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Technical Memorandum | Final

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Introduction

This Technical Memorandum summarizes information developed as part of Task 8 of the Colorado River Water Availability Study (CRWAS or Study).

The objective of Task 8 is to analyze Colorado River Compact provisions based on previous investigations of the current Compact setting and in relation to implementation of recent guidelines.

This memo is associated with subtask 8.6 (Summarize Compact Effects) and describes the methods, analysis and results of the basin-wide water availability analysis. Subsequent sections of this technical memorandum discuss: 1) the requirements of CRWAS, 2) a description of the analytical methodology, 3) a summary of results of the analysis, and 4) references.

Requirements of CRWAS

The CWCB directed that Task 8 should produce estimates of the amount of consumptive use, above existing levels, that can occur within Colorado under certain compact assumptions ("water available for future consumptive use"). To accomplish this, Task 8 also required estimating the amount of flows that may potentially be required to meet projected demands in the Upper Colorado River Basin while satisfying cumulative flow requirements based on certain assumptions of the Colorado River Compact.

Compact Assumptions

In addition to hydrologic variables, the technical evaluation of the remaining water available for future consumptive use in Colorado is influenced by consideration of the documents that govern apportionment and management of some portions of the Colorado River (referred to as the "Law of the River"). Although these documents are interpreted differently by the stakeholders who are potentially affected by their application, this Study sets forth a quantitative estimate of the amount of consumptive use, above existing levels, that can occur within Colorado under certain compact assumptions. Such assumptions are for Phase I technical purposes only and do not represent any policy or legal position of the State of Colorado.

Using these assumptions, the Study incorporates into the modeling bounding values for Lee Ferry flow obligations of 75 MAF (representing the obligation at Lee Ferry with no Mexico treaty deficiency) and 82.5 MAF (representing the obligation at Lee Ferry with a maximum treaty deficiency such that the Upper Division must supply one-half of the entire treaty obligation in every year). In addition, for purposes of this Study only, the models also incorporate assumptions concerning the distribution and allocation of Colorado River water among the Upper Division States. Specifically, the models adopt the calculations of Upper Basin water use from the 2007 Hydrologic Determination (U.S. Department of the Interior, 2007), and assumes that all Upper Basin states will be physically using their full apportionments.

Where to find more detailed information:

More detail on the provisions of relevant documents in the Law of the River can be found in CRWAS Technical Memorandum Task 8.1 – *Summarize Key Issues*, available at http://cwcb.state.co.us/ .

Figure 1 provides a reference to the physical arrangement of the important locations on the Colorado River relevant to the accounting of the cumulative flow requirement of the Colorado River Compact, in the context of the Colorado River Basin.

Figure 1 – Colorado River Basin and Important Locations near Lee Ferry

Methodology

CRWAS Technical Memorandum Task 8.2 – *Colorado River Compact Overview and Analysis, Approach* described an approach for estimating the quantity of supplementation flows (i.e, additional flows potentially required to meet projected water demands in the Upper Basin while simultaneously meeting the assumed bounding values for cumulative flow requirements) using the Bureau of Reclamation Colorado River Simulation System (CRSS) model. Subsequently, Phase I analyses included an estimation of the amount of water available for use in the Upper Basin while complying with the Colorado River Compact and an estimation of water available for future consumptive use by Colorado, using certain assumptions. Two methods of analysis were used to assure there is no underestimation of the physical ability of Colorado to consumptively use water. The two methods of analysis used were: 1) the existing CRSS and 2) a simulation based on the mass balance analysis used in the 2007 Hydrologic Determination. These methods of analysis were used because they are recognized methodologies and they are readily available. In so doing, this Study and the state of Colorado have adopted neither the methodology nor the assumptions of the CRSS or the Hydrologic Determination.

Initial analyses gave indications that the CRSS model may underestimate the ability of Upper Basin states to put their full demand for water physically to use under conditions that are drier than conditions experienced over the historical period. Accordingly, the results from the CRWAS mass balance analysis were used as the basis for quantifying the amount of water available for future consumptive use in Colorado under specific compact assumptions.

The CRWAS mass balance analysis is described below. The CRSS approach is described in Appendix A.

Hydrologic Determination Mass Balance Analysis

Section 11(a) of the Navajo Indian Irrigation and San Juan-Chama Projects Authorizing Act (P.L. 87-483) (1962) requires the Secretary of the Interior to determine "by hydrologic investigations" that there is enough water available to New Mexico under its Upper Colorado River Basin Compact allocation prior to executing any long-term contract for water stored in Navajo Reservoir.[1] In order to utilize an existing methodology for planning purposes, this Study utilized portions of the 2007 Hydrologic Determination (hereinafter “Hydrologic Determination”; U.S. Department of the Interior, 2007). In so doing, this Study and the state of Colorado have adopted neither the methodology nor the assumptions of the Hydrologic Determination.

The Hydrologic Determination employed a mass balance analysis, the results of which are provided in Appendix A of that document. The mass balance analysis encompassed the Upper Basin above the Lees Ferry gauge and was conducted on an annual basis; for each year it accounted for all inflows above Lees Ferry, any carryover storage in Upper Basin reservoirs[2],

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[1] *See* P.L. 87-483, § 13(c) (1962) ("No right or claim to the use of the waters of the Colorado River system shall be aided or prejudiced by this Act, and Congress does not, by its enactment, construe or interpret any provision of the Colorado River compact, the Upper Colorado River Basin compact, the Boulder Canyon Project Act, the Boulder Canyon Project Adjustment Act, the Colorado River Storage Project Act, or the Mexican Water Treaty…").

[2] The analysis represents storage in 66 Upper Colorado River Basin reservoirs.

shared evaporation (from Lake Powell, Flaming Gorge and the Aspinall Unit), water use in the Upper Basin (including reservoir evaporation necessary to support beneficial uses) and flows below Lees Ferry, including spills and reservoir releases.

The mass balance analysis encompassed the entire Upper Basin above the Lees Ferry gauge. It used the following relationship:

Year-end Storage = Inflow
+ Carry-over Storage
- Evaporation
- Nominal Lee Ferry Flow
- Upper Basin Use
- Spills

Year-end Storage and *Carry-over Storage* represent the contents in 66 federal and non-federal storage facilities above Lees Ferry. In calculating storage quantities the capacity of Lake Powell was reduced to reflect the amount of sedimentation estimated to occur by the 2060 planning horizon used in the Hydrologic Determination.

Two cases regarding the utilization of reservoir storage capacity were simulated in the Hydrologic Determination: 1) storage space in power pools was not used (i.e. the power pools were "protected") or 2) water stored in the power pools was released to meet flow shortfalls before beneficial consumptive uses were curtailed.

Inflow is the total natural flow entering the Colorado River above Lees Ferry. In the Hydrologic Determination inflow does not include flow from the Paria River. In the Hydrologic Determination inflows were based on the natural flows from the CRSS model input data, with some adjustments made to flows from 1971 through 1980 to reflect recalculation of historic irrigation depletions using the Soil Conservation Service (SCS) modified Blaney Criddle method with SCS effective precipitation.

Evaporation is the amount of evaporation from Lake Powell, Flaming Gorge Reservoir and the Aspinall Unit. Evaporation from these facilities is shared among the Upper Basin states while evaporation from other reservoirs is chargeable to the state in which the reservoir is located or according to the use of water from the reservoir. Evaporation was modeled in the Hydrologic Determination using a regression equation relating historic evaporation from Lake Powell, Flaming Gorge Reservoir and the Aspinall Unit to the aggregate historical storage volume in those reservoirs plus Navajo Reservoir (CRSP reservoirs). Reservoir storage was assumed to be distributed evenly in all reservoirs in proportion to reservoir capacity; i.e. each reservoir was assumed to be at the same fraction of its capacity. Accordingly, the amount of storage in the reservoirs used as a basis for estimating shared evaporation was estimated as a constant fraction of the total Upper Basin storage volume.

Nominal Lee Ferry Flow represents the amount of water flowing to the Lower Basin past Lee Ferry in one year under normal conditions. Two bounding values for the Nominal Lee Ferry Flow were used, 7.5 MAF and 8.25 MAF, corresponding to the two assumptions regarding the Lee Ferry 10-year cumulative flow obligation of 75 MAF and 82.5 MAF. The physical flow passing Lee Ferry is the sum of the Nominal Lee Ferry Flow and spills from Glen Canyon Dam. The Hydrologic Determination performed the mass balance analysis independently for each year of the inflow record and therefore did not take into account the 10-year cumulative flow provision of the Colorado River Compact. In the Hydrologic Determination, this did not affect results because more than 10 years passed between any Glen Canyon Dam spill and the next shortfall.

Upper Basin Use is the consumptive use of water charged to the Upper Basin states. It includes depletions arising directly from beneficial uses, reservoir evaporation charged to the individual states, and losses. Upper Basin use was set at different levels for each of the two cases of the cumulative flow obligation at Lee Ferry and for each of the two cases regarding use of or protection of power pools, and allowable shortages. The Table 1 shows the different values used for Upper Basin Use (Department of the Interior, 2007; Appendix A).

Table 1
Hydrologic Determination Scenarios of Upper Basin Use

Scenario	Avg. Annual Lower Basin Release, MAF	Use of Power Pools	Shortages Allowed	Avg. Annual Upper Basin Use, MAF
1	8.25	Protected	None	5.50
2	8.25	Protected	6%	5.79
3	7.5	Protected	None	6.30
4	7.5	Protected	6%	6.57
5	8.25	Used	None	5.72
6	8.25	Used	6%	5.98
7	7.5	Used	None	6.47
8	7.5	Used	6%	6.76

In 1999 the Upper Colorado River Commission (UCRC) adopted depletion estimates for the states of the Upper Division. In those estimates, total consumptive use in the Upper Basin exclusive of CRSP evaporation projected for 2060 was 5.415 MAF and shared evaporation from CRSP storage units was 0.546 MAF. The UCRC revised the estimates for the year 2060 on December 12, 2007 to 5.573 MAF; exclusive of CRSP evaporation (no value for shared evaporation was included in those estimates). All of the analyses used in the CRWAS mass balance analysis represented Upper Basin water use in excess of the depletion estimates adopted by the UCRC and assumed all Upper Basin states would use their entire apportioned amount.

Effects of the Structure of the Hydrologic Determination Mass Balance Analysis

The structure of the Hydrologic Determination Mass Balance Analysis has the following effects:

- In each year, all natural flow above Lees Ferry and all water in storage, including water in Lake Powell, less reservoir evaporation and less the amounts that flow to the Lower Basin, is available for diversion and use anywhere in the Upper Basin.
- All Upper Basin states are represented as fully using their apportioned amount.
- Hydrologic conditions in the Colorado River Basin are those experienced from 1906 – 2000.

Simulation Cases for Hydrologic Determination Mass Balance Analysis

Four simulation cases were analyzed in the Hydrologic Determination Mass Balance Analysis, consisting of combination of the following:

- Reservoir power pools: Two cases were simulated, one where power pools were protected and one where power pools were used.
- Allowed shortages: Two cases were simulated regarding shortages: 1) that no shortages would be allowed and 2) that shortages of up to 6% of the Upper Basin Use would be allowed during the critical period from 1953 through 1977.

Application of the Hydrologic Determination Mass Balance Analysis to CRWAS

The Hydrologic Determination mass balance analysis, subject to some modifications noted below, was implemented in computer codes that would automatically apply the analysis to each of the 100 56-year traces in the extended historical hydrology and to each of the ten sets of 100 56-year traces in the extended data sets representing the alternate hydrology of climate change. This implementation of the Hydrologic Determination mass balance analysis is referred to as the CRWAS mass balance analysis.

Some elements of the methodology of the Hydrologic Determination were not documented and were established based on the results shown in the report (Department of Interior, 2007; Appendix A).

- The ratio of total storage to CRSP reservoir storage was not documented in the Hydrologic Determination and was estimated from the published results.
- Applying the regression equations published in the Hydrologic Determination did not replicate the evaporation estimates published in the Hydrologic Determination. Therefore, a relationship between evaporation and CRSP reservoir contents was established based on the published results. (This relationship is similar to one published relationship; it is possible that the published value contains a typographical error.)
- The published results indicated that in some but not all years two identical sequential evaporation values were used. There was no explanation of this behavior in the Hydrologic Determination, so evaporation calculations were made on an annual basis. Average evaporation calculated in this manner agreed very closely with the evaporation published in the Hydrologic Determination.

Two modifications were made to the Hydrologic Determination mass balance analysis.

- The analysis employed a 10-year cumulative volume passing Lee Ferry and, in instances where storage in the Upper Basin is emptied, assumes that: 1) when the cumulative 10-year volume is greater than the assumed 10-year cumulative flow obligation at Lee Ferry, the Nominal Lee Ferry flow was reduced in order that consumptive use in the Upper Basin will not be reduced, and 2) the amount of Upper Basin consumptive use is reduced in the mass balance analysis when doing so is necessary to prevent the cumulative 10-year volume from falling below the assumed 10-year cumulative flow obligation at Lee Ferry.
- The analysis accounted for an additional 20,000 acre-feet per year at Lee Ferry. The Hydrologic Determination was based on flows at Lees Ferry. The CRWAS mass balance

analysis was conducted for flows at the Compact Point at Lee Ferry, just below the mouth of the Paria River. Lee Ferry flows differ from flows at Lees Ferry by the flow in the Paria River, which is about 20,000 acre-feet per year on average from 1950 through 2005.

Initial Reservoir Contents

The Hydrologic Determination simulated the reservoirs as starting full. The results of the Hydrologic Determination were not sensitive to initial reservoir contents because of a sequence of wet years early in the historical flow record, but many of the traces simulated in the re-sequenced hydrology would exhibit critical conditions early in the trace and in these cases the results would be sensitive to initial conditions. Because the CRWAS mass balance analysis represented the 10-year cumulative flow provision, an initial condition for that state variable was also required for each run. The CRWAS mass balance analysis was run iteratively in order to establish initial conditions that did not introduce bias into the water balance. In the first iteration initial reservoir contents were set to be full and the initial 10-year cumulative flow record was set to consist of 10 years of the annual Lee Ferry flow obligation. Subsequent iterations were initialized with the values of these two variables from the end of the previous iteration. Iteration was stopped when both variables did not change by more than 5% during a simulation. In all cases not more than two iterations were required for convergence.

Modeling Scenarios

The Study quantified the amount of water available for use in the Upper Basin while complying with the Colorado River Compact, using certain assumptions, for three time frames, one representing historical hydrologic conditions, one representing projected climate conditions in the 2040 time frame, and one representing climate conditions in the 2070 time frame. Each climate condition analysis was modeled under each of the two bounding values of the assumed cumulative flow obligation.

The historical climate condition was represented by one ensemble of inflows (extended historical hydrology); while each projected climate condition was represented by five alternate ensembles of inflows.

Where to find more detailed information:

Details on the extended historical hydrology are provided in CRWAS Technical Memorandum *Task 6.4 Methods for Alternate Hydrology and Water Use* and CRWAS Technical Memorandum *Task 6.7 Summarize Alternate Historical Hydrology.* Details on the projected climate conditions are provided in the CRWAS Technical Memorandum *Task 7.5 Climate Change Approach, Hydrology Model Selection* and CRWAS Technical Memorandum *Task 7.12Statistical Analysis of Climate Impacts.*

Thus, the model was run against eleven ensembles of inflows. For each ensemble of inflows, two separate runs were made to represent the two bounding values of the cumulative flow obligation. Therefore, these twenty-two cases, each of which consisted of one ensemble containing 100 individual traces, resulted in the model being run for a total of 2200 traces.

Two different scenarios regarding Upper Basin water use, the assumed compact obligations and use of the CRSP power pools were evaluated. These are shown in Table 2.

Table 2
Scenarios Used in CRWAS Mass Balance Analysis

Hydrologic Determination Scenario	Avg. Annual Lower Basin Release, MAF	Use of Power Pools	Avg. Annual Upper Basin Use, MAF
6	8.25	Used	5.98
8	7.5	Used	6.76

The amount of Upper Division consumptive use in a given year may be reduced when necessary to prevent the 10-year cumulative flow from falling below the bounding values assumed for Colorado River Compact compliance.

Estimation of Water Available for Future Consumptive Use

Model results from the CRWAS mass balance analysis included the annual volume of consumptive use available to the Upper Basin under compact assumptions. Colorado's share of the amount of water available for future consumptive use in the Upper Basin was calculated by subtracting Arizona's share (50 KAF) from the basin-wide amount and multiplying the remainder by Colorado's percentage share, set out in the Upper Colorado River Basin Compact, which is 51.75%.

Estimation of Current Colorado Consumptive Use

Estimates of current levels of consumptive use in Colorado were obtained by applying the StateMod models to simulate current conditions. StateMod was used to estimate current levels of consumptive use in Colorado based on the 56-year hydrologic period 1950 through 2005. Estimates of agricultural demand based on current levels of irrigated acreage and historical climate conditions, and current levels of municipal and industrial demands, were superimposed on historical hydrology. StateMod then estimated diversions and associated consumptive use, and reservoir contents and evaporation, based on water available to currently perfected water rights. Basin-wide consumptive use estimates have been adjusted to exclude shared evaporation from the Aspinall Unit Reservoirs, which are considered "system" losses, and exports to New Mexico through the San Juan-Chama Project, which are chargeable to that state.

The result is an estimated average consumptive use of 2.6 MAF. This estimate represents the current capacity of the water supply systems within Colorado, when used to their full capability, both legally and physically. For this reason, this estimate is higher than the estimates of actual consumptive use used by the CWCB of about 2.3 MAF as of 2010 (projected from 2004), but it is consistent with values of current consumptive use that have been used as the basis for other estimates of water available for future consumptive use in Colorado.

Modeling Considerations

Initial analyses gave indications that the CRSS model may underestimate the ability of Upper Basin states to put their full demand for water physically to use under conditions that are drier than conditions experienced over the historical period. The structure of the CRWAS mass balance analysis puts no limitation on physical use of water. While this may overestimate physical use, it ensures that the assumptions concerning the Colorado River Compact are the sole limitation to water use in the Upper Basin, which results in the best estimate of the water available for future consumptive use in Colorado. There may be other physical or legal limitations that may limit consumptive use within Colorado, but Phase 1 of this Study did not analyze those limitations. Accordingly, the results from the CRWAS mass balance analysis were used as the basis for quantifying the amount of water available for future consumptive use in Colorado under specific compact assumptions.

Summary of Results

Figure 2 shows, for different hydrologic cases and for the two bounding values of the compact assumptions used for purposes of this Study, the range of potential outcomes of the amount of water available for future consumptive use. Consistent with previous analyses, the values in Figure 2 include Colorado's share of CRSP evaporation, which is part of the Upper Basin's right to use Colorado River water. The previous analysis referred to in Figure 1 was conducted by Randy Seaholm, of the CWCB staff (CWCB, 2009).

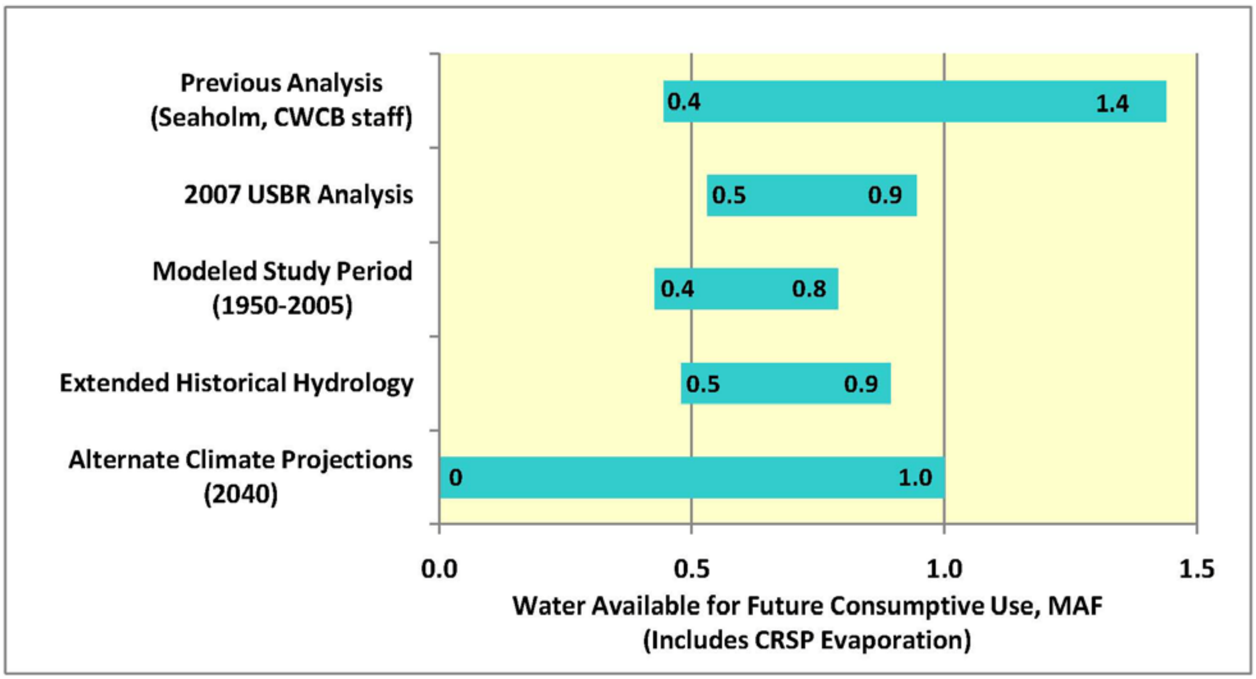

Figure 2 – Water Available for Future Consumptive Use by Colorado (MAF)
Revised from preliminary charts presented from January through March 2010 to CWCB, IBCC, Joint Agriculture Committee, and Colorado Water Congress

The analyses presented above provide a useful first step in characterizing the general magnitude of possible outcomes regarding the amount of water available for future consumptive use in Colorado. Assumptions as to the Law of the River used for purposes of this Study do not constitute Colorado's interpretation of any law or policy. The results demonstrate the broad uncertainty inherent in projections of future hydrologic conditions and in future interpretations of the terms of the compacts and the Law of the River. Consideration of the limitations of the current state of scientific knowledge regarding future climate and, to a lesser degree, regarding the methods and computer tools currently being used to support inter-state Colorado River basin water management decisions, will help the State focus future phases of the CRWAS and other studies of Colorado's water availability.

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Appendix A. CRSS Model Approach

One of the two approaches to estimate the amount of water available for use in the Upper Basin, while complying with certain compact assumptions, uses the Bureau of Reclamation Colorado River Simulation System (CRSS) model to simulate conditions in the Colorado River System under historical hydrologic conditions and under projected future climate conditions.

The CRSS model is developed and maintained by the Bureau of Reclamation (Reclamation). The CRSS currently exists within the RiverWare modeling framework which was developed at the Center for Advanced Decision Support for Water and Environmental Systems (CADSWES) at the University of Colorado. The RiverWare framework allows for alternative policies to be incorporated with relative ease while maintaining all other assumptions constant.

CRSS simulates the operation and management of the primary reservoirs in the Colorado River Basin under projected hydrologic conditions and variable future demands. CRSS simulates the Basin through a network that includes 29 inflow locations, 12 reservoirs and 171 existing or potential demand locations. The operation of the reservoirs and water deliveries is simulated through a set of prioritized logical statements or “rules” that simulate the legal framework and operational policies. Reclamation maintains the most current naturalized historical hydrologic inflows, future demand schedules, and Reclamation’s interpretations of legal and operational policies within the model. These inputs are dynamic through the execution of the model starting from initial system conditions and incorporating variable demands and policies throughout the run period of the model.

Although each of the Colorado River stakeholders may take issue with certain assumptions incorporated in the CRSS model, it is the most widely-used modeling tool in the basin. CRSS also provides some flexibility for the purposes of CRWAS because of the relative ease with which changes can be made to assumptions about future hydrology, water use, and operating rules.

Estimates of the impacts of projected climate change are made by comparison between simulated historical conditions and simulated future conditions. Each simulation was conducted using an ensemble of 100 traces generated with stochastic methods as described in CRWAS Technical Memorandum *Task 6.4 Methods for Alternate Hydrology and Water Use*.

Details of these procedures and the modifications to the CRSS model are provided below. Assumptions made are for modeling purposes of Phase I of the CRWAS only and do not represent a policy of the state of Colorado.

- CRSS was run on a monthly time step using a 56-year inflow trace. Each analysis consisted of 100 model runs of an ensemble of inflow traces.
- A running 10-year volumetric accumulation of flows through Lee Ferry was determined for each month by summing the previous 119 months of modeled flows at Lee Ferry with the proposed flow for the current month.
- The 10-year volumetric accumulation of flow through Lee Ferry was then compared to the assumed cumulative flow obligation at Lee Ferry under the bounding values, demands and other assumptions described below. The required flow for each month was determined as the amount of additional water required to satisfy the 10-year volumetric assumed cumulative flow obligation.

- Any required additional flow, using the compact assumptions, was first supplied by increasing releases from Lake Powell above that which is specified by existing operational policies within CRSS. If the quantity of water in Lake Powell was insufficient to meet the cumulative flow target using the bounding values identified below, then supplemental water was artificially introduced into the model, immediately above Lee Ferry. The amount of supplemental water was determined as the minimum of the remaining deficit in the assumed cumulative flow obligation and the total amount of depletions occurring in the Upper Basin during the current month. For Phase I of the CRWAS, no assessment was made of the degree to which present perfected rights would affect these results; neither was water in storage in the Upper Basin reservoirs other than Lake Powell released to help satisfy the cumulative flow obligation. Both of these constraints in the current analysis should be considered by the State in reviewing the Phase I work and in scoping future CRWAS phases or other State-sponsored studies.
- Two bounding values for the cumulative flow obligation were used[3], 82.5 MAF and 75 MAF.
- For each model run, a time series of the annual volumes of required supplemental water was generated as output from the model and was analyzed to determine an empirical probability distribution of expected supplementation requirements for a given set of assumptions.
- According to agreements currently in place, the Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead (Guidelines) will expire in 2026. In 2020, however, the Secretary of the Interior is required to initiate a formal review of the Guidelines to determine whether and to what extent the Guidelines should be modified and/or extended. Should the Guidelines expire prior to new criteria being developed and implemented, the Bureau of Reclamation will revert back to the strategies employed under the Long Range Operating Criteria prior to 2007 to operate Lake Powell and Lake Mead. To isolate possible climate change impacts from those caused by changes in operating criteria, the existing Guidelines were used throughout the 56-year hydrology traces in this Study.

Application of the CRSS Model

The CRSS model was modified as described in the following paragraphs. These modifications are for the purposes of Phase I of the CRWAS only and do not represent a policy of the state of Colorado:

- CRSS typically simulates variable depletions from the river starting at current conditions and increasing throughout the model run. In this Study, depletions by water users in the Upper Basin were assumed constant at the levels identified for 2060.
- CRSS simulates the provisions of the Guidelines until they expire in 2026. Although the guidelines are set to expire, for this Study, the Guidelines were simulated for the entirety of each trace to isolate possible climate change impacts from those caused by operational changes. Equalization elevations identified in the Guidelines from 2008 to 2026 were extrapolated by Reclamation to 2060.

[3] Separate runs of the model were used to quantify supplemental flows under the two bounding cumulative flow obligations.

- Modeled reservoir objects and rules for both Lakes Powell and Mead were modified to eliminate numerical instabilities in the model during extreme conditions such as complete evacuation of the reservoirs and flooding conditions not previously tested by the model. These modifications were made to allow the model to solve completely and do not have significant effects on the outputs.
- Model rules were enhanced to calculate a monthly deficit in meeting the assumed cumulative flow obligation by comparing an initial cumulative 10-year flow (calculated based on the current CRSS operating rules), to the 10-year assumed cumulative flow obligation. If the initial 10-year cumulative flow is less than the assumed 10-year cumulative flow obligation, a positive deficit is recorded.
- Model rules were modified to make an additional release from Lake Powell to meet any 10-year cumulative flow deficit. In the event that the amount of water in Lake Powell was insufficient to make the entire additional release, a supplemental flow requirement was calculated based on the remaining shortfall. The amount of the supplemental flow was limited to the total amount of depletion occurring in the Upper Basin in that month.
- Model rules were modified to simulate the introduction of the supplemental flow immediately above Lees Ferry; and
- Additional output was specified to write out the amounts of supplemental flow and other relevant simulated model output.

Initial Reservoir Levels and Preceding 10-year Flows

For each CRSS run initial reservoir elevations and historical flows at Lee Ferry during the 10-years prior to the model simulation period must be specified. Sensitivity analyses indicated that the effects of these initial conditions were negligible after the first 10 years of simulation. To reduce the influence of the initial reservoir levels and preceding 10-year flows, the inflows for each trace were extended to a total length of 66 years by duplicating the initial 10 years of inflows and adding those years to the beginning of the trace. The initial 10 years of results were excluded from the subsequent analysis and therefore the results were based strictly on the 56 years of modeled inflows.