IMPACT OF STREAMFLOW VARIABILITY ON THE COLORADO RIVER SYSTEM OPERATION

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ABSTRACT

The water supply provided by the Colorado River system is critical to millions of residents in the arid and semiarid western United States. Understanding the response of the system to possible hydrologic occurrences is important to water planners and managers for short, medium, and long term planning and operation of the system. A long sequence of historical streamflow records is available for the river system; however, this sequence is not sufficient to capture the complex temporal and spatial variability of the river system. The overall objective of the study is to determine the effect of alternative possible future hydrologic scenarios on water supply availability throughout the entire river system. Another objective is to estimate the sustainable yield of the Upper Colorado River basin.

The hydrologic scenarios are derived from a 98-year historical streamflow record and a 514-year reconstructed tree-ring derived streamflow record. Synthetic streamflows are determined based on stochastic models and modeling strategies using the software SAMS developed at Colorado State University. Additional streamflow scenarios are developed using the index sequential method (ISM).

The response of the river system to the different streamflow scenarios is evaluated using the Bureau of Reclamation's Colorado River Simulation System (CRSS) model implemented in RiverWare software, a river basin modeling program developed by CADSWES. The model outputs are analyzed in order to determine the occurrence probabilities of critical river system conditions (e.g. reservoir outflows and reservoir levels) within a specified planning horizon. The stochastic simulated streamflow resulted in occurrence probabilities that demonstrated an underlying random nature mirroring the inherent randomness of hydrologic processes. On the other hand, the occurrence probabilities resulting from streamflow simulated by ISM (with a comparable number of model runs) always followed a smoother line because the method is not random. The probabilities of reaching certain critical levels in Lakes Powell and Mead are similar across the simulation scenarios. However, the Upper Basin minimum objective release deficit probabilities are greater for the stochastic scenario than for the ISM scenarios. This release deficit is an important indicator of river system conditions, and its understanding is critical to river operators and policy makers. The stochastic scenario gives a more comprehensive understanding of release deficit probabilities because it is a random simulation method and not limited by the streamflows of the past. Furthermore, the Upper Basin sustainable yield determined using ISM is restricted by the critical period observed in the past. However, it is known that an even more critical period could occur in the future. This study demonstrates that the traditional definition of the Upper Basin's sustainable yield must be reevaluated in order to determine any sort of sustainable yield volume under stochastic simulation.

AKNOWLEDGEMENTS

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1 Introduction

The water supply provided by the Colorado River system is critical to millions of residents in the arid West of the United States. The Colorado River not only provides water to the major municipalities within the basin, but water is also transported to municipalities outside the basin, including Denver, Salt Lake City, Albuquerque, Los Angeles, and San Diego. The river is also the lifeblood of the agricultural communities within the basin as well as those in southern California. Furthermore, the hydropower generated by the Colorado River is critical to millions of people in the Southwest. Understanding the response of the system to possible hydrologic occurrences is important to water planners and managers for short, medium, and long term planning and operation of the system. In particular, the volume of water in Lakes Powell and Mead directly drives the amount of water the Lower Basin users can divert and will eventually dictate the amount of water that Upper Basin users can divert. A long sequence of historical streamflow records is available for the Colorado River system; however, this sequence is not sufficient to capture the complex temporal and spatial variability of the river system.

1.1 Problem

Traditionally, the long term planning and management decisions for the Colorado River system have been based upon computer model simulations of the system driven by streamflow sequences extracted directly and only from the historical period of record which is currently 98 years long. There are many problems with this approach. First, it is known that the future will not mirror the past, but this method only uses past streamflow to simulate possible future flows. In addition, 98 years of record is very short on the hydrologic scale and does not give an accurate picture of the possible extreme streamflows (either droughts or floods) that the system can produce. While the limitations of this approach have been recognized during its use, a more complete picture of possible future hydrologic scenarios can be obtained by simulating with alternative, longer streamflow datasets which capture more of the extreme behavior. Since it is the extreme streamflow occurrences which create the managerial difficulties of allocating water to the different users, the understanding of these extremes and their effects on the river system (in terms of reservoir levels and releases) is critical to the development of comprehensive long term planning and management strategies.

These alternative streamflow approaches can be further compared in the examination of a related problem. The Upper Basin Compact allocates a certain percentage of the Upper Basin's sustainable yield to each of the basin states. Therefore, the sustainable yield must be known in order for each of the Upper Basin states to plan for the amount of water they are allotted. However, the sustainable yield of the Upper Basin is a debatable number. In concept, the sustainable yield is the amount of water that can be reliably depleted from the system every year. It must be estimated by simulating the system, but there are many approaches which can be taken. The approach currently applied is to use the historical streamflow record to simulate all of the possible streamflow sequences. The disadvantages to this approach were explained in the previous paragraph. Examining the differences in alternative simulation approaches will help to more fully understand the possible sustainable yield of the Upper Basin.

1.2 Objectives

The main objective of this study is to determine the effect of alternative possible future hydrologic scenarios on the expected water supply availability throughout the entire Colorado River system. More specifically, this study evaluates how the probabilities of future reservoir levels, reservoir outflows, and shortage and surplus conditions compare among the different stochastic streamflow simulation approaches. Another associated objective is to determine the sustainable yield of the Upper Basin using each of the streamflow simulation approaches.

1.3 Literature Review

Kendall and Dracup (1991) compared the effects of the index sequential method (ISM) and stochastic generated streamflows on an annual Colorado River simulation model. Lake Powell and Lake Mead reservoir exceedence probabilities were analyzed for comparison. Kendall and Dracup used an autoregressive AR(1) log normal model for the stochastic Colorado River simulation. They noted that the differences in reservoir performance using more complex models designed to preserve persistence were negligible when compared to the uncertainty in the model's parameters. The river simulation model used was a modified version of the Colorado River Annual System Regulation Model (MWD, 1980) which focuses on Lake Powell and Lake Mead annual regulation. The model was originally developed by the Metropolitan Water District of Southern California (MWD) and modified by the authors to represent the then current operating conditions of the river system.

Only one naturalized streamflow station, the Colorado River at Lee Ferry, is input into the model and therefore necessary to simulate. The Colorado River at Lee Ferry streamflow includes all of the inflow above the Compact Point which is the point of separation between the Upper Basin and Lower Basins. The station represents both the inflows above the Colorado River at Lees Ferry gaging station and the Paria River inflows. The log transformation of the naturalized streamflow record (1906 through 1986) was used to build the model. Two thousand streamflow traces each 81 years long were generated. The AR(1) model average generated streamflow was slightly higher than the historical record's (15.132 MAF vs. 15.063 MAF) resulting in higher average reservoir levels towards the end of the study's planning period (32 years) because of the accumulating storage. Furthermore, the AR(1) model used resulted in slightly lower severe drought occurrences than the historical record, which may or may not represent the actual occurrence probability. The study concluded that ISM simulation is the preferred method of the two for determining average system responses (storage, power generation, reservoir releases) and AR(1) simulation is more appropriate for reliability studies in which 90 percent or higher exceedence levels are evaluated.

Ouarda, Labadie, and Fontane (1997) compared ISM and AR(1) hydrologic modeling for the purposes of analyzing hydroelectric power generation of the Colorado River. The study used the FORTRAN based version of the Colorado River Simulation System (CRSS) developed by the Bureau of Reclamation (USBR) to simulate the river system and therefore simulated the monthly naturalized flows for all 29 input stations. The available historical record from 1906 to 1983 was used to build an AR(1) model with disaggregation and 120 twenty-year runs were simulated. The study analyzed monthly power capacity, energy generation, and water deliveries that were output by CRSS run using the two simulation approaches. The statistical characteristics of the analyzed results were found to exhibit acceptable correspondence.

Tarboton (1994) used historical naturalized streamflow and tree-ring reconstructed streamflow in order to analyze the risk of drought in the Colorado River basin. The study used Lee Ferry (Compact Point) tree-ring reconstructed annual streamflow from Stockton and Jacoby (1976) which is 442 years long (1520-1961) and has an annual average of 13.5 MAF. The historical period of record Lee Ferry streamflow (1906-1983, 78 years) averaged 15.2 MAF. A disaggregation model was used to reconstruct all 29 stations on a monthly time step for input into the river simulation model. Problems with disaggregation leading to large negative flows for several of the headwater stations were encountered due to the adjustments required to maintain additivity. These stations had to be combined with nearby stations and then split proportionately to the historical mean of the stations in order to produce realistic streamflows. The study estimated that the 1579 to 1600 severe drought in the reconstructed record has a return period of 400 to 700 years while the historical record severe drought from 1943 to 1964 has a return period of 50 to 100 years.

In 1988 the Bureau of Reclamation reviewed its 1984 hydrologic investigation utilizing CRSS in order to determine the sustainable yield for the Upper Basin. The 1984 determination found that there was 5.8 MAF of water that the Upper Basin could safely deplete annually. The 1998 Hydrologic Determination (USBR, 1988) found that Upper Basin depletion volumes could “reasonably be allowed to rise to 6 MAF annually.” This sustainable yield was determined based on the assumption that the Upper Basin is required to deliver the Compact specified 75 MAF of water every 10 years as well as

750,000 acre-feet of water to Mexico every year. A mass balance analysis was performed using available reservoir storage in the system determined by CRSS, an ISM application of annual virgin flow at Lee Ferry (81-year period of record), the assumed release to the lower basin, and an assumed allowable overall shortage of 6 percent.

1.4 Approach

In addition to examining the effect of the traditionally simulated streamflows on the behavior of the Colorado River system, two alternatives for creating more comprehensive streamflow datasets are explored. Both alternatives are based upon the most current iteration of the historical record of naturalized, intervening streamflows. The first alternative is to increase the period of record. Since all of the gaged record has been used to create the historical streamflow dataset, a streamflow indicator is needed to lengthen the period of record. This study uses streamflows reconstructed back to the year 1490 using tree ring indices (Tarawneh and Salas, 2006). This reconstructed record is more than fives times as long as the historical record (514 years, 1490-2003). The second alternative is to generate synthetic streamflow traces using a stochastic modeling scheme of the historical intervening streamflows. The stochastic model preserves important statistics of the historical streamflows and has the ability to generate any number of streamflow traces of any length. This study, uses 100 samples of streamflow traces each 71 years long which were generated according to a stochastic model (Lee et al., 2006). A trace length of 71 years was chosen in order to run the river model from 2005 through 2075. Each sample of streamflow consists of intervening flows for each station within the basin. These two alternative streamflow datasets are analyzed and compared with the historical streamflows.

The historical and reconstructed intervening streamflows are input into the river basin model according to ISM which is explained in the next chapter. Thus, the historical simulation consists of 98 overlapping traces, and the reconstructed simulation consists of 514 overlapping traces. The 100 stochastically generated synthetic streamflow traces are input into the river basin model directly.

The Colorado River Simulation System developed by the USBR and implemented in RiverWare, an object oriented computer river basin modeling program, is used to represent the Colorado River system (Zagona at al., 2001). The different streamflow simulations are input, and the resulting river conditions are output for analysis. The probabilities and volumes of critical reservoir conditions and outflows as well as shortage and surplus occurrences are compared among the three simulation alternatives.

Finally, in order to estimate the sustainable yield of the Upper Basin, the upper basin demands are reduced until Lake Powell’s minimum objective release is met in the year 2075 for a given percentage of the traces. The sustainable yield is estimated according to each of the streamflow simulation scenarios.

2 Hydrologic Scenarios

This section presents the three hydrologic scenarios that were analyzed and used in the river system model. Scenario 1 is the historical streamflow simulated according to ISM. Scenario 2 is tree ring reconstructed streamflow simulated according to ISM. Scenario 3 is synthetic streamflow simulated using a stochastic model of the historical streamflow.

2.1 Introduction

The historical streamflow dataset upon which each of the hydrologic scenarios is based is the Colorado River naturalized historical streamflow database developed by USBR and Colorado State University (CSU). This is the most current iteration of the dataset that is conventionally used to characterize the Colorado River system. The dataset consists of 29 stations located throughout the basin with 21 in the Upper Basin and 8 in the Lower Basin. The station identification numbers and U.S. Geological Survey gage names and numbers are given in Appendix A. The station locations are shown in Plate 1.

At the time of this study, 98 years of monthly naturalized streamflow was available consisting of the years 1906 through 2003. These were developed by USBR by first obtaining the available gaged records for all 29 stations and removing the effects of consumptive uses and losses and reservoir operations that occurred throughout time. Then, in collaboration with CSU, the stations with records which do not extend back to

1906 were extended using appropriate correlations (Lee and Salas, 2006). Seven of the stations have records that extend back to 1906 and the remaining stations have records that terminate somewhere between 1909 and 1952. Figure 2.1 illustrates the total historical naturalized Colorado River streamflow for two of the stations: the Colorado River above Imperial Dam, AZ (Imperial Dam) which represents all of the natural flow into the system; and the Colorado River at Lees Ferry, AZ (Lees Ferry) which is the station just below Lake Powell and includes the majority the Upper Basin inflow. One can see from the figure that the majority of the Colorado River inflow originates in the Upper Basin. The overall average annual streamflow volume for the two stations are indicated by the dashed lines: the Lees Ferry annual average is approximately 15.1 million acre-feet (MAF) and the Imperial Dam annual average is approximate 16.4 MAF.

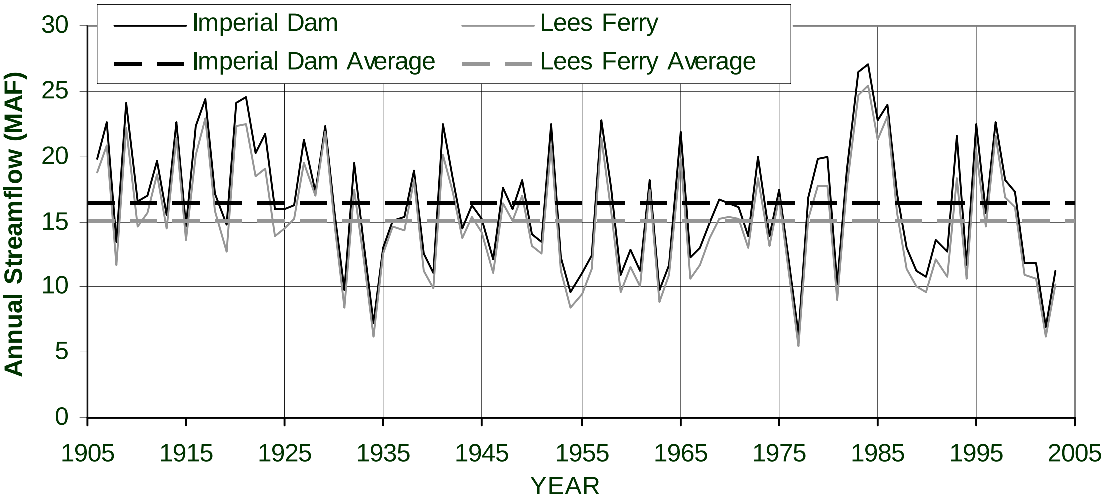


Figure 2.1 1906 – 2003 Annual historical naturalized Colorado River streamflow at Lees Ferry and above Imperial Dam

2.2 Scenario 1: Historical ISM

The previously described naturalized historical intervening Colorado River streamflows from 1906 to 2003 are input directly into the model according to ISM for

Scenario 1. This scenario is the traditional approach to streamflow simulation to which the other two alternative streamflow scenarios are compared.

ISM is the simulation method that has been traditionally used by USBR in order to simulate streamflow within CRSS. This method directly extracts every possible trace from the period of record. Figure 2.2 illustrates the method as it is used in the ISM historical streamflow scenario.

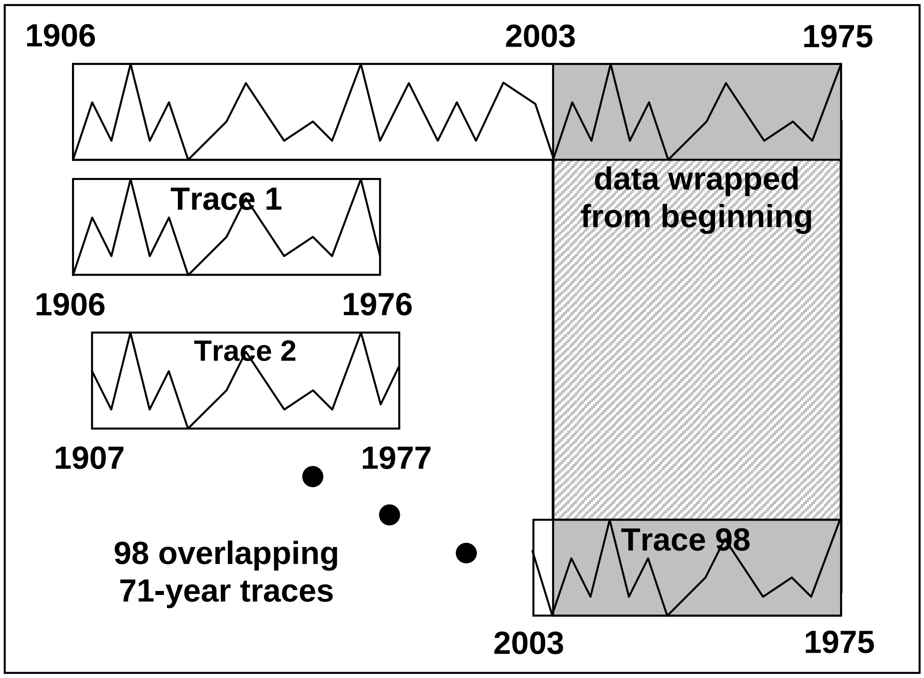


Figure 2.2 Index sequential method illustration

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. The overlapping nature of the simulation is clearly shown in Figure 2.3 which has all 98 of the Lees Ferry annual historical ISM traces plotted over the river simulation time period. Most of the flows are between 10 and 20 MAF with a handful of extreme streamflow years extending beyond those bounds from 5 to 25 MAF. These extreme flows illustrate the lack of randomness in the simulation method. The same trace is simply offset by one year over and over again.

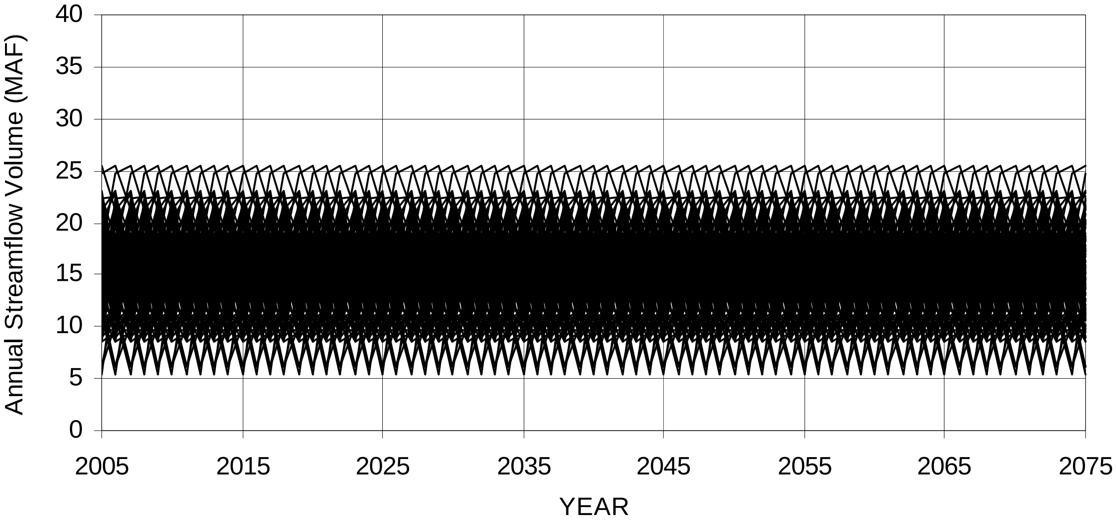


Figure 2.3 All 98 Lees Ferry annual historical ISM streamflow traces

There are several advantages to the ISM approach. First, it is the simulation approach traditionally used by USBR so the results can be directly compared with previous studies. Furthermore, since it extracts traces directly from the historical record, it produces streamflow scenarios to which people can relate. Perhaps most importantly, ISM is guaranteed to preserve the complex spatial relationships which are present in multi-site models like CRSS. Finally, it is a straightforward method to implement, and in general, water managers understand it and trust its results.

However, there are some significant drawbacks to the method. It can only simulate conditions that have occurred in the past, so it only captures the hydrologic variability that occurred during the length of record. In hydrologic terms, 98 years is a relatively short record. More extreme conditions than those that have occurred in the recent past, are not simulated. For example, the period from 2000 to 2003 had the lowest cumulative 4-year streamflow on record for the Colorado River system. Prior to 2003, this extreme scenario could not be simulated using ISM. While we do not know when other more extreme events are going to occur, simulating these extremes will enable water managers to acknowledge and better prepare for them. Furthermore, the wrapped sequences do not represent the random nature of the hydrologic process. Thus, analyzing probability curves of the results is not entirely appropriate, but it does give an idea of future probabilities as long as the shortcomings are acknowledged.

2.3 Scenario 2: Reconstructed ISM

The second scenario uses streamflows reconstructed from tree ring indices that have been correlated with naturalized historical Colorado River streamflow. This streamflow dataset was developed by CSU in collaboration with USBR using tree ring indices obtained from the NOAA Paleoclimatology Program, Boulder, Colorado (Tarawneh and Salas, 2006). Appropriate indices from a large collection of trees sampled in and around the river basin were correlated with the following 4 streamflow stations.

1. Colorado River above Imperial Dam, AZ
2. Colorado River at Lees Ferry, AZ
3. Green River at Green River, UT
4. Colorado River above Cisco, UT

These correlations were used in a statistical model to reconstruct the annual streamflows from 1490 to 1905. Each of the key stations was disaggregated to appropriate upstream stations using a spatial disaggregation model. Finally, the annual streamflows were split into monthly streamflows using Lane's (1979) temporal disaggregation model. The resulting reconstructed dataset consists of 29 stations with monthly naturalized streamflow from 1490 through 2003. The intervening flows from this dataset were input into the river basin model according to ISM which was explained in the previous section. Figure 2.4 is a plot of all 514 ISM simulated traces of the annual Lees Ferry reconstructed streamflow. Again, the nonrandom, overlapping nature can be seen. In this case, the majority of the streamflows appear to cover the range from 6 to 24 MAF with a handful of extremes reaching between 4 and 30 MAF. As with the historical ISM scenario, only a handful of extreme realizations are being simulated, but they are repeated over and over to give the impression of more extreme simulations.

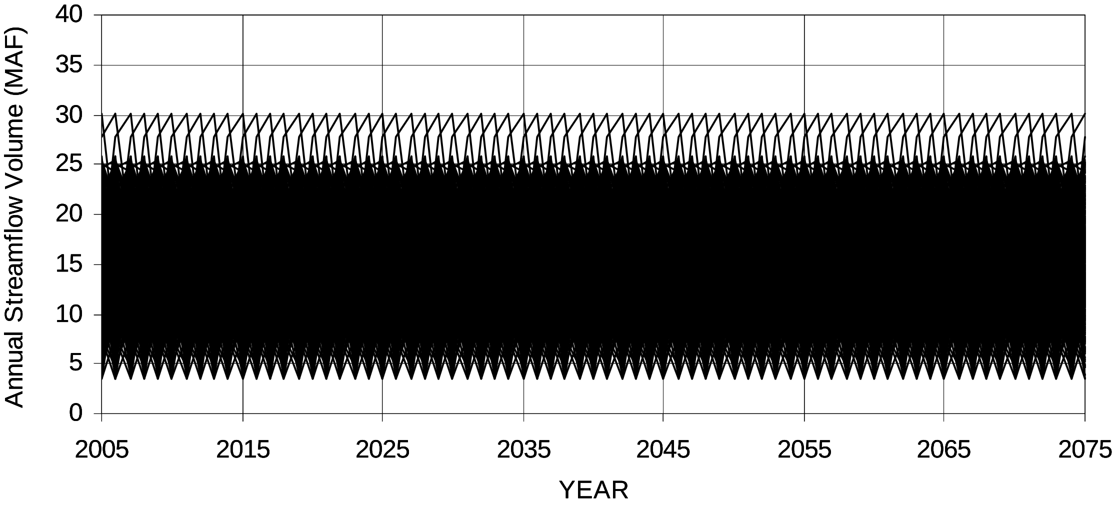


Figure 2.4 All 514 Lees Ferry annual reconstructed ISM streamflow traces

2.4 Scenario 3: Stochastic Generation

The third scenario consists of a synthetic streamflow dataset. A parametric stochastic statistical model was developed based upon the naturalized historical intervening flow record. The individual station streamflows were transformed to normal prior to modeling if they did not naturally exhibit normal behavior. An annual bivariate contemporaneous autoregressive order-1 model was used to model two key streamflow stations, the Colorado River above Imperial Dam and the Colorado River at Lees Ferry. The general form of the model is given by the following equation (Lee et al., 2006).

$$Y_t = \mathrm{A}Y_{t-1} + \mathrm{B}\varepsilon_{\mathrm{t}} \tag{2.1}$$

$$\begin{bmatrix} Y^1 \\ Y^2 \end{bmatrix}_t = \begin{bmatrix} a_{11} & 0 \\ 0 & a_{22} \end{bmatrix} \begin{bmatrix} Y^1 \\ Y^2 \end{bmatrix}_{t-1} + \begin{bmatrix} b_{11} & 0 \\ b_{21} & b_{22} \end{bmatrix} \begin{bmatrix} e^1 \\ e^2 \end{bmatrix}_t \tag{2.2}$$

This model was used because it represents well the lag-0 cross-correlation between the two stations as well as their respective lag-1 autocorrelations. Also, the model excludes parameters that would preserve the lag-1 cross-correlations since they are not significant. This exclusion helps to reduce the size of the parameter set.

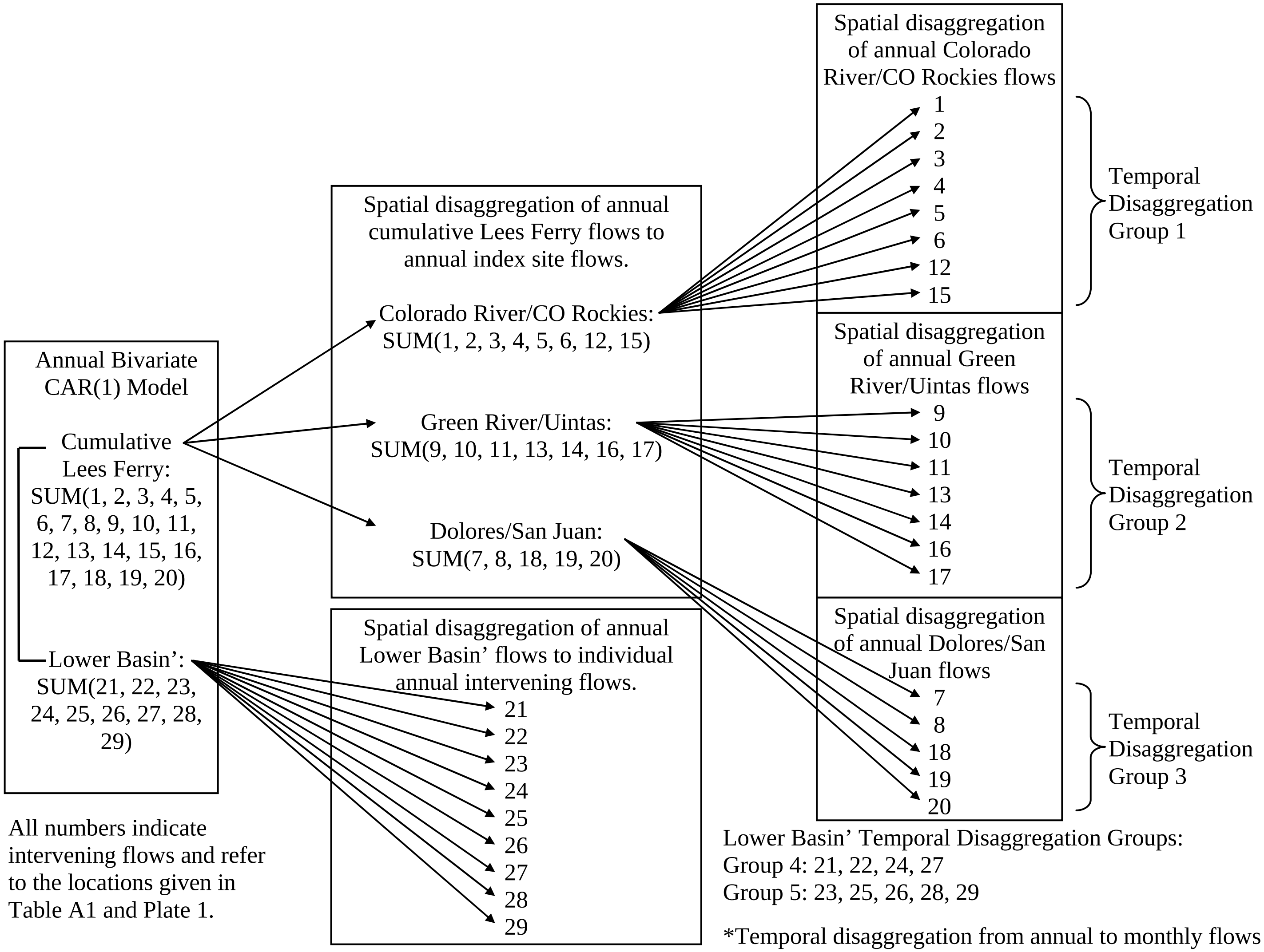
The disaggregation scheme is shown in Figure 2.5. Lees Ferry streamflow is disaggregated to three different streamflow summations representing different river basins/mountain ranges in the Upper Basin (Green River/Uinta Mountains, Upper Colorado River/Rocky Mountains, Dolores and San Juan Rivers). The groupings represent the strongest cross-correlations among the Upper Basin stations. Each of these groupings is further disaggregated spatially to their individual intervening streamflow stations. The Paria River at Lees Ferry is excluded from the Upper Basin disaggregation scheme because the station's streamflow exhibits statistical characteristics similar to the Lower Basin stations. The Colorado River above Imperial Dam is disaggregated spatially directly to the intervening streamflow Lower Basin stations as well as to the Paria River at Lees Ferry station. This grouping is referred to as Lower Basin' in Figure 2.5. Finally, all of the stations are disaggregated temporally to monthly streamflow volumes grouped according to their spatial groupings, except in the Lower Basin', the gains nodes are grouped separately from the headwater nodes. The spatial disaggregation model used is Mejia and Rousselle's and is expressed according to the following equation,

$$Y_t = AX_t + B\varepsilon_t + CY_{t-1} \tag{2.3}$$

where Y_t is a single column vector of the key stations, X_t is a single column vector of the substations, ε_t is a single column vector of independent normally distributed noise terms with mean equal to zero and the variance-covariance matrix equal to the identity matrix, and Y_{t-1} is a single column vector of the key stations for the previous year. A, B, and C are the parameter matrices (Mejia and Rousselle, 1976). Lane's temporal disaggregation model was used to split the annual flows into monthly flows (1979).

$$Y_{\nu,\tau} = A_\tau X_\nu + B_\tau \varepsilon_{\nu,\tau} + C_\tau Y_{\nu,\tau-1} \tag{2.4}$$

$Y_{\nu,\tau}$ is a single column vector of a group of monthly streamflows for a given year, ν, and month, τ, X_ν is a vector of the annual streamflows with the same dimensions as $Y_{\nu,\tau}$, $\varepsilon_{\nu,\tau}$ is a single column vector of independent normally distributed noise terms with mean equal to zero and the variance-covariance matrix equal to the identity matrix, and $Y_{\nu,\tau-1}$ is a single column vector of the streamflows for the previous month. A_τ, B_τ, and C_τ are the parameter matrices. Finally, adjustments were applied in order to maintain additivity conditions for downstream flows.



All numbers indicate intervening flows and refer to the locations given in Table A1 and Plate 1.

Lower Basin’ Temporal Disaggregation Groups:
Group 4: 21, 22, 24, 27
Group 5: 23, 25, 26, 28, 29

*Temporal disaggregation from annual to monthly flows

Figure 2.5 Disaggregation model for stochastic Colorado River streamflow generation (modified from Lee et al. 2006)

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. The random nature of these simulated streamflows can be seen in Figure 2.6 which contains all 100 Lees Ferry annual streamflow traces. The figure shows that the majority of the flows are between 9 and 22 MAF with many different extreme values extending from about 3.5 to 37 MAF. Unlike the ISM simulated streamflow, this stochastically generated streamflow appears to produce over 100 different extreme streamflow values. Also, there appears to be no repetition of traces as expected since each trace is different.

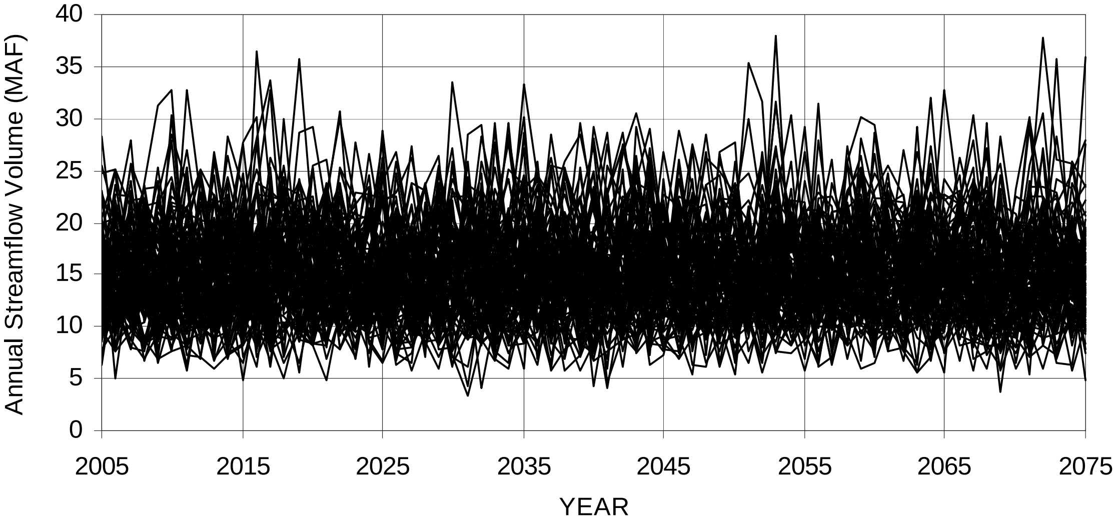


Figure 2.6 All 100 Lees Ferry annual stochastic streamflow traces

2.5 Comparison

The statistical characteristics of these three sets of streamflow were calculated and compared based upon the flow at Lees Ferry because the station comprises the majority of flow in the system and is commonly used for reference and comparison. Figure 2.7 illustrates the historical and tree-ring reconstructed streamflows at Lees Ferry.

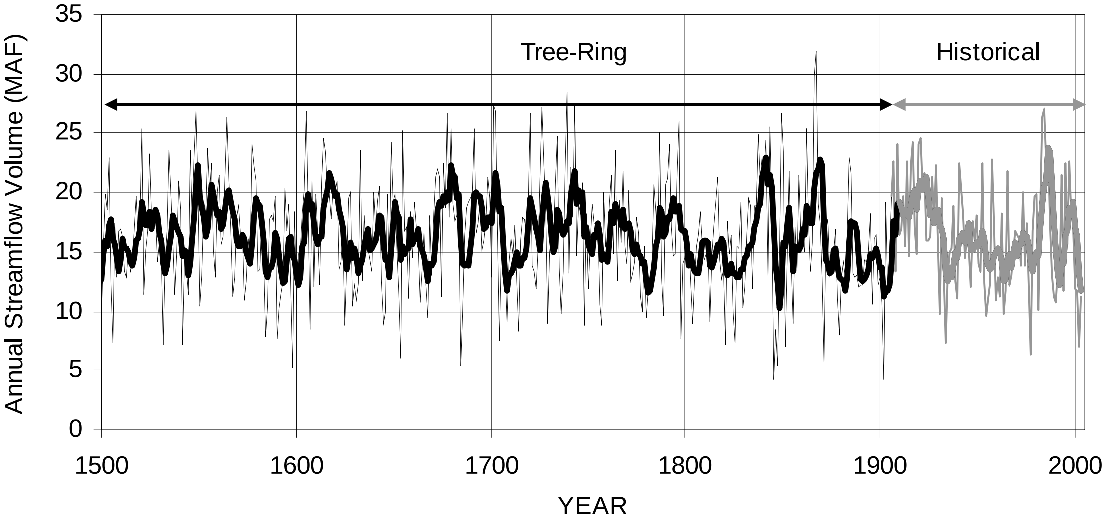


Figure 2.7 Annual historical (1906-2003) and tree-ring reconstructed (1490-1905) streamflow at Lees Ferry

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. The stochastic generated streamflow cannot be easily compared graphically with the ISM streamflows since it consists of 100 samples of 71 years.

Table 2.1 gives a summary of the overall annual cumulative Lees Ferry streamflow statistics for the different datasets, and Table 2.2 summarizes the average statistics of the annual cumulative Lees Ferry streamflow for the different simulation scenarios.

Table 2.1 Colorado River at Lees Ferry overall annual streamflow statistics (acre-ft)

	Historical Record	Reconstructed Record	Stochastic Overall
number of years	98	514	7,100
average	15,076,151	14,992,249	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	4,518,297	4,551,642
10 percentile	9,831,611	9,409,842	9,730,271
25 percentile	11,431,919	11,826,304	11,832,905
50 percentile	14,894,084	14,828,851	14,541,917
75 percentile	18,319,905	17,774,334	17,810,294
90 percentile	21,398,659	21,214,138	21,090,461

Table 2.2 Colorado River at Lees Ferry average annual streamflow statistics (acre-ft)

	Historical ISM	Reconstructed ISM	Stochastic
number of traces	98	514	100
average	15,076,151	14,992,249	15,069,342
minimum	5,619,661	4,864,904	6,490,082
maximum	24,740,573	25,642,534	28,261,742
standard deviation	4,430,494	4,510,223	4,491,913
10 percentile	9,833,017	9,470,282	9,825,025
25 percentile	11,520,801	11,916,278	11,944,717
50 percentile	14,846,710	14,868,420	14,566,048
75 percentile	18,133,710	17,707,407	17,765,336
90 percentile	21,251,223	20,970,592	20,916,402

The historical annual streamflow record averages just over 15 million acre-feet (MAF) and covers a range from 5.4 to 25.4 MAF with a standard deviation of 4.4 MAF. The tree-ring reconstructed annual streamflow record 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 consists of 7,100 years of streamflow, a considerably longer sequence than the tree-ring and historical records. Even though the averages and standard deviations are all about the same for each scenario, 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.

The percentiles of the different streamflows are all fairly similar. The reconstructed and stochastic percentiles are consistently lower than the historical percentiles except for the 25th percentile of streamflows which are both higher, 11.8 MAF, than the historical 25th percentile of 11.4 MAF. In order to predict how the different streamflow scenarios will affect the river simulation runs, it is helpful to calculate the Lees Ferry streamflow statistics at each timestep across all of the traces. Due to the nature of ISM the statistics of the ISM scenarios remain constant throughout time and equal to those values presented in Table 2.1. The statistics of the stochastic generated streamflows do change from one timestep to the next since every trace is different. A plot of the statistics throughout the river simulation time period is given in Figure 2.8.

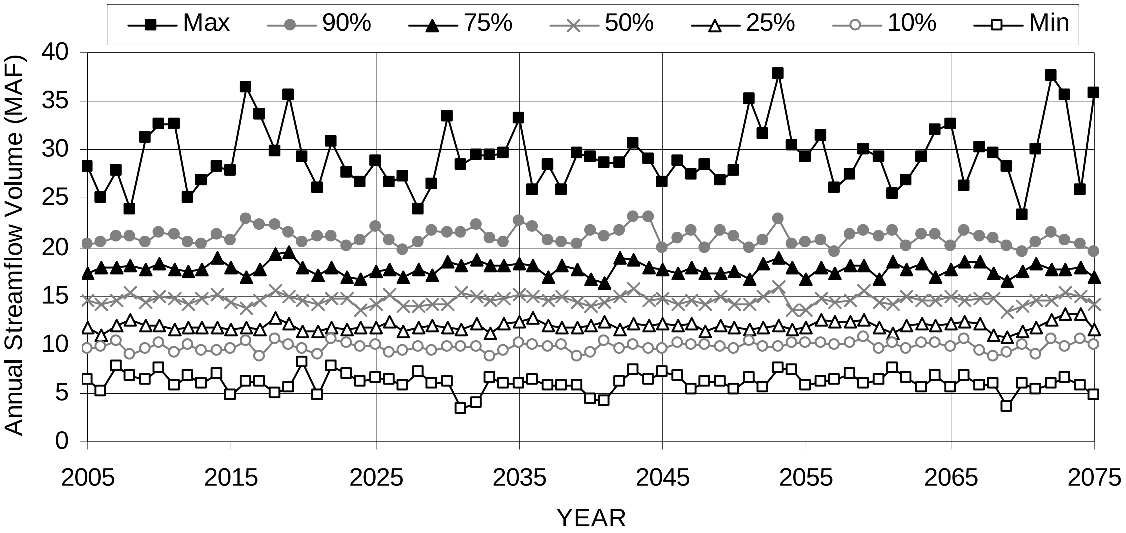


Figure 2.8 Annual Lees Ferry stochastic generated streamflow statistics throughout time (statistics calculated each year across all 100 traces)

Again, the random nature of the stochastic generated streamflows is demonstrated since the percentile traces are not straight. However, they are fairly consistent throughout time due to the simulation of 100 traces. There is more scatter in the maximum annual streamflow values than in the minimum streamflows because the maximums are not bounded whereas the minimums at least have to be some number greater than zero.

The required storage capacity of each streamflow dataset was also calculated for comparison. This analysis was performed using the entire Upper Basin streamflow in order to use an appropriate and meaningful demand volume. The entire Upper Basin flow is the sum of the cumulative Colorado River at Lees Ferry and the Paria River at Lees Ferry. The Paria River is a tributary just downstream of Lake Powell, but just upstream of a point referred to as Lee Ferry which is the Compact Point that separates Upper Basin streamflow from Lower Basin streamflow. The average annual streamflow of the Paria River is approximately 20,000 acre-ft. A build-out Upper Basin streamflow demand of 14.45 MAF was used in the analysis. The demand consists of 6.2 MAF of

Upper Basin water user demand, 7.5 MAF of Lower Basin water user demand, and 0.75 MAF of Mexico's delivery volume. The required storage capacity was determined by calculating a running sum of the difference between the annual streamflow volume and demand volume without allowing the sum to rise above zero. The largest negative of this volume was computed for each scenario in order to determine the required storage capacity. The historical streamflow requires a storage capacity of 40.9 MAF in order to always satisfy a demand of 14.45 MAF. The tree ring reconstructed streamflow requires a storage capacity of 60.4 MAF to satisfy the same demand. These two required storage capacity sequences are plotted in Figure 2.9.

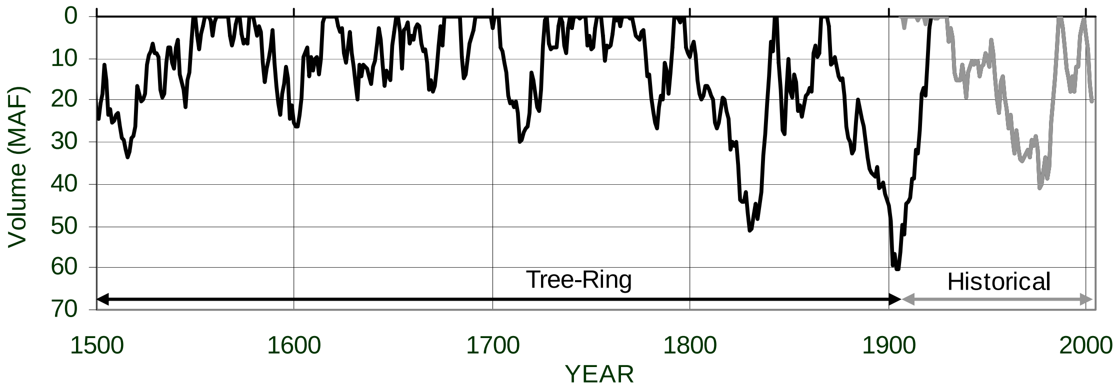


Figure 2.9 Historical and reconstructed required storage capacity traces using total Upper Basin streamflow and an annual demand volume of 14.45 MAF

Table 2.3 gives the required storage capacity for the historical and reconstructed records as well as the required storage capacity statistics for the three different simulation scenarios. The maximum required storage capacity for all of the stochastic Upper Basin streamflow traces is 131.6 MAF. This is considerably larger than either of the other scenarios: more than three times the historical required storage and more than twice the reconstructed required storage. Again, this is expected since the stochastic scenario simulates a considerably longer period of record than the other scenarios. In addition, the average stochastic required storage capacity is 5 percent larger than the average historical ISM required storage capacity, and the maximums and minimums are more extreme. The same is true except to a lesser extent for the reconstructed ISM required storage capacity.

Table 2.3 Required storage capacity statistics using total Upper Basin streamflow and an annual demand volume of 14.45 MAF (acre-ft)

Historical	40,862,349			
Reconstructed	60,426,631			
	Average	Maximum	Minimum	Standard Deviation
Historical ISM	31,554,559	40,862,349	20,223,698	8,002,357
Reconstructed ISM	34,608,524	60,426,631	14,098,386	12,129,291
Stochastic	37,710,695	131,597,534	9,086,406	20,267,056

An analysis restricted to just the streamflows has revealed similar statistical characteristics across each of the scenarios in all but their extreme values. The historical ISM streamflow covers the smallest range of values while the stochastic generation covers the widest range of values. Furthermore, the dependent nature of the ISM method has been illustrated as well as the random nature of the stochastic method.

3 Colorado River Simulation System Model

In order to understand the output produced by the model, one must understand the model itself. This chapter gives a general overview of the model used to represent the Colorado River system, describes the different model inputs that are manipulated in this study, and gives a detailed explanation of the model processes that relate to the output which will be analyzed. A schematic of the modeling process is illustrated in Figure 3.1.

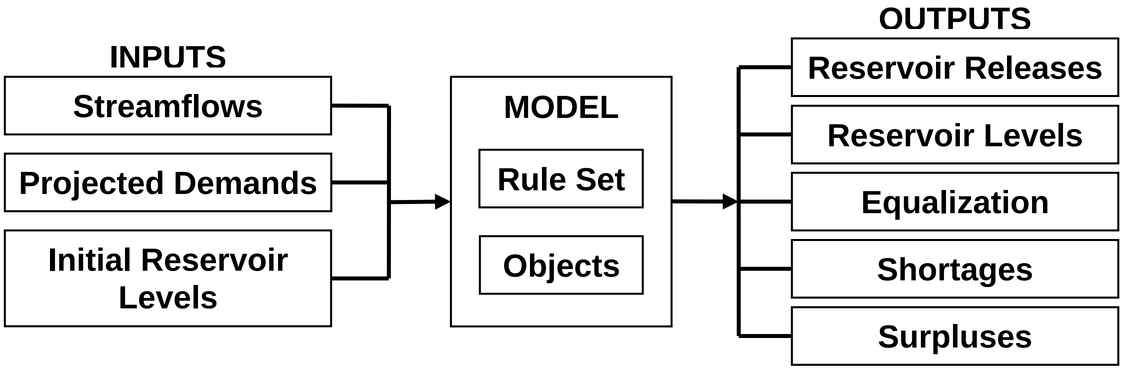


Figure 3.1 River Modeling Schematic

3.1 Overview

CRSS developed by USBR and implemented in RiverWare is used to simulate the physical and operational processes of the Colorado River. RiverWare is an object oriented river basin modeling software package developed by CADSWES at The University of Colorado, Boulder. The objects simulate the physical processes, and a rule set is used to represent the operational practices.

CRSS is a fairly coarse representation of the Colorado River since it is primarily used for long term planning and management. There are 12 reservoirs (9 power reservoirs and 3 storage only reservoirs), 31 aggregate reaches, 1 solitary reach, 9 confluences, 117 aggregate diversion sites, 53 solitary water users, and 34 data objects. Not all of the data objects are used for simulation of standard operations. Also, some of the diversions do not request any water but are included in order to model possible future changes. The model runs on a monthly time step and can be run for any length of time. For the purposes of this study, the model is run from 2005 to 2075. This length of run allows for the analysis of the river system response after the leveling off of the demands. The probabilities of certain events occurring in the more recent future can still be determined simply by omitting the later output from the analysis.

3.2 Model Inputs

This section describes the different model inputs that were manipulated in the completion of this study and which are critical to understanding the outputs of the model. As explained earlier, three different streamflow scenarios were input and run through the model in order to compare their effects on the system. Another critical input is the projected demands of the water users. Some of these demands are altered in order to estimate the sustainable yield. Finally, during the first decade of the model run, the river system response is significantly influenced by the initial reservoir conditions.

3.2.1 Streamflows

The different streamflow scenarios were explained in the previous section. However, it is important to note other model inputs associated with the streamflow which were necessary to change as well. Some object slot values had to be changed to reflect the new streamflow inputs.

3.2.2 Projected Demands

The demands on the river system have also been input into the model. Normal diversion and depletion schedules are set as the projected diversion and depletion schedules for each particular user. Each state has developed its own schedules for use within the model. These schedules extend the length of the model run, 2005 to 2075, and are the same for each streamflow trace and scenario. However, a water user's actual diversion and depletion depend upon the availability of water and the declaration of surplus and shortage conditions which are explained in Section 3.3.3. Table 3.1 gives a summary of the projected depletions for each state, each subbasin, and the total for the entire Colorado River system.

Table 3.1 Normal Annual Depletion Schedule Amounts (acre-ft)

	2005	**2060**
Colorado	2,493,500	2,784,000
Utah	899,000	1,230,000
Wyoming	506,500	760,000
New Mexico	501,000	605,000
Arizona UB	45,000	50,000
California	4,400,000	4,400,000
Arizona LB	2,800,000	2,800,000
Nevada	300,000	300,000
Mexico	1,515,000	1,515,000
Upper Basin	4,445,000	5,429,000
Lower Basin	7,500,000	7,500,000
Total	13,460,000	14,444,000

The Upper Basin's normal annual depletion increases from 4,445,000 AF in 2005 to 5,429,000 AF in 2060 and then remains constant. The Lower Basin's normal annual depletion remains constant at 7,500,000 AF as does Mexico's at 1,515,000 AF since these are the maximum normal depletions set by the Compact. This amounts to an increase in the total normal annual depletion on the Colorado River from 13,460,000 AF in 2005 to 14,444,000 AF in 2060. Figure 3.2 gives a visual representation of the normal depletion schedules for each state as well as the total for the system.

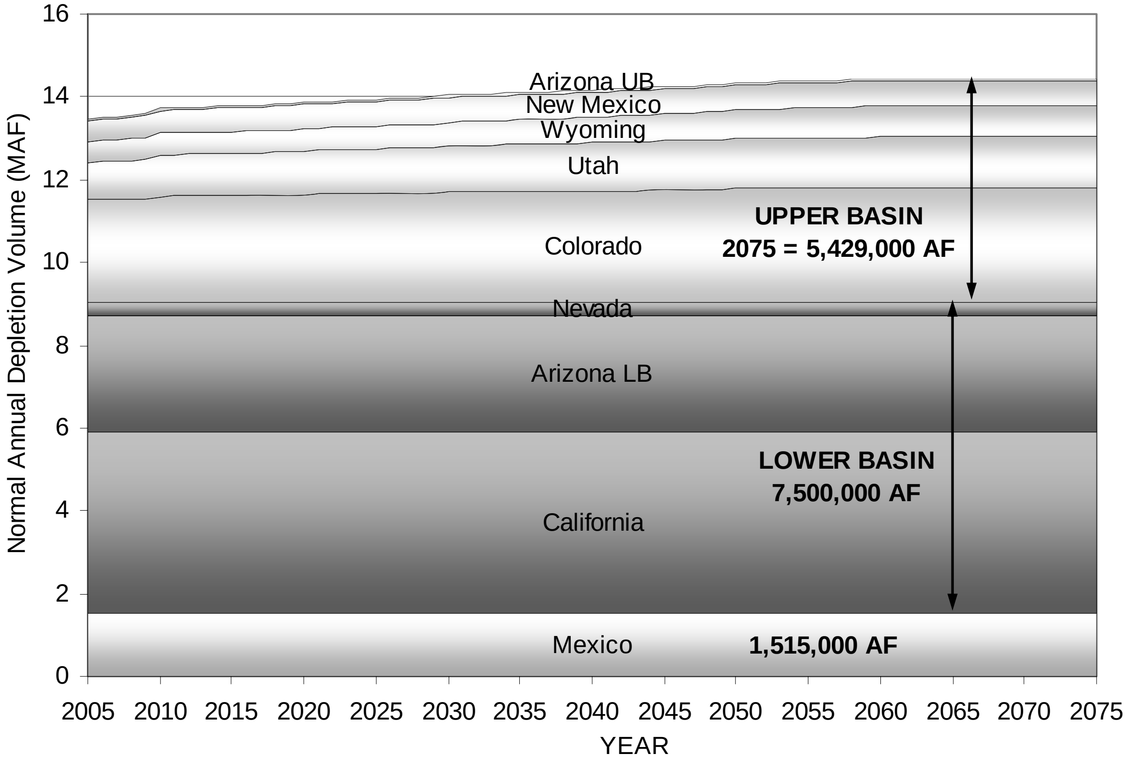


Figure 3.2 Normal Annual Depletion Schedules

3.2.3 Initial Reservoir Levels

The initial conditions of the CRSS model were set to December 31, 2004 reservoir levels. These pool elevations are listed in Table 3.2, with the exception of Starvation Reservoir which has a specified initial storage. The Starvation Reservoir object is a composite of eight reservoirs on the Duchesne River, and therefore its storage is the relevant descriptor. The storage value is based on the average total storage of the eight reservoirs and does not necessarily reflect December 2004 conditions. Also listed are the model defined minimum and maximum reservoir pool elevations for comparison.

Table 3.2 Initial and model defined minimum and maximum reservoir pool elevations (ft)

Reservoir	December 2004 Elevation	Model Zero Storage Elevation	Model Max Live Storage Elevation
Blue Mesa	7477.99	7358	7519
Crystal	6751.64	6670	6755
Flaming Gorge	6013.09	5741	6041
Fontenelle	6489.78	6408	6506
Havasu	446.96	400	450
Mead	1130.01	895	1220
Mohave	640.56	570	647
Morrow Point	7150.76	6770	7160
Navajo	6028.28	5775	6085
Powell	3564.42	3370	3700
Taylor Park	9307.98	9180	9330
Starvation (acre-ft)	255,000	-	-

These initial pool elevations have a significant effect on the river model results because they reflect the recent drought conditions.

3.3 CRSS Model

Critical to the understanding of the model results is the understanding of its workings. The physical processes are straightforward, but the model's rule set dictates how the reservoirs are operated and how shortages and surpluses are allocated. The difference in the modeling of the Upper and Lower Basins is explained as well as the interaction of the two basins through the operations of Lakes Powell and Mead.

3.3.1 Upper Basin

All water users in the Upper Basin are modeled the same way: if the diversion requested is in the stream at the diversion point, that water is diverted. If not, the user will divert all the water down to the model specified minimum stream requirement. Downstream water users are dependent upon return flows until another tributary provides an inflow. During wet periods, there are no surplus diversion requests. Water users divert the amount of water the stream provides up to their normal schedule. A surplus is never declared in the Upper Basin. A shortage is noted when any water user does not divert its entire scheduled amount.

3.3.2 Powell and Mead Operation

Lake Powell is operated in relation to the level of Lake Mead as well as Upper Basin reservoir levels and demands while attempting to maintain the minimum objective release volume which is defined in Section 3.3.2.2. This section explains the interconnecting relationships. Figures A.2 and A.3 give the storage and elevation profiles for Lakes Powell and Mead respectively.

3.3.2.1 Equalization

The probability of declaring equalization conditions indicates the overall state of the Upper Basin. The process of equalization is used to ensure that water storage is distributed evenly between Powell and Mead when the system is experiencing certain conditions. Equalization conditions are declared if Powell's end-of-water-year storage forecast is greater than Mead's, if the Upper Basin's end-of-water-year storage exceeds the 602(a) storage level for that year (as explained below), and if the month is January through September. Furthermore, through 2016, in order for equalization conditions to be declared, Powell's pool elevation must be greater than 3,630 feet which corresponds to approximately 14.85 MAF of storage. The 602(a) storage level is determined by summing the average annual Upper Basin depletion over the next 12 years (varies), the average annual Upper Basin evaporation (560,000 AF), and the annual minimum objective release from Powell (8,230,000 AF) and subtracting the average annual inflow to the Upper Basin during the critical period, 1953-1964 (12,180,000 AF). This is then multiplied by the length of the critical period (12 years), and the Upper Basin's required minimum power pool storage (5,179,000 AF) is added. This required level of Upper Basin storage is designed to ensure Powell's minimum objective release during the critical period without hampering Upper Basin depletions. The 602(a) required storage level changes every year through 2060 because the Upper Basin depletions increase every year until 2060. Since it does not depend on the current state of the system, the 602(a) data series remains the same for each run of the model.

3.3.2.2 Lake Powell Release and Storage

A very pertinent indicator of the state of the Colorado River system is Lake Powell's ability to meet the minimum objective release. This release amount, 8.23 MAF per water year, is required by the Operating Criteria but is not an absolute requirement in the model. The rules that protect Lake Powell's minimum power pool level, 3,489.96 ft, take precedence over Lake Powell's minimum objective release schedule. The reservoir operation in the future will consider these constraints which indicate the critical state of the system. Similarly, the sum of Powell's releases over ten consecutive water years is an important indicator. This release sum in addition to the total tributary flows from the Paria River just downstream from Lake Powell (20,000 AF average annual flow) indicates whether or not the Upper Basin's Compact point volume delivery objective of 82.5 MAF over ten years has been satisfied. There is no requirement in the model for the Upper Basin to ensure a delivery of 82.5 million acre-ft every ten years as specified by the Compact.

Under normal conditions, Powell follows a set release schedule so that 8.23 MAF is delivered from Powell to the Lower Basin every year. If equalization, wet, or dry conditions exist, the normal release schedule is modified. The conditions for equalization were explained in a previous section. During "wet" periods, when Powell is near full capacity, releases are increased in order to reach target storages at the end of a season. January through July releases are made according to forecasted spring runoff in order to reach a July end-of-month live storage level of 23.822 MAF. August through December releases are made in order to arrive at a December end-of-month live storage level of 21.9 MAF. The maximum release is set to be 1.5 MAF per month unless a live storage level of 23,822,000 AF (3,700 ft) is to be exceeded. In this case, more is released to prevent the pool elevation from surpassing 3,700 ft. During "dry" periods, when Powell is near minimum power pool, Powell's minimum objective releases are reduced. Powell's pool elevation is never permitted to drop below the minimum power pool of 3,489.96 feet (3,995,000 AF live storage). If necessary, releases below the minimum objective amount are made to keep the elevation right at the minimum power pool.

3.3.2.3 Lake Mead Release and Storage

Lake Mead's releases are set to match downstream demands unless flood control releases are required. The downstream demands are set to change depending upon the following conditions: normal, shortage, or surplus. These conditions are explained in the following section which explains the Lower Basin demand schedules. Lake Mead reacts to the conditions by releasing more or less water than the normally scheduled amount. In addition, Mead will increase releases above the Lower Basin surplus demand schedule if flood control releases are necessary. Flood control releases are required when Mead's storage volume would otherwise encroach upon the 1.5 MAF of flood control space for a period greater than one month. The bottom of this empty space corresponds to a pool elevation of 1,219.61 feet and a live storage volume of 25,883,237 AF. In addition, runoff and drawdown season flood control rules also apply. During the runoff season (January through July), the greater of the computed minimum average release and downstream demand release is made. The minimum average release is designed to enable Mead to receive the maximum forecasted inflow while reaching a pool elevation of 1,219.61 feet at the end of July. During the drawdown season (August through December), the flood control release is made (limited to 28,000 cfs) to maintain a specified amount of flood control space each month. If there is sufficient Upper Basin storage space available, these monthly volumes can be reduced to 1.5 MAF.

Critical low Mead pool elevations are 1,050 feet and 1,000 feet. Mead's estimated minimum power pool elevation is located at the 1,050 foot elevation. This is also the minimum operational elevation of the upper Southern Nevada Water Authority (SNWA) diversion intake. The 1,000 foot elevation is the minimum operational level of SNWA's lower intake. 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 added in anticipation. The model is set up to continue delivering SNWA's full permitted diversion even when the lake level drops below the intakes. SNWA is never shorted in the model due to inaccessibility.

3.3.3 Lower Basin

The Lower Basin states follow the same procedure as the Upper Basin states concerning the allocation of streamflow: if the diversion amount is in the stream, the water is diverted. However, rules that simulate the priority system govern the amount of water that certain Lower Basin water users can demand and thus divert. When drought conditions are present in the model, Mead does not release the full normal downstream demand. In these instances, shortage conditions are declared, and specific diversions are shorted by decreasing the amount of water they can demand. Similarly, when certain surplus conditions are met in the model, Mead releases more water than the downstream users would “normally” demand. In these surplus conditions, rules are used to allocate a certain amount of the surplus for specific diversions to demand. There are different levels of shortages and surpluses depending on the condition of the system.

3.3.3.1 Shortage

A level 1 shortage is declared for an entire year when, in December of the previous year, Lake Mead drops below the 80P1050 trigger level. This trigger level is predefined in the model and increases with time because it is a function of the projected Upper Basin demands. The USBR developed trigger levels (80P1050) prevent Mead’s pool elevation from dropping below 1050 feet with an 80 percent assurance probability. In the event of a level 1 shortage, the Central Arizona Project (CAP) is only allowed to divert one million acre-ft during the given year. Furthermore, SNWA is shorted a certain percentage of its normal diversion schedule. A level 2 shortage is declared if the projected end-of-water-year Mead pool elevation is less than 1000 feet when following the level 1 shortage allocation. During a level 2 shortage, CAP and SNWA are further reduced to keep Mead above 1000 feet. If CAP and SNWA must be reduced to zero, MWD and Mexico are each shorted by half of the normal amount.

3.3.3.2 Surplus

A Lower Basin surplus can be declared when other system requirements are met. There are five different modeled instances in which a surplus can be declared. Three of the triggers were set by the Interim Surplus Guidelines and therefore only apply through 2016. They are the level 1, 2, and 3 surplus triggers. Converse to the shortage classification, level 1 indicates the largest degree of surplus, and level 3 indicates the smallest degree of surplus. A level 3 surplus is triggered in January for the entire year when Mead's pool elevation in the previous December is between 1125 feet and 1145 feet. In this case, SNWA and MWD are allowed to divert their level 3 surplus schedule volumes. Similarly, a level 2 surplus is triggered in January for the entire year when Mead's pool elevation in the previous December is greater than or equal to 1145 feet and level 1 surplus conditions have not been met. When this is the case, SNWA and MWD are allowed to divert their level 2 surplus schedule volumes. A level 1 surplus is triggered in January for the entire year when the computed surplus release is greater than zero. The surplus release is computed every January as a function of Mead and Powell storages, required flood control space, probable inflow, and demands. It is basically the amount of extra water that must be released for Mead to have a designated amount of flood control space. When this is the case, SNWA, MWD, CAP, the Imperial Irrigation District (IID), and the Coachella diversion are allowed to divert their designated fraction of the surplus release up to the amount of their level 1 surplus schedule volumes.

The other two surplus triggers are the flood control surplus trigger and the normal surplus trigger. The flood control surplus trigger applies to all years of the simulation. It is triggered at any time between January and July when Mead's outflow is computed to be less than the required runoff season release, and any time between August and December when Mead's outflow is computed to be less than required release corresponding to Mead's storage. The objective is to always maintain at least 1.5 MAF of flood control space in Mead. When a flood control surplus is triggered, SNWA, MWD, CAP, IID, Coachella, and Mexico are allowed to divert their normal surplus schedule volumes. After 2016, a normal surplus is triggered in January for the entire year when the computed surplus release is greater than zero. When this is the case, SNWA, MWD, CAP, IID, and Coachella are allowed to divert their normal surplus schedule volumes.

4 Results and Analysis

CRSS was run under each streamflow scenario, producing three different sets of output that could be compared. This chapter analyzes and compares the key indicators of the state of the system. First, Lake Powell’s outflow is analyzed by its ability to satisfy the minimum objective release. Then, Powell’s storage volume statistics and probabilities of reaching critical levels are compared. Similarly, the statistics and critical probabilities of Lake Mead’s storage volumes are compared. Finally, the shortage and surplus volumes of the Upper and Lower Basins are analyzed and compared.

4.1 Lake Powell Outflow

As explained previously, Lake Powell’s annual release volume is an important indicator of the state of the system. The lake level fluctuates depending on lake inflows, evaporation, and releases, e.g. lake releases are decreased in order to prevent Lake Powell’s live storage volume from dropping below its live capacity. Powell’s inability to meet the minimum objective release gives an indication of the severity of a drought the system may experience. This section compares Lake Powell’s actual release volume with its minimum objective release volume of 8.23 MAF per year. 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 4.1 through 4.3.

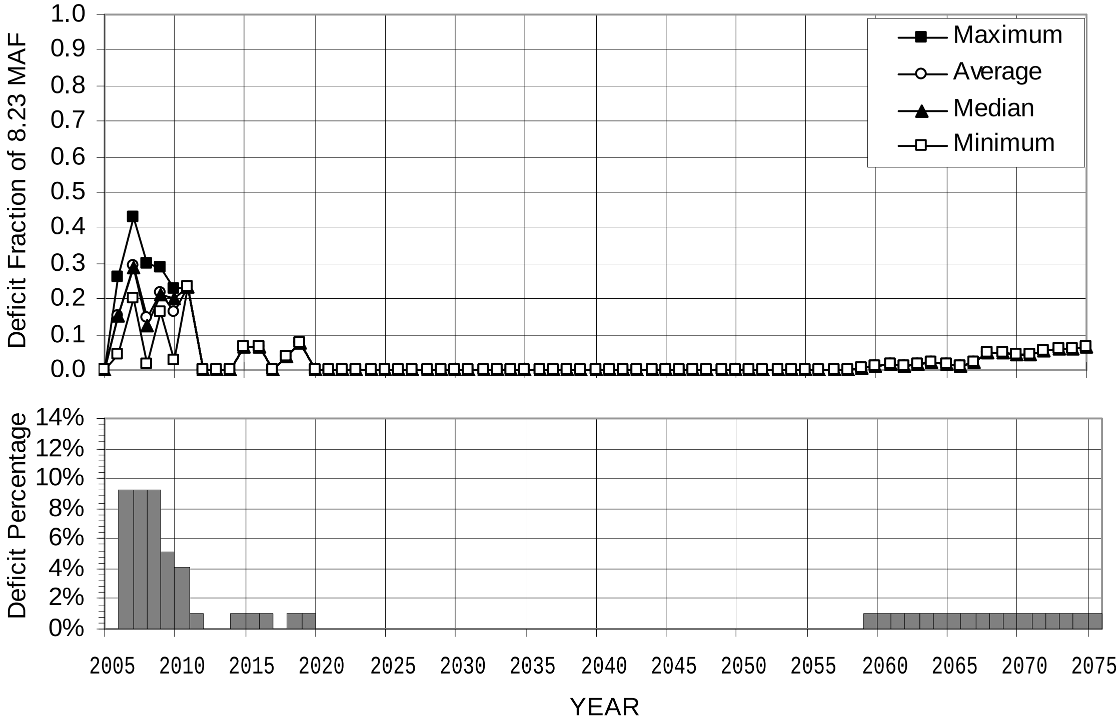


Figure 4.1 Minimum objective release deficit volume statistics and percentage of occurrence – Historical ISM

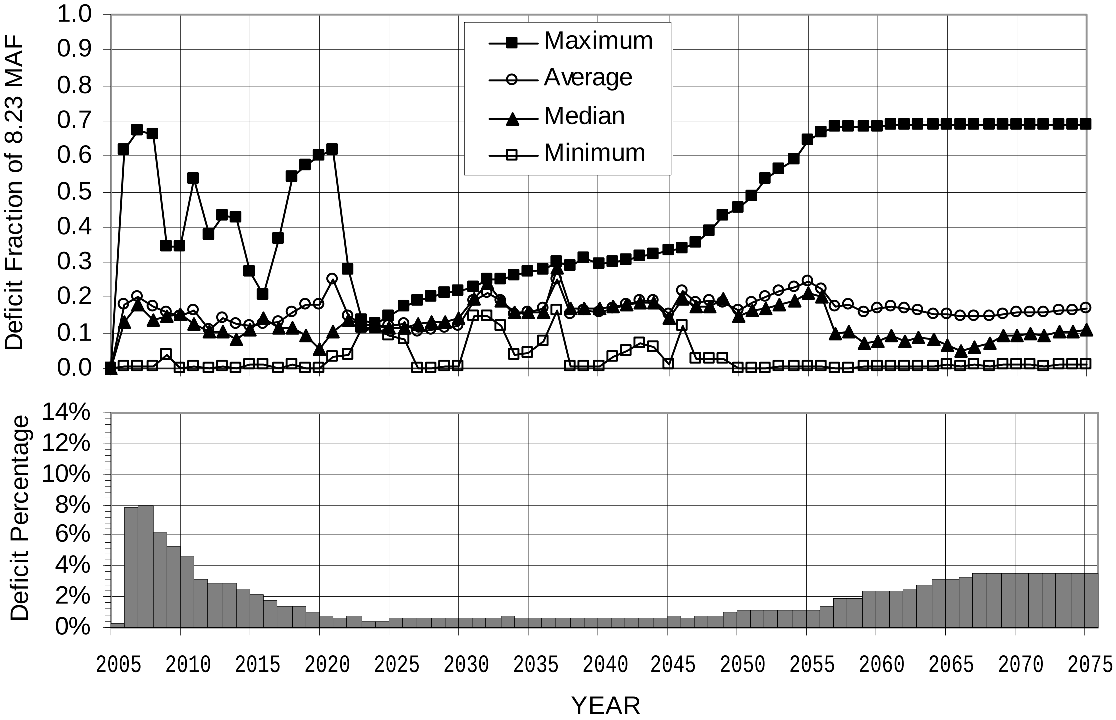


Figure 4.2 Minimum objective release deficit volume statistics and percentage of occurrence – Reconstructed ISM

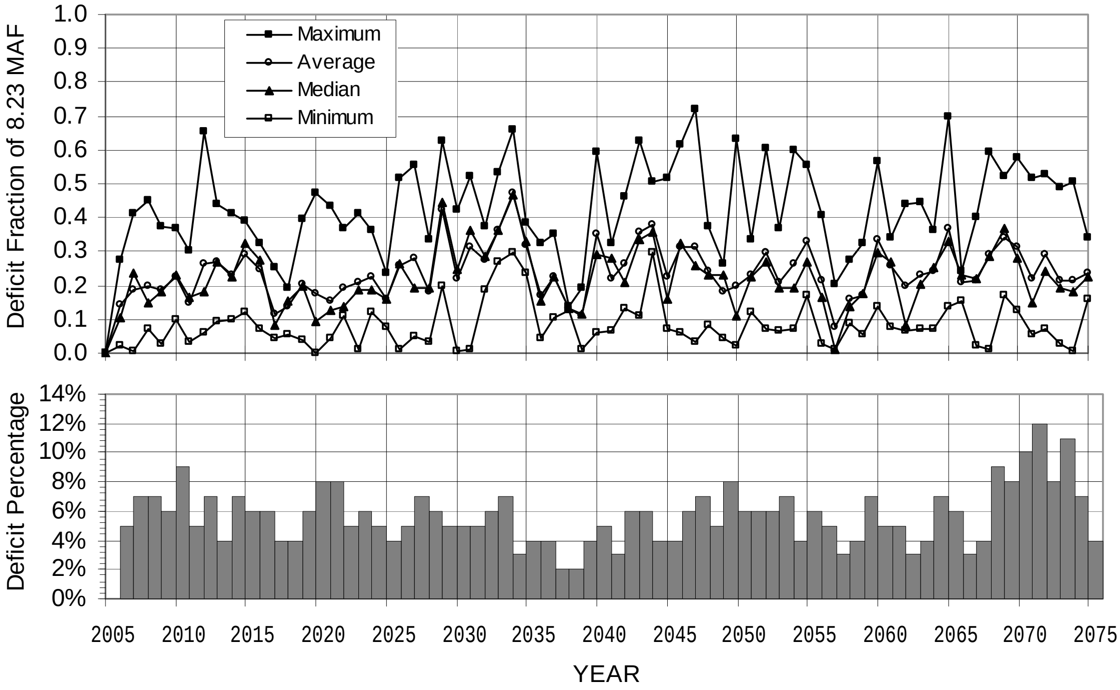


Figure 4.3 Minimum objective release deficit volume statistics and percentage of occurrence - Stochastic

The results are consistent with the previous streamflow analysis. The historical ISM 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 historical ISM streamflow resulted in a 0 to 1 percent chance of a release deficit occurring past 2020, while the reconstructed ISM 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 historical ISM or reconstructed ISM. A distinct pattern of the annual deficit volume and deficit probability may be observed for the runs based on ISM. Both the ISM historical and the ISM 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 ISM 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 in terms of very low reservoir levels. Once the initial reservoir conditions are overcome, the probability of a deficit decreases down to zero for the historical ISM scenario and to one for the reconstructed ISM scenario. Another similarity between the outputs based on historical and reconstructed ISM 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.

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 is appropriate. 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 Figure 4.3. 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 historical ISM scenario gave a deficit probability of one percent in the last 15 years of the study period, the reconstructed ISM 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.

Table 4.1 gives the overall probabilities of deficit for the different scenarios and for different planning horizons. These probabilities were determined by calculating the percentage of runs that exhibited a minimum objective release deficit (or a 10-year minimum objective release deficit) in at least one year of the planning horizon. As expected the overall probability of deficit increased as the length of the planning horizon increased. Furthermore, the table reveals that the stochastic scenario gave the largest overall probability of a deficit occurring in any of the streamflow traces, followed by the reconstructed ISM and then historical ISM scenarios. This would indicate that the stochastic streamflow simulation resulted in a greater occurrence of critical low flow events than the ISM simulations. Similarly, the reconstructed ISM simulation resulted in a greater occurrence of critical low flow events than the historical ISM simulation. These critical low flow characteristics are difficult to determine directly from a streamflow simulation analysis. Chapter 2 showed similar annual streamflow volume percentiles across all the different simulations. This discrepancy indicates the need to run streamflow simulations through a river system model in order to fully understand the manner in which the simulations impact the system.

Table 4.1. Overall minimum objective release deficit probabilities

	10 Years	25 Years	50 Years	71 Years
Single year minimum objective release deficit				
Historical ISM	22.4%	24.5%	24.5%	36.7%
Reconstructed ISM	22.0%	26.5%	36.4%	49.2%
Stochastic	24.0%	37.0%	53.0%	64.0%
10-year minimum objective release deficit				
Historical ISM	19.4%	23.5%	23.5%	36.7%
Reconstructed ISM	18.3%	24.5%	34.6%	48.2%
Stochastic	19.0%	34.0%	50.0%	60.0%

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.

4.1.1 Lake Powell Storage

Lake Powell’s live storage volume is also an important indicator of system conditions. This section presents plots of some statistical traces and critical probability traces for each scenario. In addition, it presents the probabilities of reaching critical storage conditions for different planning horizons.

Figures 4.4 through 4.6 display for each streamflow scenario Powell's maximum, June median, and minimum live storage volumes across all runs for each year of the model run. For example, examining the historical ISM scenario, in 2005 the maximum annual storage volume, the June storage volume, and the minimum annual storage volume was determined as a result of each of the streamflow input traces resulting in 98 different values for each statistic. Then, the maximum of all the maximums was computed, the median of all the June storages was computed, and the minimum of all of the minimums was computed. Each of these values is plotted on its respective curve for the year 2005. The same computations were performed for each subsequent year of the model run. Identical calculations were performed for the reconstructed ISM scenario and the stochastic scenario but across 514 and 100 different traces respectively. In addition, the top of Powell's live storage volume, 24,322,000 MAF, and the bottom of its active storage volume, 3,995,000 MAF, are plotted for reference.

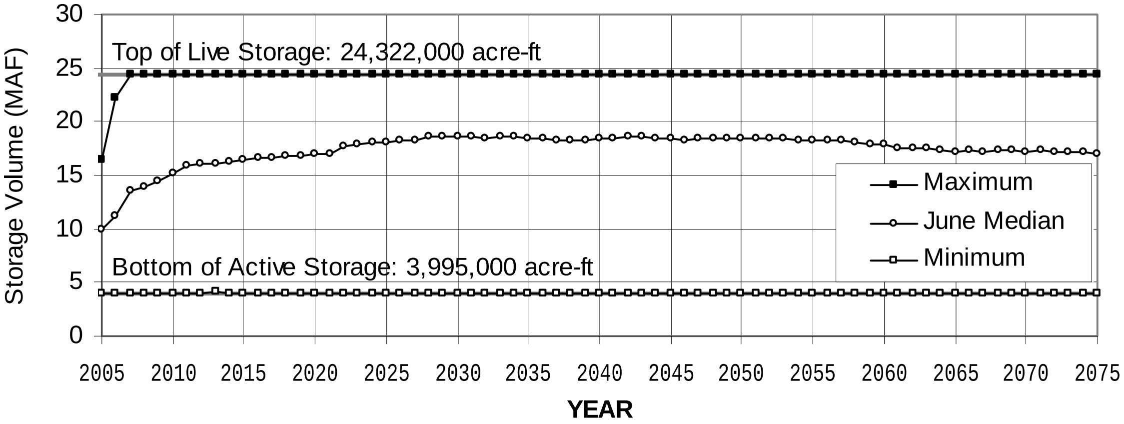


Figure 4.4 Lake Powell annual live storage volume statistics – Historical ISM

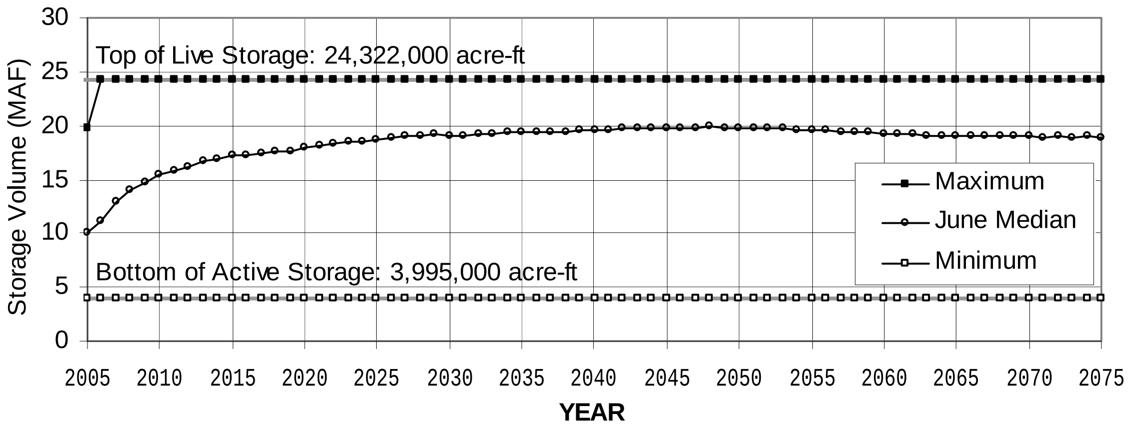


Figure 4.5 Lake Powell annual live storage volume statistics – Reconstructed ISM

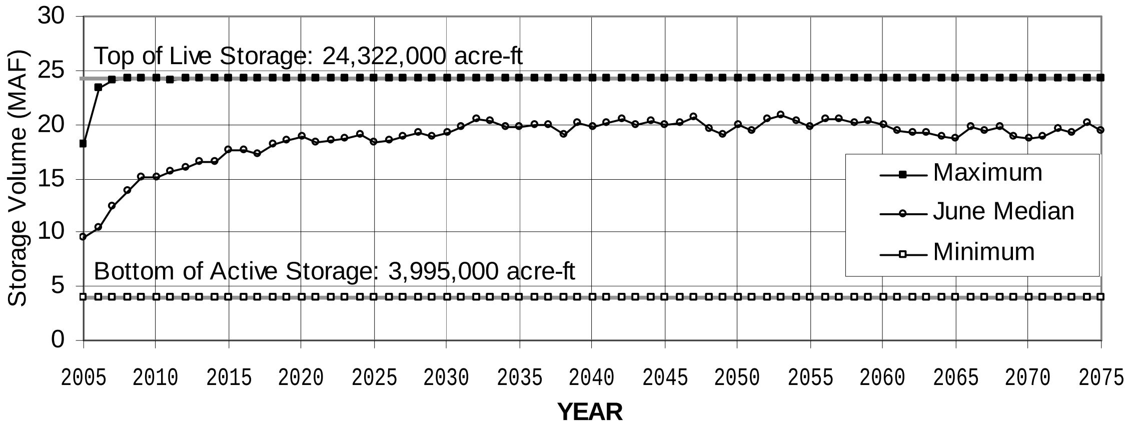


Figure 4.6 Lake Powell annual live storage volume statistics – Stochastic

The figures illustrate that Powell's expected maximum and minimum possible live storage volumes are basically unchanging regardless of which scenario is being considered or how far into the future one is looking. After the first year or so, the maximum expected storage volume is always the top of the live storage pool, and the minimum expected storage volume is always the bottom of the active storage pool. This corresponds to the rules governing Lake Powell's storage volume which bounds it with these two values.

The June median trace is slightly different across the scenarios. All three scenarios exhibit the same trend of recovery from the initial reservoir volume to a fairly constant level around 2030 and then a very slight decrease around 2060. Again, the random nature of the stochastic streamflow generation is exhibited in the slightly jumpy behavior of the output parameter. Since the median of all of the different traces is taken for each year, a trend can be seen, but there is still a random nature to it. On the other hand, the ISM scenarios show the same smoothed line for the June median output that is inherent to their streamflow generation process. Examining the magnitude of the June median storage volume across the three scenarios reveals slightly lower values for the historical ISM scenario throughout time than for the reconstructed ISM and stochastic scenarios which are about equal to each other. This occurrence appears to result from the characteristic of the historical ISM scenario to simulate slightly more moderate low flow sequences than the other two scenarios. This is reflected in Lees Ferry 25 percentile streamflow volume which is approximately 400,000 acre-ft less in the historical ISM scenario than the reconstructed ISM and stochastic scenarios. The most likely reason that this lower 25 percentile streamflow volume is not offset by a higher 75 percentile volume is because of the upper bound of Powell’s reservoir volume which appears to mute the higher flows (with respect to their effect on Powell’s storage level) more than the lower bound mutes the lower flows.

The probability traces of Powell’s live storage volume reaching certain critical levels are given in Figures 4.7 through 4.9. These figures allow for a more revealing comparison of the maximum and minimum live storage volumes to be made. The probability traces were calculated by first flagging every year in which the critical storage volume was reached for each trace. The probability of reaching the critical storage in any year was then determined by dividing the total number of flags across all of the traces for a given year by the total number of traces. The two critical storage probabilities plotted for Lake Powell are the top of live capacity storage and the top of inactive capacity storage. As explained in Chapter 3, filling to the top of live storage corresponds to very wet conditions in the basin and dropping to the top of inactive capacity storage (minimum power pool elevation) corresponds to very dry conditions in the basin.

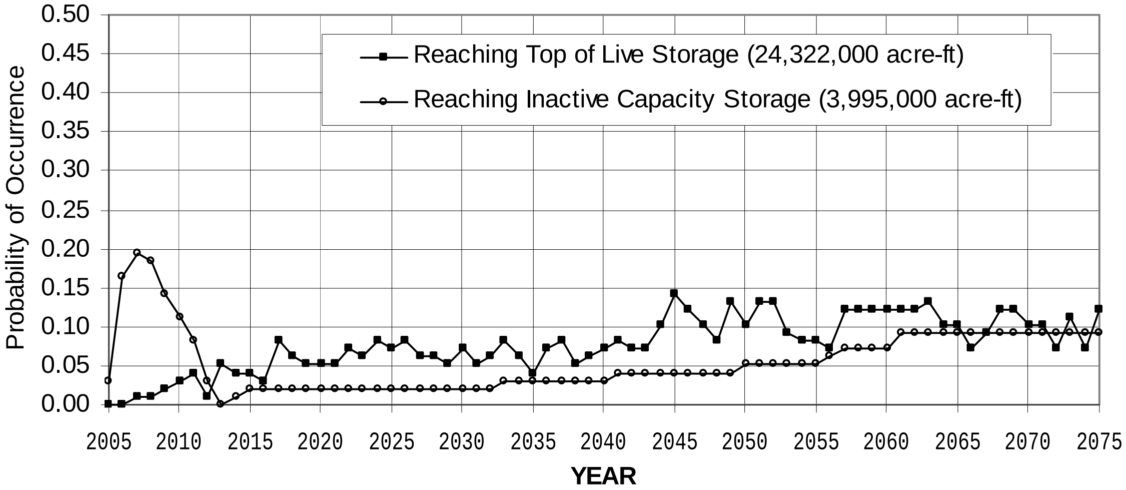


Figure 4.7 Lake Powell critical storage probabilities – Historical ISM

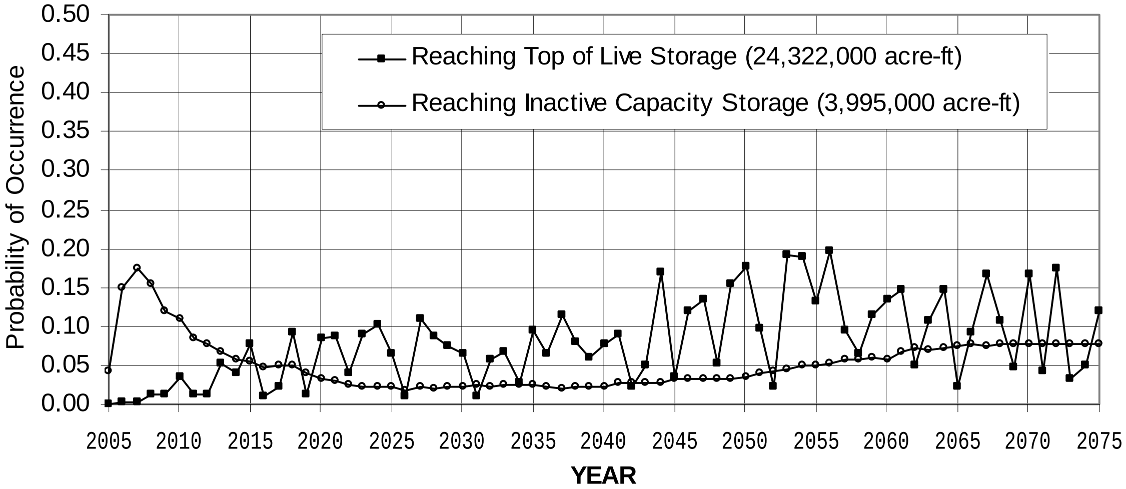


Figure 4.8 Lake Powell critical storage probabilities – Reconstructed ISM

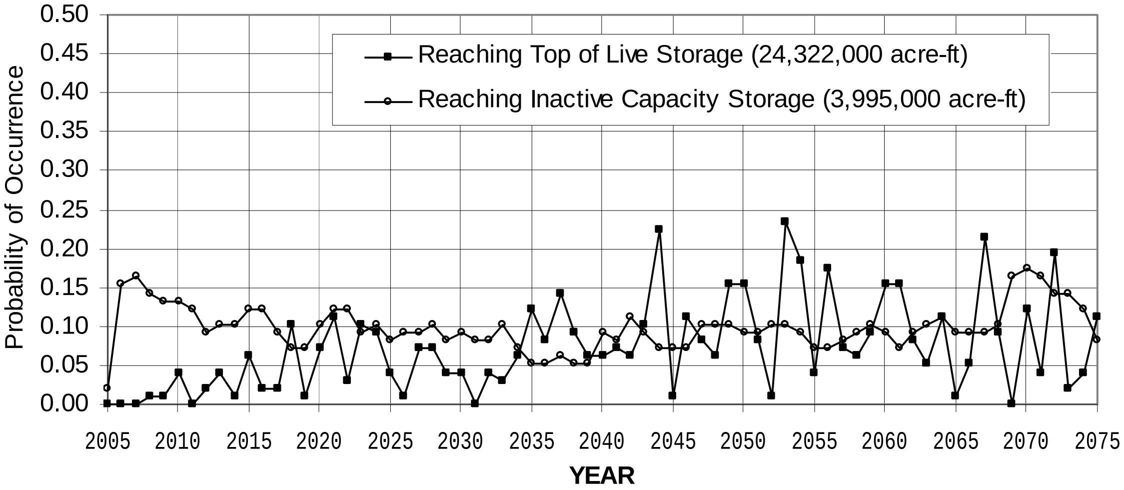


Figure 4.9 Lake Powell critical storage probabilities – Stochastic

The ISM scenarios have very similar results. The probability of reaching the top of inactive capacity approaches 20 percent initially and then drops to about 2 percent for around 20 years, after which it increases to just under 10 percent. This is the same pattern that was exhibited in the with minimum objective release probabilities. The plots do not exactly match because Powell is set to offset monthly deficits that occur during a water year if possible by releasing water in the following months so that the minimum objective release will be satisfied. The stochastic scenario's probability of reaching the top of inactive capacity does not exhibit the same pattern as the ISM scenarios. It initially rises above 15 percent, but then drops to 10 percent where it hovers until nearly the end of the run when it increases to the 15 percent range again. This pattern is also represented in the stochastic scenario's minimum objective release deficit probability. Due to the simulation nature of ISM, the probabilities it produces cannot be taken as genuine. The stochastic simulation method, on the other hand, produces genuine probabilities, and thus its output is the most indicative of possible future conditions.

All three scenarios show the same general pattern for the probability of Powell reaching the top of live storage. The reconstructed ISM and stochastic scenario plots have more variable behavior than the historical ISM plot, but all three have generally the same probabilities throughout time.

Another way to analyze the probability of reaching critical storages is to determine the percent of traces that reach the critical storage at any time in a given planning horizon. Table 4.2 gives these overall probabilities for Powell reaching the top of inactive storage. The results are fairly similar across all the scenarios. They all indicate that it is more likely than not that Powell will fall to the top of inactive capacity sometime within the next 50 years.

Table 4.2. Lake Powell overall critical storage probabilities

	10 Years	25 Years	50 Years	71 Years
Reaching Top of Live Storage (24,322,000 acre-ft)				
Historical ISM	13.3%	44.9%	81.6%	100.0%
Reconstructed ISM	12.1%	46.3%	89.9%	99.6%
Stochastic	9.0%	41.0%	76.0%	93.0%
Reaching Inactive Capacity Storage (3,995,000 acre-ft)				
Historical ISM	30.6%	40.8%	61.2%	77.6%
Reconstructed ISM	30.5%	39.1%	54.1%	63.2%
Stochastic	35.7%	50.0%	64.3%	77.6%

4.2 Lake Mead Storage

Lake Mead live storage volumes obtained based upon the different streamflow scenarios were also compared. Lake Mead's live storage volume is an important indicator of the system because there is not an absolute protect condition imposed upon it.

Figures 4.10 through 4.12 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 year in order to give an estimated range of possible future pool levels. Once the initial conditions are overcome, 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. As with Powell, Mead's June median for the historical ISM scenario is slightly lower than for the other two. Another important behavior to note is that the possible future minimum storage levels are significantly lower for the reconstructed ISM and stochastic flow scenarios than for the historical ISM flow scenario. In this case, the reconstructed ISM and stochastic streamflow scenarios give a more comprehensive picture of possible future conditions in the Colorado River system than the historical ISM streamflow scenario.

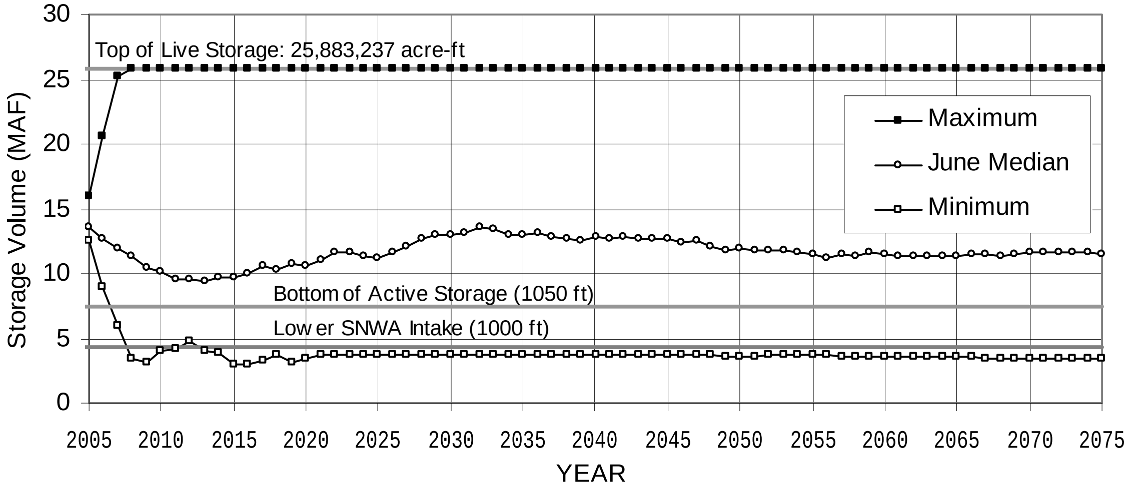


Figure 4.10 Lake Mead annual live storage volume statistics – Historical ISM

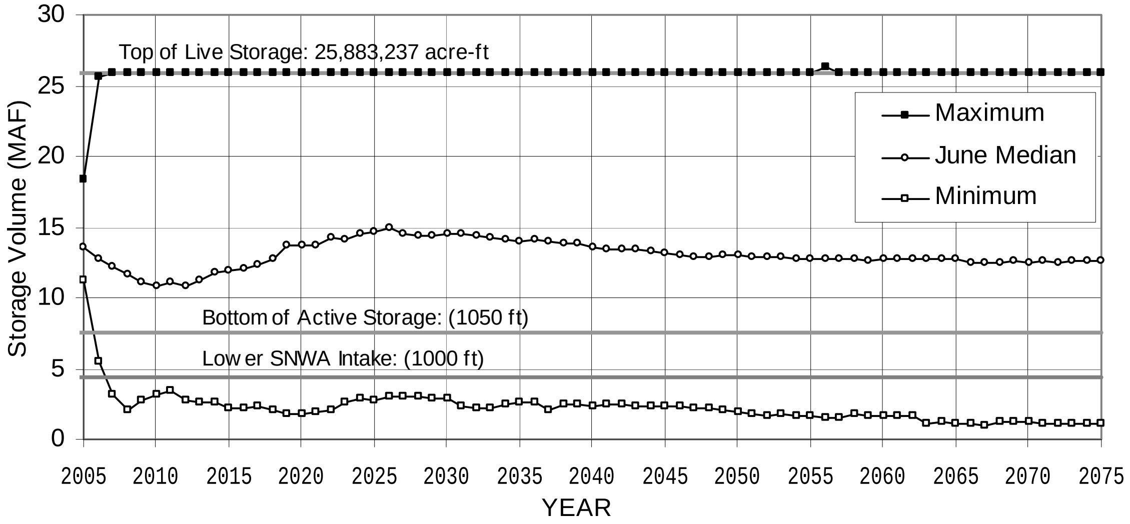


Figure 4.11 Lake Mead annual live storage volume statistics – Reconstructed ISM

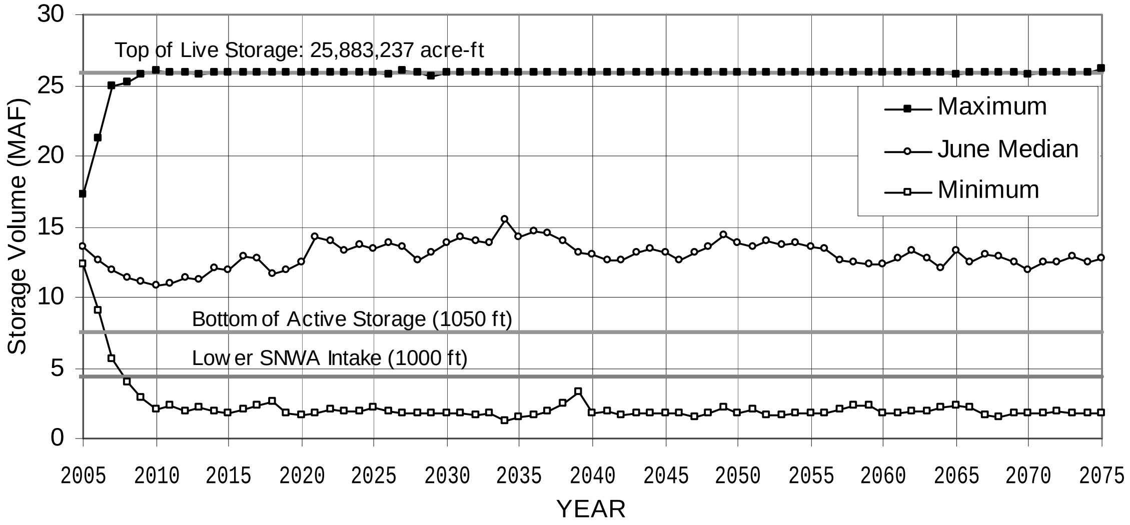


Figure 4.12 Lake Mead annual live storage volume statistics – Stochastic

Lake Mead's annual critical storage probabilities are plotted in Figures 4.13 through 4.15 in order to give an indication of how often Mead's storage hit or surpassed the critical lines in the previous figures. These probabilities were calculated in the same manner as Powell's annual critical storage probabilities.

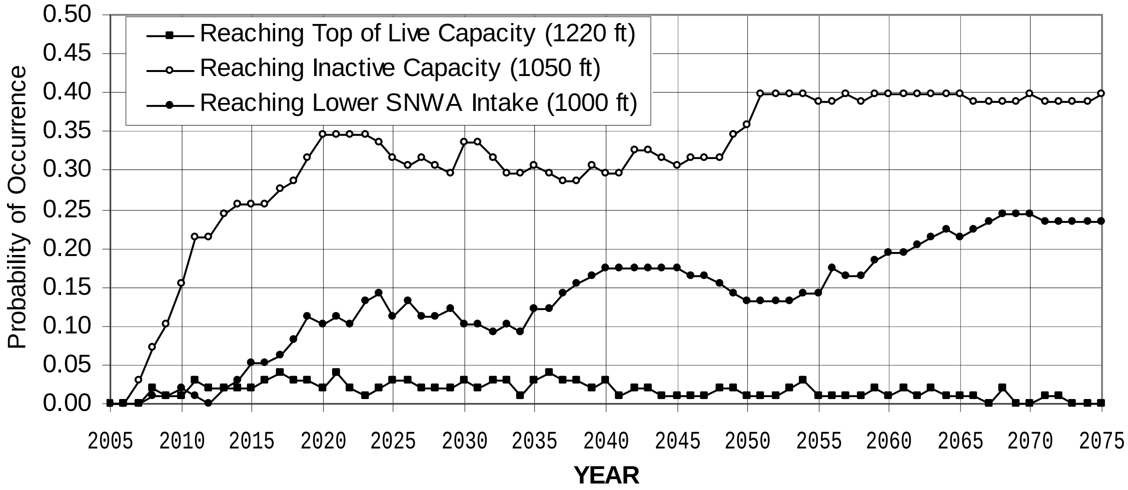


Figure 4.13 Lake Mead critical storage probabilities – Historical ISM

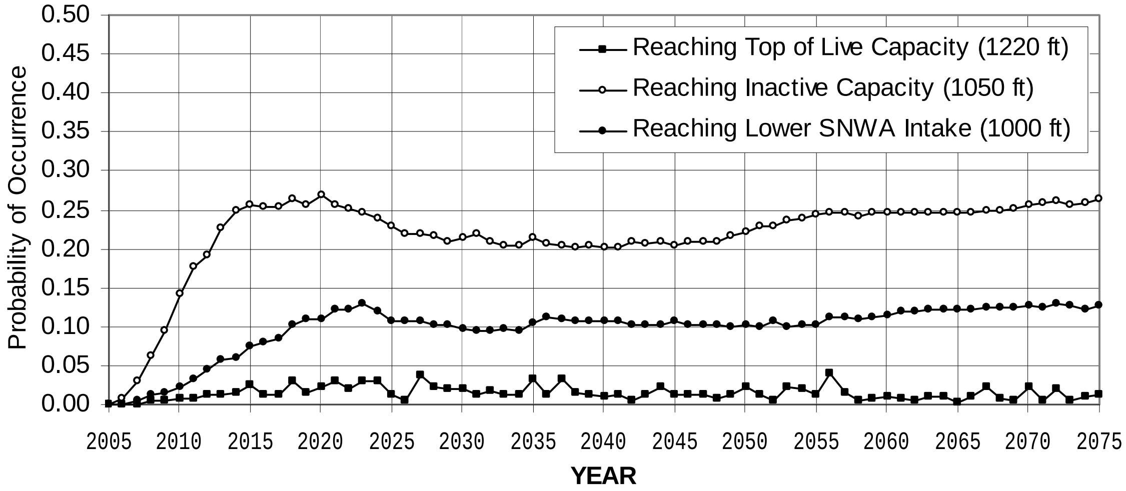


Figure 4.14 Lake Mead critical storage probabilities – Reconstructed ISM

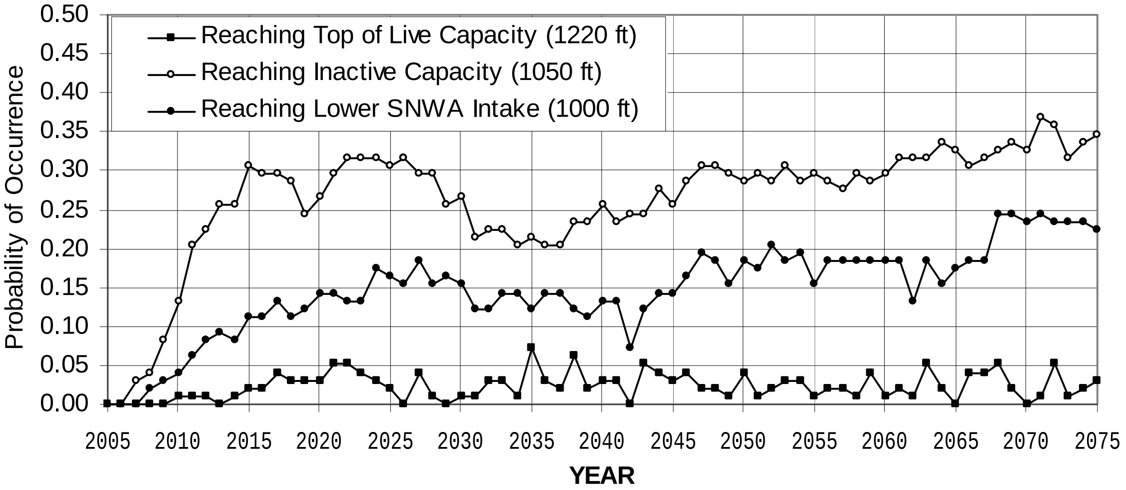


Figure 4.15 Lake Mead critical storage probabilities – Stochastic

All three scenarios exhibit approximately the same probability of Mead reaching the top of live capacity throughout time. The stochastic scenario probability is a little more irregular and has a slightly higher overall average than the ISM scenarios. The same pattern is exhibited across all scenarios in the probability of Mead reaching its inactive capacity, however, the magnitudes are notably different. The stochastic ISM scenario shows the highest probability throughout time, followed by the stochastic scenario, with the reconstructed ISM scenario showing the lowest probability throughout time. This corresponds to the historical ISM scenario's lower June median trace. The same behavior is true for the probability of Mead reaching the lower SNWA intake, except that the stochastic scenario's probability is highest throughout time followed by the historical and then reconstructed ISM scenarios. While the historical ISM scenario drops below the lower SNWA intake more often than the reconstructed ISM scenario, Figures 4.10 and 4.11 demonstrate that the reconstructed ISM scenario can potentially drop lower than the historical ISM scenario when it does fall below the lower SNWA intake. Again, the reconstructed ISM and stochastic scenarios simulate a wider range of probable storage conditions.

Table 4.3 gives the overall probabilities that in any trace at anytime within the indicated planning horizon Lake Mead will reach or drop below the inactive capacity and the lower SNWA intake. In general, the historical ISM and stochastic scenarios have higher probabilities of reaching the critical storages in any of the planning horizons. Both scenarios indicate that Mead will more likely than not reach its inactive capacity sometime within the next 25 years and will more likely than not reach the lower SNWA intake sometime within the next 50 years. The reconstructed ISM scenario generally has slightly lower probabilities but still in the same vicinity as the other two scenarios.

Table 4.3. Lake Mead overall critical storage probabilities

	10 Years	25 Years	50 Years	71 Years
Reaching Top of Live Storage Capacity (1220 ft)				
Historical ISM	10.2%	37.8%	61.2%	62.2%
Reconstructed ISM	5.8%	37.2%	53.5%	65.2%
Stochastic	4.0%	28.0%	48.0%	62.0%
Reaching Inactive Capacity (1050 ft)				
Historical ISM	36.7%	51.0%	75.5%	93.9%
Reconstructed ISM	31.1%	46.5%	68.7%	80.7%
Stochastic	29.0%	53.0%	70.0%	84.0%
Reaching Lower SNWA Intake (1000 ft)				
Historical ISM	6.1%	30.6%	52.0%	83.7%
Reconstructed ISM	9.7%	27.0%	44.2%	62.5%
Stochastic	13.0%	37.0%	54.0%	70.0%

4.3 Shortage and Surplus Conditions

The analysis of water user shortage and surplus conditions reveals the ultimate effects of the previously analyzed reservoir levels and releases. This section presents Upper and Lower Basin shortage and surplus probabilities as well as Upper and Lower Basin expected shortage and surplus volumes.

4.3.1 Shortage and Surplus Probabilities

As explained in Chapter 3, the Upper and Lower Basin have two critically different characteristics which cause there respective shortage and surplus results to be quite different. The Upper Basin is composed of the headwaters of the Colorado River. Thus, its reservoirs are scattered and unable to distribute the streamflow to satisfy all of the user demands even when there is sufficient streamflow in the basin as a whole. As a result, if a shortage is defined at any time that any water user in the Upper Basin receives an amount of water that is less than its scheduled amount, there is always a 100 percent probability that the Upper Basin will experience a shortage in any year. Another key difference is that Upper Basin water users never divert more than their projected normal depletion for a given year. Therefore, an Upper Basin surplus never occurs. On the other hand, the Lower Basin relies chiefly upon the storage in Mead to satisfy water user demands. In this case, system reservoir levels, not local inflow, are the decisive factors which determine Lower Basin shortage, surplus, and normal conditions. Furthermore, surplus conditions can actually be defined and extra water diverted depending on the system reservoir levels.

Figures 4.16 through 4.18 give just the Lower Basin shortage and surplus probabilities throughout time. The Upper Basin's probabilities are not plotted because, as stated previously, there is always a 100 percent probability of shortage, and there is never a probability for surplus. The graphs all display the same general trends, but the stochastic scenario has a more random nature to it. The probability of any shortage (level 1 or 2) is initially zero and then begins to rise rapidly after 2008. For the historical ISM scenario, the probability of shortage levels off in 2012 at 50 percent for about 15 years.

After which, it declines slightly before beginning a steady increase with time, reaching 80 percent in 2075. The second steady rise in the annual shortage probability is due to the increase in Upper Basin demands which decreases the amount of water available to the Lower Basin. However, the shortage probability continues to increase after 2060 when the Upper Basin demands have leveled off demonstrating a lagged effect on the system. The reconstructed ISM shortage probability follows the same pattern as the historical ISM with the initial rise only reaching around 4 percent but the final rise reaching the same 80 percent annual 2075 probability. The same is true for the stochastic scenario shortage probabilities. The initial rise dances around 4 percent and the final rise ends at 80 percent in 2075. However, the shortage probability does rise slightly above 80 percent between 2070 and 2075.

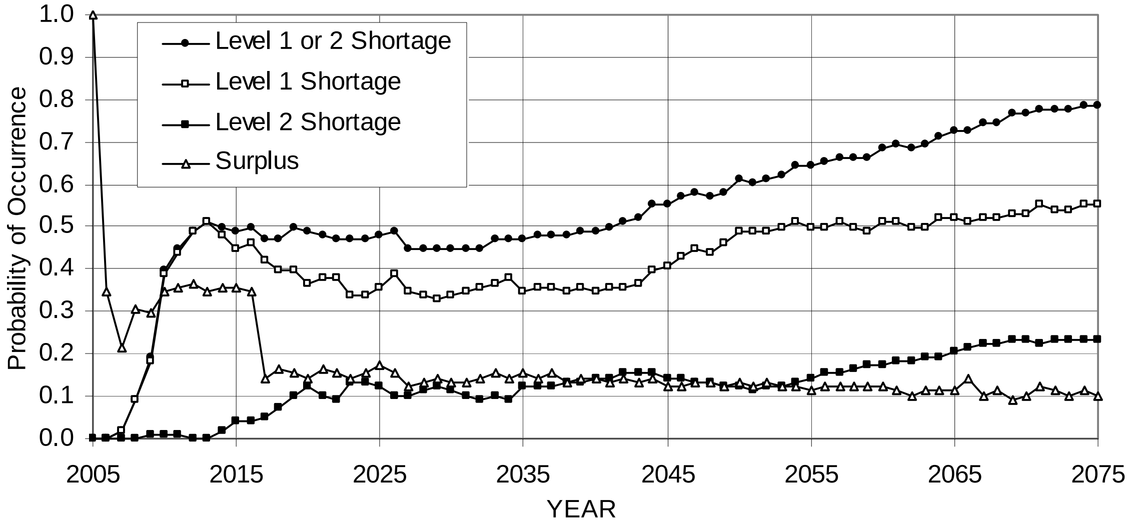


Figure 4.16 Lower Basin annual shortage and surplus probabilities – Historical ISM

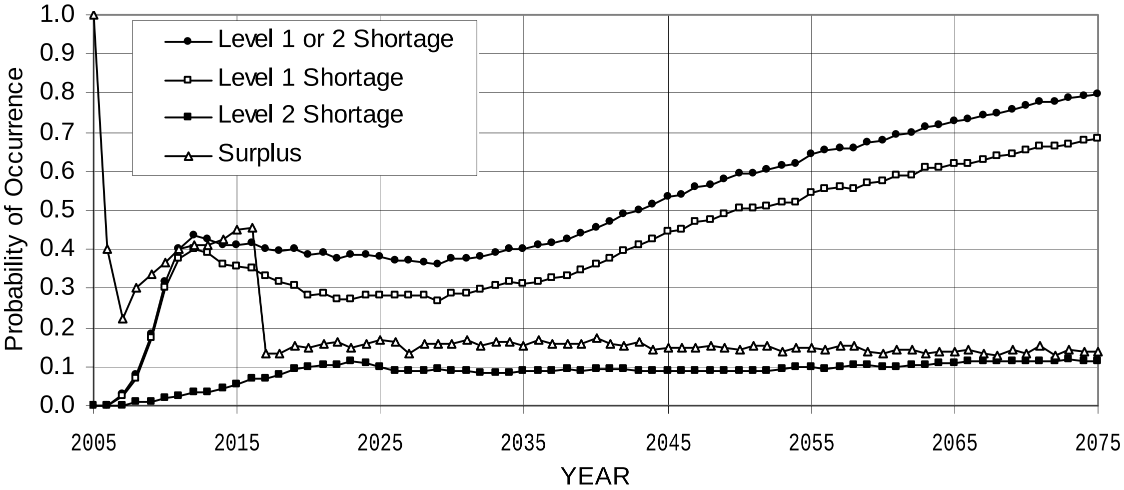


Figure 4.17 Lower Basin annual shortage and surplus probabilities – Reconstructed ISM

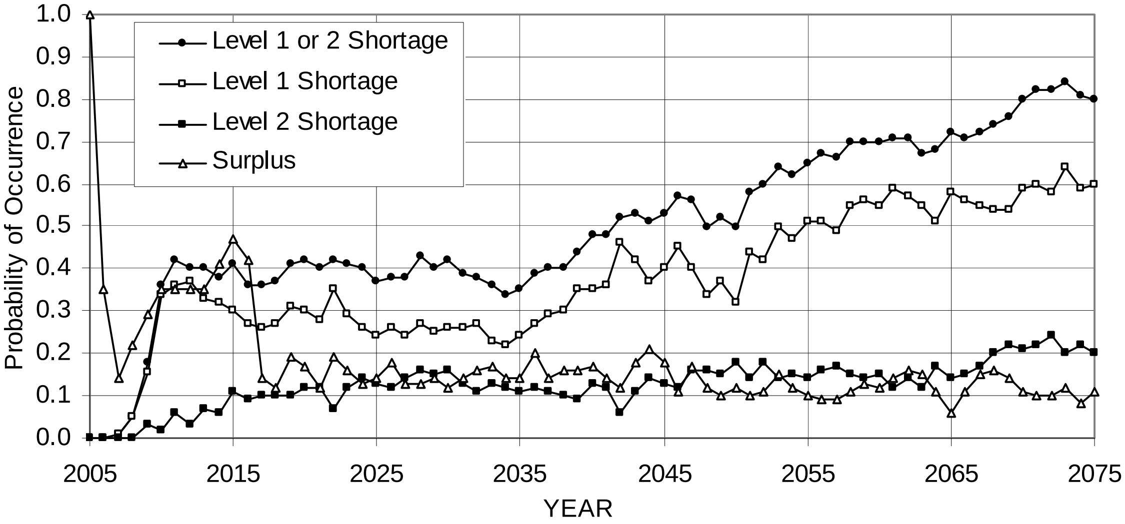


Figure 4.18 Lower Basin annual shortage and surplus probabilities – Stochastic

The annual probabilities of a severe, level 2 shortage, throughout time is very similar for the historical ISM and stochastic scenarios. The initial level 2 shortage probability is zero and rises to above 20 percent by the end of the model run. The reconstructed ISM annual level 2 shortage probability only rises to just above 10 percent by the end of the run. The lower severe shortage probabilities for the reconstructed ISM scenario are consistent with the scenario's lower probabilities of critically low Mead storage levels.

The annual surplus probabilities exhibit similar patterns across the different scenarios as well. In 2005 there is always a 100 percent probability of declaring a surplus condition because the governing rule is based upon Mead's December 2004 reservoir level which is a fixed input into the model and thus the same across all scenarios. According to the model's rules, the December 2004 Mead pool elevation of 1130 feet (between 1125 and 1145 feet) triggers a level 3 surplus. After 2005, the probability for surplus conditions drops considerably across all scenarios, and then drops again after 2016 when the Interim Surplus Guidelines expire. All scenarios exhibit a very slight downward trend in the surplus probability from around 15 percent in 2016 to 10 percent in 2075 for the historical ISM and stochastic scenarios and 12 percent in 2075 for the reconstructed ISM scenario. The slight downward trend is due to the increasing Upper Basin demands. However, the trend is not as marked as the shortage probability trend because very high flows will result in surplus conditions regardless of a one million acre-foot increase in Upper Basin demands. Only the moderately high flows will be affected by the increasing demands whereas any sort of low flow will be affected by a one million acre-feet increase in demands.

Table 4.4 gives the overall Lower Basin shortage and surplus probabilities for different planning horizons for each scenario. The calculations were performed in the same manner described for the overall critical reservoir probabilities. For each scenario, there is always a 100 percent probability that surplus conditions will occur sometime in the next 10 years and beyond. For each scenario, there is a 99 or 100 percent probability that shortage conditions will occur sometime in the next 71 years. The historical ISM scenario has the highest 10 and 25 year overall probabilities of shortage at 60 and 80 percent respectively, followed by the stochastic and then reconstructed ISM scenarios which are between 5 and 12 percent lower. The overall probability of shortage for the 50 year planning horizon is highest for the stochastic scenario at 98 percent, followed by the reconstructed ISM scenario at 97 percent, and then the historical ISM scenario at 92 percent. The level 2 shortage probabilities demonstrate relatively larger differences across the different scenarios. During the first 10 years, the probability of a level 2 shortage for the stochastic scenario is more than double the probability of shortage for the historical ISM scenario at 11 and 5 percent respectively. The reconstructed ISM scenario is also much larger than the historical at 9 percent. However, after the first 10 years, the reconstructed ISM always has the lowest overall probability of level 2 shortage, consistent with its annual probability curves. Stochastic scenario level 2 probabilities are still larger than, although relatively close to, the historical ISM level 2 probabilities for the 25 and 50 year planning horizons. For the 71 year planning horizon, the probability of a level 2 shortage jumps considerably for the historical ISM scenario to about 84 percent. This is 23 percent larger than the stochastic scenario probability of 69 percent. While the historical ISM scenario shows a much higher probability of reaching a level 2 shortage in the next 71 years, an examination of the possible shortage volumes will give a better understanding of the potential severity of the shortages under the different scenarios.

Table 4.4. Lower Basin overall shortage and surplus probabilities

	10 Years	25 Years	50 Years	71 Years
Surplus				
Historical ISM	100.0%	100.0%	100.0%	100.0%
Reconstructed ISM	100.0%	100.0%	100.0%	100.0%
Stochastic	100.0%	100.0%	100.0%	100.0%
Shortage				
Historical ISM	60.2%	80.6%	91.8%	100.0%
Reconstructed ISM	53.1%	74.1%	96.5%	100.0%
Stochastic	55.0%	76.0%	98.0%	99.0%
Level 2 Shortage				
Historical ISM	5.1%	30.6%	50.0%	83.7%
Reconstructed ISM	9.1%	27.0%	44.9%	63.4%
Stochastic	11.0%	36.0%	53.0%	69.0%

4.3.2 Shortage and Surplus Volumes

This section presents the estimated maximum shortage volumes for the Upper and Lower Basins, as well as for their combined maximum shortage volumes and Mexico's maximum shortage volumes. The Lower Basin and Mexico shortage volumes were determined based upon the shortage schedules that were in effect. The Upper Basin's shortage volumes were determined based upon the difference between the actual total annual diversion volumes and the scheduled annual diversion volumes. Finally, the shortage volume of the entire basin was determined by adding the Upper and Lower Basin volumes for each year in each run (Mexico's shortages are not included). Then, the maximum shortage volumes were determined for each basin by finding the maximum across all runs in every year for each of the previously defined shortage volume data sets.

Figures 4.19 through 4.21 give the maximum expected annual shortage volumes for each of the scenarios. The historical ISM scenario presents much lower maximum shortage probabilities than the other two scenarios. This is consistent with the initial streamflow analysis because the reconstructed ISM and stochastic scenarios had much lower minimum flows than the historical ISM scenario. While the historical ISM scenario has an overall higher probability of experiencing a level 2 shortage, Figures 4.19 through 4.21 indicate that the maximum potential shortage that would be experienced is much lower than for the reconstructed ISM and stochastic scenarios. The maximum entire basin shortage for the historical ISM scenario is just under 2.5 MAF compared to just under 8 MAF and 7 MAF for the reconstructed ISM and stochastic scenarios respectively. The maximum estimated reconstructed ISM and stochastic shortage volumes are over half of the entire basin's demand whereas the historical ISM maximum shortage volume is less than a quarter of the entire basin's demand. These different maximum shortage volumes would have much different impacts on the river system and require significantly different planning strategies.

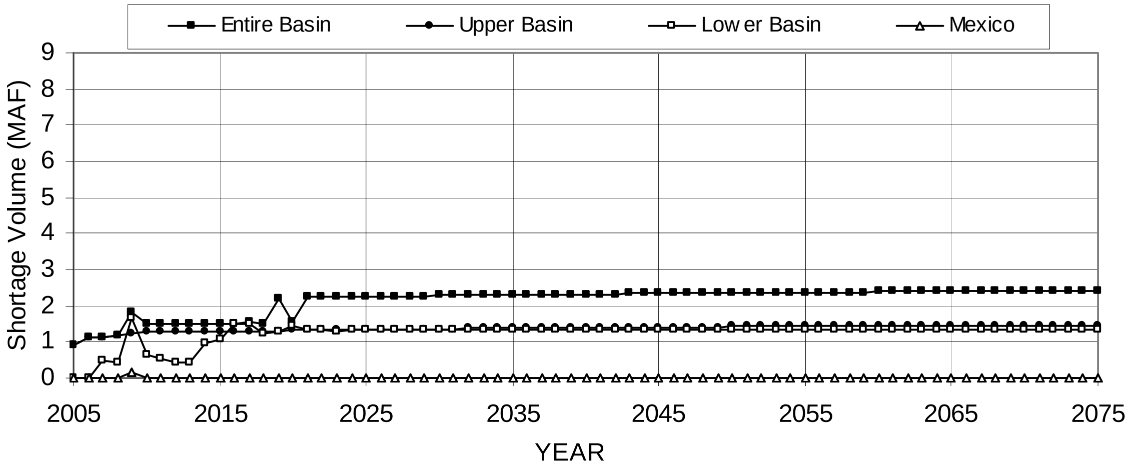


Figure 4.19 Maximum expected shortage volumes – Historical ISM

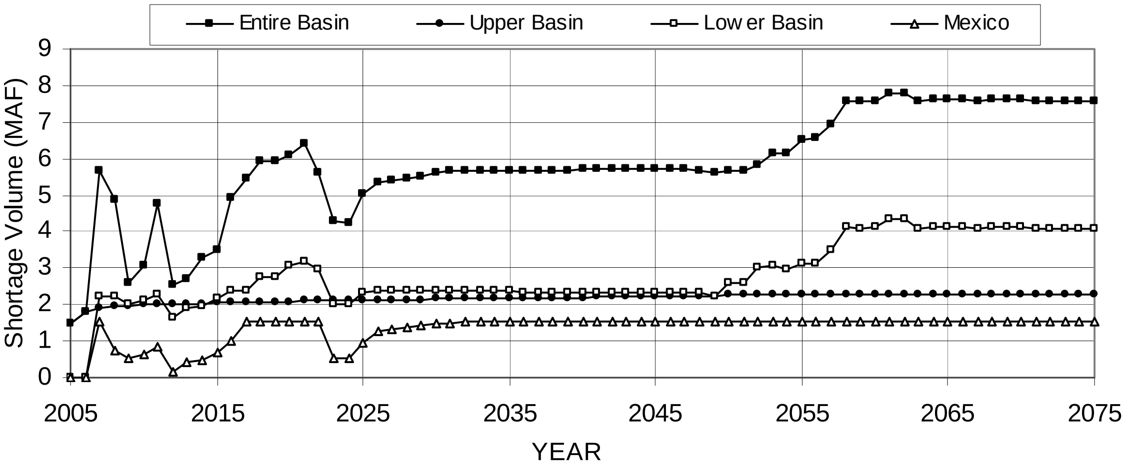


Figure 4.20 Maximum expected shortage volumes – Reconstructed ISM

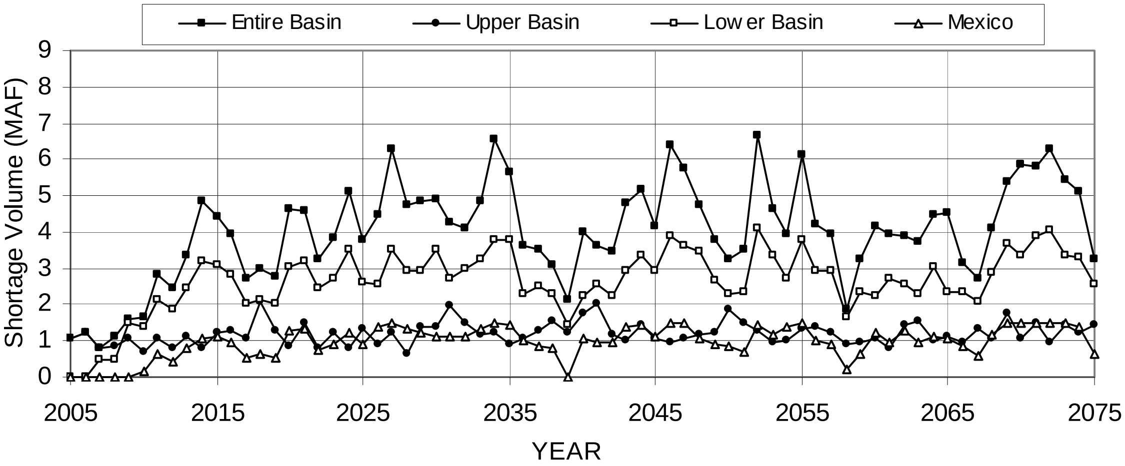


Figure 4.21 Maximum expected shortage volumes – Stochastic

Another apparent trend in the maximum shortage volumes is that the Lower Basin has the potential to endure larger shortages than the Upper Basin for the reconstructed ISM and stochastic scenarios. Their maximums follow the same curve for the historical scenario. Furthermore, Mexico barely has any potential for shortage in the historical ISM scenario, but the reconstructed ISM and stochastic scenarios show the potential for Mexico to receive no water in a calendar year.

4.4 Study Comparison

The results presented are consistent with Kendall and Dracup's findings that the AR(1) model better predicts the higher exceedence probabilities of reservoir levels than ISM and that the AR(1) model results in slightly higher 50 percent exceedence levels than ISM. In this study, the stochastic scenario gave a more comprehensive understanding of the lower reservoir storage volumes and in turn shortage volumes. Furthermore, for both Lakes Powell and Mead, the median reservoir levels were slightly higher for the stochastic scenario than for the historical ISM scenario.

The Ouarda et al study found that ISM streamflow simulation was comparable to stochastically generated streamflow in producing power capacity, energy generation, and downstream water delivery statistics for the Colorado River system. This study did not look at power capacity or energy generation, but it did analyze Mead release volume statistics. Ouarda et al determined that the MWD delivery volumes for the 2 different simulation methods had very similar average and standard deviation values for the 20th year. However, these statistics are only part of the picture and do not indicate possible differences in exceedence probabilities or minimum delivery volumes, which are of concern to water managers. Furthermore, the MWD delivery (along with the Mexico delivery) is one of the last deliveries to be affected by shortage conditions and therefore is not an adequate representation of the state of the overall Lower Basin delivery. Again, this study found the stochastic scenario to give a more comprehensive picture of possible future Lower Basin deliveries.

Finally, the much lower minimum reservoir storage and release volumes (higher maximum shortage volumes) exhibited by the reconstructed ISM scenario as compared to the historical ISM scenario are consistent with Tarboton’s findings that Colorado River tree-ring reconstructed streamflow has a much greater return period for the severe drought than the historical streamflow record. However, the average of the tree-ring reconstructed streamflow used in this study is only slightly less (about 0.6 percent) than the historical record, while the average of the tree-ring reconstructed streamflow used in Tarboton’s study is considerably less (about 11 percent) than the historical record. The reconstructed streamflow used in this study were developed more recently using modern techniques, and the reconstructed streamflow used in Tarboton’s study was one of the first sequences to be developed for the Colorado River.

5 Upper Basin Yield

This chapter presents the estimated sustainable yield of the Upper Basin according to the three different streamflow simulation scenarios. As explained previously, the understanding of the sustainable yield of the Upper Basin is critical to water managers as it specifies the maximum demand each of the Upper Basin states can dependably expect to be satisfied. This estimated sustainable yield does not attempt to guarantee that all Upper Basin water users will receive their full demand. As shown in the previous chapter, it is entirely likely that at any time at least one Upper Basin water user will not receive its full demand since the it is in the headwaters of the system. Furthermore, while not modeled, inherent in the Upper Basin's priority system is the inevitability of shorting junior water users of their desired demand. The sustainable yields determined in this chapter only attempt to estimate the amount of water that can be reliably demanded of the system from year to year either without inducing an inability to meet Powell's minimum objective release, or only expecting a minimum objective release deficit to be incurred a certain percentage of the time.

5.1 Approach

The sustainable yield is estimated as the sustainable annual depletion demand plus annual reservoir evaporation. The sustainable annual depletion demand was determined by performing model runs with reduced Upper Basin depletions so that Powell is either always able to meet the minimum objective release or is expected to meet it a certain percentage of the time after the initial reservoir conditions have been overcome. Unfortunately, the hydrologic scenarios are too different to determine the estimated sustainable yield in exactly the same manner, so the yields presented cannot be directly compared, but general comparisons can be made.

5.2 Scenario 1: Historical ISM

For the historical ISM scenario, the Upper Basin depletions were leveled off at some time before 2060 so that Powell was always able to release the minimum objective amount in all runs after the initial conditions were overcome. In order for Powell to have a zero probability of not meeting the minimum objective release after 2025, the Upper Basin depletion demands have to be capped at their 2055 values. If 2056 projections were used, they would have resulted in minimum objective release deficits beginning in 2059. The total Upper Basin scheduled depletion demand for 2055 is 5,373,000 acre-ft per year. This is the estimated sustainable depletion demand and is 56,000 acre-ft less than the maximum projected depletion demand. The Upper Basin's annual evaporation must be added to this volume in order to estimate the total sustainable yield. However, the evaporation volumes change with changing reservoir levels. The average annual evaporation over all the traces from the time of constant demand (2055-2075) was calculated. This evaporation volume of 593,000 acre-feet per year was added to the sustainable demand volume to estimate a total annual Upper Basin sustainable yield of 5,966,000 acre-ft per year. This is very similar to the sustainable yield given in the 1988 Hydrologic Determination of 6 MAF per year which also used historical ISM simulated streamflows for its estimation.

5.3 Scenario 2: Reconstructed ISM

Due to the more extreme hydrology present in the reconstructed ISM streamflows, the sustainable yield could not be determined for the case where the minimum objective release is always expected to be met after 2025. For this scenario, the Upper Basin depletion schedule was set constant at the 2005 levels, of 4,445,000 acre-feet per year throughout time. Even under these conditions, Powell is unable to meet the minimum objective release just under one percent of the time every year after 2025. The maximum release deficit after 2025 is 440,000 acre-feet per year, about ten percent of the total demand. It is assumed that this modeled deficit volume is bearable as an annual volume of shortage that Upper Basin water users are willing and able to sustain. The average annual upper basin evaporation under these conditions is 600,000 acre-feet. Therefore, according to the reconstructed ISM scenario the estimated sustainable yield with a minimum objective release deficit occurring one percent of the time in any year is 5,045,000 acre-ft per year, nearly one million acre-feet less than the 1988 Hydrologic Determination.

5.4 Scenario 3: Stochastic Generation

Similar to the reconstructed ISM scenario results, the hydrology of the stochastic scenario is too extreme to assume that the sustainable yield allows for Powell's minimum objective release to always be met. Year 2005 depletion demands of 4,445,000 acre-feet were put into the model throughout time as with the reconstructed ISM scenario. However, the hydrology of the stochastic scenario results in a release deficit an average of three percent of the time in any given year (after initial conditions have been overcome). The maximum release deficit volume is approximately 5 MAF. This deficit volume is obviously unacceptable in that it is greater than the total depletion demand of the Upper Basin. This demonstrates that the indicated demand is not sustainable, and that it is possible for the Upper Basin to not use any water for an entire year and still be unable to deliver the minimum objective release amount to the Lower Basin under the modeled operating rules. Unfortunately, this approach to determining the Upper Basin's sustainable yield cannot be applied successfully to the stochastic scenario. However, it does demonstrate a much bleaker outlook for the Upper Basin sustainable yield than the 6 MAF the 1988 Hydrologic Determination estimated.

6 Conclusions and Recommendations

Three different scenarios of streamflow simulation of the Colorado River were examined. One scenario simulated the historical record according to ISM, another simulated tree-ring reconstructed streamflow according to ISM, and the third used a stochastic simulation and disaggregation model based upon the historical record to generate synthetic hydrology. The stochastic scenario was clearly shown to generate random streamflow traces while the patterned and repetitive nature of ISM was demonstrated. As expected, the stochastic scenario which has by far the most number of different streamflow values had the most extreme hydrology, followed by the reconstructed and then historical ISM scenarios. The primary behavior of interest was the response of the Colorado River system to the more extreme hydrology.

6.1 River System Response

The response of the Colorado River system in terms of reservoir storage levels and release volumes to the different streamflow scenarios was on average about the same, and the probabilities of reaching or passing certain critical storage levels were very similar. However, the extremes of Powell's release volumes, Mead's reservoir levels, and the Lower Basin's shortage volumes were shown to be quite different. The massive river system storage volume was not enough to even out the differences in the scenarios' extreme hydrology. Lake Powell's minimum objective release volume was shown to have a higher likelihood of not being met and a larger possible deficit volume for the stochastic and reconstructed ISM scenarios than for the historical ISM scenario. Due to the constraints on Lake Powell storage levels, all scenarios exhibited about the same overall behavior. The difference in the hydrology is seen in Powell's ability to meet the minimum objective release. Lake Mead does not have the same minimum constraints as Powell, and the minimum storage volumes were shown to have the potential to drop much lower under the stochastic and reconstructed ISM scenarios than under the historical ISM scenario. Finally, the maximum Lower Basin shortage volumes were much larger under the stochastic and reconstructed ISM scenarios than under the historical ISM scenario. Again, it is important to capture these possible extremes in the simulation of the river system so that water managers have an idea of the worst conditions for which to prepare. It is the stochastic simulation technique be used to examine the response of the river system to possible future hydrology because it has the ability to produce extremes not seen in the historical record while still reproducing the behavior of the historical record. Furthermore, the simulation technique creates random samples and therefore does not skew the results of the probability analysis.

6.2 Upper Basin Yield

The historical ISM scenario resulted in an Upper Basin sustainable yield determination of approximately 6 MAF which is consistent with the 1988 Hydrologic Determination. The reconstructed ISM scenario resulted in a sustainable yield of only approximately 5 MAF. This yield is 16 percent less than the yield estimated by the historical ISM scenario. Furthermore, unlike the historical ISM scenario, minimum objective release deficits could still occur. The stochastic scenario sustainable yield could not be estimated in a similar manner because of its more extreme hydrology. It is recommended that another approach be taken to estimate the sustainable yield under this scenario.

References

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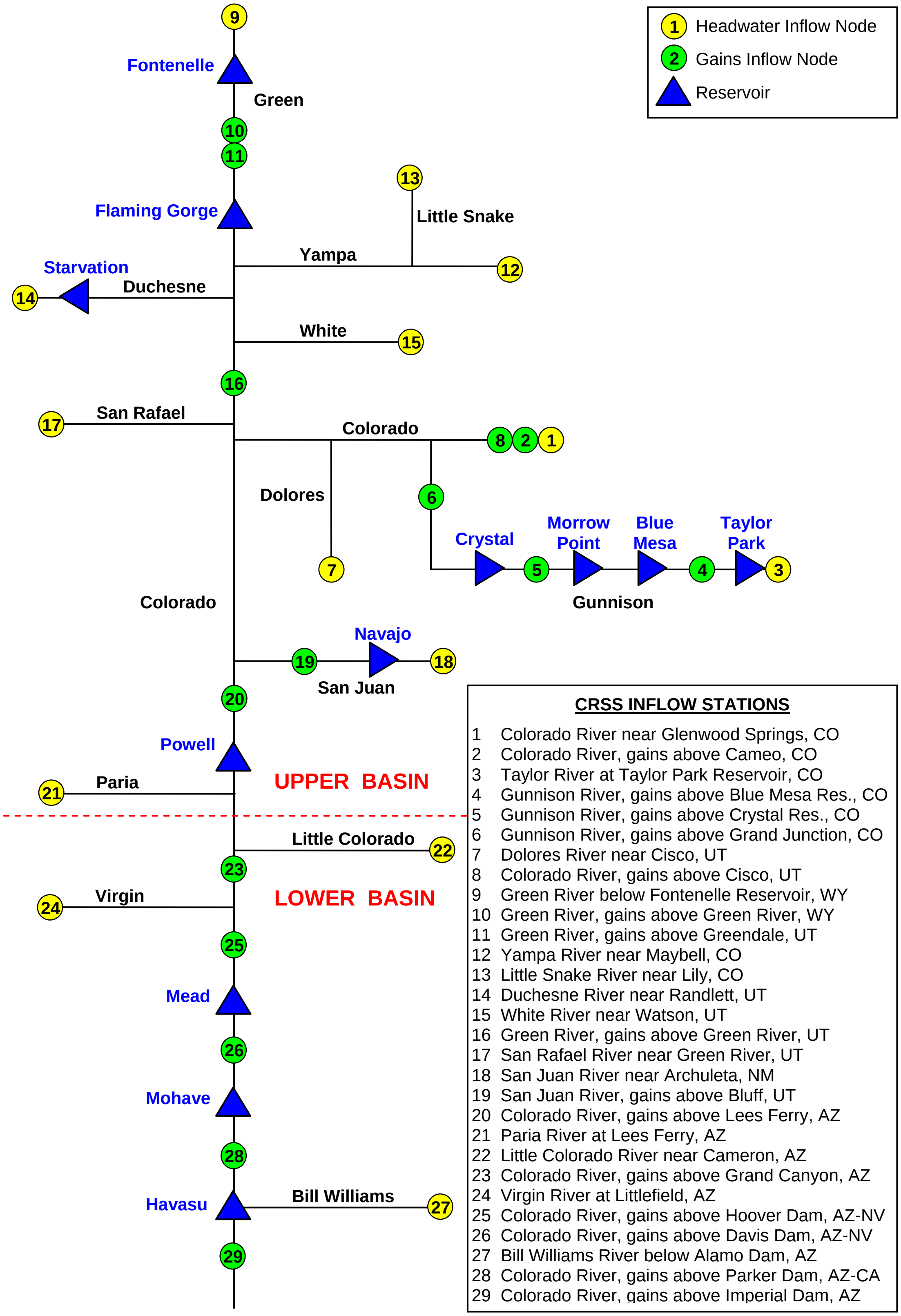
APPENDIX A. Supplementary Tables and Figures

Table A.1 Colorado River Streamflow Station Identification Numbers and Names

Station ID Number	USGS Gage Number	USGS Gage Name
1	09072500	Colorado River near Glenwood Springs, CO
2	09095500	Colorado River, gains above Cameo, CO
3	09109000	Taylor River at Taylor Park Reservoir, CO
4	09124700	Gunnison River, gains above Blue Mesa Res., CO
5	09127800	Gunnison River, gains above Crystal Res., CO
6	09152500	Gunnison River, gains above Grand Junction, CO
7	09180000	Dolores River near Cisco, UT
8	09180500	Colorado River, gains above Cisco, UT
9	09211200	Green River below Fontenelle Reservoir, WY
10	09217000	Green River, gains above Green River, WY
11	09234500	Green River, gains above Greendale, UT
12	09251000	Yampa River near Maybell, CO
13	09260000	Little Snake River near Lily, CO
14	09302000	Duchesne River near Randlett, UT
15	09306500	White River near Watson, UT
16	09315000	Green River, gains above Green River, UT
17	09328500	San Rafael River near Green River, UT
18	09355500	San Juan River near Archuleta, NM
19	09379500	San Juan River, gains above Bluff, UT
20	09380000	Colorado River, gains above Lees Ferry, AZ
21	09382000	Paria River at Lees Ferry, AZ
22	09402000	Little Colorado River near Cameron, AZ
23	09402100	Colorado River, gains above Grand Canyon, AZ
24	09415000	Virgin River at Littlefield, AZ
25	09421000	Colorado River, gains above Hoover Dam, AZ-NV
26	09422500	Colorado River, gains above Davis Dam, AZ-NV
27	09426000	Bill Williams River below Alamo Dam, AZ
28	09427500	Colorado River, gains above Parker Dam, AZ-CA
29	09429490	Colorado River, gains above Imperial Dam, AZ



CRSS INFLOW STATIONS

1	Colorado River near Glenwood Springs, CO
2	Colorado River, gains above Cameo, CO
3	Taylor River at Taylor Park Reservoir, CO
4	Gunnison River, gains above Blue Mesa Res., CO
5	Gunnison River, gains above Crystal Res., CO
6	Gunnison River, gains above Grand Junction, CO
7	Dolores River near Cisco, UT
8	Colorado River, gains above Cisco, UT
9	Green River below Fontenelle Reservoir, WY
10	Green River, gains above Green River, WY
11	Green River, gains above Greendale, UT
12	Yampa River near Maybell, CO
13	Little Snake River near Lily, CO
14	Duchesne River near Randlett, UT
15	White River near Watson, UT
16	Green River, gains above Green River, UT
17	San Rafael River near Green River, UT
18	San Juan River near Archuleta, NM
19	San Juan River, gains above Bluff, UT
20	Colorado River, gains above Lees Ferry, AZ
21	Paria River at Lees Ferry, AZ
22	Little Colorado River near Cameron, AZ
23	Colorado River, gains above Grand Canyon, AZ
24	Virgin River at Littlefield, AZ
25	Colorado River, gains above Hoover Dam, AZ-NV
26	Colorado River, gains above Davis Dam, AZ-NV
27	Bill Williams River below Alamo Dam, AZ
28	Colorado River, gains above Parker Dam, AZ-CA
29	Colorado River, gains above Imperial Dam, AZ

Figure A.1 CRSS model schematic of streamflows and reservoirs

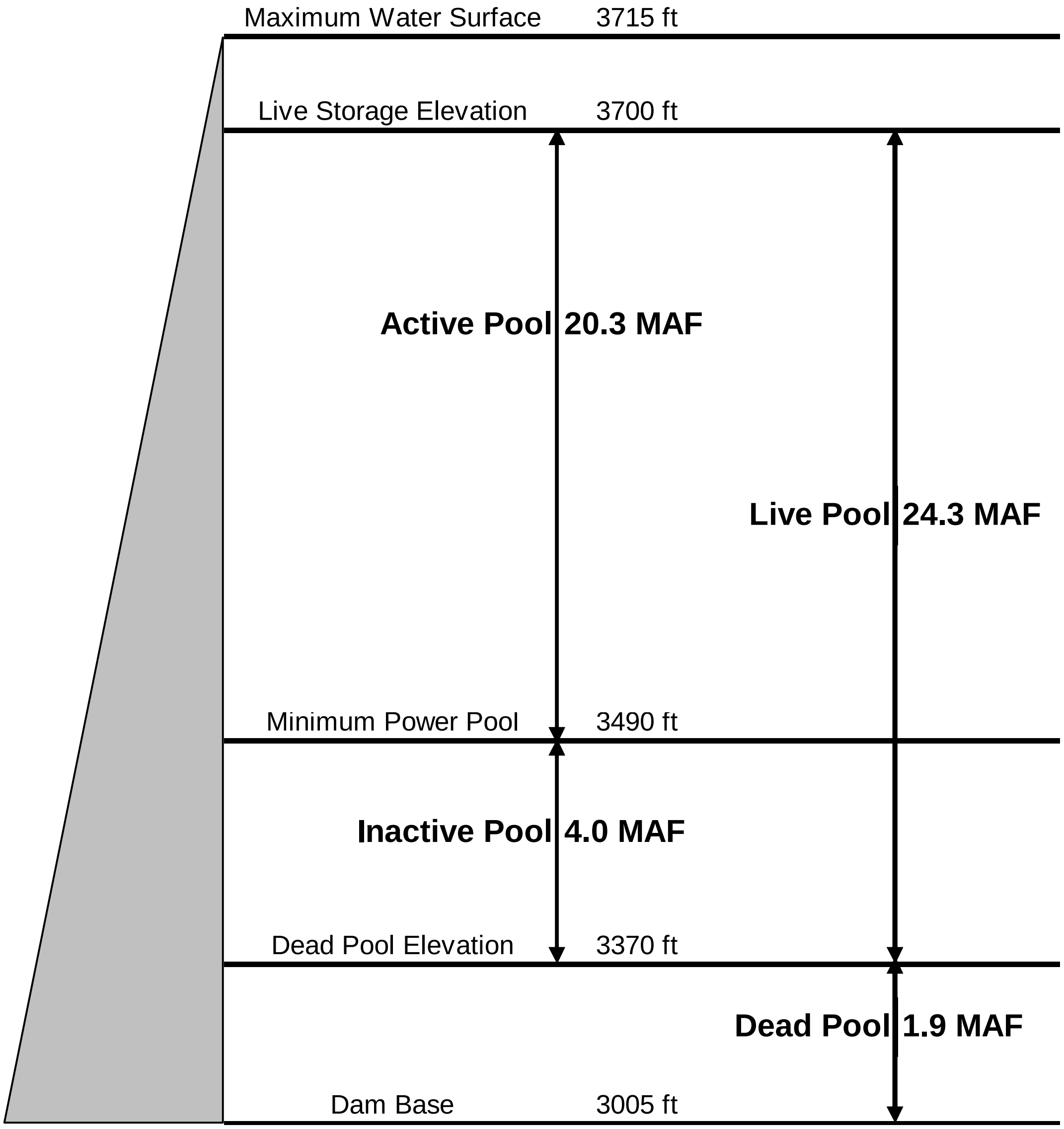


Figure A.2 Lake Powell storage and elevation profile

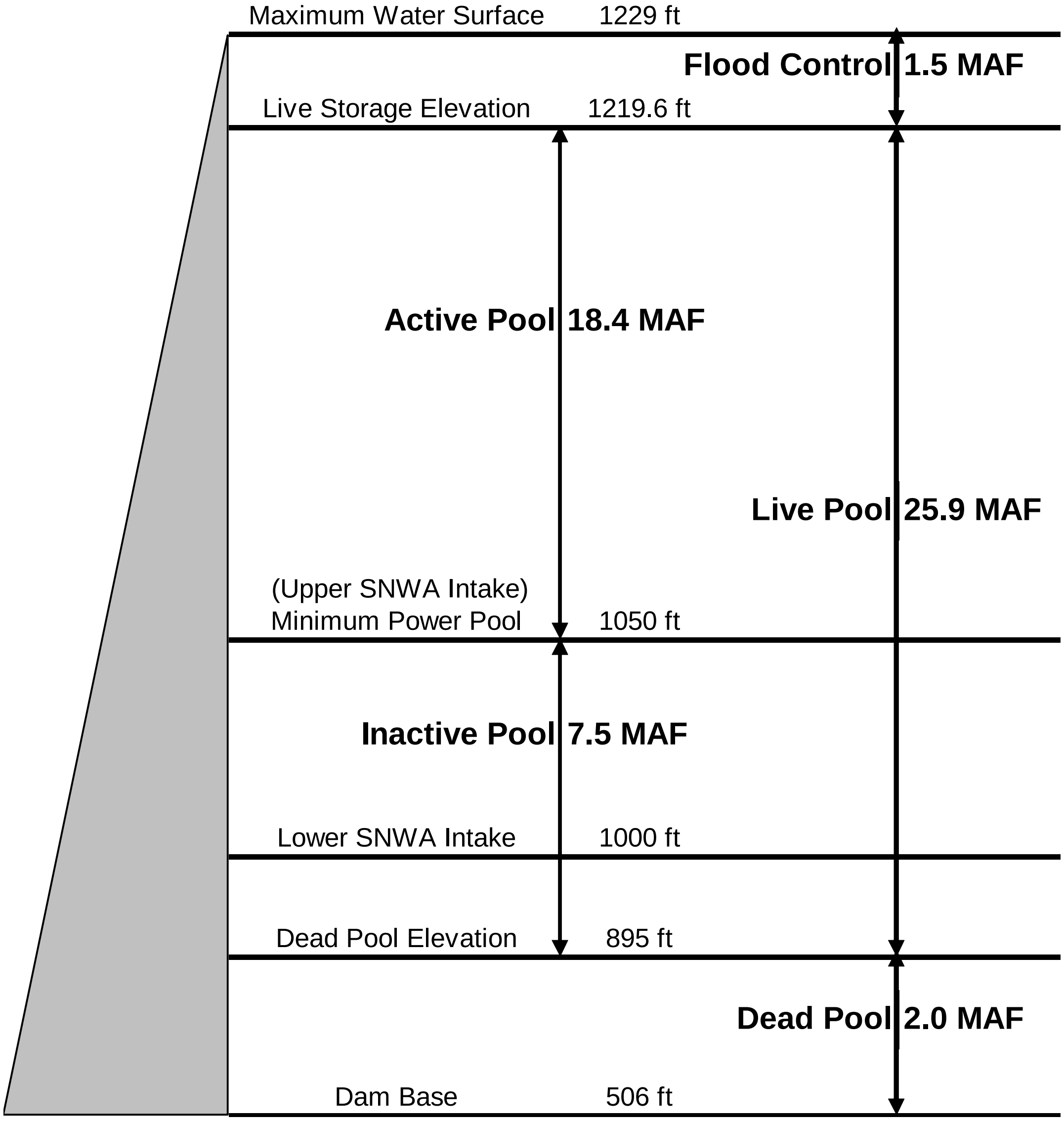


Figure A.3 Lake Mead storage and elevation profile

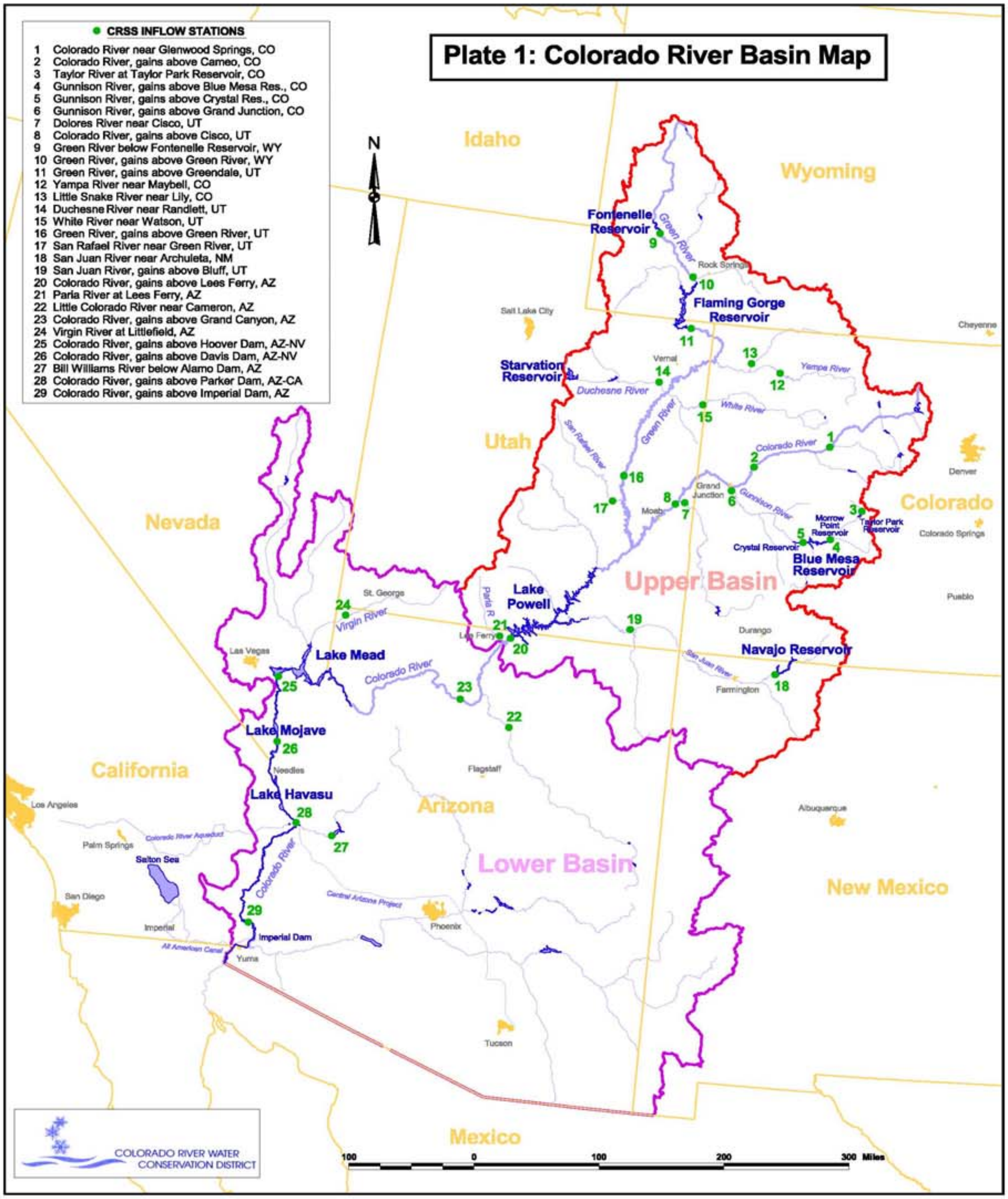


Plate 1: Colorado River Basin Map

● CRSS INFLOW STATIONS

1 Colorado River near Glenwood Springs, CO
2 Colorado River, gains above Cameo, CO
3 Taylor River at Taylor Park Reservoir, CO
4 Gunnison River, gains above Blue Mesa Res., CO
5 Gunnison River, gains above Crystal Res., CO
6 Gunnison River, gains above Grand Junction, CO
7 Dolores River near Cisco, UT
8 Colorado River, gains above Cisco, UT
9 Green River below Fontenelle Reservoir, WY
10 Green River, gains above Green River, WY
11 Green River, gains above Greendale, UT
12 Yampa River near Maybell, CO
13 Little Snake River near Lily, CO
14 Duchesne River near Randlett, UT
15 White River near Watson, UT
16 Green River, gains above Green River, UT
17 San Rafael River near Green River, UT
18 San Juan River near Archuleta, NM
19 San Juan River, gains above Bluff, UT
20 Colorado River, gains above Lees Ferry, AZ
21 Paria River at Lees Ferry, AZ
22 Little Colorado River near Cameron, AZ
23 Colorado River, gains above Grand Canyon, AZ
24 Virgin River at Littlefield, AZ
25 Colorado River, gains above Hoover Dam, AZ-NV
26 Colorado River, gains above Davis Dam, AZ-NV
27 Bill Williams River below Alamo Dam, AZ
28 Colorado River, gains above Parker Dam, AZ-CA
29 Colorado River, gains above Imperial Dam, AZ