UTILIZING PROBABILISTIC FORECASTS FOR COLORADO RIVER RESERVOIR OPERATIONS USING A MID-TERM PROBABILISTIC OPERATIONS MODEL FOR DECISION MAKING AND RISK MANAGEMENT

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Abstract: The Bureau of Reclamation (Reclamation) manages reservoirs on the Colorado River Basin (Basin) from the headwater sub-basins down to the border with Mexico. Ensemble inflow forecasts are utilized to develop probabilistic information that supports decision-making at various temporal scales, from daily operations and spring runoff routing to annual operations and multi-year planning. The Upper Basin reservoirs, from the headwaters to Lake Powell, are supply driven and their operations depend heavily on forecasted inflows. Risk management in the Upper Basin balances water supply, hydropower, flood control, endangered species, fish and wildlife, and recreation. Operations of Lower Basin reservoirs, from Lake Mead to the border with Mexico, utilize Upper Basin probabilistic operational scenarios to manage risk by identifying a range of future Lake Mead elevations and potential impacts on water delivery in the Lower Basin. Probabilistic risk management helps to inform decision making for Basin stakeholders concerned with flood control, hydropower, recreation, environment, water supply, and water delivery in the Lower Basin.

Reclamation has developed a suite of RiverWare™ operations and planning models to aid with different aspects of decision making and risk management in both the Lower and Upper Basins. The Mid-Term Probabilistic Operations Model (MTOM) is the newest model utilized by both basins to support decision making by Reclamation and other Basin stakeholders. The MTOM System provides 5-year probabilistic projections for the Basin's major reservoirs and critical reaches at a monthly time step. The MTOM system is comprised of several components that include an ensemble forecast from the Colorado Basin River Forecast Center, a RiverWare™ operations model of the major reservoirs of the Colorado River System, and probabilistic output with an analysis and visualization tool. The system is currently being used to generate a 5-year probabilistic operational outlook for the Basin that is distributed monthly to stakeholders and decision makers.

This paper will present an overview of key components of the MTOM System and also highlight sample results and applications of the system for particular Basin operations.

INTRODUCTION

Current climate and hydrologic conditions in the Southwestern United States and predictions of increased climatic variability in the future give rise to the need for improved predictive tools for managing water resources in the region. The Bureau of Reclamation (Reclamation) is responsible for the operation of the infrastructure that provides water, hydropower, and flood control to the Colorado River Basin (Basin) states of Arizona, California, Colorado, Nevada,

New Mexico, Utah, and Wyoming. Historically, Reclamation has used two primary Basin-wide modeling and decision support tools. These are (1) the 24-Month Study and (2) the Colorado River Simulation System (CRSS). The 24-Month Study, which is used in the Annual Operating Plan (AOP) process, is an operational model with a 2-year outlook that uses most a probable inflow forecast (updated monthly) provided by the National Weather Service's Colorado Basin River Forecast Center (CBRFC). The 24-Month Study is limited in its ability to incorporate hydrologic uncertainty because it is designed to simulate only one hydrologic and operational scenario and future reservoir operations must be input manually. CRSS, which is used in long-term planning studies (e.g., the Colorado River Basin Water Supply and Demand Study and development of the 2007 Interim Guidelines for the Coordinated Operations of Lake Powell and Lake Mead), is a planning model that simulates Basin conditions decades into the future. Although CRSS accounts for hydrologic uncertainty in its ability to simulate hundreds of future hydrologic scenarios, it is limited in its ability to incorporate real-time forecasts and operations. Reclamation and Basin stakeholders have desired a decision support tool that blends the probabilistic strength of CRSS with the operational knowledge of the 24-Month Study. The Mid-Term Probabilistic Operations Model (MTOM) System was developed to meet this need. It provides probabilistic information about risk and uncertainty associated with Basin reservoir operations in the 1- to 5-year timeframe. The MTOM System consists of a RiverWare™ model and supporting components that enable the model to access input and produce output in an efficient manner. The MTOM System uses an ensemble of hydrologic forecasts to produce probabilistic 5-year operational projections for the major reservoirs in the Basin. The model results are then analyzed collectively to quantify the likelihood of significant future system conditions.

ENSEMBLE FORECASTS

The primary input, and main driver of operations, for the MTOM System is an ensemble of unregulated inflow forecasts at various forecast points in the Upper Basin. Unregulated flow is the forecasted flow that would arrive at a specific point if there were no dams located upstream of that point. The CBRFC provides thirty 60-month traces for 12 forecast points in the Upper Basin (locations of Upper Basin inflow points are provided in Figure 1). Each inflow forecast is derived from historical sequential climatology (temperature and precipitation based on the period from 1981 to 2010) that is applied to the current Basin conditions (e.g. soil moisture, antecedent streamflow, snowpack). The CBRFC utilizes the data to develop 30 traces of hydrologic inflow forecasts.

The CBRFC methods of producing the forecasts involve the use of the Ensemble Streamflow Prediction (ESP) System which is part of the National Weather Service Forecast System (NWSFS). A continuous hydrologic model comprised of two main sub models, the Sacramento Soil Moisture Accounting Model (SAC-SMA) and the SNOW-17 snow model, are used to simulate the soil moisture and snow states throughout the Basin, which determine the initial conditions for the ESP System, Brandon (2005).

The ESP System then generates multiple scenarios of forecast streamflow time series from which probability functions for water supply volume can be computed. The future scenarios are based on a combination of the current soil moisture and snow states mentioned above and the historical sequences of precipitation and temperature to produce the ensemble of streamflow forecasts. Each year of historical climatology data is assumed to be a possible representation of future

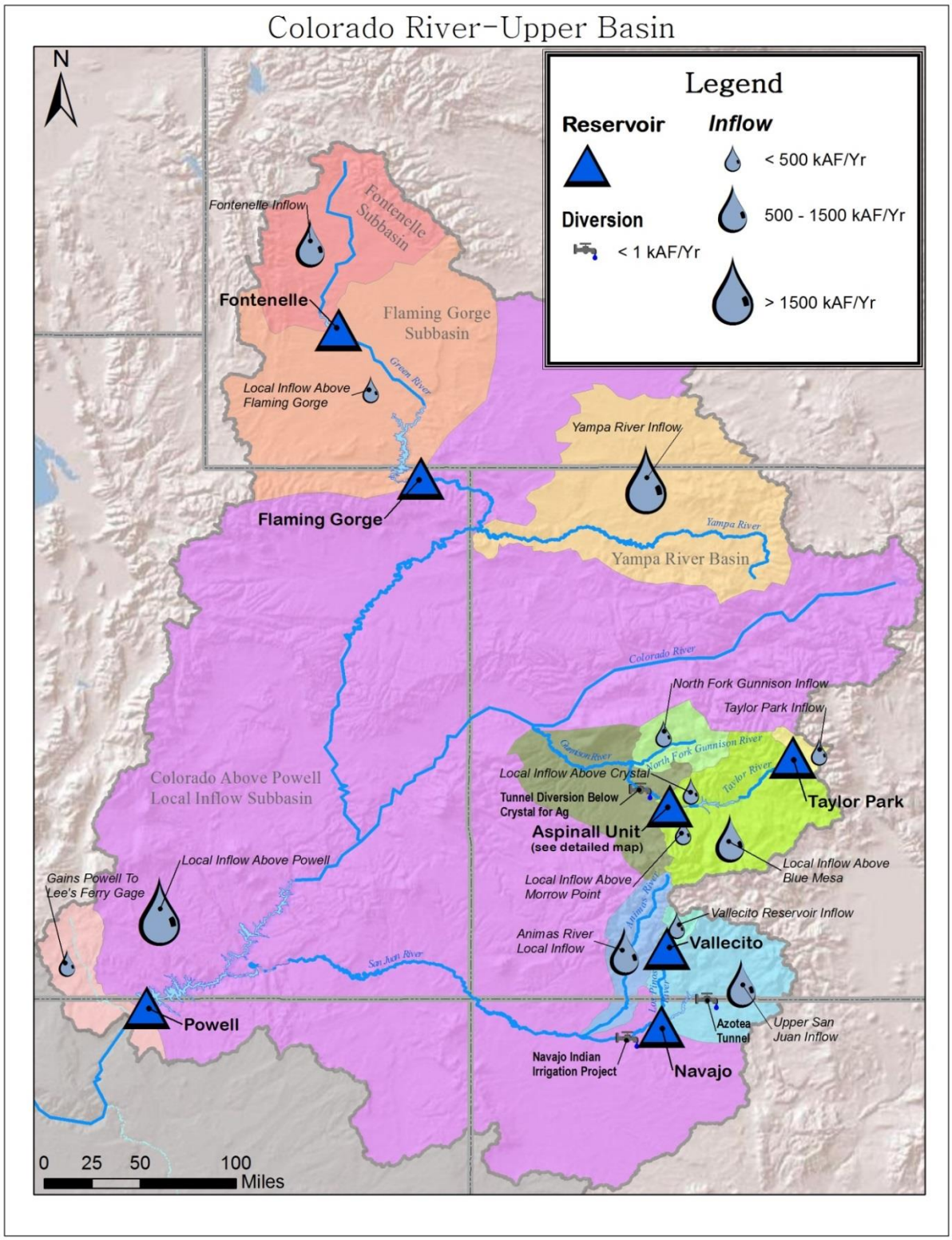


Figure 1 Upper Colorado River Basin as Represented in the MTOM System Model

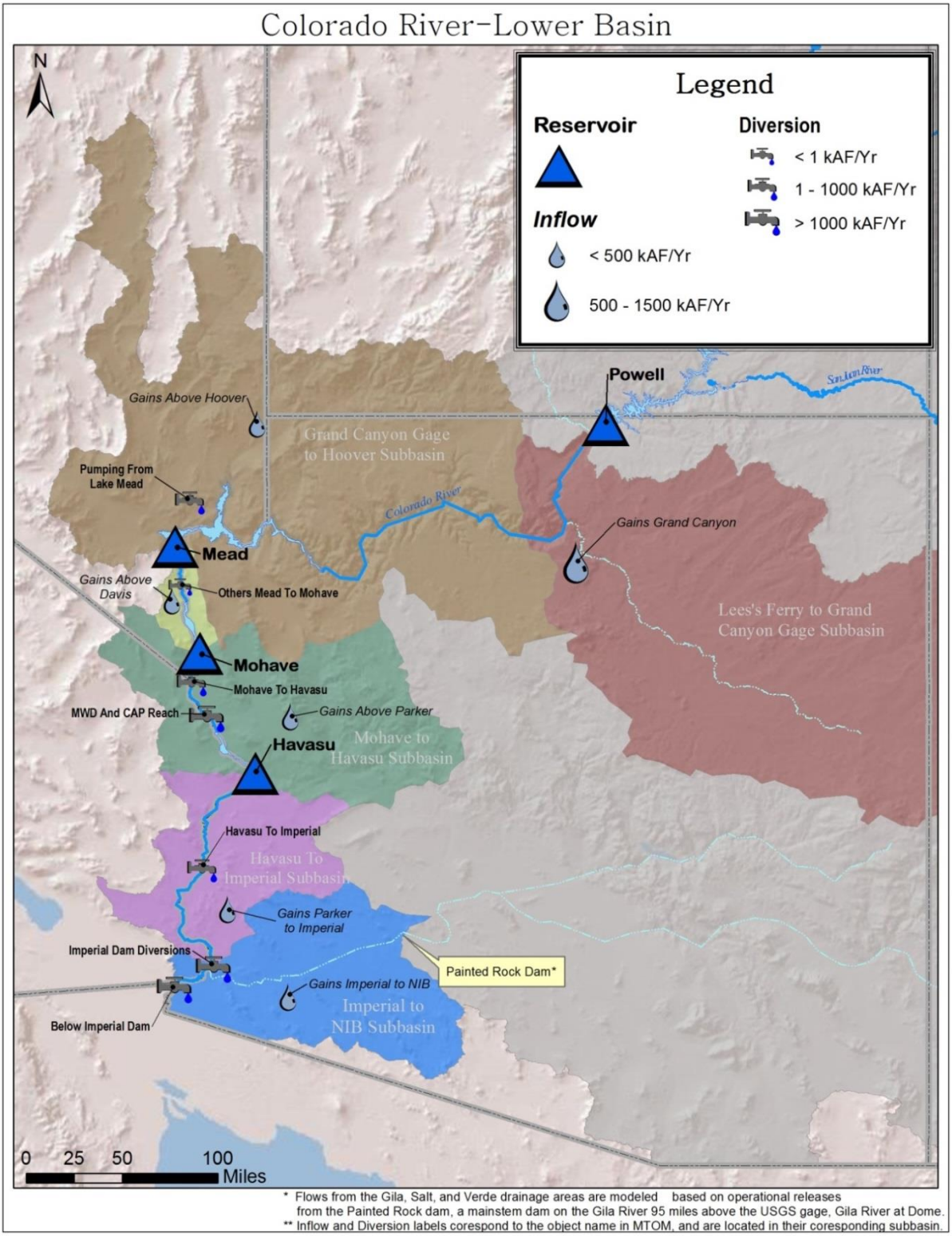


Figure 2 Lower Colorado River Basin as Represented in the MTOM System Model

streamflows in the Basin and each forecast trace produced by the ESP System is treated as equally likely to occur

The ensemble of 30 equally likely unregulated inflow forecasts is run through MTOM to produce an ensemble of potential operations and system conditions. The results can then be analyzed collectively to project potential future conditions within the Basin, and quantify the uncertainty in those projections.

Lower Basin intervening inflow projections are based on a resampling of historical data over the period from 1981 through 2010 in the reaches above Lake Mead and on statistics (median, 10th percentile, and 90th percentile) from the same 30-year period for reaches below Lake Mead (locations of Lower Basin inflow points are provided in Figure 2).

MID-TERM PROBABILISTIC OPERATIONS MODELING SYSTEM

The MTOM System consists of a RiverWare™ model and supporting components that enable the model to access input and produce output in an efficient manner. The modeling system as a whole is comprised of six components that allow for MTOM to function either as (1) a single run (deterministic) simulation model, which allows the users to compare the results of the MTOM run to those from the 24-Month Study model; or (2) as an ensemble, or probabilistic, modeling tool that can be used to estimate the probability of outcomes given an ensemble of inflow forecasts as demonstrated in Figure 3. This paper focuses on MTOM's strength as a probabilistic operations modeling system.

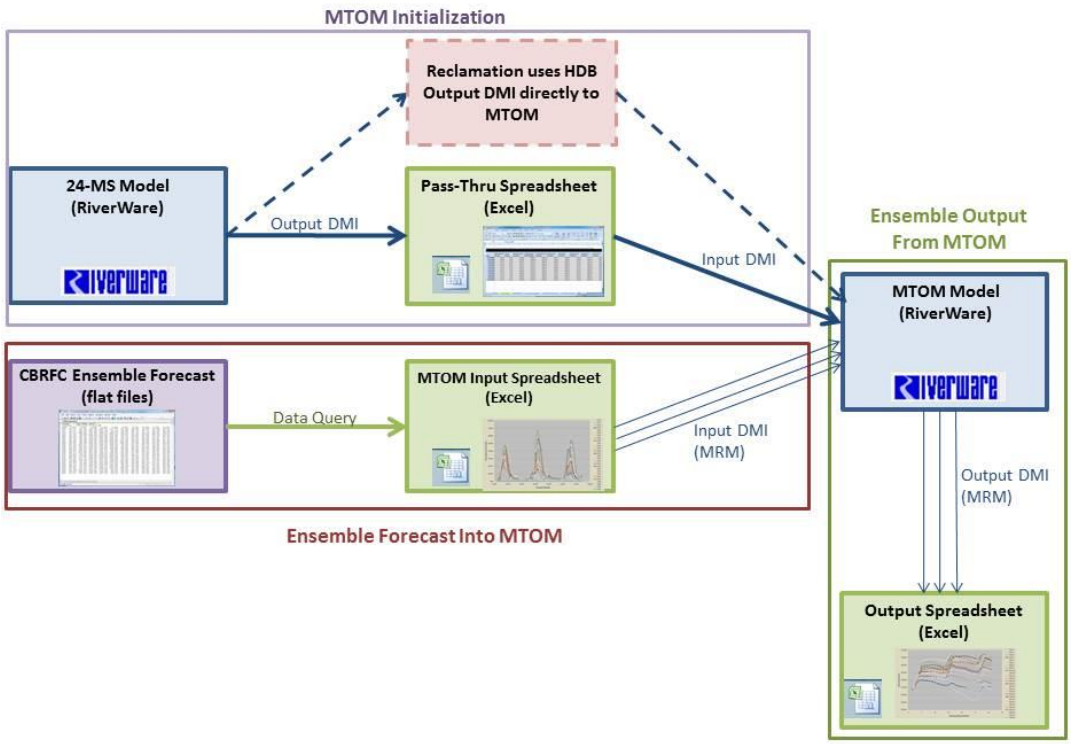


Figure 3 MTOM System Schematic

The MTOM Input Spreadsheet is a Microsoft Excel spreadsheet application designed to import the CBRFC forecast ensembles from data files and provide a platform for MTOM to access those data. The spreadsheet includes forecasts for each of the 12 forecast points in the Upper Basin as well as intervening flows (derived from the historical record) for reaches between Glen Canyon Dam and Hoover Dam. The spreadsheet provides users the capability to view the ensemble of forecasts for each forecast point, and formats the data for import into the RiverWare™ model.

MTOM is a basin-wide RiverWare™ model which simulates reservoir operations at a monthly time step. MTOM uses two RiverWare™ components to correctly model the Basin. The first is a workspace which represents Basin. This allows for the setup of reservoirs, reaches, diversions, and data objects to describe the physical characteristics of the Basin.

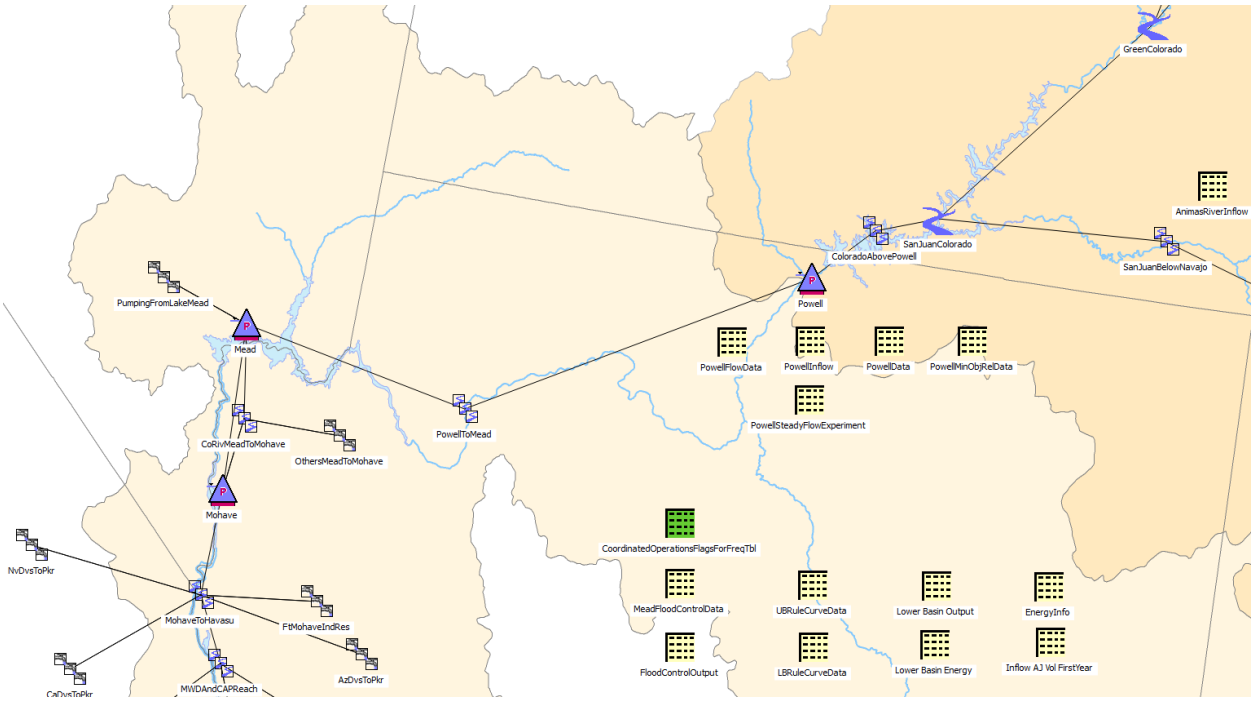
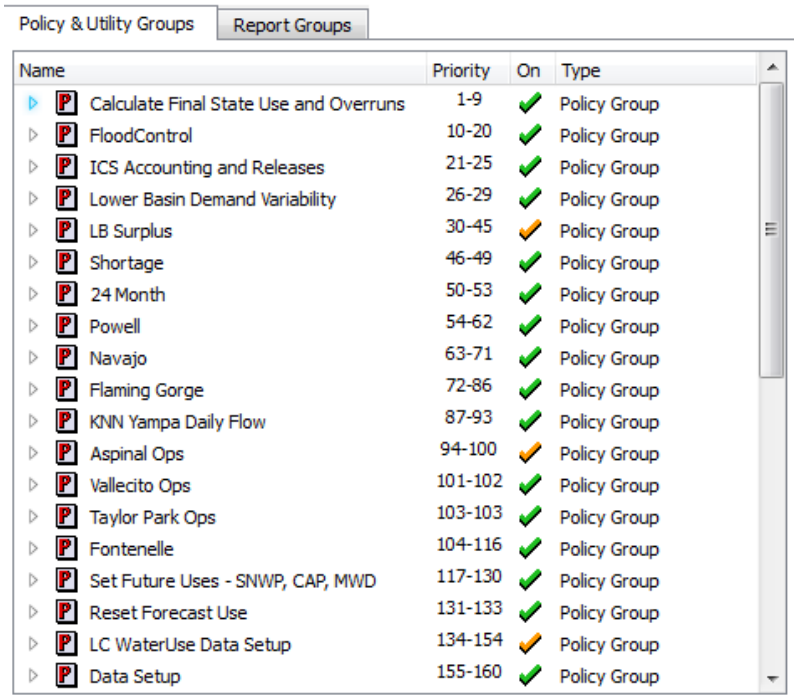


Figure 4 MTOM Workspace above Lake Powell to Below Davis Dam

The second component is a unique programming language known as the RiverWare™ Policy Language or RPL. This language allows users to code operational policy into MTOM. RiverWare™ then uses this policy to determine the various physical components within the model to solve the mass balance equations in place of user inputs for operations in MTOM. The RPL policy is developed in separate components called rules. Rules are written to contain a specific piece of policy language, such as a guide curve for simulating releases from a reservoir, or implementation of flood control operations under high inflow conditions. The individual rule format, as opposed to a single script containing all of the policy coding, is used to order policy components by priority. The rules guide the simulation of the Basin and are based on the law that governs the operations of the reservoirs in the Basin as well as operational guidance provided by reservoir operators.



Policy & Utility Groups | Report Groups

Name	Priority	On	Type
Calculate Final State Use and Overruns	1-9	✔	Policy Group
FloodControl	10-20	✔	Policy Group
ICS Accounting and Releases	21-25	✔	Policy Group
Lower Basin Demand Variability	26-29	✔	Policy Group
LB Surplus	30-45	✔	Policy Group
Shortage	46-49	✔	Policy Group
24 Month	50-53	✔	Policy Group
Powell	54-62	✔	Policy Group
Navajo	63-71	✔	Policy Group
Flaming Gorge	72-86	✔	Policy Group
KNN Yampa Daily Flow	87-93	✔	Policy Group
Aspinal Ops	94-100	✔	Policy Group
Vallecito Ops	101-102	✔	Policy Group
Taylor Park Ops	103-103	✔	Policy Group
Fontenelle	104-116	✔	Policy Group
Set Future Uses - SNWP, CAP, MWD	117-130	✔	Policy Group
Reset Forecast Use	131-133	✔	Policy Group
LC WaterUse Data Setup	134-154	✔	Policy Group
Data Setup	155-160	✔	Policy Group

Figure 5 MTOM RiverWare™ Policy Language Interface

In addition to the physical workspace and the rules that that drive reservoir operations in the model, MTOM uses a unique capability in RiverWare™ called run cycles. Run cycles allow the model to solve the entire system in pieces using select portions of RPL logic to solve a portion of the system in each run cycle. This is useful because it allows the model to provide needed information from one piece of the reservoir system to the next. In MTOM, once operations are set for the most upstream reservoirs, operations for the next downstream reservoirs can be simulated. Information about upstream reservoir operations is required before operations can be set for the downstream reservoirs because a full year of projected inflow is required for planning reservoir releases at those downstream reservoirs (in accordance with the distinct RODs that govern operations of those reservoirs). Additionally, operations for Lake Powell and Lake Mead are frequently set in an iterative manner, as Lake Powell and Lake Mead operations are coordinated based on their respective releases and resulting elevations. Four run cycles are utilized in the MTOM RiverWare™ model. The upstream reservoirs in the headwaters of the system (Fontenelle Reservoir, Vallecito Reservoir, and Taylor Park Reservoir) are solved in the first run cycle, the remainder of the Upper Basin reservoirs (Flaming Gorge Reservoir, Navajo Reservoir, and the Aspinall Unit) down to Lake Powell are solved in the second run cycle, Lake Powell and the Lower Basin are solved in the third run cycle, and any operations at Lake Powell or Lake Mead that need to be fine-tuned in an iterative manner solve in the fourth run cycle. The run cycles allow the MTOM model to solve the basin according to the Law of the River and various operational guidelines throughout the Basin.

The Output Spreadsheet is a Microsoft Excel spreadsheet application that stores and processes the results of each simulation of a multi-trace model run. The spreadsheet is used to process the model's output so that information can be disseminated in a way that is useful for stakeholders and decision makers within the Basin. Data can be viewed in the raw output form for a given

output variable of interest, or data can be viewed post-processing to give an in-depth look at the frequency of occurrence for certain conditions within the Basin. The Output Spreadsheet is a tool that summarizes the probabilistic analysis and risk assessment that is provided through the MTOM System.

OUTPUT FOR DECISION MAKING AND RISK MANAGEMENT

The output from the MTOM System model is an ensemble of results throughout the Basin that includes inflow, outflow, and content for reservoirs; diversions for water users; and indicators of specific operational conditions such as lower Basin shortage, surplus and flood control. The Output Spreadsheet compiles the output data into useful plots and tables that can be used by Reclamation to disseminate information to stakeholders throughout the Basin. Using an ensemble of equally likely forecasts to drive multiple runs of the model and then collecting and analyzing the ensemble of results provides stakeholders and water managers with an estimate of uncertainty at any point in the time range of the model run. Because the MTOM System provides a more complete characterization of what the future condition of the Colorado River Basin might be, it enables decision-makers to more effectively manage their water supplies.

The most informative and standard product of the MTOM System process is a table that gives the percent of traces showing the occurrence of system conditions at Lake Mead and Lake Powell. Table 1 displays a template of this frequency table, where the system conditions are defined in the Interim Guidelines for Lower Basin Shortages and the Coordinated Operations of Lake Powell and Lake Mead (2007). Events that are categorized in this table include the annual release tier at Lake Powell and the annual release volume (if the volume is categorized further). In the Lower Basin the water supply conditions Shortage, Surplus, or Normal are categorized.

Table 1 Example of Percent of Occurrence of System Conditions Produced by the MTOM System

	Event or System Condition	WY1	WY2	WY3	WY4	WY5
Upper Basin - Lake Powell	**Equalization Tier**					
	Equalization - annual release > 8.23 maf					
	Equalization - annual release = 8.23 maf					
	Upper Elevation Balancing Tier					
	Upper Elevation Balancing - annual release > 8.23 maf					
	Upper Elevation Balancing - annual release = 8.23 maf					
	Upper Elevation Balancing - annual release < 8.23 maf					
	Mid-Elevation Release Tier					
	Mid-Elevation Balancing - annual release = 8.23 maf					
	Mid-Elevation Balancing - annual release = 7.48 maf					
	Lower Elevation Balancing Tier					
	Lower Elevation Balancing - annual release > 8.23 maf					
	Lower Elevation Balancing - annual release = 8.23 maf					
	Lower Elevation Balancing - annual release < 8.23 maf					
Lower Basin - Lake Mead	**Shortage Condition - any amount (Mead <= 1,075 ft)**					
	Shortage - 1st level (Mead<= 1,075 and >= 1,050)					
	Shortage - 2nd level (Mead<1,050 and >= 1,025)					
	Shortage - 3rd level (Mead< 1,025)					
	Surplus Condition - any amount (Mead >= 1,145 ft)					
	Surplus - Flood Control					
	Normal or ICS Surplus Condition					

The output spreadsheet also provides a tool to view any number of the output traces for any of the mass balance components of the reservoirs included in MTOM. The graphics produced from this tool, sometimes referred to as spaghetti plots, give a visual representation of the probabilistic outcome of an MTOM System run. Figure 6 shows an example of results for the Lake Mead pool elevation.

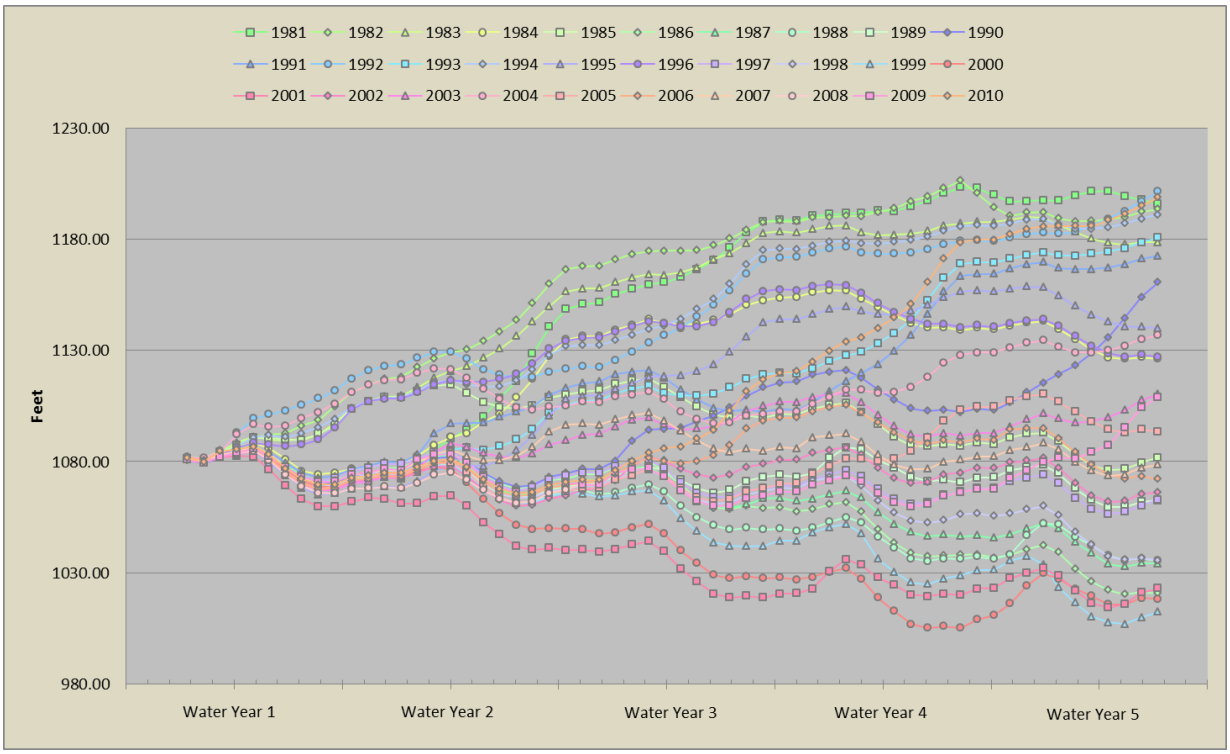


Figure 6 Example of Raw Lake Mead Pool Elevation Output from the MTOM System

The raw output traces are further processed using a month by month exceedance algorithm that can provide further analysis of the ensemble output. This month by month exceedance analysis can provide a possibly more informative view of the MTOM System output as demonstrated in Figure 7. It is important to note, however, that the exceedance algorithm produces traces that could be outside of the bounds of any given ensemble forecast; meaning that the driest (90 percent) trace may be drier than any one of the 30 output traces and the wettest (10 percent) trace may be wetter than any one of the 30 traces. This is due to the monthly exceedance analysis performed on the data which calculates an exceedance value for each month based on the raw data. The exceedance analysis is performed month-by-month such that the 90 percent trace is the 90 percent value for each individual month appended together into a single trace. Each exceedance trace is actually a compilation of the driest 90 percent value of each month in the run. This makes a very dry trace and this effect is more pronounced at the extremes than the raw ensemble output. The month by month exceedance value calculation is demonstrated with Table 2 and Equation 1 to obtain the 35 percent exceedance value for Lake Mead Pool Elevation using linear interpolation; which solves to a value of 1,081.50 feet for Month 1.

Table 2 Ranking of Lake Mead Pool Elevation (PE) for Exceedance Calculation Algorithm

Rank	8	9	10	11	12	13
Rank/n observations	25.81%	29.03%	32.26%	35.48%	38.71%	41.94%
Month 1 Ranked Mead PE Values	1,081.51	1,081.51	1,081.48	1,081.43	1,081.41	1,081.36
Month 2 Ranked Mead PE Values	1,080.49	1,080.48	1,080.46	1,080.41	1,080.30	1,080.23
Month 3 Ranked Mead PE Values	1,083.44	1,083.40	1,083.29	1,083.19	1,083.14	1,083.06

$$LakeMeadPE_{30\%,Month1} = \mathrm{PE}_9 + (\mathrm{PE}_{10} - \mathrm{PE}_9) * \frac{(30\% - \%_9)}{(\%_{10} - \%_9)} \quad (1)$$

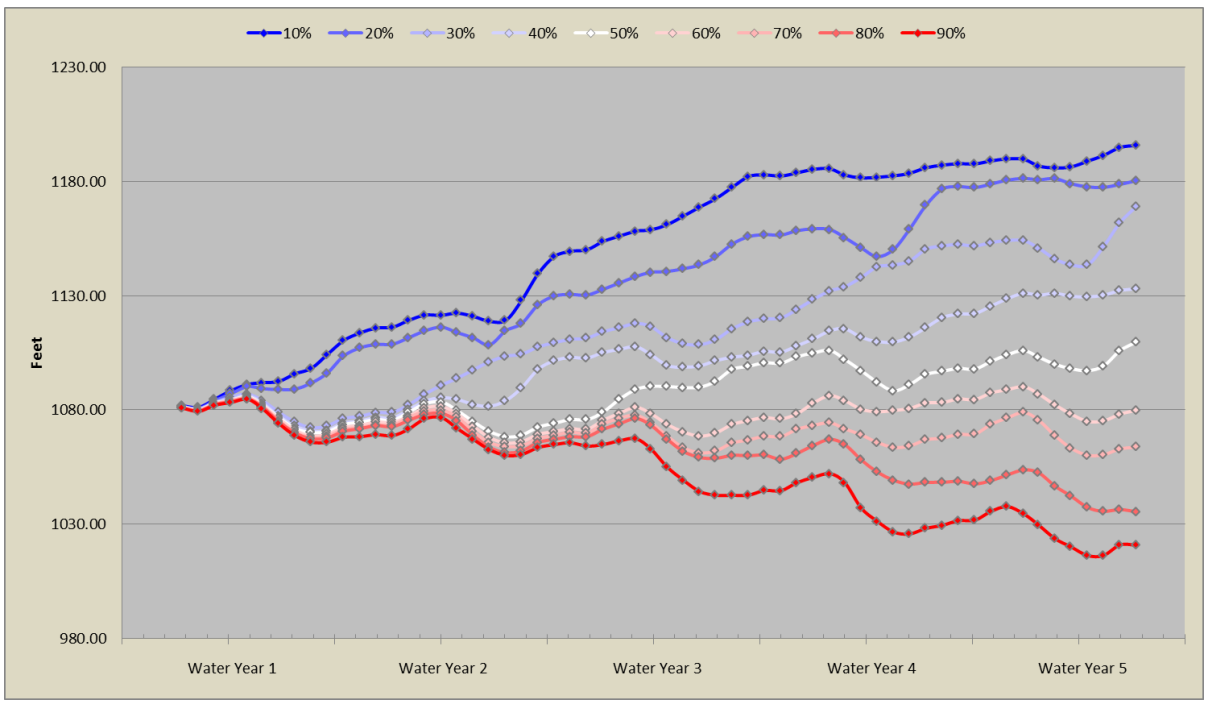


Figure 7 Example of Monthly Exceedance Processing of Lake Mead Pool Elevation Output

SUMMARY

MTOM has been developed to compliment two established and well-used models of the Colorado River Basin. It builds on the operations-specific strength of the 24-Month Study and the probabilistic strength of the Colorado River Simulation System to provide a probabilistic 60-month outlook for reservoir operations throughout the Basin. MTOM is a RiverWare™ model that uses RiverWare™ Policy Language and run cycles so that the specific operational policy and guidelines in the Basin can be modeled correctly at a monthly time step. The MTOM System includes the use of Colorado Basin River Forecast Center ensemble forecasts as the probabilistic input for the model. The System includes input and output spreadsheets as components that allow users to interact with the input and output data easily. The MTOM System outputs probabilistic data for reservoir operations and specific Basin conditions that aid in the understanding of risk and uncertainty in future conditions within the Basin. With MTOM

and the other modeling tools used in the Basin, Reclamation and Basin stakeholders obtain greater information for decision-making through ensemble forecasting and probabilistic analysis.

REFERENCES

Brandon, David G., (2005) Using NWSRFS ESP for Making Early Outlooks of Seasonal Runoff Volumes into Lake Powell, National Weather Service – Colorado Basin River Forecast Center (CBRFC). Web October 15, 2014 <http://www.cbrfc.noaa.gov/papers/forecastpaper.pdf>

U.S. Department of the Interior, Bureau of Reclamation. Record of Decision Colorado River Interim Guidelines for Lower Basin Shortages and the Coordinated Operations for Lake Powell and Lake Mead. USBR, December 2007. Web September 20, 2013 <http://www.usbr.gov/lc/region/programs/strategies/RecordofDecision.pdf>

Zagona, Edith A., Terrance J. Fulp, Richard Shane, Timothy Magee, and H. Morgan Goranflo (2001), RiverWare: A Generalized Tool for Complex Reservoir Systems Modeling, Journal of the American Water Resources Association, AWRA 37(4):913-929.