Technical Memorandum

Blue Mesa Water Banking Study

Task 1: Hydrologic Scenario Development

1. Task Objectives and Scope

The objective of this task was to develop hydrologic scenarios to incorporate into the Blue Mesa Water Bank Model. These scenarios are intended to allow for the investigation of how the proposed water bank might respond to various future hydrologic conditions and the extent to which the water bank might mitigate against potential compact curtailments. A range of hydrologic scenarios are needed to rigorously test the modeled water bank against a broad range of projected conditions. In addition, the scenarios are needed for the comparison of water bank design options and strategies given varying hydrology. Since the water bank model was developed to specifically investigate banking activity during times of severe drought (resulting in compact curtailment), all of the hydrologic scenarios selected under this task include curtailment projections. As described below, the scenarios have been put into context with respect to a larger dataset of hydrologic projections, used by the Bureau of Reclamation (Reclamation) in the Basin Study, to quantify levels of modeling consensus associated with the selected forecasts.

2. Approach

For this task, Reclamation provided river flow data developed under the *Colorado River Basin Supply and Demand Study* (the Basin Study) for each Upper Basin flow node included in their Colorado River Simulation System (CRSS) model. The CRSS includes a simplified representation of the entire mainstem Colorado River Basin hydrologic system. It includes 12 major reservoirs and over 500 water user demand nodes. The model simulates routing, storage, and allocation of river water on a monthly timestep for an extended simulation period. Key reservoir operating rules are also included. As part of the Basin Study, the CRSS was used to project basin-wide water availability and demands into the future (Reclamation 2011). The flow data provided by Reclamation, and used in this banking study, therefore reflects the combination of future demand projections, future hydrologic projections, and current basin operational strategies and infrastructure.

Reclamation provided these data for 20 flow nodes distributed across the Upper Basin. For each node, there are multiple sets of 49-year monthly flow projections representing the time period 2012 – 2060. The data were generated assuming various combinations of increasing demands (to reflect changing demand over time in the future) and potential future hydrologic conditions. These model perturbations include four distinct methods for quantifying future hydrology in the basin: sampling from historical gage records (DNF), sampling from paleo reconstruction records of stream flows (DPNF), sampling from paleo reconstruction records after statistical conditioning (PCNF), and a combination of climate change and macroscale hydrologic modeling (VIC). These supply side methods are coupled with six assumptions of future Upper Basin demand trends through 2060: current trends (CT), slow growth (ES), two levels of expansive growth (C1 and C2), and two levels of expansive growth with enhanced environmental management (D1 and D2). The highest projected demands on Colorado River water are seen in the expansive growth scenarios. Further details on the development of these supply and demand scenarios can be found in Reclamation (2011). The coupling of the

4 supply methods with the 6 demand methods results in 24 distinct methods for projecting future basin hydrologic situations developed under the Reclamation Basin Study.

For each of the 24 methods, there are multiple 49-year flow projections representing different perturbations of the same supply methodology. The intent in generating multiple perturbations for each was to address and reflect the uncertainty associated with the hydrologic (supply) projections (timing, sequencing, and magnitude) generated by each method. Further details on these perturbations are provided below.

- For the historical gage method (DNF), there are 103 perturbations for each of the 6 demand scenarios. These were developed using historical gaged stream flows and Reclamation's "Indexed Sequential Method (ISM)." The ISM is a stochastic (random) sampling approach designed to generate different sequences of the historical data and thereby capture uncertainties.

- For the paleo reconstruction method (DPNF), there are 1,244 perturbations for each of the 6 demand scenarios. These perturbations were developed using an extended paleo stream flow record (reconstructed using tree ring data) and the same ISM stochastic sampling method used for the historical gage datasets.

- For the paleo reconstruction with conditioning method (PCNF), there are 500 perturbations for each of the 6 demand scenarios. The conditioning method is a statistical approach that effectively blends the magnitudes of the historical gage record with the sequencing of the paleo reconstruction record. The perturbations generated for this method were again generated using a random sampling approach to sequencing.

- For the climate change model projections (VIC), there are 112 perturbations for each of the 6 demand scenarios. These represent the full set of published global climate model (GCM) projections spanning multiple GCMs and multiple potential greenhouse gas emission scenarios. Each of the climate model projections were used to drive a large-scale hydrologic model (Variable Infiltration Capacity model, or "VIC") to generate stream flow projections. As above, these multiple perturbations were included to capture uncertainties associated with climate change modeling.

The end result of application of the above methods is a total dataset of over 11,000 49-year monthly flow records for each of the model nodes. It is from this data set that the scenarios to be used in this study were selected. To guide the selection of these scenarios, Lee Ferry 10-year rolling total flow values were calculated for each of the 11,000+ projections at each monthly timestep. The minimum 10-year total associated with a 2050 (± 10 years) planning horizon was calculated and recorded for each projection. The 2040 – 2060 period was identified by project participants as a useful planning horizon for the banking study and reflects maximum demand expansion projected by the Reclamation data sets. Percentile plots were fitted to these data to provide a graphical summary of the full range of projections and associated levels of modeling consensus (**Figure 1**). For example, this figure indicates that 10% of the 11,000+ 49-year flow records include a minimum 10-year rolling total at or below the 75 million acre-feet (MAF) compact obligation (dashed red line). Figure 1 was used to guide the selection of specific scenarios for use in the water bank study, as described below.

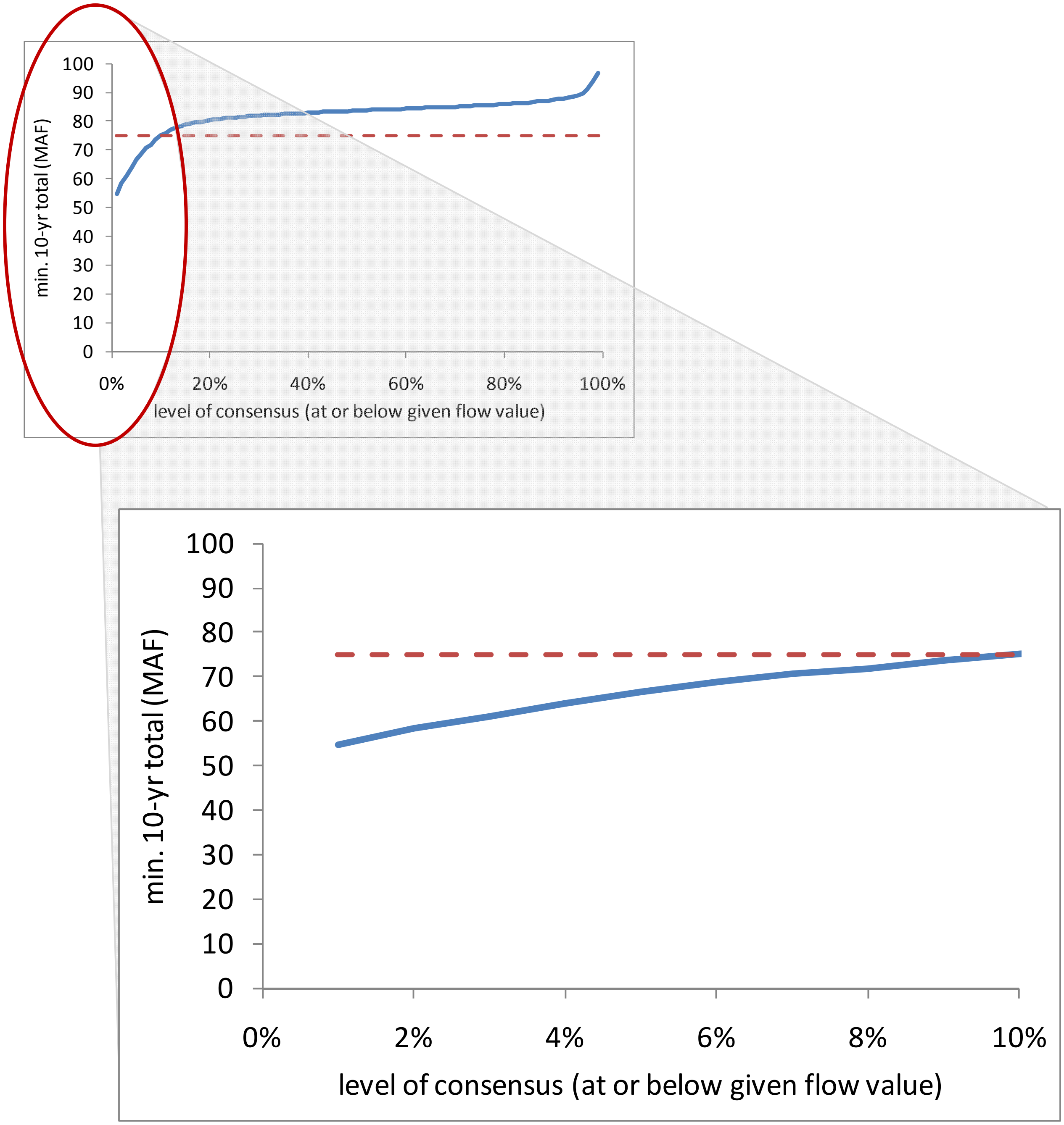

Figure 1: Basin Study Flow Projections (2040 – 2060): Colorado River at Lee Ferry (AZ)

3. Results

Projection scenarios corresponding to the 1st, 3rd, 5th, 7th, and 9th percentiles of minimum 10-year total flow projections were selected for this study based on the plot shown in Figure 1. These scenarios were selected to provide an adequate representation of the full range of deficits projected in the Reclamation data sets. Selected scenarios are summarized in **Table 1**.

Table 1: Selected Hydrologic Scenarios for Blue Mesa Water Bank Study

Percentile	Minimum 10 yr Total Q (MAF): Fitted Value	Selected Projection	Minimum 10 yr Total Q (MAF): Actual Value
1st (0.01)	54.9	VIC, D1, Perturbation 55	55.1
3rd (0.03)	61.0	PCNF, C2, Perturbation 19	61.0
5th (0.05)	66.7	PCNF, CT, Perturbation 152	67.1
7th (0.07)	70.5	DPNF, CT, Perturbation 348	70.6
9th (0.09)	73.5	VIC, CT, Perturbation 26	73.5

The selected hydrologic projections (Table 1) include two climate change projections: one with enhanced environmental management (VIC, D1) and a second with current growth trends (VIC CT), two paleo hydrologic projections with statistical conditioning: one with rapid growth (PCNF, C2) and a second with current growth (PCNF, CT), and one paleo projection without conditioning and with current growth trends (DPNF, CT). Monthly timeseries plots of the projected flows at Lee Ferry for each selected projection are shown in **Figure 2**. For reference, one of the historical gage record (DNF) perturbations with current demand trends (CT) is also provided. This reference data set is provided to illustrate differences between future projections using expanded hydrologic data sets versus those based on recent historical measurement only. Calculated 10-year rolling totals are presented in **Figure 3**. The full 49-year monthly timeseries for each projection will be incorporated into the Blue Mesa Water Bank Model at each of the flow nodes in that model. These projections will be available in the water bank model as separate user-selected hydrologic scenarios.

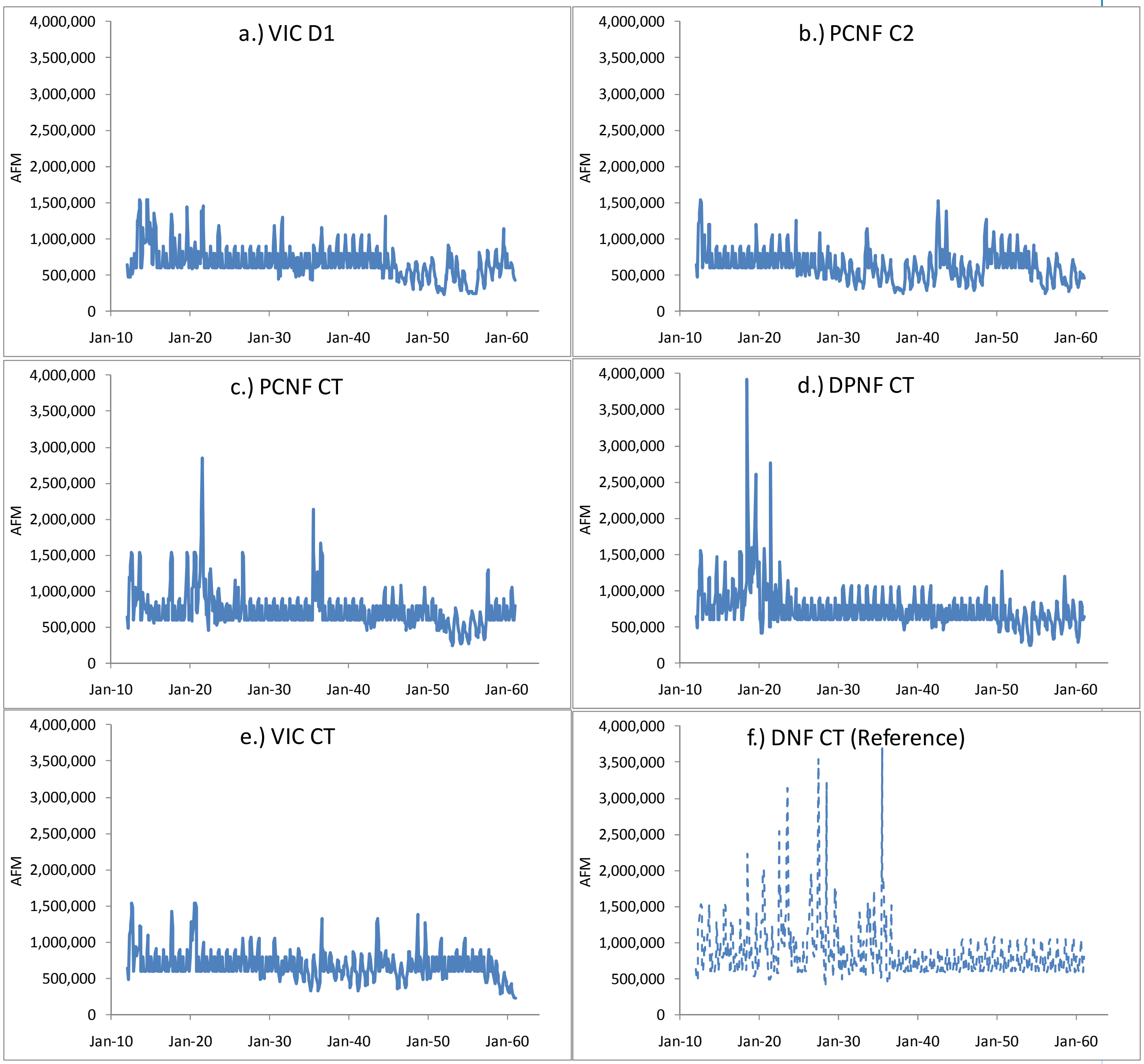

Figure 2: Selected Hydrologic Scenarios, Projected Monthly Flow at Lee Ferry (2012 – 2060)

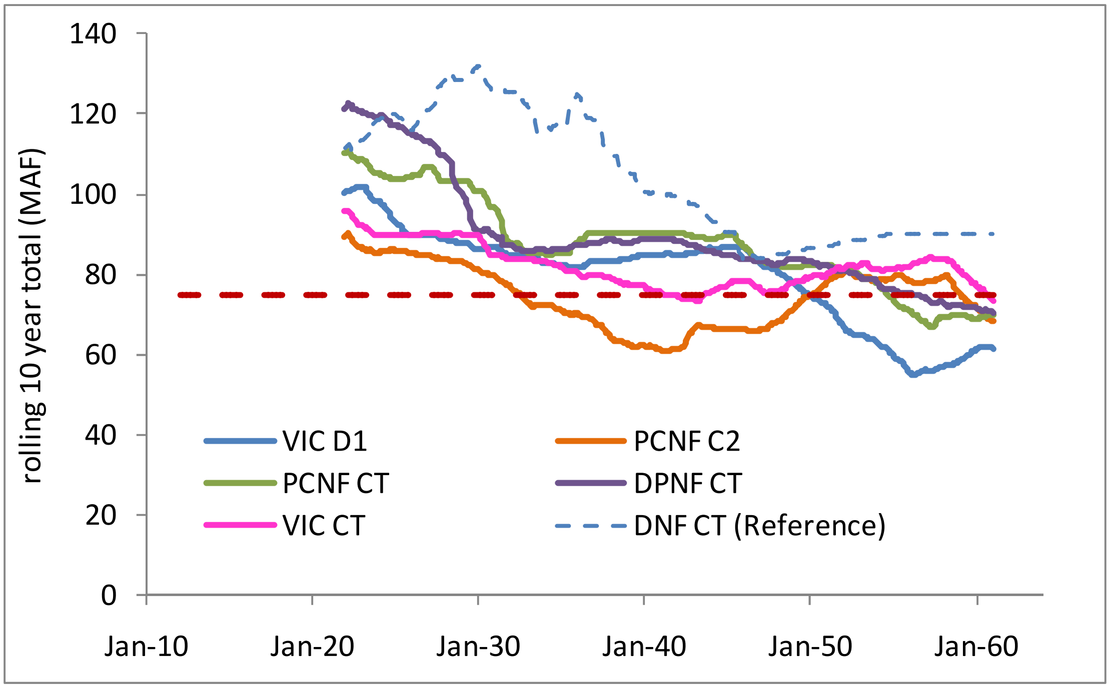

Figure 3: Selected Hydrologic Scenarios, Rolling 10 year Total Flow at Lee Ferry (2022 – 2060)

Task 2: Model Tool Evaluation and Selection

1. Modeling Objectives and Scope

As stated in the Statement of Work, the overriding objective of the proposed project modeling is to "assess the effectiveness of using excess storage in Blue Mesa Reservoir to avoid, forestall, and/or mitigate the magnitude and duration of potential Colorado River Compact curtailment in Colorado," and further to "evaluate the use of Blue Mesa Reservoir as a potential location for a Colorado water bank." More specifically, the constructed model will be used to answer the following key questions:

a. What yields can be expected from a water bank in Blue Mesa Reservoir given a range of upstream hydrologic conditions and operating constraints?

b. How do these yields compare to potential curtailment volumes projected with assumptions of varying future basin supply and demand forecasts?

c. What are the implications of the quantified yields with respect to mitigating or avoiding curtailment calls on the State of Colorado?

d. How sensitive are projected yields to Blue Mesa Reservoir operating strategies?

e. How might future reservoir operations be adapted to optimize the yield of a water bank while continuing to meet existing environmental flow and hydropower requirements?

f. How sensitive are projected yields to basic banking program design features (e.g., top vs. bottom bank alignment, banking initiation thresholds)?

For this task, modeling tool options were evaluated with respect to their ability to ultimately answer the questions posed above within schedule and budget constraints. Tools were also evaluated with the recognition that the above list does not represent a comprehensive list of possible model applications. Modeling objectives and applications are unlikely to be finalized until other project tasks have been initiated and/or completed.

2. Model Functionality

In order to meet study objectives and to address the questions posed above, the constructed model will need to include some or all of the following:

- Blue Mesa Reservoir storage routing calculations (a function of reservoir inflows, withdrawals, releases, spills, and evaporative losses)
- Water bank storage account calculations (a function of bank water inflows and releases, account capacity, spills, evaporative losses)
- A range of input hydrologic conditions and time periods representing varying forecasts of both future river supply and basin demands (developed under Task 1 of this study)
- A range of prescribed Colorado River compact curtailment projections and/or flow targets
- Prescribed water bank inflows (calculated externally as a function of senior agricultural lands potentially available for fallowing)
- Prescribed water bank design features, including capacity of storage account, top vs. bottom storage alignment, and hydrologic threshold criteria for banking program initiation
- Projected changes in in-state Colorado River Basin depletions
- Prescribed Colorado and Gunnison River flow transit losses (if significant)
- Calculations of Colorado and Gunnison River flows at key downstream locations
- Reservoir operational rules governing the release of water to meet existing downstream needs, including environmental flow targets (Reclamation 2012)
- New reservoir operational rules that might be implemented to facilitate the management of the proposed water bank and potentially improve water bank yields while still meeting existing authorized purposes
- A monthly timestep to capture seasonal dynamics of the modeled system at an adequate resolution

A basic conceptual model is depicted in **Figure 4**. As shown, the initial model structure will be relatively simple, consisting of reservoir storage calculations dependent on monthly inflows and outflows. However, many of the details of the model applications to be performed for this study have not yet been fully defined. For example, it is not known how sensitive bank yield will be to the details of reservoir operations. Given this uncertainty, it is critical that the selected modeling tool be flexible to allow for continued development throughout the study. While model development might start simply, it will be important to be able to add layers of complexity to the model, as needed, to perform specific investigations. Many of these investigations will be defined as part of Task 5 of this study

("Evaluate Management Options"). The model will also need to allow for easy and efficient manipulation of input data to accommodate multiple "what if" scenario simulations. Input and output handling and simulation run times are therefore also important considerations in final model selection.

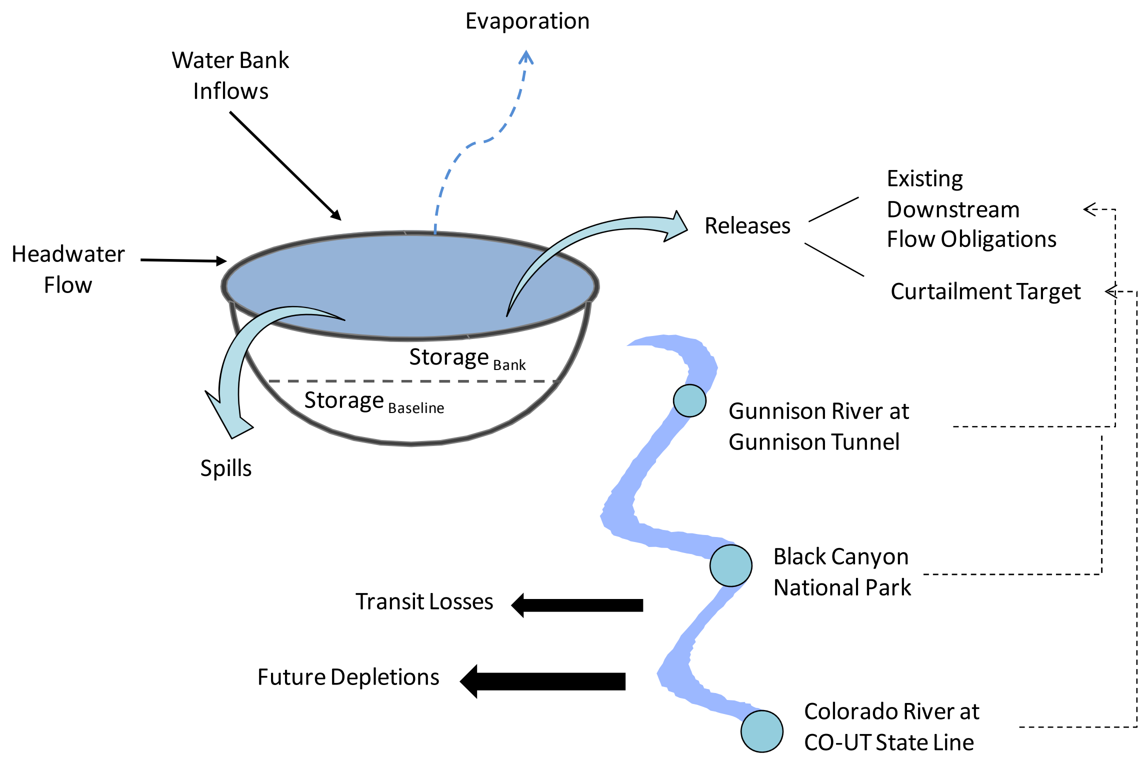

Figure 4: Blue Mesa Water Bank Conceptual Model

A key assumption in this evaluation is that water bank inflows, representing various levels of hypothetical farmer participation, will be provided by the independent Water Banking Group study. This water might be assumed to come from fallowing or deficit irrigation of lands above Blue Mesa Reservoir or by similar agricultural practices on lands below Blue Mesa Reservoir if exchange arrangements are possible. If no information is available from the Water Banking Group, then a set of hypothetical scenarios will be derived in consultation with the Colorado Water Conservation Board (CWCB) staff.

Lastly, the selected model will need to be able to accommodate, in an efficient manner, a large range of hydrologic conditions defined according to multiple discrete scenarios, as described in Section 1. The scenarios developed under Task 1 will serve as inputs to the developed model.

3. Review of Existing Model Options

A number of numerical models have been previously developed that include, to some degree, the spatial domain and functionalities described above. These tools were reviewed with respect to their suitability for this study. Reviewed models include: State of Colorado CDSS, Reclamation CRSS and Aspinall Environmental Impact Statement (EIS) RiverWare models, MWH Water Bank Feasibility Study spreadsheet model, and CDM Smith spreadsheet model developed for the Front Range Water Council (FRWC) as part of the FRWC Study of the Colorado River Storage Project. Summaries for each are provided below.

The State of Colorado has developed as part of their CDSS a detailed water allocation model of the Gunnison River Basin. This model has been developed using StateMod; a generalized surface water allocation tool. The model domain includes the entirety of the Gunnison River hydrologic basin including the entire length of the Gunnison River down to the confluence with the Colorado River. It includes explicit representation of Blue Mesa Reservoir and 12 other key reservoirs, more than 50 tributaries to the Gunnison River, 25 instream flow reaches, and approximately 300 diversion structures. Water demands, including irrigation requirements, and estimates of naturalized flow at key locations are also part of the populated model. It is a highly sophisticated and complex model designed primarily for water resources planning. A number of operational constraints are included in the representation of Blue Mesa Reservoir, including Reclamation storage curve targets, Black Canyon environmental flow targets, and the Uncompahgre Valley Water Users Association exchange agreement. However, it is not known at this time whether the model would include all of the reservoir operational constraints important to this study. Additionally, the model spatial domain does not extend to the location of anticipated curtailment information (Colorado River at CO-UT state line) and would need to be coupled with the Colorado River Basin StateMod model to achieve this desired domain. This model likely includes more detail, particularly with respect to individual water users, than is needed for this study. The complexity of the code would also limit its ability to be customized to meet the needs of this study.

Reclamation's CRSS was developed to support long-term planning and management of the Colorado River. It is currently being used in Reclamation's Colorado River Basin Study (Reclamation 2011), which aims to project long-term supply and demand in the entire river basin. The CRSS was originally developed as FORTRAN code but has since been updated and reconstructed in RiverWare, a generalized river basin modeling tool. The model runs on a monthly timestep and simulates the mainstem Colorado River Basin down to the Mexican border. It includes 12 major reservoirs, including Blue Mesa, and over 500 individual "water users." Blue Mesa Reservoir operations are simulated simplistically as a function of a single storage curve. Neither water rights nor the ability to simulate multiple "paper" accounts in a single reservoir are included in RiverWare. The model does include a user friendly interface that would enable changes to basic model structure, flows, demands, etc., if the CRSS were available for this study. Additionally, RiverWare can be run in "rule based" simulation mode whereby users are able to define operational rules with simple programming scripts. However, the RiverWare software code is highly complex and our ability to customize the tool as necessary to meet the objectives of this study will be somewhat limited. Additionally, the CRSS includes a much larger spatial domain, albeit at a coarse resolution, than appears to be needed for this study, confounding our ability to customize the tool and to perform efficient focused analyses. Baseline CRSS simulation times are on the order of 1 to 2 hours.

In support of a recently released EIS (Reclamation 2012), Reclamation developed a RiverWare model to simulate operations of the Aspinall Unit. The spatial domain of this model encompasses the Gunnison River Basin from Blue Mesa Reservoir to the confluence with the Colorado River. The model operates on a daily timestep and simulates historical hydrology for the period 1975 – 2000. The focus of the model is the day-to-day operations of the Aspinall reservoirs and it allows for the simulation of both current and future alternative operating strategies. The model includes detailed operational "rules" developed to address various combinations of downstream water demands and flow needs. The daily timestep and the level of reservoir operational detail are likely beyond what is needed for this study. Additionally, the limited spatial domain of the EIS model would likely be inadequate. However, this model may be a valuable resource for this study with respect to understanding and simulating Blue Mesa Reservoir operations.

As part of the Colorado River Water Bank Feasibility Study (MWH 2012), a spreadsheet model of the Colorado River storage system was developed and applied to estimate water banking yields necessary to address potential future Colorado River curtailments. The model includes a coarse representation of the Upper Colorado River Basin and simulates on an annual timestep. Total Upper Basin reservoir storage and total water demands are lumped into single units. For a given prescribed annual hydrologic sequence, the model calculates Upper Basin shortfalls and surpluses by allocating water in the following order of priority—1. total pre-compact demands, 2. bottom-of-basin (Lee Ferry) compact requirements, and 3. total post-compact demands. This model provides an adequate "big picture" simulation of the Upper Basin, but lacks sufficient temporal and spatial resolution to fully meet the needs of this study.

CDM Smith developed a simple model of Blue Mesa Reservoir as part of the FRWC Study of the Colorado River Storage Project (CDM Smith 2011). The objective of this work was to quantify storage potential in the reservoir for a water bank assuming historical conditions and operations. Spreadsheet calculations were used to calculate water bank storage on an annual basis assuming a constant bank inflow of 50,000 acre-feet per year. Storage availability for the bank was strictly based on measured historical (1990 – 2010) reservoir storage availability. Top versus bottom bank alignments were compared. Curtailment obligations, bank releases, and reservoir operations were not explicitly included in this modeling exercise.

4. Modeling Tool Recommendation

None of the existing modeling tools reviewed here appears to be ideally suited, by themselves, to fully meet the needs of this study. As described above, tool flexibility is a high priority to allow for customization of the model. Many of the required complexities of the model have not yet been determined. **Therefore, it is recommended that a new model be developed specifically for this study. The recommended programming platform is Microsoft *Excel*, supported by Visual Basic for Applications.** This option scores well with respect to the key attributes of flexibility, power, programming ease, portability, and familiarity for a broad range of potential users. A graphical user interface can also easily be constructed in this platform to make the resulting tool as user friendly as possible. Strict quality control and quality assurance measures will be employed throughout model development to ensure accuracy of algorithms. Additionally, existing models (described above) may be used to support the new model, such as through verification exercises, and may serve as sources of input data for the new model.

References

CDM Smith (formerly CDM). 2011. FRWC Study of the Colorado River Storage Project. Prepared for Front Range Water Council and Grand River Consulting. May.

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