THE COLORADO RIVER BASIN WATER SUPPLY AND DEMAND STUDY: MODELING TO SUPPORT A ROBUST PLANNING FRAMEWORK

Alan Butler, Hydrologic Engineer, Bureau of Reclamation, Lower Colorado Region, rabutler@usbr.gov; Carly Jerla, Operations Research Analyst, Bureau of Reclamation, Lower Colorado Region, cjerla@usbr.gov; Ken Nowak, Hydrologic Engineer, Bureau of Reclamation, Lower Colorado Region, knowak@usbr.gov; Jim Prairie, Hydraulic Engineer, Bureau of Reclamation, Upper Colorado Region, jprairie@usbr.gov; Bill Oakley, Software Engineer, Center for Advanced Decision Support for Water and Environmental Systems, University of Colorado-Boulder, billo@colorado.edu; Neil Wilson, Software Engineer, Center for Advanced Decision Support for Water and Environmental Systems, University of Colorado-Boulder, nwilson@colorado.edu; Edie Zagona, Director, Center for Advanced Decision Support for Water and Environmental Systems, University of Colorado-Boulder, zagona@colorado.edu

BACKGROUND

The Colorado River provides drinking water to nearly 40 million people and supplies water to irrigate over five million acres of farmland across seven western states and is vital to agricultural and municipal needs within the United Mexican States. The Colorado River also supports numerous ecological and recreational resources, provides water for hydropower generation, and is the lifeblood for 22 federally recognized tribes within the Colorado River Basin (Basin) (Bureau of Reclamation, 2012). The Basin is depicted in Figure 1.

As part of the Bureau of Reclamation's (Reclamation) WaterSMART program, the Colorado River Basin Water Supply and Demand Study (Basin Study) was conducted by Reclamation and the seven Colorado River Basin States in collaboration with stakeholders throughout the Basin. The Study's objectives were to assess future water supply and demand imbalances in the Basin over the next 50 years and develop and evaluate options and strategies to resolve the imbalances. To address the considerable amount of uncertainty in projecting the future state of the Colorado River system, the Study adopted a scenario planning approach that resulted in four water supply scenarios (each with over 100 future realizations), six water demand scenarios, and two reservoir operation scenarios. The combination of all of these scenarios is referred to as the baseline in the Basin Study. The Basin Study shows that by 2060, the median supply and demand imbalance in the baseline is approximately 3.2 million acre-ft, though it can range from 0 to over 7 million acre-ft. Though these estimates ignore both the effectiveness of using reservoirs to help meet demands in times of drought and the geographic disparity of supply and demand, it indicates that in the absence of any actions, there is potential for large imbalances in the future (Bureau of Reclamation, 2012).

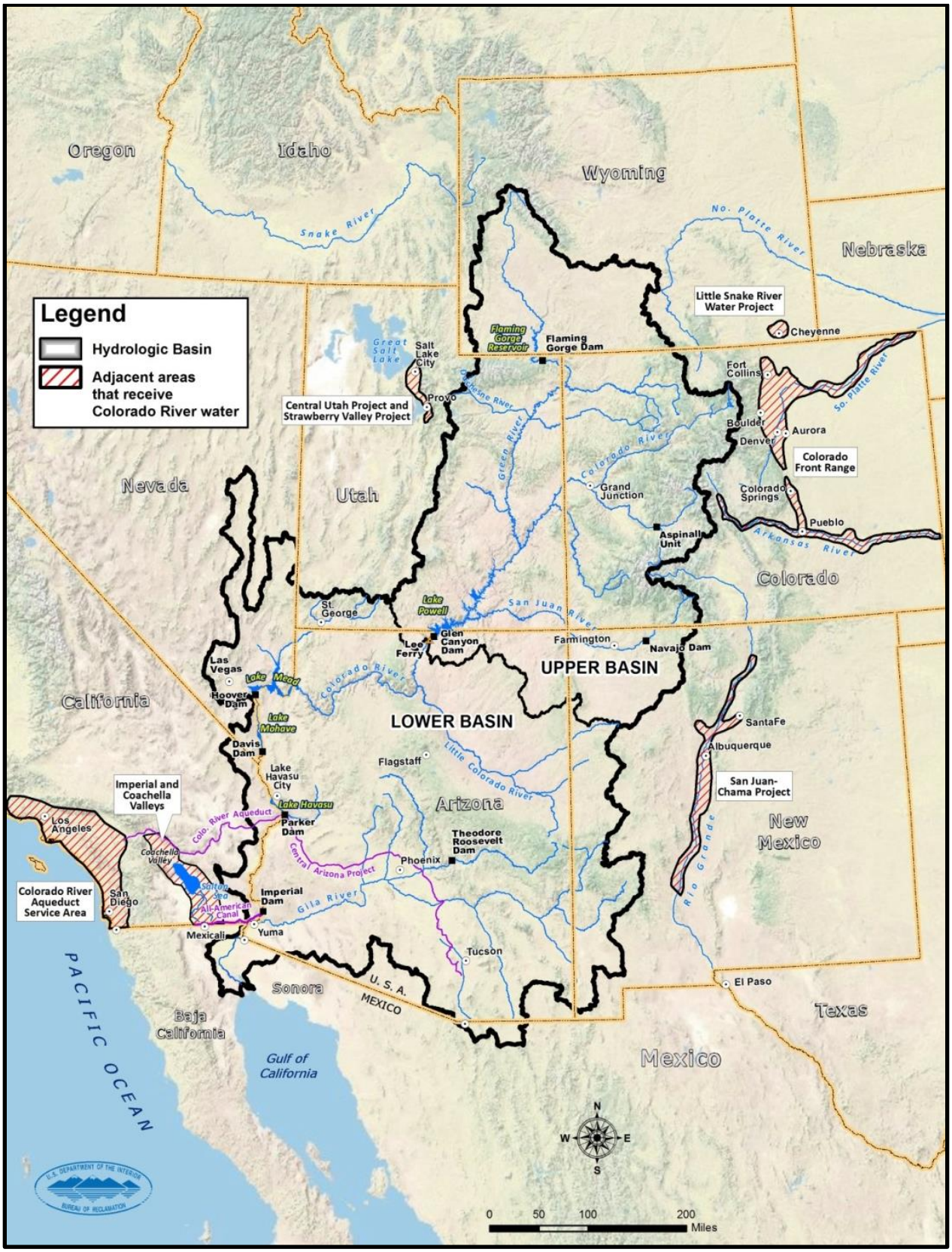

Figure 1 The Colorado River Basin

Options to help address the projected imbalances were solicited from the public. 160 options ranging from increasing the supply through importations or desalination to decreasing demand through various conservation efforts were submitted during the Study. Four unique portfolios, or strategies combining various options, were then developed from the many options as examples of different strategies for resolving system imbalances. The combination of each portfolio combined with all baseline scenarios to analyze the performance of the portfolios across a wide range of plausible future scenarios. The tradeoffs between price, yield, and ability to improve system performance were compared across portfolios using a robust decision making framework. System performance was indicated through reliability metrics that were developed for water delivery, electrical power, water quality, flood control, recreational, and ecological resource categories. The metrics were evaluated to understand how resource vulnerabilities changed through time, geography, and across resources, and the extent to which vulnerabilities could be mitigated through actions.

The Study concluded that the Basin faces an uncertain future with a range of potential imbalances between supply and demand, and that all resources within the Basin are increasingly vulnerable through time, due to both increasing demands and the potential for decreasing supply due to climate change. However, the Basin Study's portfolios demonstrated that actions do help meet the imbalances and reduce vulnerabilities. Actions and diligent planning are necessary at the local, state, regional, and Basin-wide levels, as there is no single solution. Rather, as demonstrated by the many options comprising the portfolios, a wide-range of solutions are necessary and it is imperative to begin work to further some of the concepts in the near future. Though there was no decision made in the Basin Study, the modeling tools and methods employed during the Study provide a common technical foundation for future actions. A suite of modeling tools forms the basis of this technical foundation and was necessary to conduct the Basin Study.

MODELING TOOLS

In order to carry out the scenario planning approach employed by the Basin Study, a suite of modeling tools was necessary. The foundation of the suite was an existing model, though some enhancements were necessary, and several new tools were developed to both help meet the needs of the Study and provide for generalized tools with application beyond the Basin Study.

The Colorado River Simulation System (CRSS): The Colorado River Simulation System (CRSS) has been Reclamation's long-term planning model since the 1980's. Originally developed in Fortran, CRSS was converted to RiverWare®, a generalized reservoir operations modeling platform (Zagona et al., 2001), in 1996. CRSS models the entire Basin, from headwaters in the Upper Basin, e.g., Green, San Juan, and Gunnison, down to the northerly international boundary with Mexico. The operations of nine Upper Basin Reservoirs and three Lower Basin reservoirs, including Lakes Powell and Mead, are represented in CRSS while deliveries are simulated to hundreds of users throughout the Basin. The basis of the simulation is a mass balance (or water budget) calculation that accounts for water entering the system, water leaving the system (e.g., from consumptive use of water, trans-basin diversions, evaporation),

and water moving through the system (i.e., either stored in reservoirs or flowing in river reaches). The model is used to simulate the future conditions of the Colorado River system on a monthly time-step for decades into the future (2012-2060 in the Basin Study). See Reclamation (2012) for more details on CRSS.

CRSS was used as the modeling tool in the Basin Study to simulate all 240 scenarios (the combination of all four supply scenarios, six demand scenarios, two reservoir operating options, and four portfolios). As each scenario contains over 100 future realizations, all together over 110,000 unique 50-year simulations were made. Studies such as the Basin Study or the modeling to support the Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead EIS (Reclamation, 2007) that utilize CRSS take advantage of RiverWare's features and policy language to perform efficient "what-if" analysis. Features in RiverWare make it easy to import different data to perform such analyses; however, until recent development, this was a manual step. In the case of the Basin Study, which simulated 240 total scenarios, this would require many human hours to complete. Additionally, manually launching each scenario increases the total run time for such an effort.

RiverSMART: To help alleviate these issues while supporting the Basin Study and other similar scale studies, development of the RiverWare Study Manager and Research Tool (RiverSMART) was undertaken. The RiverSMART facilitates the creation, execution and archiving of planning studies that compare the results of many scenarios, all steps one must manually take when using RiverWare to simulate multiple scenarios. RiverSMART provides a user friendly interface as shown in Figure 2. For construction of a study, this also provides a graphical representation of the study to help conceptualize all of the components and their interactions.

RiverSMART is built on a plug-in architecture and provides the framework for communication amongst the various plugins. In general, the plugins generate hydrologic ensembles, specify alternative input data to the RiverWare model, define alternative model configurations and policy, and post process desired outputs. Each individual instance of a plugin is called an event. Each event has settings that are configured by the user. Following is a description of some of the plugins available in RiverSMART (input side) and utilized in the Basin Study:

- Hydrology Simulator and Disaggregation Plugins: The Hydrology Simulator plugin synthesizes an ensemble of streamflows from reference values, usually observed historical or paleo reconstructed values. There are various methodologies available including K Nearest Neighbor resampling, Paleo Conditioned Homogenous Markov Chains, and Paleo Conditioned Non-homogenous Markov Chains. There is also a Spatial Disagg plugin to disaggregate the flows from one site to a number of sites according to correlations of the reference data. The Temporal Disagg plugin disaggregates annual ensemble data to a monthly timestep.
- RiverWare Model: The RiverWare Model plugin instructs which RiverWare model to use. This allows the user to develop alternative facilities or model configuration as a component in the study.
- RiverWare DMI: The Data Management Interface (DMI) plugin instructs which RiverWare DMIs in the model should be run to bring in alternative data. DMI events are grouped into user-named categories that contain input alternatives. For example there might be a category of DMI events named "Supplies" that contains several ensembles of

hydrologic inflows, and a category of DMI events named "Demands" that includes different demand schedules. DMI events instruct RiverWare to bring in data from specified sources such as a database, text files, or excel spreadsheet. In addition, the Demand Input Tool (DIT) can be used to develop the sets of demands. This Excel-based tool generates the detailed demands for water in the entire basin and allows easy modification of demand projections and automatic loading of the new demands into a RiverWare model. The DIT enables users to enter baseline demand data, create and enter alternative demand scenarios and plot the baseline and scenario data to visualize changes.

- RiverWare Policy: The RiverWare Policy plugin specifies the RiverWare ruleset to use. This allows the user to develop alternative operations as one of the scenario components.

Once the study network has been defined and all of the events have been configured, the user instructs RiverSMART to generate the list of scenarios. Scenarios are specific combinations of input data, policy sets, models, and run configurations. RiverSMART first creates a list of all possible combinations of alternatives and then the user can then look through the list of scenarios and deactivate those that are not of interest. Figure 2 illustrates the different supply and demand scenarios in the Basin Study organized in RiverSMART.

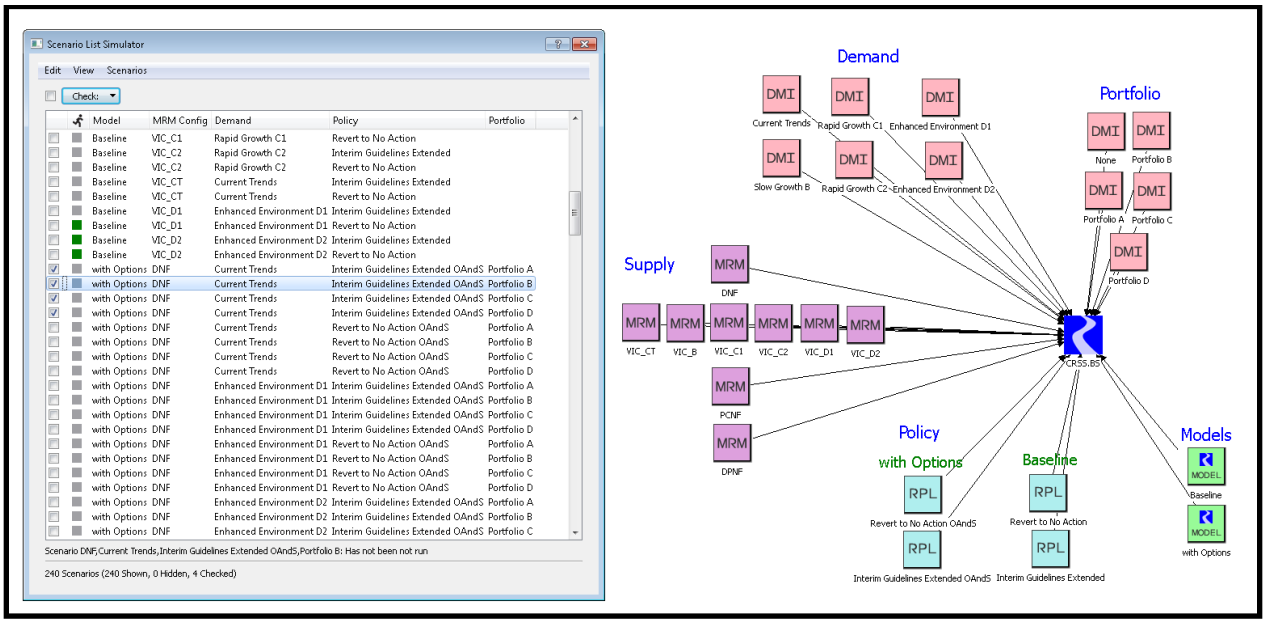

Figure 2 Screenshot of Basin Study in RiverSMART

The user then runs the specified scenarios with RiverSMART managing the data archiving, importing data for new scenarios, and starting the next scenario. The runs utilize RiverWare's distributed Multiple Run Management where individual runs are spread over available computer processors.

Once the scenarios are simulated, the user instructs RiverSMART to post process the scenarios by executing events that act on each scenario or on sets of scenarios. The plugins for post processing scenarios include plugins to convert files from RiverWare's Data Format (RDF) to Excel and annualize monthly data to an annual timestep. Plugins can generate plots using an R

Script plugin or generate graphs in Excel using the Graphical Policy Analysis tool, GPAT. This Excel tool allows users to visualize and analyze RiverWare model outputs as well as other data sets. This tool is designed to allow statistical comparisons and graphing of multiple modeling runs that may vary with respect to hydrology, operational policy, or other parameters.

The Basin Study utilized the R programming language to process results from all scenarios simultaneously, evaluate the reliability metrics, and prepare the data for plotting. For the Basin Study, the post-processing step was critical to distill the results of 240 scenarios into understandable and meaningful figures. R was used to process the data and prepare it for use within Tableau, software for interactive data visualization and analytics. Figure 3 is taken from the Basin Study and shows the percent of future simulations in which Lake Mead drops below 1,000 feet, a critical elevation for water deliveries to Las Vegas. This figure distills the results from over 20,000 simulations and 48 scenarios into 144 points. This type of visualization allows one to understand how the results for the particular variable vary with supply scenario, demand scenario, operational option, and through time. Additionally, Tableau helped the modelers understand and verify model results during the Basin Study by utilizing its interactive features, a step that is critical in any modeling exercise.

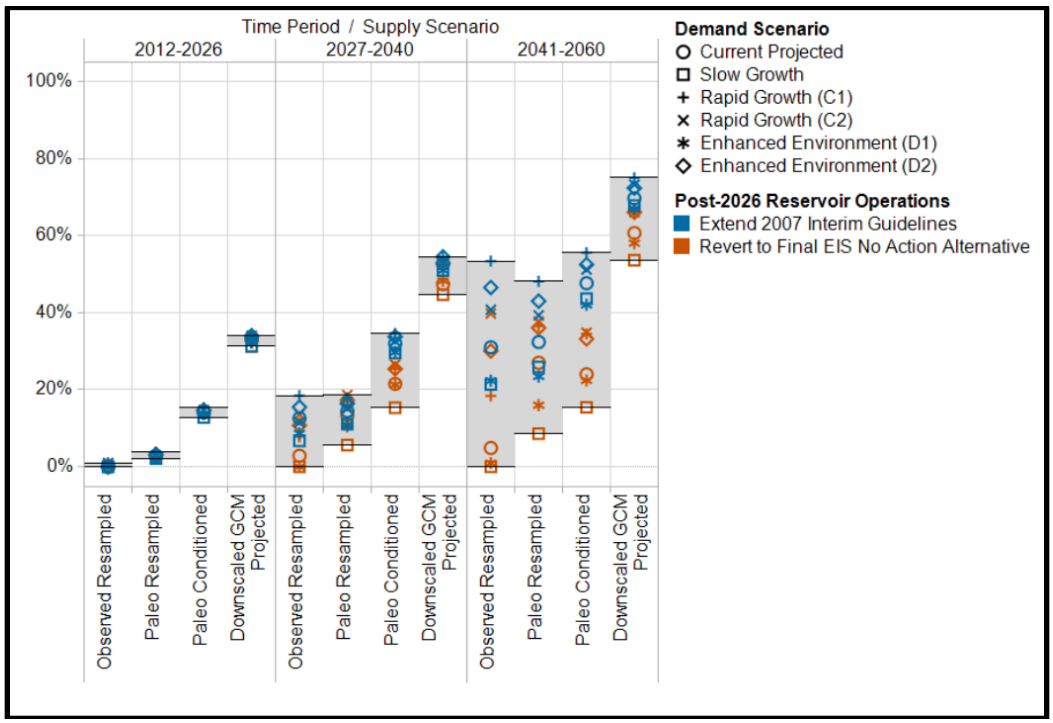

Figure 3 Percent of Baseline Future Simulations Resulting in Lake Mead Less than 1,000 feet

Even with the efficiency of RiverWare, RiverSMART and R, the total computing time for simulating and processing the scenarios was on the order of 4-6 weeks. To help decrease the computing time and based on other lessons learned during the Basin Study, Reclamation has continued to support targeted development for RiverWare and RiverSMART components. An R plugin was added to RiverSMART and RiverWare now supports exporting data in a format directly readable by Tableau, which will expedite the analysis process and cutout one of the post-

processing steps. Additional work is underway to support exporting data from RiverWare to NetCDF files; a step that could help make modeling results machine readable, and could decrease the total storage size of results. The RiverSMART tool has also become part of Reclamation's widely relied upon modeling tools utilized in many different studies. As RiverWare helped CRSS evolve in 1996, RiverSMART is the next step in this evolution of Reclamation's modeling tools.

SUMMARY

The Basin Study helped quantify the potential supply and demand imbalance on the Colorado River Basin over the next 50 years, while analyzing potential options for alleviating such imbalances. A scenario planning approach led the Basin Study to use many scenarios to quantify a wide range of plausible future outcomes. All together 240 scenarios were simulated using CRSS—the Basin-wide model developed in RiverWare.

The suite of tools employed in the Basin Study, i.e., RiverWare, RiverSMART, R, and Tableau, was critical to the development and management of the numerous simulations necessary for the robust decision making framework utilized in the Basin Study. This suite of tools can be used to support any planning study or "what-if" analyses that require many iterations of input or assumptions. Since the completion of the Basin Study, the tools have become part of Reclamation's standard suite of modeling tools, and development has continued to enhance their capabilities.

REFERENCES

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