Colorado River Risk Study: Phase II Task 2 Report

Final

April 18, 2018

Updated: August 1, 2018

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Prepared for the Colorado River District and Project Participants

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Disclaimer

The findings presented herein are for discussion purposes only, and do not represent the official position of any entity with respect to factual or legal matters concerning the Colorado River.

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I. Introduction

A. Background

The Colorado River Basin is in the midst of a drought that began in 2000 and continues today. Average naturalized flows at Lee Ferry during the period 2000-2017 are approximately 12.6 maf (million acre-feet), or 4.0 maf less annually than would be needed to meet the full compact allotments of the seven basin states and deliveries to Mexico. Recent droughts have significantly reduced storage levels in Lake Powell. If these droughts were to repeat themselves today, the viability of Lake Powell would be threatened (Figure 1). Drought Contingency Plans (DCP) are being developed for both the Upper and Lower Basins (See Hydros 2015 report "Summary Report on Contingency Planning in the Colorado River Basin"). While those plans, if implemented, would reduce the risk of a compact deficit or critically low storage levels at Lake Powell, they do not completely eliminate the risk for the Upper Basin States.

Concurrent with the DCP efforts, Colorado completed its Water Plan (https://www.colorado.gov/pacific/cowaterplan/plan), which lays the foundation for a secure water supply for the State. Point #4 of the Plan's Seven Point Framework is to take actions that minimize the risk of a Colorado River Compact curtailment. That objective, plus concerns voiced by the Colorado River Basin Round Tables (BRTs) in a joint meeting in December 2014, provided the catalyst for this work.

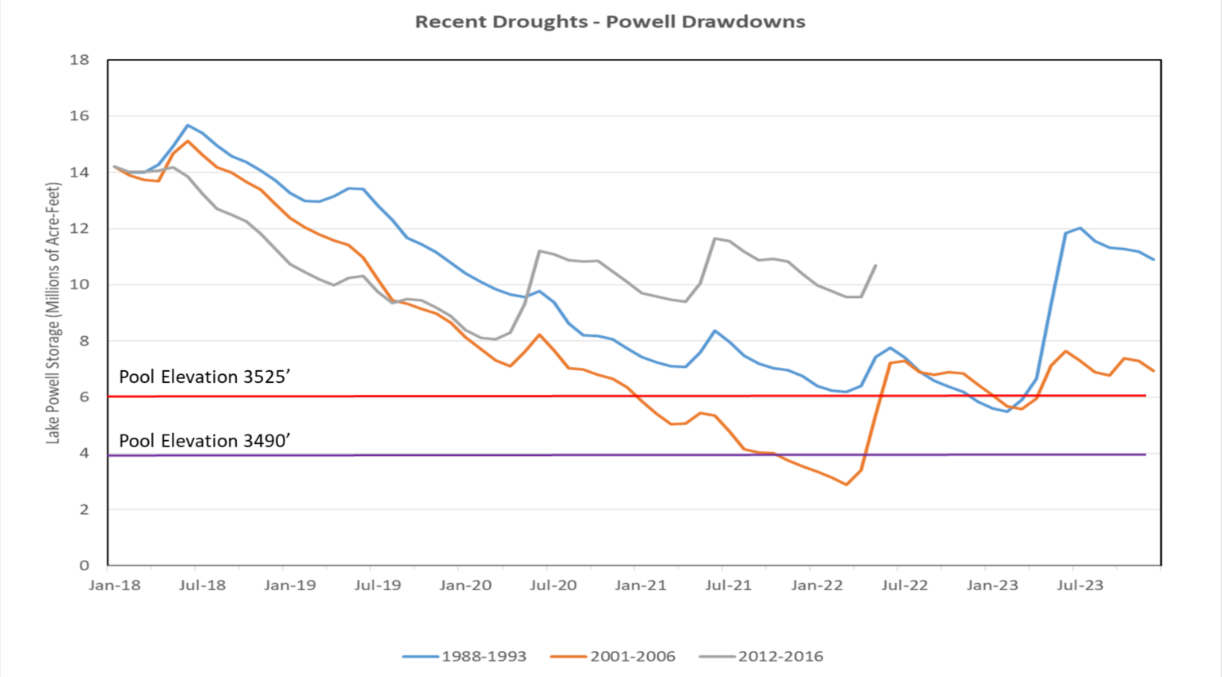

Figure 1. Past Lake Powell drawdowns superimposed on January 2018 initial conditions.

B. Project Phasing

The project has been structured as a multi-phase process. Phase I work was completed in the fall of 2016, and is documented in the (draft) report "Colorado River Risk Study – Phase I Summary Report" dated October 18, 2016. Phase II was initiated in the spring of 2017, and consists of two distinct tasks. Task 1 addresses questions that were raised during the Phase I process specific to the modeling performed using CRSS. A supplemental document to the Phase I report describes those analyses.

This report documents the Phase II Task 2 work, which focuses on the use of StateMod to address in-state questions related to demand management, resulting yields of conserved water, water banking, and the potential to couple StateMod with CRSS. The report also outlines recommendations for model enhancements and provides a template for simulation of demand management within Colorado coupled to "big river" operations as modeled in CRSS.

C. Basin Roundtable Participation and Communication

The CWCB (Through the four west slope BRTs), Colorado River District, and Southwestern District contributed funding to Phase II. Project guidance and communications were handled through two stakeholder committees. The Technical Advisory Committee (TAC) consisted of Hydros Consulting, representatives from sponsoring roundtables, funding sponsors, and CWCB staff. This committee worked closely with Hydros on refinement of model details, StateMod model investigations, coupling of CRSS and StateMod, and other technical issues.

The Outreach Committee acted as a conduit for dissemination of project status reports and results, and as a mechanism for feedback from a broader set of stakeholders. The committee consisted of Hydros staff, representatives from sponsoring roundtables, representatives of the funding sponsors, CWCB staff, and other interested parties. This group met 4 times during Phase II, via webinar, and generally had between 30-50 participants.

Presentations of project results were also made to the sponsor agencies in-person, and the final meeting of Phase II was a joint west-slope basin round table meeting in Grand Junction on April 25, 2018.

D. StateMod as Modeling Framework

Phase I and Phase II Task 1 of this project used Reclamation's CRSS model to simulate Colorado River operations, including drought contingency plans, demand management and water banking. While CRSS is very good at simulating "big river" operations across the entire basin (e.g., 2007 Interim Guidelines), its ability to simulate demand management is limited. Because CRSS aggregates many water users and diversion structures into lumped model nodes, does not simulate water right administration, and does not include many significant reservoirs within Colorado, it cannot be used to accurately analyze the availability of water, impact to stream flows, and state line yields from specific demand management activities. To address these critical aspects of demand management, this work utilizes StateMod (http://cdss.state.co.us/software/Pages/StateMod.aspx), part of Colorado's Decision Support System for water resources. Questions specific to demand management that cannot be addressed in CRSS include:

- What is the timing and magnitude of increased river flows when specific water users participate in conservation actions to create demand management water?
- How does the location of participants in a demand management program impact yield?
- How does yield change with or without a mechanism to shepherd water?
- How do yields from demand management activities vary across basins, and with different hydrologic year-types (wet, average, dry)?
- Is there existing storage that could be used to store conserved water, and what is the timing and volume of available storage space throughout the basin?

II. Demand Management

Results from Phase I (Figure 2) indicated that under certain drought sequences, as seen in the early part of this century, significant volumes of water could be needed to maintain Lake Powell elevations at or above elevation 3525. These volumes would be required even AFTER taking in to account the release of stored water from other CRSP reservoirs as anticipated by the Upper Basin's DCP. In Phase I we conceptualized the creation of this water as voluntary and compensated conservation actions by upper basin states that would result in reduced consumptive uses and hence increased flows to Lake Powell. These actions were modeled as single year reductions (with the possibility of consecutive years of conservation during extended drought), for purposes of identifying required volumes. There appears to be broad consensus, based on feedback from various groups including the Colorado River Water Bank Work Group, the System Conservation Pilot Project, and the UCRC, that single-year conservation volumes of the magnitudes shown in Figure 2 are likely not feasible under a voluntary program.

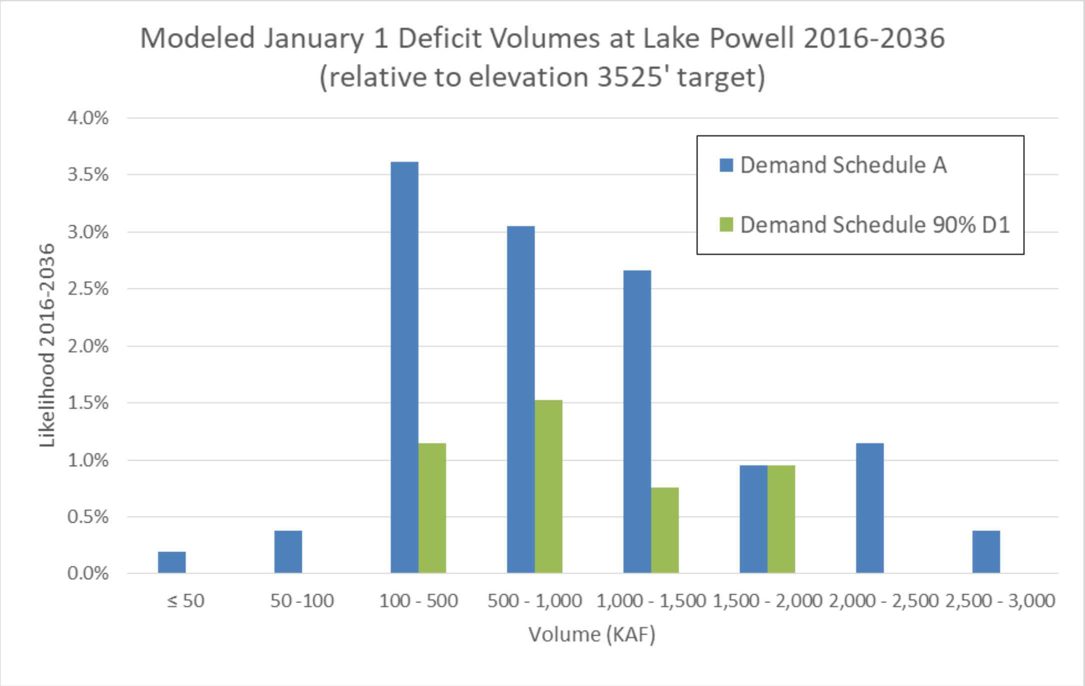

Figure 2. January 1 volumes required AFTER CRSP drought operations to maintain Powell at 3525'. Simulations using Stress Test (1988-2012) hydrology.

An alternate approach to creating conserved water to mitigate the risk to Lake Powell is to create a water bank, into which conserved consumptive use water could be deposited pro-actively over a number of years. This water bank would then be available if and when needed, as additional water supply to preserve critical elevations at Lake Powell. This bank would be used only if the drought operation of CRSP reservoirs was insufficient to meet the target elevation at Lake Powell.

A. Factors Impacting Demand Management Yield

One of the most critical aspects in determination of the yield that can be achieved through demand management is the amount of decreed consumptive use that would occur with full levels of demand under the variable hydrologic conditions that occur from year-to-year in Colorado. Although the "stress test" period from 1988-2012 is a generally dry period, there are also a variety of average and wet years included within the period, and the analysis of results in this study presents the yields of demand management by year type to provide insight into the relationship between water availability and demand management yield for each of the West Slope basins.

B. Shepherding

Another factor that impacts the yield of demand management is whether or not the conserved water can be "shepherded" to storage. If water cannot be shepherded, some of the water saved from reductions in depletions by senior water users may be diverted by junior water users that would have otherwise experienced shortages, resulting in overall lower yields at the state line or location of the water bank. Unanswered questions relating to implementation of shepherding resulted in the decision to simulate demand management both with and without shepherding. Note that "shepherding" of previously stored waters is commonplace in Colorado, as is the movement of direct flow rights to alternate points of diversion, both of which have similarities to the demand management shepherding issue. It may be that the quantification of conserved consumptive use may present a bigger problem than shepherding itself, as defining specific foregone consumptive volumes that need protection could be difficult.

III. Proof of Concept in StateMod

Demand management simulations were carried out as proof-of-concept runs in each of the west-slope (Colorado River Basin) StateMod models. Preliminary results in terms of consumptive use reductions were in line with expected magnitudes for each basin, and comparison of results between basins highlighted some opportunities for future methodological enhancements.

A. Using StateMod to Simulate Reduced CU

The most recent version of the StateMod executable at the time of this study, version 15.00.01, was used for all simulations described here. The latest versions of each West Slope StateMod model data sets were also used:

1. 2015 Upper Colorado Model
2. 2015 Gunnison Model
3. 2015 San Juan / Dolores Model
4. 2015 White River Model
5. 2015 Yampa River Model

The input files for each of the models include hydrology from the years 1909-2013, which covers the "stress test" period of 1988-2012 that was used in Phase I CRSS simulations. The model runs were carried out for the full period of available hydrology, but the results presented here are extracted from the 1988-2012 "stress test" period in order to compare outputs directly with those developed by CRSS in Phase I.

Both the Baseline and Historical versions of each of the West Slope models were used to analyze the impacts of large-scale demand management programs.

1. Model Setup

To ensure that the desired levels of reductions in consumptive use were achieved, each of the models was switched from variable to fixed efficiency. When the models are run using fixed efficiency, soil moisture accounting cannot be used. The changes in consumptive use that resulted from turning off soil moisture use and switching to fixed efficiency were recorded and reviewed, and the changes were found to be similar across all basins. The differences in consumptive use resulting from these changes are tabulated by basin in Table 1. Generally, turning off soil moisture use results in decreased consumptive use, and switching from variable to fixed efficiency increases consumptive use. While these model changes will impact the total consumptive use, and could result in consumptive use higher than the crop irrigation requirement, it was a reasonable compromise in order to efficiently simulate the broad patterns of reduced consumptive use without requiring revisions to CIR and head gate demands through use of the CDSS TSTool. If specific water rights or irrigation ditches are identified for demand management in the future, use of TSTool to simulate changes in CIR and head gate diversions should be considered.

Table 1. Changes in Consumptive Use from Soil Moisture Use Removal and Fixed Efficiency

Model		No Soil Moisture Use (AF/yr)	Fixed Efficiency (AF/yr)
Yampa	Baseline	-7,201	+25,712
	Historical	-18,560	+13,616
White	Baseline	-590	+8,627
	Historical	-2,857	+6,643
Upper Colorado	Baseline	-77,124	+33,417
	Historical	-30,591	+49,322
Gunnison	Baseline	-16,616	+59,344
	Historical	-37,248	+14,285
San Juan and Dolores	Baseline	-16,630	+29,670
	Historical	-29,773	+10,300

In some cases, the switch to fixed efficiency required additional modifications to the models. These modifications were required when the additional depletions resulting from fixed efficiencies caused dry up points that prevented the models from functioning. In each case, the models stopped functioning while carrying out a “reservoir release to direct flow by exchange” operational rule (type 4). Table 2 lists the models that required this type of adjustment for fixed efficiency simulation to function, and the rules that had to be turned off in each case. The changes to depletions that result from turning these exchanges off cannot be directly calculated, because the exchanges cause the model run to abort. These exchanges are deactivated for the fixed efficiency depletion adjustments in Table 1.

Table 2. Exchange Rules Turned off to Enable Fixed Efficiency Simulation

Model		Rule ID	Rule Description
Upper Colorado	Historical	72038440.25	Vega Res to New Erie Canal Exchange
	Baseline	72038440.46	Vega Res to New Erie Canal Exchange
Yampa	Baseline	58042400.39	Yamcolo Res to Bijou Ditch Exchange
	Baseline	58042400.4	Yamcolo Res to Bijou Ditch Exchange

	Baseline	58042400.58	Yamcolo Res to Rossi High Line Ditch Exchange
	Baseline	58042400.59	Yamcolo Res to Rossi High Line Ditch Exchange

2. Demand Adjustments

Uniform reductions in direct-flow demands at levels of 5%, 10%, and 15% of total direct flow demands were simulated for each model. The methodology used for adjustment of demands varied between scenarios in which "shepherding" was or wasn't enacted as a component of the demand management plan, as described below in Section III.B. Demands for all direct flow diversions were altered as part of this process. These include direct-flow-only water rights, trans-basin diversions, and diversions with supplies that can be augmented through exchange or deliveries from storage. Diversions that use exchanges or deliveries from storage to augment their supply were only altered by changing the overall demand; the rules that operate the exchanges or deliveries from storage were not altered (except as noted in Table 2 above).

3. Additional Model Details

Each model was run for the entire period of available hydrology input, from 1909-2013, although summary and analysis of results focused on the stress test period from 1988-2012. The Historical and Baseline versions of each model were run for comparison purposes. Additional analyses were focused on the Baseline model versions, which superimpose future levels of estimated demand on historical hydrology. The results from the Historical model versions, which use each historical year's estimated demands and operations directly, were found to be similar to the Baseline results, especially for the stress test period.

B. Shepherding vs Non-Shepherding

In months where a (junior) water user would have experienced a shortage under normal operations, demand management by other users in the same basin may make additional water available to the (junior) water user, unless provisions are made to "shepherd" the water saved through demand management past the head gate of a junior user. It is worth noting that shepherding is a relevant concept regardless of the relative upstream/downstream positioning of junior and senior users, because a reduction in either downstream or upstream senior demand would increase the amount of water legally available for diversion by a junior water user. In other words, a shepherding mechanism is needed to move water past any and all diverters in the model, if the modeling objective is to "deliver" the full amount of conserved CU to the state line or a banking reservoir.

In StateMod there is currently no straightforward mechanism to deliver demand management water from an entire basin's direct flow water users downstream to a particular location without having that water be subject to appropriation by other water users. There are, however, mechanisms that allow specific water rights or small groups of rights to curtail use and deliver that water to specific locations. Through a combination of Plan Structures and operating rules, the shepherding of conserved water can be achieved. This work did not attempt to use these model mechanisms, as it was more interested in general analysis of yields basin-wide. Future efforts that identify specific sets of water rights or diversion structures should make use of the Plan Structure and operating rules to simulate demand management deliveries.

The effect of shepherding is important even if the junior and senior water users are both involved in the demand management plan, because the reduction in demand for the junior user might not be as large as the shortage would have been in the absence of demand management implementation. In some instances, if shepherding is not implemented, a junior user who was shorted in a no-demand-management simulation could potentially divert *more* in a demand management scenario in spite of having a lower total demand, due to an increase in supply. This would diminish the overall effectiveness of the demand management plan. Comparison of scenarios including and without shepherding was carried out to analyze the importance of shepherding across the basins, and in various hydrologic year types.

1. Methodology for Shepherding

Consideration was given to a number of possible mechanisms for implementing shepherding dynamically within the StateMod model simulation across entire sub-basins, with particular emphasis given to the potential for use of return flow adjustments to route saved water directly to a node where it could be accounted for. Use of altered return flow parameters was not an effective method to implement shepherding. Diversions with monthly-varying efficiencies require monthly-varying return flow parameters to achieve the desired result of shepherding a uniform percentage of depletions for each month, and monthly-varying return flow parameters are not currently an option in StateMod. In the future, if monthly variation of the pro-rata distribution of return flows among the return flow nodes assigned to a diversion is incorporated as an option in StateMod, use of this mechanism would enable dynamic simulation of shepherding within a StateMod model run.

The use of instream flow rights was also evaluated as a potential mechanism for shepherding. Unfortunately, the flows associated with these rights cannot be set dynamically within the model during the course of the simulation. This is a necessary condition for the model, as demand management yields will most likely change over time, and knowing those water amounts a priori for the instream flow node is not possible.

In the absence of an identified method to dynamically simulate shepherding of saved water within the model run, a method was developed to estimate the theoretical yield that shepherding would have based upon use of post-processing techniques applied to full-demand simulations. The post-processing technique applied to estimate savings in the shepherding scenarios used model output obtained from Water Balance (*.xwb) output files as its basis. The *.xwb output files generated by StateMod include monthly tabulations of basin-wide depletions, which were multiplied by the assumed percentage of depletion reduction for each scenario to calculate the volumes that would be achieved if all saved water could be shepherded. Depletions associated with out-of-Colorado water use were calculated from the diversion output summary (*.xdd) files, and were not included in the proportional reductions calculated for the entire basin from the *.xwb output.

2. Methodology for Non-Shepherding

In the non-shepherding scenarios, demand reductions were achieved through adjustment to demands associated with direct flow diversions, using the "*.ddm" input files. The *.ddm demands are monthly requests for diversions that can vary from year-to-year. The modifications to the *.ddm files were carried out using a custom script written in the Perl scripting language. These reductions in diversion requests resulted in proportional reductions in depletion requests, because of the use of the fixed efficiency method as described above. Saved water in non-shepherding scenarios was quantified as the increase in basin outflow in the demand management scenario of interest.

It is important to note that not all demands in the *.ddm files were modified, due to unique characteristics of two distinct groups of water users. The first group of unmodified water users includes all out-of-Colorado users. These water users, located in Wyoming in the Yampa River Model and in New Mexico in the San Juan / Dolores Model, are excluded from demand reduction in this study, due to the focus on potential actions that could be taken in the State of Colorado to mitigate for the risks associated with prolonged drought. The second group of unmodified water users includes all non-consumptive water users and diversions. Example members of this second group include the Shoshone Power Plant in the Upper Colorado Model, and the Redlands Power Canal in the Gunnison Model.

3. Additional Methodological Distinctions

In addition to shepherding saved water past points of diversion that would have been shorted in the absence of demand management, the difference in methodology between the shepherding and non-shepherding scenarios has an impact on reservoir operations that is important to note. In the non-shepherding scenarios, the operations of on-stream reservoirs were not altered as part of the demand management plan. This resulted in differences in reservoir operations between the shepherding and non-shepherding scenarios.

Another difference between the two types of scenarios relates to changes in return flow patterns. In the non-shepherding scenarios, the diversion request is reduced in proportion to the depletion request for each water user. This has the effect of re-timing some of the return flow that would have otherwise accrued to the stream through seepage and application inefficiency to instead occur immediately. This effect of re-timing should not be important on an annual basis, after the model run has progressed past the length of time for the longest return flows to accrue.

C. Results

Analysis of results focused on the Baseline models, because that model is the State's best available representation of present levels of demand and operations. Present levels of demand and present operations were considered to be more appropriate than historical demands and operations for analysis of the potential results of implementation of demand management plans. Results for the stress test period (1988-2012) are shown in Table 3. Average annual demand management volumes conserved in each of the 5%, 10% and 15% scenarios are shown as "conserved CU". The average annual increase in flow at the state line is for the un-shepherded scenarios (we would expect all the conserved water, minus some loss factor, to make it to the state line in a shepherded scenario). The yield is a reflection of the expected "loss" incurred in transit for waters conserved but not shepherded (i.e., made available to other water users). Table 4 contains the same information, but for the 8 driest years of the stress test period. Note the change in flow at the state line and yield percentages and the variation across the sub-basins.

Table 3. Conserved consumptive use and state line yields by sub-basin, 1988-2012

	5%			10%			15%		
	Conserved CU (AF/yr)	Flow at State Line (AF/yr)	Yield %	Conserved CU (AF/yr)	Flow at State Line (AF/yr)	Yield %	Conserved CU (AF/yr)	Flow at State Line (AF/yr)	Yield %
Yampa	10,134	8,774	87%	20,269	17,930	88%	30,403	27,189	89%
White	2,982	2,917	98%	5,963	5,894	99%	8,945	8,940	100%
Upper Colorado	52,673	42,873	81%	105,346	87,250	83%	158,019	133,701	85%
Gunnison	28,655	20,631	72%	57,310	42,056	73%	85,964	64,256	75%
San Juan & Dolores	23,439	14,476	62%	46,879	31,387	67%	70,318	49,449	70%

Table 4. Conserved consumptive use and state line yields by sub-basin, 8 driest years, 1988-2012

	5%			10%			15%		
	Conserved CU (AF/yr)	Flow at State Line (AF/yr)	Yield %	Conserved CU (AF/yr)	Flow at State Line (AF/yr)	Yield %	Conserved CU (AF/yr)	Flow at State Line (AF/yr)	Yield %
Yampa	9,809	7,101	72%	19,617	14,852	76%	29,426	22,678	77%
White	2,916	2,720	93%	5,833	5,545	95%	8,749	8,434	96%
Upper Colorado	51,685	21,110	41%	103,370	40,213	39%	155,055	67,529	44%
Gunnison	26,345	8,427	32%	52,689	21,877	42%	79,034	37,658	48%
San Juan & Dolores	20,706	9,541	46%	41,412	19,744	48%	62,118	28,870	46%

IV. Water Banking

As indicated by Figure 2, the amount of water that could be needed to keep Lake Powell above elevation 3525, even after implementation of CRSP drought operations, is significant. An alternative to trying to reactively conserve large volumes over a short period is to develop a banking mechanism whereby conserved water could be created and stored over a longer time horizon, and used only if and when needed to protect critical elevations at Lake Powell.

A. Water Bank Concept

The concept of a water bank to protect Lake Powell is based on the idea that demand reduction would need to occur over a number of years or decades, and that a mechanism is needed to both store and control the use of that water. A water bank could allow flexibility in the timing of demand management activities, may reduce the short-term economic impact of large single-year reductions in consumptive use, and would ideally be located such that the State of Colorado (and/or Upper Basin States) maintained control of its use. Note that a water bank would not necessarily need to exist in just a single location. While Lake Powell has long been considered the best physical location for an upper basin bank, other storage locations may provide bank space and could in fact offer benefits over federally-controlled reservoirs. In general, a water bank would operate in three phases:

1. Filling phase: water saved through intentional reduction of consumptive use is stored in the water bank
2. Storage phase: once the water bank is filled, water use from participants in the demand management program may return to full-use level
3. Release and refill phase: when the water stored in the water bank is needed to protect critical system storage (e.g. at Powell), stored water is released from the bank, and demand management activity resumes until the bank refills

B. Storage Availability

One of the primary goals of this study was to assess the impact of multiple years of proactive reduction in consumptive use through modeling. This required development of model constructs whereby “savings” from prior years could be stored until they were required for protection of critical reservoir elevations. The model constructs used to store saved water were not designed to physically represent a specific place of storage, in order to separate the analysis of the effectiveness of water banking in an abstract form from analysis of the suitability of specific sites where water banking might be carried out.

An unanswered question regarding water banking is the potential suitability of reservoirs within Colorado for maintaining a bank. A post-processing analysis of StateMod results was undertaken to address this question. Reservoir storages from the Baseline scenario were summarized for 20 large reservoirs in the Colorado River Basin in Colorado (excluding the Aspinall Unit of CRSP) that have a combined capacity greater than 2,100,000 AF. The annual maximum storage for each reservoir was compared for each year in the Stress Test period to the reservoir capacity, and the remaining space in all 20 reservoirs was totaled for each year, resulting in the data displayed in**Error! Reference source not found.**:

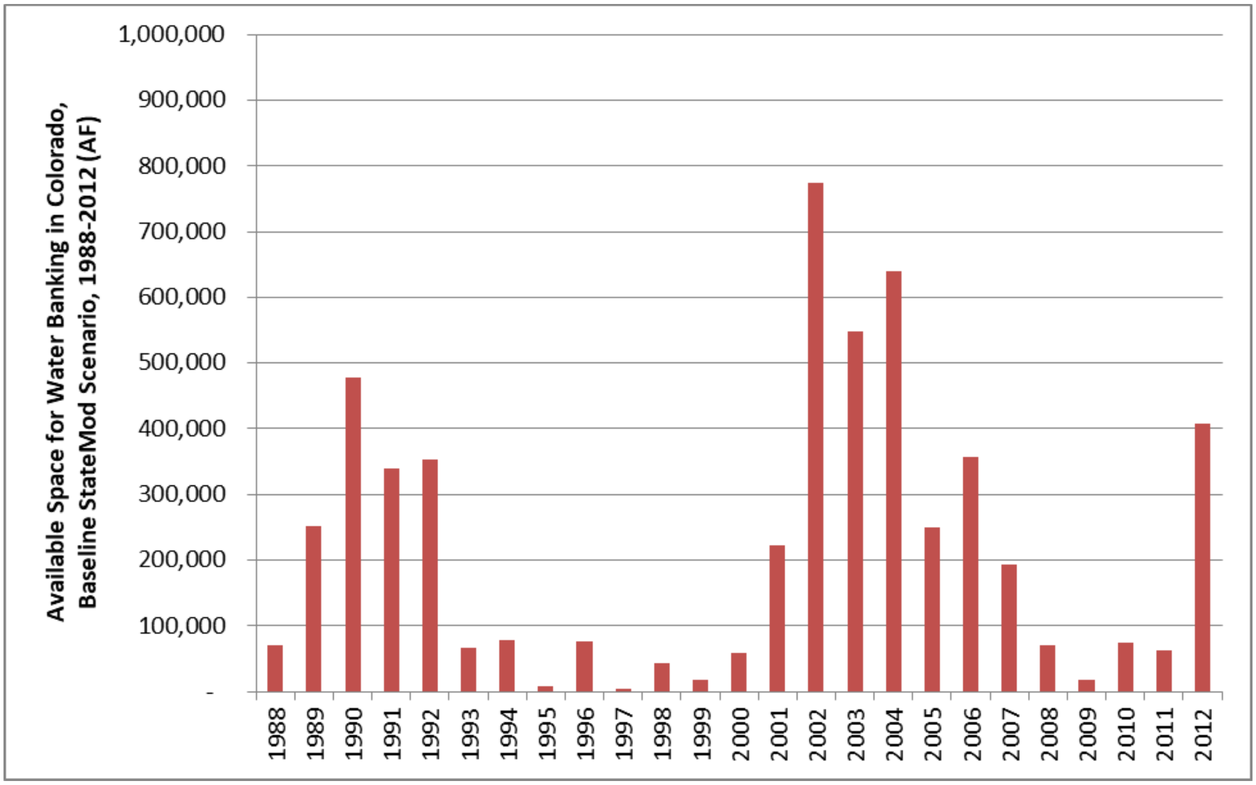

Figure 3. Available Space in Colorado Reservoirs for Water Banking. This analysis excludes the Aspinall Unit of CRSP.

Although there are some years in which significant amounts of space exist that could be used for water banking, those years tend to be dry years in which less water would be available from the demand management programs that would be used to fill the water bank (recall Table 4). Perhaps more important is the lack of persistently-available space over the entire period. This analysis implies that there may not be sufficient unused reservoir storage on Colorado's west slope – absent a reallocation of existing storage space, and excluding the Aspinall Unit – to develop and maintain a long-term water bank of significant volume.

C. Model Requirements and StateMod Capabilities

Accurate modeling of a water bank requires detailed representation of the water rights of the participants in the associated demand management program, which StateMod includes, but also the ability to "turn on" or "turn off" the operational policies associated with its implementation, which is currently difficult to model within StateMod. The dynamic operational policy component is necessary because of the conditional logic involved in determining whether demand management is required in a given year. If a specified amount of water has already been saved (i.e., the bank is full), then demand management is not necessary. Similarly, the operational decision as to when to make releases from a bank, and in what amounts, is determined by factors external to the bank (i.e., Lake Powell's elevation).

Because StateMod is the best modeling framework available for simulation of the yield from the demand management component of a water bank, it would be useful for the storage component and the associated demand management activation trigger to be represented in StateMod as well. At this time, input rule types for StateMod do not provide a mechanism to implement the conditional logic required to operate the bank, but updates to StateMod capabilities could be made to allow such simulations in the future.

Additionally, in order for a model to be able to accurately represent the operations of a water bank designed to protect critical levels of system storage in Lake Powell, the model must be able to dynamically simulate Lake Powell storage. In the case of StateMod, the model domain ends at or near the Colorado state line. Even if a scenario defining storage in Lake Powell was outlined before the StateMod simulation and the code of StateMod was altered so that this storage time series could be entered into StateMod as an input that would guide operations of the water bank, this would not be sufficient to capture the interaction between the water bank and Lake Powell operations accurately. The difficulty arises from the feedback loop necessary to analyze the impact of the water banking actions on storage in Powell (and from possible actions taken by other upper basin states). Adjustment of Powell's storage can impact the volume released from Powell, due to stipulations in the Interim Guidelines, so dynamic simulation of Powell's and Mead's operations would be necessary to fully capture the impact of water banking on storage in Lake Powell.

D. Linked StateMod/CRSS

To overcome the current limitation of StateMod in simulating reactive operational policies, a hybrid methodology was developed to run a linked simulation with both StateMod, and CRSS. This linked simulation methodology also makes it possible to use the information contained within CRSS about the state of the system, particularly in terms of storage in Lake Powell, to guide operations of the water bank.

1. Methodology

The methodology for linking StateMod and CRSS involves running the models sequentially, with two StateMod simulations for each sub-basin model occurring first, followed by a single CRSS simulation that uses output from the StateMod simulations as input data. The StateMod simulations for this process proceed as described above, with a pre-defined level of demand management, and a single model configuration selected for each sub-basin model (e.g. 5% reduction, Baseline, no shepherding). Note that more complex implementations of demand management are possible. For example, different reduction percentages for each sub-basin could be developed, resulting in multiple different yields per simulation year.

For the CRSS simulations, the network structure of the model needs to be altered to allow the StateMod results to replace the CRSS nodes representing Colorado's water users, and to allow for reactive switching between reduced and full demands. The previous Water Bank structure at Lake Powell was not used in this linked model. Instead, each Colorado sub-basin had its own hypothetical water bank reservoir. Each of these reservoirs was configured to capture conserved water, and to release that water as needed by Lake Powell. An example of the modified network structure in CRSS is given in Figure 4. After modifying the structure of CRSS to allow for import of StateMod results, the methodology for carrying out the linked simulation proceeds as follows:

1. Run the Baseline and Demand Management StateMod simulations in each of the models
2. Import the StateMod results into their corresponding data objects within the modified CRSS
3. Specify a size for the maximum combined storage of all of the water bank objects
    a. 1 Million Acre-Feet was used in this study
4. Specify a trigger for water bank storage to be released
    a. A forecast in which Lake Powell January 1 Elevation is predicted to be below 3,525' after CRSP Drought Operations is used in this study
5. Run CRSS, using rules to operate the water banks as described above in Section IV.A. with a combined maximum storage for all of the sub-basin water banks.

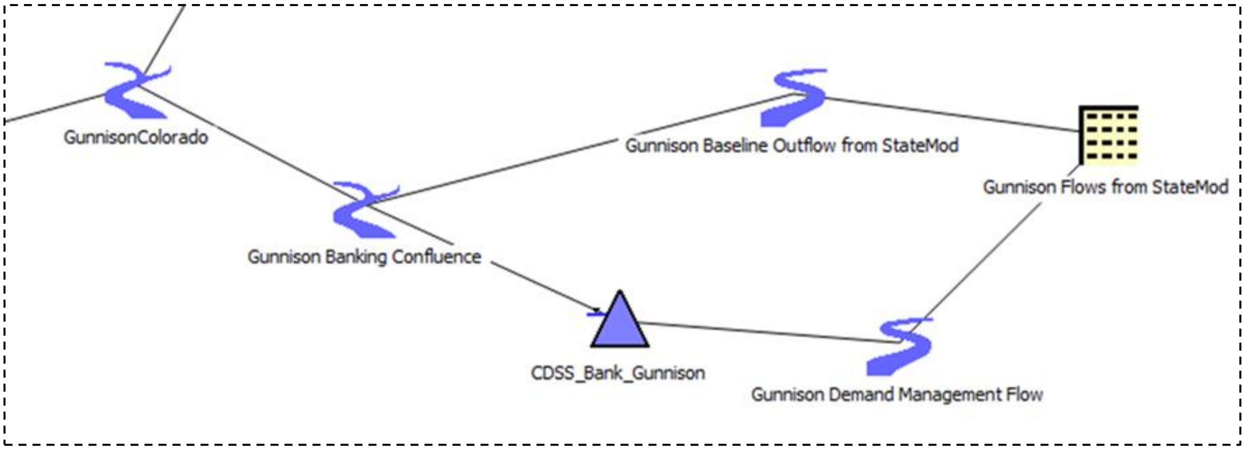

Figure 4. Gunnison Basin Modification to CRSS

2. Model Coordination

Prior to carrying out the linked simulations, model input datasets were compared to ensure that demands and hydrology were aligned between the models to the extent possible, and to ensure that no "double-counting" was occurring, where a demand or an inflow source existed separately in both models. The alignment of inflow hydrology was achieved by simulating the years 1988-2012 (the "Stress Test" period) in both StateMod and CRSS. The 1988-2012 hydrology can be used in either the single-trace or Index Sequential Method (ISM) multiple-trace configuration in CRSS. Only a single StateMod run is necessary to develop the inputs for the multiple-trace ISM configuration, because the RiverWare Multiple Run Manager (MRM) can apply the index sequential method to generate multiple traces from the StateMod-derived inputs. Synchronization of hydrology and demands were sufficient for this proof-of-concept implementation. However, additional work on CRSS and StateMod datasets are needed to ensure the models are using the same assumptions if moving forward into a "production" mode with the combined models.

Comparison of demand datasets indicated that the Current Trends (Scenario A) demand dataset from the Colorado River Basin Study was most comparable to the Baseline demands in StateMod. Depletions in CRSS were found to be 7% lower than those in StateMod for the Stress Test period. In addition to the general model coordination steps described above, the following basin-specific challenges were taken into consideration to coordinate modeling for individual basins:

- **Yampa Basin**
    - Connect the YampaAtDeerlodge gage in RiverWare to the baseline basin outflow reach for the Yampa StateMod linkage, so that the Deerlodge gage dispatches prior to determination of water banking operations. This step is important for simulation of Flaming Gorge operations in CRSS.
    - Do not apply demand management to uses in Wyoming on tributaries of the Yampa that are included in StateMod.
- **Upper Colorado and Gunnison Basins**
    - Recognize that CRSS does not include the storage associated with trans-basin diversions, such as Granby and Dillon, when comparing results.
    - Note that Aspinall operations may differ between StateMod and CRSS, and that the method used for model linkage uses output from StateMod for Aspinall operations.
    - Account for the simplified representation of the Gunnison River in the Upper Colorado Model in processing of the Upper Colorado StateMod results.
- **San Juan and Dolores Basins**
    - Summarize the StateMod model output in three distinct sections:
        - Dolores River
        - San Juan River above Navajo Reservoir
        - San Juan River and Tributaries below Navajo Reservoir
    - Do not apply demand management to San Juan-Chama project depletions that are included in StateMod

3. Benefits of Each Model

This linked-model methodology makes use of the strengths of both StateMod and CRSS. StateMod's strengths are focused on its ability to accurately simulate water rights operations in the State of Colorado at a high level of detail. The strengths of CRSS are focused on "big river" questions of operational policy across the Colorado River Basin. Additionally, the linking exercise showed that a distributed bank approach is also feasible, wherein individual sub-basin banks were created to store and manage conserved water within each sub-basin. This is not intended to suggest that is the best approach to a banking mechanism, but it is a potentially useful modeling construct. By linking the models in the manner described above, the strengths of both models can be utilized without either diminishing the effectiveness of the other.

4. Example Output Trace

Using the outputs from the 10% un-shepherded scenario as an example, model performance when implementing the water bank can be evaluated. A particularly interesting trace in the ISM simulation of this scenario is the trace that begins with hydrologic year 2000, and ends in hydrologic year 1999. The results from this trace are displayed in Figure 5.

In the first two years of this trace, conserved water via demand management is used to begin filling the water bank (black line, left y-axis), while dry hydrology causes the pool elevation in Lake Powell to drop significantly. By April of the third year of the simulation, Powell has lost so much storage (red line, right y-axis) that the forecast for the upcoming January 1 indicates a shortage of over 1 million acre-feet (MAF) as compared to the targeted elevation of 3,525'. This forecast shortage then triggers drought operations for the Upper Basin CRSP reservoirs, and the release of water bank storage (which is now 367,778 AF). From this point in the model simulation, until a subsequent forecast indicates likely recovery, demand management continues in the Upper Basin, with savings immediately accruing to Lake Powell, instead of being stored in the water bank reservoirs. A forecast in April of the fourth year of simulation indicates a likely recovery, but the August forecast returns the Upper Basin to drought operations, which continue until large inflows in the sixth year of simulation begin a period of recovery that brings Powell's storage back above the 3,525' threshold.

Demand management in the Upper Basin continues from year 6 until year 10 of the simulation, at which point the targeted maximum for water bank storage (1 MAF) is reached. After the specified amount of water bank storage has been filled, the Colorado depletions return to their full demand schedule (90%D1) from years 11-17. In August of year 17, however, Powell's pool elevation has dropped significantly, and a forecast indicates a likely shortfall for the January 1 storage in year 18, which triggers a release of all banked water, enacts drought operations at the Upper CRSP reservoirs, and re-activates the Upper Basin demand management program. Demand management and filling of the water bank then continues for the next 5 years of the simulation, after which storage in the bank reaches full capacity, and remains full as storage in Powell remains high for the remainder of the simulation.

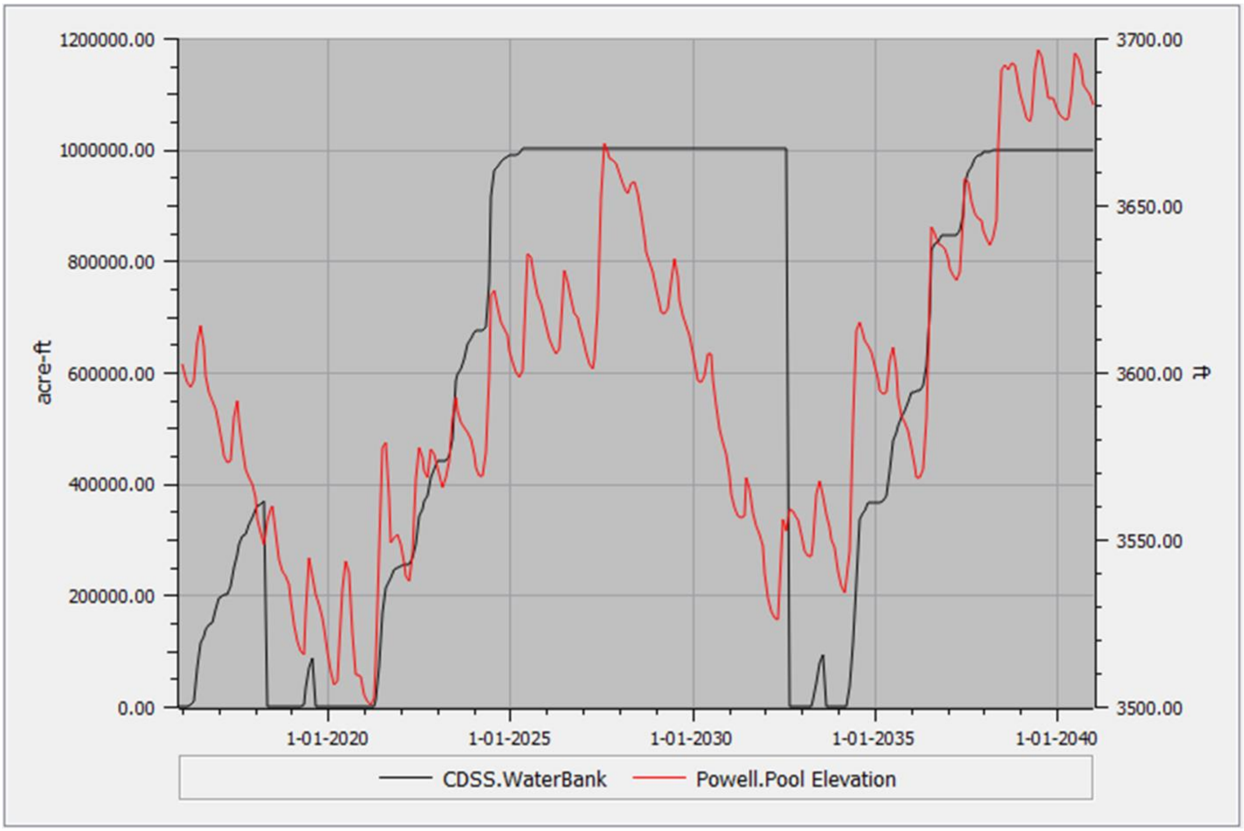

Figure 5. Water Bank Storage and Powell Pool Elevation Example Results

5. Limitations

This linked model methodology still has limitations in its ability to simulate a water bank, some of which could be alleviated through updates to StateMod, and some of which could be handled through additional modifications to the CRSS network and/or ruleset. StateMod could benefit from the ability to react to state information coming from one or more model nodes throughout the basin. For example, the ability to turn off a specific demand management action based on combined storage across several reservoirs or accounts. CRSS could also be enhanced to better represent certain aspects of these basins. For example:

1. Inability to dynamically modify the operations of some important West Slope reservoirs
    a. Lakes Granby and Dillon exist in CRSS as demand nodes that represent the evaporation losses from those reservoirs, but does not allow for modification of the operations of those reservoirs.
2. Inability to analyze the impacts to operations of various existing reservoirs if the proposed water bank was to exist alongside existing uses

V. Recommendations

This work provides a template for scenario modeling wherein both detailed simulation of in-state demand management and shepherding can be combined with “big river” contingency plan activities, including water banking and CRSP drought operations. If and when more detailed analyses are required for demand management activities within Colorado, it may be beneficial to develop additional capabilities within StateMod to more accurately reflect these actions. Potential enhancements include:

- The ability to turn demand management on or off based on system conditions (for example, cease demand management when a water bank reservoir is full)
- Water bank reservoir functionality to allow dynamic diversion into storage for conserved water, and dynamic release of banked water. This functionality would require “real-time” feedback from other model nodes or external forcing such that the model could react to changing conditions elsewhere in the model.
- Shepherding mechanisms to simplify the conservation and delivery accounting of demand management water
    - Enhancements to main stem reservoirs (e.g., the Aspinall Unit) to allow bypassing of demand management water
    - Avoid duplication of existing network or need to create new “demand management” network

VI. Appendices (Attached Separately)

A. Index of model files
B. Index of presentations to project participant groups