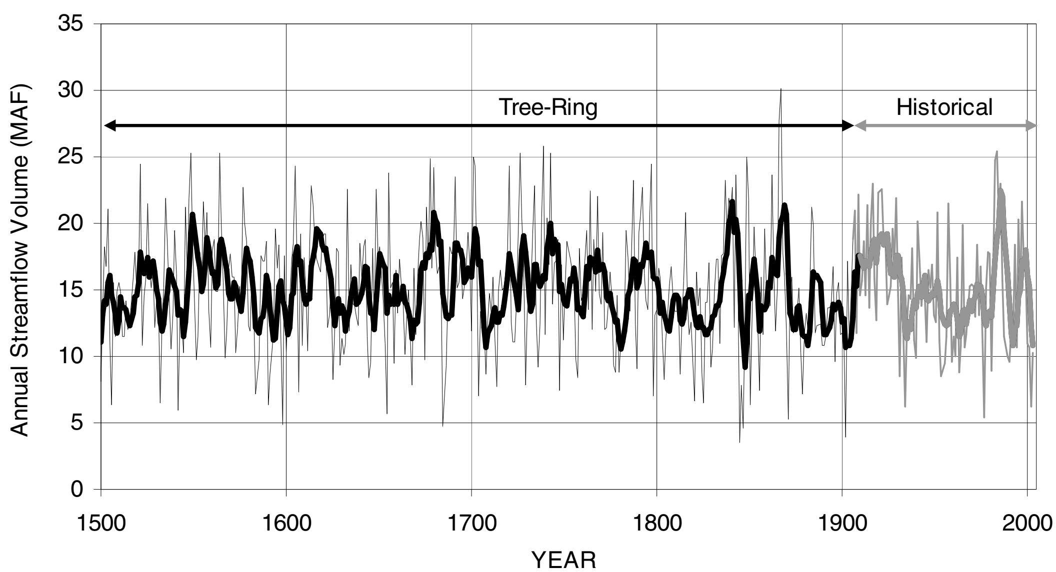

Figure 2. Annual historical (1906-2003) and tree-ring reconstructed (1490-1905) streamflow at Lee's Ferry

The historical annual streamflow averages just over 15 million acre-feet (MAF) and covers a range of 5.4 to 25.4 MAF with a standard deviation of 4.4 MAF. The tree-ring reconstructed annual streamflow averages just under 15 MAF and the standard deviation is about 4.5 MAF, very similar to those of the historical record. As expected with a longer period of record, the tree-ring streamflows cover a wider range than the historical streamflows, i.e. 3.5 MAF to 30.1 MAF. The stochastic generated streamflow's annual average is nearly the same as the historical average and the standard deviation is within about 2 percent of the historical value and about the same as the standard deviation of the reconstructed streamflows. This is expected since the stochastic model is built to reproduce the historical annual average and standard deviation. The stochastic streamflow covers an even broader range than the tree-ring streamflow, 3.3 to 37.9 MAF. This is consistent because the stochastic streamflow simulates 7,100 years of streamflow, a considerably longer sequence than the tree-ring and historical records. Table 1 summarizes these statistics and shows that the mean and standard deviation for the three streamflows are similar. However, the table also shows that their extremes are quite different. It is these extremes that are of greatest concern to policy makers because the high and low flows are the most difficult and most important to consider for planning purposes.

Table 1. Lees Ferry Annual Streamflow Basic Statistics (acre-ft)

	Historical	Tree-Ring	Stochastic
Average	15,076,151	14,972,483	15,069,342
Minimum	5,407,262	3,464,657	3,304,391
Maximum	25,397,639	30,107,969	37,865,046
Standard Deviation	4,444,186	4,540,639	4,551,642
Number of Years	98	514	7,100

River Simulation

The index sequential method (ISM) was utilized to generate synthetic flow traces based on the historical and reconstructed streamflow data. The ISM is a simple method that has been used in some practical cases for generating synthetic flows. The ISM generates the flows by sequentially block resampling the historical (or reconstructed) series. This method extracts every possible trace directly from the period of record. For the historical streamflow dataset, trace 1 consists of the streamflow from 1906 to 1976, the first 71 years of record. Trace 2 is offset one year from trace 1, so that it consists of the streamflow from 1907 to 1977. This one year of offsetting is continued until the end of the record is reached at which time the beginning of the record is wrapped around so that the offsetting may continue. The last trace, trace 98, consists of 2003 streamflow followed by 1906 to 1975 streamflow. Using this method places every year of streamflow in every year of the simulation model across all the traces. This simulation method has been the standard method used for long term river planning and management of the Colorado. The tree-ring reconstructed streamflows were simulated in the same manner. However, since there are 514 years of reconstructed streamflows, there are 514 different overlapping traces. Finally, the stochastically generated synthetic streamflows are the 100 traces, 71 years in length as referred to above. The model in which the simulated streamflows are input is the Colorado River Simulation System (CRSS), which has been implemented in RIVERWARE, software developed at the University of Colorado. CRSS was developed by Reclamation and is used for the long term planning and management of Lakes Powell and Mead. The model operates on a monthly timestep and includes 12 major reservoirs and 8 major tributaries to the Colorado River. River objects simulate the physical processes while a comprehensive rule set simulates the reservoir operations.

The model is run with three key inputs, initial reservoir conditions, projected water demands, and river inflows. The initial conditions were set to December 2004 reservoir levels because this study began in 2005. The model's projected water demands were unchanged. Reclamation obtained these projections from each state within the basin and then implemented them in the model. The Upper Basin's normal annual depletion increases from 4,445,000 AF in 2005 to 5,429,000 AF in 2060. The Lower Basin's normal annual depletion remains constant at 7,500,003 AF as does Mexico's at 1,515,000 AF since these are the maximum normal depletions set by the Compact. These demands dictated the model run length. Seventy-one years (2005-2075) was chosen because the projected demands level off in 2060 and running the model out to 2075 gives an indication of steady state conditions. Finally, the river inflows, which were explained previously, were input to make three different modeling scenarios.

Analysis of Results

CRSS was run under each streamflow scenario, producing three different sets of output that could be compared. Of the entire model output, two key indicators, Lake Powell release volumes and Lake Mead storage volumes are analyzed.

Lake Powell's release volume was analyzed in terms of the ability to satisfy the minimum objective release amount of 8.23 MAF per year which is the currently agreed upon release volume in order for the Upper Basin states to satisfy their obligations to the Lower Basin states and Mexico. CRSS allows for a minimum objective release deficit because Powell's pool level is never allowed to drop below the minimum power pool elevation of 3,489.96 feet. This is not necessarily how the reservoir will be operated in the future, but it indicates the critical state of the system. The percentage of runs in which the minimum objective release was not met for any given year of simulation was computed in order to give an estimate of the probability that a deficit could occur at some point in the future. Then, among the deficits, the basic statistics were calculated for each year. These two results are plotted for each of the streamflow scenarios in Figures 3 through 5.

The results are consistent with the previous streamflow analysis. The ISM (historical) streamflow produced the smallest possible deficit volume of approximately 3.5 MAF while the stochastic streamflow produced the largest possible deficit volume of 6 MAF. Furthermore, the ISM (historical) streamflow resulted in a

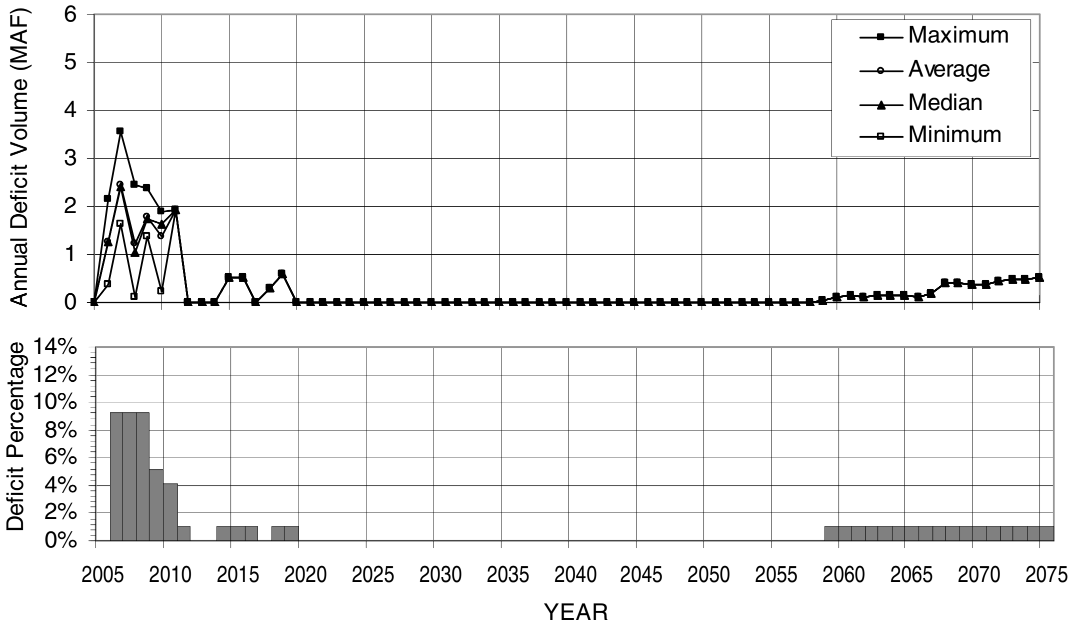

Figure 3. Minimum objective release deficit volume and percentage of occurrence for Lake Powell- ISM (Historical)

0 to 1 percent chance of a release deficit occurring past 2020, while the ISM (reconstructed) streamflow resulted in a 0.4 to just under 4 percent chance of occurring past 2020, and the stochastic streamflow resulted in a 2 to 12 percent chance of occurring past 2020. These results are expected since the stochastic streamflow has the most extreme hydrology compared to the ISM (historical) or ISM (reconstructed). A distinct pattern of the annual deficit volume and deficit probability may be observed for the runs based on ISM. Both the IMS (historical) and the IMS (reconstructed) streamflows result in high probabilities of deficit and large maximum deficit volumes in the first few years. This behavior occurs because the streamflows generated based on the ISM (for both historical and reconstructed) can place critical droughts back to back. In effect, entire severe drought streamflow sequences are placed just after the 2000 to 2005 severe drought, which corresponds to the initial conditions of the system, e.g. very low reservoir levels at Powell and Mead. Once the initial reservoir conditions are overcome, the probability of a deficit decreases down to zero for the ISM (historical) and to one for the ISM (reconstructed). Another similarity between the outputs based on ISM (historical) and ISM (reconstructed) flow scenarios is the increase and then leveling off of the deficit probability at the end of the simulation time period. This increase is due to the increase in Upper Basin demands, and the evenness is due to the nature of the index sequential method. Thus, because of the way in which the ISM creates synthetic flow traces, it appears that the time series patterns of deficits become distorted, creating a trend in the deficit statistics through time. The most disturbing result is that the deficit probability obtained from the ISM (historical) becomes zero in 45 out of 71 years and remains zero continuously for the period 2020 to 2058 thereby giving the impression of zero risk through a good part of the study period. The results obtained from the ISM (reconstructed) are similar in that the deficit probability remains near 1 percent or less during the same time period.

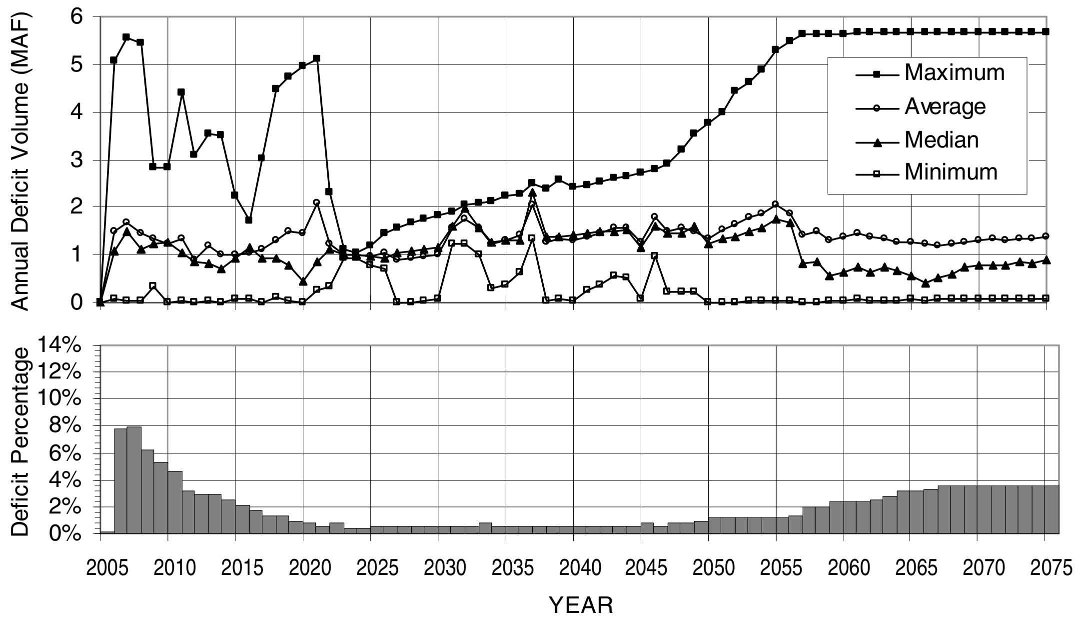

Figure 4. Minimum objective release deficit volume and percentage of occurrence for Lake Powell- ISM (reconstructed)

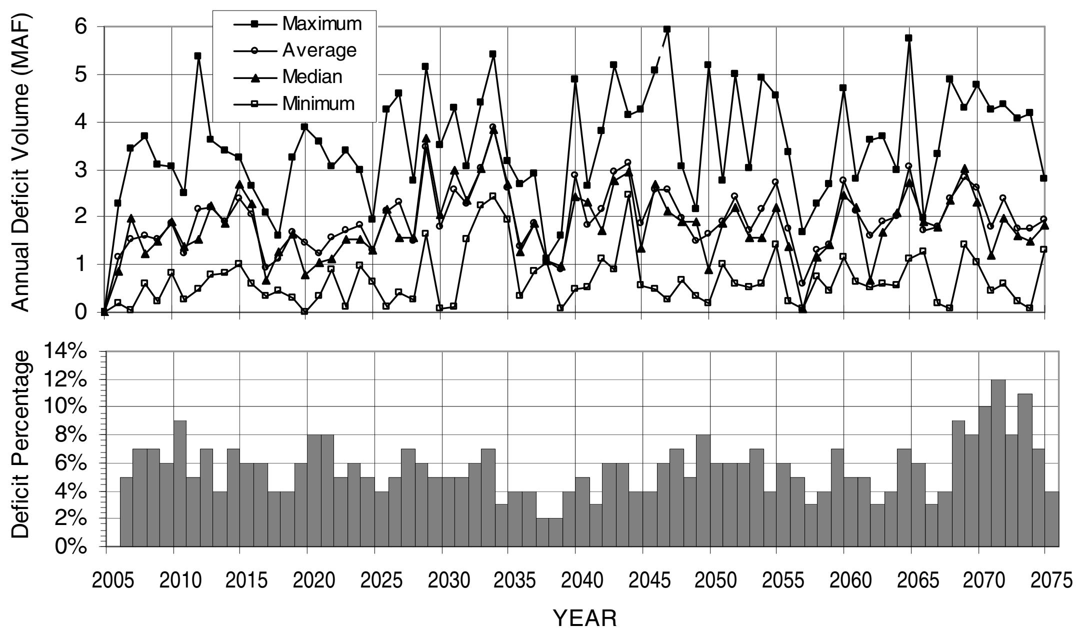

Figure 5. Minimum objective release deficit volume and percentage of occurrence for Lake Powell- Stochastic

On the other hand, the results based on the stochastic flow scenario do not exhibit the same patterns as those based on the other two scenarios. The random behavior of the stochastic simulation's output occurs because each streamflow trace is entirely different and equally likely to occur, as it should be. This independence of traces is not maintained in the flow scenarios obtained from ISM. The independent nature of the stochastic simulation flow traces results in a random output pattern in all statistical metrics as shown in Fig. 5. However, as expected, the increase in the probability of deficit at the end of the simulation period is still present due to the increase in demands as cited above. In order to obtain the steady state probability, especially under increasing demands a simulation period much longer than the 71 years used in this study is required. Nevertheless, the probability obtained towards the end of the simulation period may give an indication of such a deficit probability. The probability of a minimum objective release deficit is an important statistic to compare because water managers must plan river operations with an idea of this probability in mind as well as the probability that is acceptable to water users. The ISM (historical) scenario gave a deficit probability of 1 percent in the last 15 years of the study period, the ISM (reconstructed) flow scenario gave a probability just under 4 percent for the final 10 years of the study period, while the stochastic flow scenario gave a probability varying around 9 percent in the final 8 years. Clearly, the results based on the stochastic flow scenario give a more comprehensive and realistic picture of possible and expected future conditions and behavior of the Colorado River system.

Lake Mead live storage volumes obtained based on the different streamflow scenarios were also compared. Lake Mead's live storage volume is an important indicator of the system as it comprises the majority of the Lower Basin's storage volume, and there is not an absolute protect condition imposed upon it. The storage level reflects the state of the system without any lower boundaries. Lake Mead does have an upper boundary of 25.88 MAF of live storage. However, there is still 1.5 MAF of flood control storage on top of the live storage, but water is never allowed to remain in the flood control storage for an extended period of time. Critical low pool elevations are 1,050 feet and 1,000 feet. The upper Southern Nevada Water Authority (SNWA) diversion intake is located at the 1,050 foot elevation. This is also the estimated minimum power pool elevation. The lower SNWA diversion intake is located at the 1,000 foot elevation. If Lake Mead were to fall below this level, an alternative plan would need to be implemented in order for SNWA to actually make a diversion. It may be possible for the water to be pumped up to the intakes, or another lower intake could be constructed in anticipation.

Figures 6 through 8 illustrate Lake Mead's live storage volume possibilities and their relation to the critical levels in terms of annual maximum, June median, and annual minimum for each of the streamflow scenarios. These plots were developed by calculating the indicated statistics across all traces for each timestep in order to give an estimated range of possible future pool levels. All of the scenarios demonstrate a decline and then leveling off of the medium June storage level as the Upper Basin demands increase and then level off. This behavior is expected because Mead receives nearly all of its water from the Upper Basin. Interestingly, the June median for the ISM (historical) scenario is slightly lower than for the other two. This could occur if the ISM (historical) streamflow has a slightly greater frequency of low flows, though not necessarily severe, than the ISM (reconstructed) and stochastic streamflows. Another important behavior to note is that the possible future minimum storage levels are significantly lower for the ISM (reconstructed) and stochastic flow scenarios than for the ISM (historical) flow scenario. In this case, the ISM (reconstructed) and stochastic streamflow scenarios give a more comprehensive picture of possible future conditions in the Colorado River system than the ISM (historical) streamflow scenario.

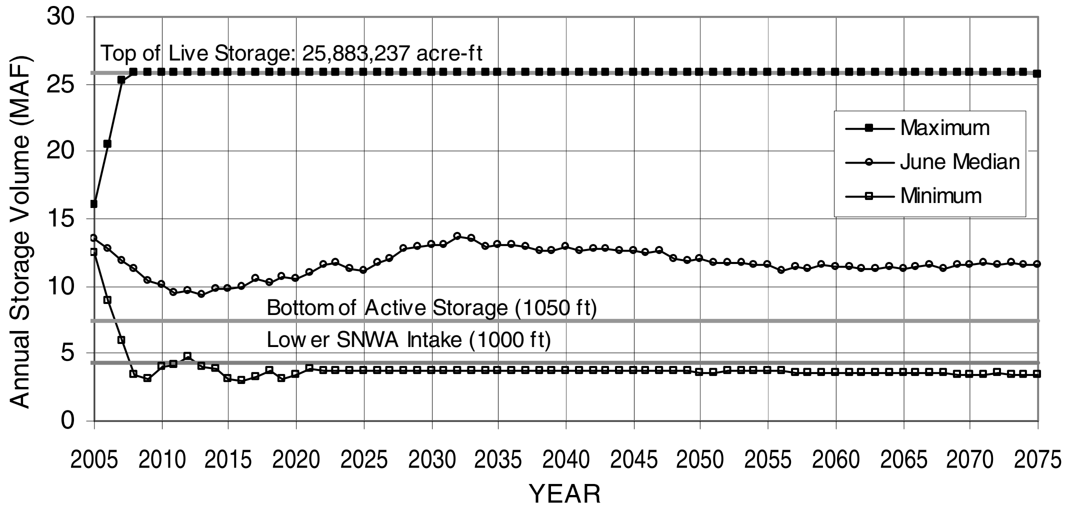

Figure 6. Lake Mead annual storage statistics – ISM (Historical)

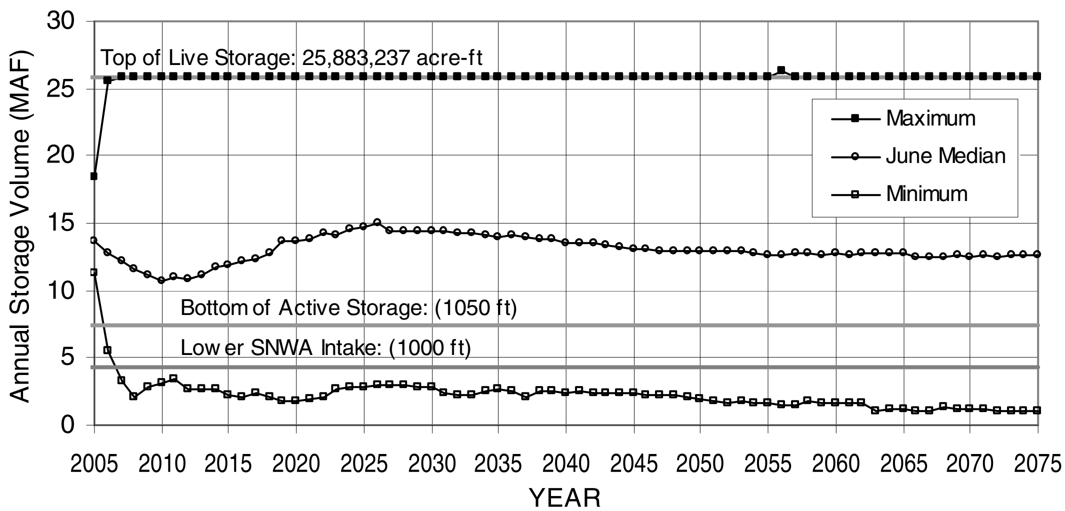

Figure 7. Lake Mead annual storage statistics – ISM (reconstructed)

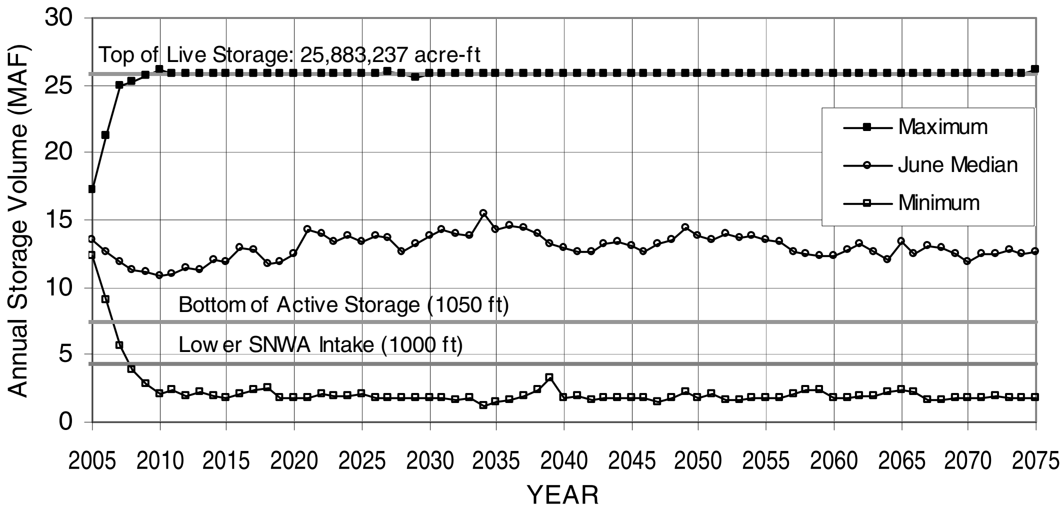

Figure 8. Lake Mead annual storage statistics – Stochastic

Conclusions

In order to assess the expected future behavior of the Colorado River system one must test it under possible and likely streamflow scenarios that may occur in the system in the (future) study period. This paper applied three streamflow simulation techniques, namely, the ISM (historical), ISM (reconstructed), and stochastic. This study has shown (and confirmed previous findings) that the ISM produces flow traces limited to the range of flows utilized in the method, i.e. the ISM (historical) will not produce flows beyond the maximum or minimum observed in the historical record. This would still be the case even if a longer record is utilized, e.g. reconstructed flows obtained from tree ring indices. This limitation will underestimate particularly the magnitude of short term droughts, e.g. one or two-year droughts. In the case of the Colorado River study, ISM produces unrealistic patterns (trends) of deficit volumes and probability of deficits and underestimates their values, e.g. zero deficit for a 40-yr time span during the study period. On the other hand, the stochastic flow scenario does not produce such distortions and instead gives a random pattern of deficits and probabilities through the study period, which is realistically expected to occur in the future. In addition, Lake Powell release volumes and Lake Mead storage volumes exhibited a wider range of possible occurrences in the ISM (reconstructed) and stochastic flow scenarios than in the ISM (historical) flow scenario. By simulating these more extreme river system scenarios water managers can better prepare for whatever the future may have in store.

References

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