# Adaptation of the Existing Fryingpan-Arkansas Project RiverWare Planning Model to Support Operational Modeling, Forecasting, and Probabilistic Decision-Making

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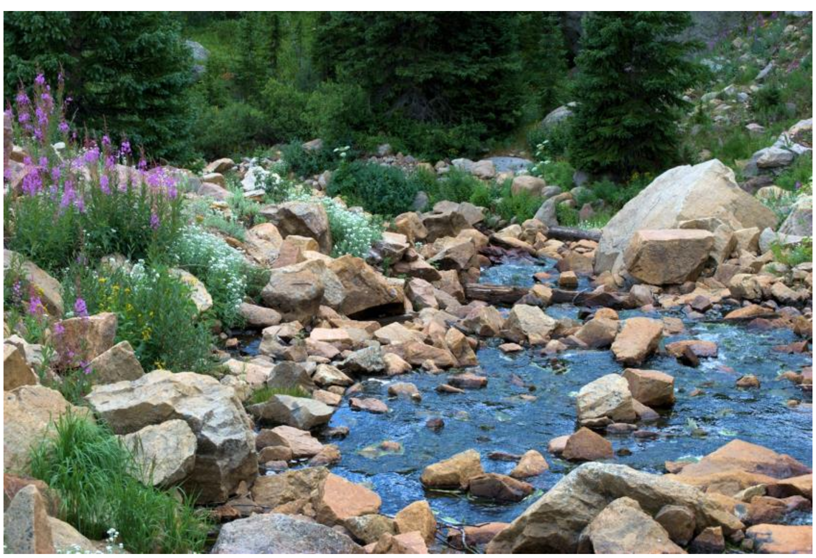
**Final Report No. ST-2020-PROJECT ID 200044-REPORT NUMBER-01**



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## Bureau of Reclamation
## Research and Development Office
## Science and Technology Program

Final Report No. ST-2020-PROJECT ID 200044-REPORT NUMBER- 01

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# Acronyms and Abbreviations

| | |
|---|---|
| ABRFC | Arkansas Basin River Forecasting Center |
| ABRW | Arkansas Basin RiverWare model |
| HDB | Hydrologic Database |
| IR | Inflow Rule |
| PFO | Pueblo Field Office |
| Precision | Precision Water Resource Engineering, LLC |
| RCL | RiverWare Control Language |
| Reclamation | Bureau of Reclamation |
| RFC | River Forecast Center |
| WR | Water Rights |
| WRS | Water Rights Solver |
| WW | Winter Water |
| WWSP | Winter Water Storage Program |

# Contents

Page

# Executive Summary

The purpose of S&T Grant 20044 "Adaptation of the Existing Fryingpan-Arkansas Project RiverWare Planning Model to Support Operational Modeling, Forecasting, and Probabilistic Decision-Making" was to begin the process of adapting a long-term planning model into a short-term operational forecasting model that could use ensemble, synthetic or analog year runoff forecasts along with past operations or individual entity plans to determine optimal operations. The model needed to remain congruent for both long-term and short-term uses.

The Fryingpan-Arkansas Project–Arkansas Basin RiverWare (ABRW) model was developed by Precision Water Resource Engineering, LLC for Reclamation to support Reclamation's 2018 *Final Programmatic Environmental Assessment (EA) for Pueblo Reservoir Temporary Excess Capacity Storage Contracting Program*. That resulted in a multi-purpose planning model that began with inputs from the west-slope collection system through transbasin diversions to the Arkansas Basin and modeled for water usage into Kansas. It was designed to support decisions for Reclamation's Pueblo Reservoir storage contracts but relied on data from federal, state, local, public, quasi-public, private, municipal, and agricultural entities.

The updated modeling system uses data from Reclamation's Hydrologic Database (HDB) as input, performs necessary pre-processing of the data through a series of Excel workbooks, and uses RiverWare Data Management Interfaces (DMIs) to use transfer the data to and from the model. A controller workbook allows the model to be run with single or multiple trace runoff forecasts. Model results can be examined as charts and tables in an output viewer workbook. The system's directory structure is designed to allow users to easily compare different runs, store models for analysis and to archive data and results used to make decisions.

Significant progress has been made in the implementation of the ABRW Operations modeling system. This progress represents a proof-of-concept in the feasibility of reaching the project's ultimate objectives and the modeling system's design. Furthermore, it highlights the substantial potential value and benefits that the modeling system can achieve. The pathway to successful application of the modeling system in practice now depends upon focus on database quality and model performance and accuracy. As with any novel implementation of a state-of-the-art decision support tool, the best chance for overall success and realization of potential benefits will come from focusing on these aspects while continually testing, evaluating, and enhancing the modelling system alongside the existing real-world operational planning and decision-making processes.

# 1 Overview

## 1.1 Background

The Fryingpan-Arkansas Project–Arkansas Basin RiverWare (ABRW) model was developed to its incoming (prior to this effort) level-of-development by Precision Water Resources Engineering, LLC, (Precision) for Reclamation primarily during the 2016-2018 period, to support Reclamation's 2018 *Final Programmatic Environmental Assessment (EA) for Pueblo Reservoir Temporary Excess Capacity Storage Contracting Program*. That primary phase of model development saw the basic structure and network of the previously existing Pueblo Field Office (PFO)'s Fryingpan-Arkansas Project RiverWare accounting model expanded to a multi-purpose planning model of the Arkansas basin and Fryingpan-Arkansas Project.

This effort reflects the first significant effort to adapt the model to support short-term operational modeling and decision-making. This effort was undertaken by Precision Water Resources Engineering, LLC, (Precision) in conjunction with the Bureau of Reclamation's Pueblo Field Office (PFO) as part of a FY2020 Bureau of Reclamation Science and Technology Program grant project awarded to and managed by PFO. The Principal Investigator and Project Manager of this project is Theresa Dawson of MB-ECAO-PFO. The primary water resource engineer and model developer on this project for Precision is Todd Vandegrift.

## 1.2 Objectives and Approach

The primary objective in this project was to adapt and enhance the existing ABRW model, and to develop the data pathways and tools necessary to allow the model to be used to support Reclamation's FryArk Project and Arkansas basin operations. The starting point model is a data intensive and dependent model. It's simulation processes and rules, most notably the water rights solver that provides the fundamental basis for simulation, are dependent on a "complete" view of the basin's current and recently observed status and conditions. Thus, in order to run, the model needs a lot of data that is not readily available in short-term operational modeling time frames.

However, the incoming ABRW planning model does contain flexible rules, methods, and processes, and has the previously developed historical datasets to allow it to simulate everything it needs to in its planning model functionality. Thus, the pathway to successfully adapting the model for operations modeling lies in leveraging the comprehensiveness of the planning model rules and datasets to fill in the data gaps in the real-time and recently observed datasets. We can also utilize the data about current and year-to-date conditions, and forecasted or projected future conditions, to help inform the model as best as we can and contribute to its accuracy and usefulness in supporting short-term operations.

Logically, this model adaptation process is essentially the reverse of an operations model to planning model progression. In a progression like that, the process would involve developing rules to replace factors that were previously model inputs (e.g., water user's diversion demands). In this case, we are tasked with adapting things that were previously estimated and set by rules to instead be able to use actual or observed data. This is a straightforward concept, but in a complicated and data intensive model and basin, the implementation of this is more challenging than it seems.

## 1.3 Challenges

The ABRW is an accounting-driven model, where overall system operations and conditions are less the result of top-down control, but rather are the result of aggregated, detailed, accounting-level operations and administration in a bottom-up fashion. The "bottom" level in this case is the Colorado water rights system. While it may not be apparent from afar, these details ultimately make a significant difference in overall basin conditions and operations in a bottom-up type system like the Arkansas basin, and are thus important in ABRW simulation. This, along with the basins large size, complexity, and interconnectivity, is also why the ABRW model is especially data intensive.

A primary reason that using the ABRW planning model to operations model adaptation process is challenging is because the observed data that we have readily available is not generally at the level of detail or fidelity required by the model. Thus, for many factors, we must determine the best manner to utilize and transform the blunt, "square peg" available data so that it fits appropriately into the discrete, "round holes" of the model. For the ABRW model, this largely means utilizing the "raw", total physical data in ways that reasonably approximate the detailed accounting breakdown required by the model. Providing the model with sufficient breakdowns of accounting-level data is difficult due of the sheer size of the basin, the number of autonomous entities (e.g., Reclamation, SECWCD, CO DWR, municipalities, water users, and other stakeholders) involved, their interdependence, and the level of detail with which the system is administered and operated.

An additional and related challenge in this process remains the accessibility of the data required. Integrated and accessible real-time and observed databases and pathways are generally developed alongside operational models. Thus, hand-in-hand, the databases are enhanced to contain the data utilized by the model and the model is developed to utilize the data that is readily available.

However, planning models typically rely on complete, but relatively static or infrequently updated datasets. These datasets can be developed over time to be more much complete and more detailed than they would have been during the short-term time frames needed to support operations modeling. This is the situation that currently exists with the ABRW model.

While data intensive in its own right, specific operational and administrational duties are not necessarily as dependent on the completeness, level of fidelity, or accessibility of these databases as a detailed system model can be. This is because these tasks are accomplished in a distributed manner by many different parties working both independently and together, with each relying upon and separately maintaining the data needs for their specific purposes. Essentially, the objective of a model of this complex system is to bring enough of this data, and simulation of the processes for which it is used, into a centralized place so that it can be used to inform useful simulation.

To sum this all up, there are different dataset requirements for different modeling objectives, and the task during this effort was to begin to bridge the gap between them. Databases such as Reclamation's HDB and the State of Colorado's HydroBase are being adopted and integrated to supply more and more detailed data for all sorts of purposes. The objective of this effort is to rely on HDB to provide the available real-time and observed conditions data to drive the ABRW Ops model system. There has thus far been (and undoubtedly will continue to be) a back-and-forth process to both enhance the HDB database by QA/QC'ing its existing data and bringing in new data sources beneficial to the model, as well adapting the model to rely more on data that is readily available.

Overall, the challenge of this effort on the ABRW modeling side comes in determining how to best utilize the imperfect and incomplete HDB data within the ABRW model to create a tool that will be useful and valuable for operational forecasting and decision-making purposes.

## 1.4 Progress and Status

The effort associated with this S&T project has represented the preliminary steps in the process of implementing the ABRW operations modeling system in a manner that will support and inform Reclamation's short-term operational decision-making for the FryArk Project and it's other Arkansas basin roles. It is important to note that developing this modeling system to a sufficient level enabling it to begin to be used to support real-world application was originally scoped as a minimum two-year effort with the first year focusing more on the development of the fundamental modeling system mechanics and the necessary datasets, and the second year focusing more on model performance, accuracy, and real-world application. Ultimately, the Reclamation S&T Program resources that were made available for this preliminary effort were approximately in-line with those of the first year of the scoped two-year project. The overall progress made ended up being in-line with that scoped for the first year, and therefore this progress and the project's current status are well aligned with original expectations.

This report details the significant progress made on this project and its current status. On an overall summary basis, the progress and status of these fundamental steps include:

- Identification, scoping, and initial construction of the data pathway, model control, and output viewing systems. This is the series of Excel workbooks, the HDB database, and the RiverWare model, that provide the mechanisms to obtain, process, and transfer various important data into the model. These configure and execute model runs in a manner that is efficient, automated, and versatile enough to support the heavy demands of operational modeling.
- Update, adapt, and enhance of the ABRW planning model (i.e., the RiverWare model itself) into a form which supports the overall operational modeling system.
- Review of the HDB datasets, including identification of critical issues and necessary additions.
- Status of model accuracy and performance. Preliminary model results are very promising; however, they are not observed to be accurate enough to purport that any WY 2021 lookaheads are accurate. However, there is significant known direction and potential for improvement. It is fully expected that with, first, data corrections and QA/QC, and subsequently with pointed rule and method development and enhancement, the model's performance will be greatly improved. Further information on the current validation, calibration, and model performance status is presented and discussed in Section 12.

## 1.5 Continued and Future Development Priorities

Significant progress has been made in the implementation of the ABRW Ops modeling system. This progress represents a proof-of-concept of the overall project objective and system design. Furthermore, it highlights the substantial potential value and benefits of the modeling system.

Successful implementation of similar operational modeling systems in other Reclamation basins of similar levels of both basin and model complexity has relied upon operators/decision-makers and modelers working side-by-side to continuously make model runs, review their results, revise things accordingly, and remake runs. Likewise, an implementation process along these lines is needed for the most successful possible implementation of the ABRW Ops modeling system.
Continued and future development priorities that have been identified thus far include:

- Continued update, review, and QA/QC of the HDB datasets.
- Continued incorporation of more and better data sources, including but not limited to: CO DWR HydroBase data, WWSP data, Arkansas Colors of Water Tool and other DWR administrational datasets and basin conditions, detailed accounting breakdown data as it becomes more readily available, etc.
- Continued implementation of available, improved, and new observed period data.
- Continued review, modification, and enhancement of the RiverWare model's rules and methods. While many rules and methods have already been enhanced to support operational modeling purposes, more remain where there is significant potential for improvement.
- Implementation of Input Schedules. These mechanisms will allow model users to begin to "override" specific aspects of the general "planning model"-type rules that drive simulation. Some examples include the application of planned drawdown and/or release schedules (e.g., Turquoise Lake fall/winter drawdown), major entity demand and diversion schedules (e.g., FVC diversions from Pueblo Reservoir), and specific storage and flow targets (e.g., VFMP and PFMP flow targets).
- Pueblo Reservoir EC Account configurations for WY 2018, 2019, and 2021 need to be developed and an automated process needs to be developed so that the right configurations will be applied for validation and calibration runs relying on these previous Ops WYs.
- Implementation of enhanced hydrology calculations to generate improved model inflows. There remain various options how this could be implemented, the selection of which will ultimately depend on the conditions of updated datasets. It is possible that the originally scoped Hydrology Calculations workbook could work, however there may be significant benefit to implementing a purpose-built "naturalized" flow RiverWare model to achieve this purpose. A model along these lines would essentially be the same network as the ABRW Ops model but would be simplified to be physical only. It would benefit from RiverWare's strengths in terms of network and object methods and rules to achieve improved estimates of the actual observed hydrologic inflows. It is recommended that this possibility be given serious consideration.
- Incorporation of ABRFC Water Supply Forecasts. Following the analysis and development of appropriate translations and conversions, these will allow for forecast-informed single run analog year selection based on the official and/or median forecasts. The statistical aspects of the RFC forecasts can be incorporated to inform historical year-based forecast ensembles that are more consistent with the RFC forecasts. Ultimately, the RFC forecast ESP traces themselves will be able to be used to create forecast ensembles for use in the model, which would reflect the best and more appropriate use of the available forecast information.
- Continued development of the Output Viewer. The current status of the Output Viewer is that it's functional but focused mainly on high-level, overall basin conditions. There remains significant potential to tailor the results reporting to the specific needs and interests of Reclamation's Arkansas Basin operators and decision-makers.

# 2 General Orientation and Definitions

## 2.1 Model Run Period, Ops Water Year, and Ops Start Date

The model run period of the ABRW Ops model is from the previous October 1st (the start of the **"Ops Water Year"**) to December 31st of the following year, for a total of 15 months. The model is initialized with September 30th storage conditions throughout the basin's reservoirs and storage accounts. Thus, the model simulates the entire Ops Water Year (plus three extra months) in every run that is made.

The "**Ops Start Date"** is the day before which the model will utilize observed data where and when it has it available. It can sometimes be thought of as "today", however, given lags in data availability, forecast dates and periods, and other factors, this often may end up being some other recent date.

Thus, there are two distinct model periods in a model run, divided by the Ops Start Date:

- Pre-Ops Start Date – Previous October 1 to the day before the Ops Start Date (aka "observed period")
- Ops Start Date and post-Ops Start Date – Ops Start Date to the following Dec 31 (aka "operational forecasting period" or "forecast period")

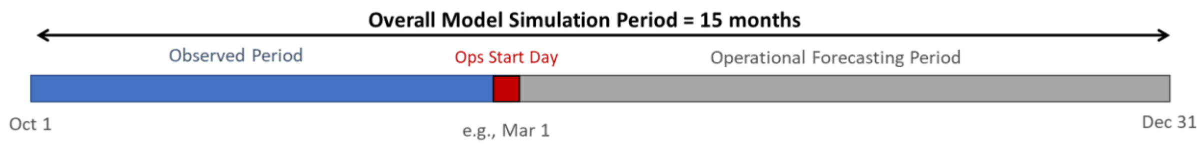



Figure 2-1. Illustration of Model Run Periods and Ops Start Date.

Note: In the ABRW Ops model, the model dates are always 10/1/1990 to 12/31/1991.

It is important to note, that while the model simulates from the Ops Start Date through the end of the year, its results and the analysis and outlooks informed by them can and often should be for much shorter forecast periods depending on an understanding of the model's performance and accuracy for various parameters.

The Ops Start Date can also be set at any date back to the start of the water year (10/1). The ABRW Ops modeling system is designed to be flexible and thus runs can easily be made with varying Ops Start Dates (as well as other factors). These runs and results can be kept distinct from each other and will not impact the base observed datasets or each other's results. This helps to facilitate analysis of how well the model would have (or did) project observed conditions from a given date and can help inform users of the model's accuracy throughout the various results.

**<u>Primary Development and Testing Dates and Periods</u>**

Thus far, model and dataset development and testing has been focused on WY2020. Therefore, the run dates are currently 10/1/2019 to 12/31/2020. The Ops Start Date has been varied throughout the development period, but most often it has been set at 12/31/2020, which is the run end date.

Being within WY2020 (and in Oct-Dec 2020, within the extra three-month period), this causes the model to use observed data everywhere it exists where it's use has been implemented in the model.

## 2.2 Observed and Real-time Conditions and Data

Observed and real-time conditions and data generally refers to the basin data that exists for the current Ops Water Year. While this sometimes include data going back into previous years and further, within this user's guide it generally refers to the dataset for the pre-Ops Start Date period.

For example, for an ABRW Ops model run for WY2020, with Ops Start Date of 4/1/2020, the observed data period (including the initialization date) is 9/30/2019 to 3/31/2020.

While they may have slightly different meanings elsewhere, for the purposes of the ABRW Ops model and user's guide, the terms observed and real-time are often used interchangeably.

## 2.3 Model Input Hydrology Dataset Types

Model input hydrology refers to the hydrologic inputs (i.e., timeseries of daily inflows) that are used to drive the model. Since they are calculated to remove the impacts of diversions, reservoir operations, and other processes, ABRW model input hydrology datasets are referred to as "naturalized flows". This should not be confused with pure "natural flows" because there are impacts that remain in the naturalized flows that have not been entirely accounted for, most significantly water user return flows. Overall volumes and magnitudes of model input hydrology cannot and should not be compared "apples-to-apples" with natural flow volumes or even "naturalized" flows from any different source (like another model), since they undoubtedly are based on different mass balances.

There are three distinct categories of model input hydrology utilized for various purposes in the ABRW Ops model:

- **Historical Year Hydrology (aka Historical Hydrology)**
    - This refers to the existing model input hydrology dataset, originally developed from historical data for planning modeling purposes.
    - Full period = 10/1/1990 to 12/31/2015, (25 full years and water years)
    - Any year can be extracted and used individually.
    - These can be used as analog years to drive the model.
    - The group can also be used to run a "historical ensemble", described below.
    - This dataset is stored in data objects ("Boundary Inflows", "Local Inflows", and "Reservoir Inflows") in the model to make it readily available when needed.
    - Note that the historical hydrology currently provides the basis for all ABRW ops model runs. I.e., the input hydrology from some historical year is *always* set to the model network at the very beginning of a model run by an initialization rule (IR). Subsequent IRs will replace those base hydrology inputs for the appropriate periods. However, because those datasets may not be complete or available for all input nodes, the underlying historical year hydrology is essentially used to fill any missing time periods or locations.

- **Realtime (/Observed) Hydrology**
  - This refers to the model input hydrology calculated from the observed dataset for the current Ops Water Year's observed period.
  - During a model run, the Realtime Hydrology replaces the otherwise set historical year hydrology for the pre-Ops Start Day period.
  - This dataset is calculated in a supporting workbook and input to a data object ("Realtime Hydrology") in the model by the "ABRWOps_RealtimeHydrology" DMI.

- **Forecast Hydrology**
  - This refers to model input hydrology calculated (or otherwise informed) using Arkansas Basin River Forecast Center (RFC) water supply forecasts or other hydrologic forecasts.
  - While the process of developing model input forecast hydrology from RFC forecasts in the ABRW Ops model has been explored and some preliminary steps taken, this has not been utilized in the model.
  - When implemented, and when configured to do so, the Forecast Hydrology inputs will be set to the appropriate input nodes for the post-Ops Start Date period, overwriting the run's base historical year hydrology.
  - Until this occurs, the historical year hydrology applied in any given run can be considered the forecast hydrology for the post-Ops Start Date period.

## 2.4 Types of Model Runs

There are different categories of model runs that can be utilized for various purposes in the ABRW Ops model. The first distinction is made between "single runs" and "ensemble runs" (or multiple trace runs).

- **Single Runs** – One model run intended to represent some type of best guess at the basin conditions through the model period.
- **Ensemble Runs** – These are model runs that consist of multiple runs, or "traces", for which results are analyzed statistically from the group as a whole rather than any single trace individually. Ensemble runs are very useful for helping to characterize a range of potential conditions due to uncertain future hydrology.

Based on the model input hydrology datasets available, there are two types of operations model runs that can be run in the ABRW Ops modeling system:

- **Analog Year Run** (Single Runs)
  - The user can select an analog year from the available historical year period (1991-2015), and that year's model input hydrology is used to drive the model run for the post-Ops Start Date period (and for areas of the observed, pre-Ops Start Date period where data or hydrology calculations are not available).
- **Historical Year Ensemble Run** (Multiple Runs)

- This is an ensemble run that treats the 25 historical hydrology years as individual traces of potential hydrology inputs for the post-Ops Start Date period (and for areas of the observed, pre-Ops Start Date period where data or hydrology calculations are not available). Each trace here is essentially the same as an analog year run if it were to be analyzed individually.

The ABRW Ops Controller (described later) is configured so that there is always an Analog Year run being made. On top of that single run, the user can also select whether to also run the Historical Year Ensemble.

## 2.5 Main Components and Data Pathways Schematic

The following schematic summarizes the main components and data pathways used in the ABRW Ops model system.

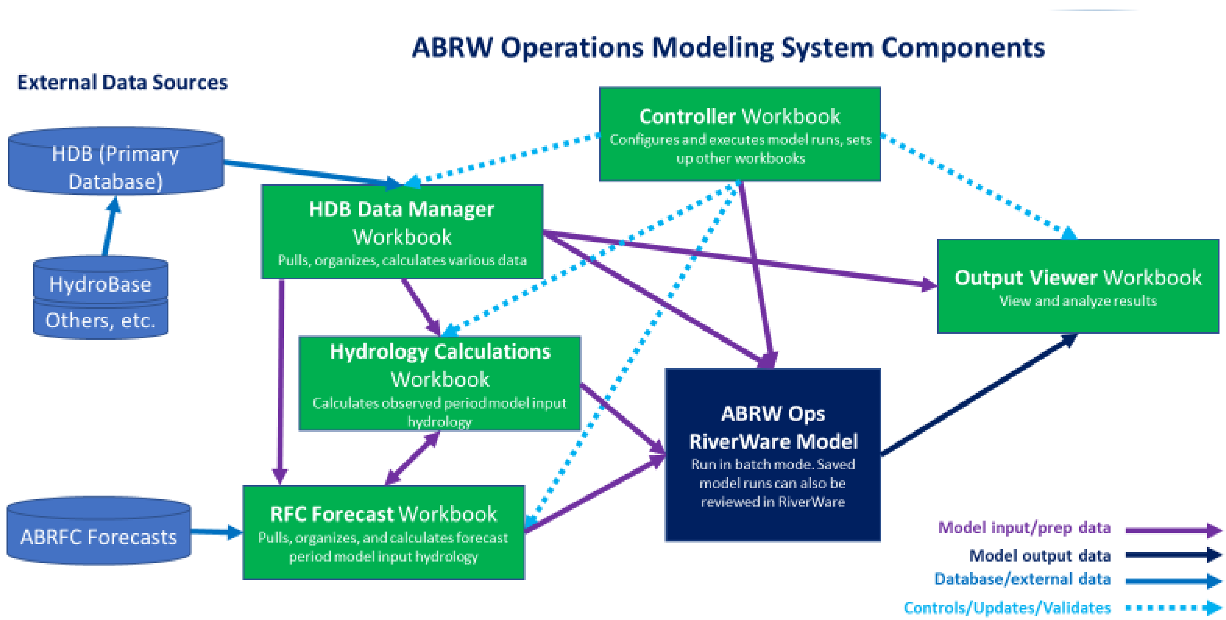



Figure 2-2. ABRW Operations modeling system components.

# 3. ABRW Ops Modeling System Directory and File Structure

## 3.1 Overview

The ABRW Ops modeling system consists of a base directory with a consistent structure that contains the ABRW Ops RiverWare model and a series of 5 primary Excel workbooks developed to collect and process model input data, configure the model file with input data and settings according to user selections, execute model runs, and view and analyze model results.

The workbooks utilize macros to accomplish many of their tasks, along with relative directory references, advanced formulas, and named ranges to increase their usability and capabilities. Conditional formatting is also often used to highlight specific information for various purposes. The workbooks avoid using direct data links to other workbooks as these would often become problematic and disrupt their function.

## 3.2 Directory and File System Structure

The ABRW Ops model system uses a consistent directory/folder and file structure to keep its components organized and maximize usability and efficiency. The base directory, termed "ABRWOps_ModelController" is shown below. Copies can be made of the entire directory and they will function independently. This makes it easy to clone the entire system to make runs for different purposes, or to revert to base model files and workbooks if something unintended happens. Care should be taken to avoid cross configuring distinct directories or attempting to work with or open files with the same names at the same time.

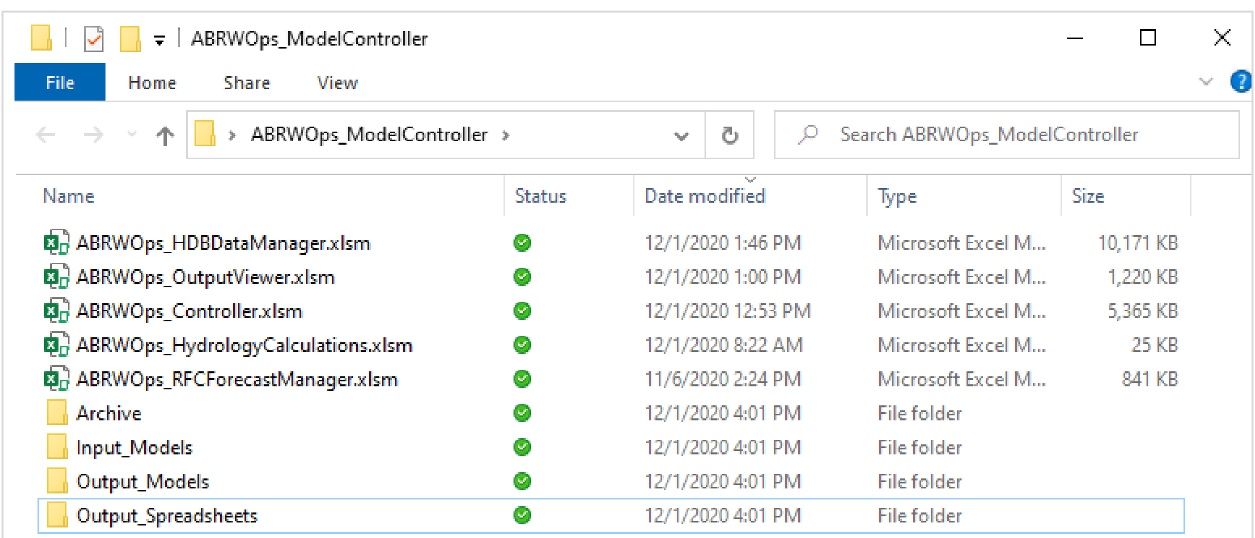



Figure 3-1. ABRW Directory Structure.

The subfolders present in the main directory are as follows:

- **Input_Models**: This folder contains the base ABRW Ops model, as well as any alternative "manually configured" (i.e., from within the model itself, rather than from the Controller workbook). The user selects the desired base model from this folder in Controller to be used for a given "Controller" model run or set of runs.

- **Output_Models**: Model runs made using the Controller are automatically saved with output within this folder. To help keep things organized and accessible, runs are saved within a subfolder with the user defined "Run Name Extension" for that run. Run diagnostic text files are also saved to this directory.
    - The "analog year" run model file will always be saved with a "*_*RunNameExtension*_0.mdl.gz" extension, while ensemble runs will have the 0 replaced with their trace number (from 1 to 25).
    - The model files saved into this directory have been configured with the inputs and settings for the appropriate model runs (for both single run and ensemble runs), but otherwise are the same as the base model file used for the run.
    - When something breaks or is changed in any of the models, that particular model file can be opened and edited as necessary to correct the issues, and that file can be saved back into the "Input_Models" directory to be used in place of the previous base version.
    - If this is done, be sure to remove the "RunNameExtension" and index number parts and appropriately update the new base model file name. It's always recommended to keep the previous base model version as well.
    - Whenever the base model file is updated, the Controller's "Base RiverWare Model" then simply needs to be updated to point to the new model file.
    - Since the model files are saved with output, any given Controller model run can be opened and viewed using the RiverWare GUI to access additional results.

- **Output_Spreadsheets**: Model runs made using the Controller have their output saved (via Excel output DMI) within this folder. Like the output models, these are saved within a subfolder with the user defined "Run Name Extension" for that run.
    - The results spreadsheets saved into these folders are "raw" model output files that contain a set of over 600 "standard" output slots from the "ABRWOps_MasterDailyOutput" DMI in the model.
    - The results in these raw output spreadsheets are categorized into different sheets.
    - The "Output Viewer" workbook uses a macro to load data from these raw results spreadsheets.
    - These raw output spreadsheets should not need to regularly be viewed or accessed independently, although they can be.

- **Archive**: Throughout the data setup and model configuration process, various macros will save off archive copies of the main workbooks into this folder. This is done to help prevent data loss or other unintended mistakes that can sometimes occur during the process.

# 4. ABRW Ops Workbooks

## 4.1 Overview

The ABRW Ops modeling system contains 5 primary Excel workbooks. Their purposes are summarized in the table below. As shown above, these workbooks reside in the top-level "ABRWOps_ModelController" directory. They can interact where appropriate, configure each other, and transfer data between themselves with macros. During ABRW Ops model runs, input DMIs pull data from these workbooks. The Output Viewer also pulls model results via macros from the raw output spreadsheets in the appropriate subfolders.

| Workbook | Main Purpose |
|---|---|
| **Controller** | This workbook is used to configure and execute ABRW Ops model runs. This workbook can also be used to verify the status of, and set off updates within, the other ABRW Ops workbooks. This is also where "Input Schedules" are created and applied by the user. |
| **Output Viewer** | This workbook is used to collect, organize, view, and plot model results. |
| **HDB Data Manager** | This workbook is used to organize, pull, view, and facilitate QA/QC (e.g., filling) of the HDB dataset used by the ABRW Ops model. This workbook also performs calculations with the raw HDB data and translates and organizes it so it can be pulled into the ABRW model and other workbooks. |
| **Hydrology Calculations**<br>(NOT YET IMPLEMENTED) | This workbook is used to perform the model input hydrology calculations that are used for the observed, pre-Ops Start Date period. This workbook pulls the necessary observed data from the HDB Manager Workbook and utilizes it together with data from the developed historical hydrology and diversion dataset. |
| **RFC Forecast Manager**<br>(NOT YET IMPLEMENTED) | This workbook is used to collect and manage ABRFC water supply forecasts. It will apply the appropriate translations to facilitate comparison of the forecasts with available historical hydrology to facilitate analog year selection. Conceptually, the forecasts can also be used to create forecast hydrology model input datasets for both "official" forecasts (single run) and forecast ensembles. |

The ABRW Ops workbooks are internally documented using Excel comments with instructions, guidance, and other important information and tips. Many of the primary worksheets contain a primary overview comment that resides in the top left (often "A1") cell or in another obvious place. Cells that contain these comments should be colored dark red and usually say "INFO", see the example in the screenshot below. These comments can be minimized or moved to get them out of the way once the user is comfortable with the sheet. These contain much the same information that is also contained in this user guide.

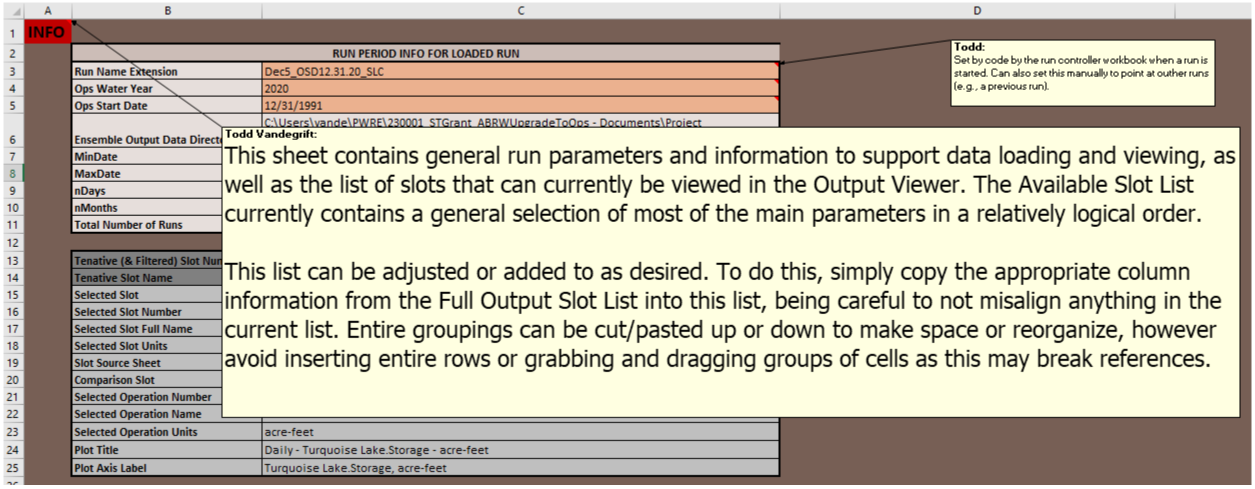



Figure 4-1. An example of comments in the workbooks.

It is critical to run the workbooks and models consistently to keep them from breaking. Various data and configuration checks are done throughout the workbook configuration and data loading process to try to catch potential issues before a model run is started. These checks will often use conditional formatting to turn cells or groups of cells bright red, indicating that an issue is present.

## 4.2 RiverWare Batch Mode

ABRW model runs executed via the controller are run using RiverWare's batch mode. Since they are run in the background, they do not use the RiverWare GUI. Batch mode runs appear in a black command prompt-type window with limited messages that indicate the overall run status. These windows can be minimized but must be left open until the run finishes, at which point they can be closed. If there are multiple run batches being used, there will be multiple batch windows. The ABRW Ops Controller writes and runs RCL (RiverWare Command Language) script files to make these runs, however the scripts are automatically deleted once the runs are started.

## 4.3 Other Practical Items and Tips

A single ABRW Ops model run should take ~5-10 minutes, depending on the computer.

- The ABRW model is particularly RAM intensive and will use, on average, nearly 16 GB of RAM during a run. It is advised to not attempt to complete other RAM intensive activities during model runs on machines with lower amounts of RAM.

- The ABRW Ops Controller supports executing simultaneous runs in multiple, parallel "Run Batches". **USE CAUTION HERE**, as the ability to take advantage of this functionality depends on computer performance. This can be configured in the Controller workbook. Each batch will consist of a set of model traces that will be run one after another in series. This can allow a larger number of traces to be run in a shorter amount of time, which can be very helpful. A computer with 16 GB RAM may be able to handle 2 at a time, but it will probably slow the runs down quite a bit. A 32 GB machine can handle 2 or maybe 3 simultaneous batches.

- A shared/cloud directory (e.g., through SharePoint or Dropbox), together with remote desktop software, can be used to run models on a different computer without bogging down the main machine. As the models finish and automatically run their output DMIs and save, the output and model files will be available on any machine that is synced to the same directory.

- Some of the workbook macros (particularly the HDB Data Loader) may cause all Microsoft applications to freeze up while they run their macros. It is recommended to not attempt to do too much at once here and rather let the macros complete before moving on.

# 5. Summary of ABRW Ops Data Update and Run Process

The basic steps and process involved in making a ABRW Ops model run or set of runs is summarized below:

1. Update the **HDB Data Manager** workbook
    a. Open the HDB Manager workbook and select the "Index" sheet.
    b. Click the "Read All HDB Data, Fill, Save, and Close WB" button to load, fill, save, and close the workbook. This will take a few minutes and the workbook will close when it is done.
    c. Reopen the workbook and review all the relevant data for accuracy and completeness.
    d. Ensure that the Storage Initialization is still valid. (This generally will only need to be done at the beginning of the year but should be updated if better storage account breakdown data becomes available.)
    e. Save and close the workbook.
2. Configure the **Controller** workbook for desired run.
    a. Enter a unique "Run Name Extension"
    b. Point the Controller at the correct model file and RiverWare version
    c. Enter the desired "Ops Water Year"
    d. Enter the desired "Ops Start Date"
    e. Select an Analog Year for the Single Run from the dropdown menu.
    f. Select whether to run the historical year ensemble.
    g. Click the "Check HDB Data WB" button to perform that check.
    h. Click the "Start Model Run" button at the top of the sheet. This will kick off the model run(s) in batch mode.
    i. Wait for the macro to perform the necessary workbook setup and script creation and execution, and for a "Model run started successfully" dialog to appear.
    j. Close the workbook
3. Open the **Output Viewer** workbook.
    a. The Output Viewer has been oriented to the appropriate model results directory by the controller.
    b. Once the model run is complete, click a "Reload Plot" or "Reload Data" button on the plot or data pages or make a new slot selection from the dropdown menu, and the desired results will be loaded into the viewer.
    c. If multiple runs are being made, the results from finished runs will become available as they finish, without needed to wait for all model runs to complete.

# 6. Controller Workbook

## 6.1 Purpose

This workbook is used to configure and execute ABRW Ops model runs. This workbook can also be used to verify the status of, and set off updates within, the other ABRW Ops workbooks. This is also where "Input Schedules" are created and applied by the user.

## 6.2 Worksheets

### 6.2.1 Controller Sheet

The Controller sheet is the gateway to running the ABRW Ops model.

**To make a run from the "ABRW Ops Controller" workbook, on the "Controller" sheet:**

1) Enter a unique and descriptive "Run Name Extension". This will be used to identify/organize the output files for the model run.

2) Ensure that the correct "Base ABRW Ops Model" file and RW version are selected. Use the buttons to update.

3) Select an "Ops Water Year". In practice, this will generally be the current water year. For testing and validation/calibration purposes, it can also be set to WY 2018, 2019, and 2020.

4) Enter an "Ops Start Date". In practice, this will generally be the current date or a recent date for which observed data is generally available. The observed data used by the model is managed in the "HDB Data Manager" workbook and can be viewed there. For testing, this can be any date during the run period. Before this date, observed data is used where available and where implemented in the model. On and after this date, Input Schedules will be applied (not yet implemented).

5) Select the Analog WY and Import Analog WY to be used for the Single Year Run. The hydrology(/imports) from that year will be the base inflows used to drive the model for the Analog Year "single" run, however, it will be overwritten with the calculated estimated observed "Realtime Hydrology" inputs for the observed period, where they are available based on the observed dataset. To support selection, the "HydroAnalysis" sheet (preliminary) can be used to view the hydrology chosen in the context of the estimated observed hydrology, the historical ensemble, and full historical range (see notes on that sheet for more info).

6) Select "Yes" or "No" in the "Run Historical Year Ensemble too?" cell. See the description and comment there for more information. It is recommended that the user is comfortable with the process and making "single" runs before making running ensemble runs.

7) Click the "Check HDB Data WB" button to check the status. Then, ensure that the "HDB Data Manager Validation Status" cell is green and says TRUE. If it is FALSE it will be bright red. If it is FALSE, open the HDB Data Manager workbook and check the issue. Most of the time it will just need to have it's data reloaded. This data should be reloaded frequently, and certainly every time that the Ops Start Date is moved forward to ensure that all available and implemented data is being used

in the model run. The macro will also ask if the most recent hydrology data from the HDB workbook should be pulled into this workbook, which should be done whenever that data changes.

8) When a run is started, the "ABRW Ops Output Viewer" will be updated to be oriented to the current run. This will clear the previous run from the Viewer; however, a copy will be made into the "Archive" folder. The output workbooks will be made when the model is started but will not have output until the model is finished running. A copy of this configuration sheet will be put in the output viewer workbook(s).

9) After all user inputs are configured as desired, click the "Start Model Run" button at the top of the sheet to begin a run. After the Excel prompts, in just a few seconds, a "status window" will open and a batch-mode model run will be started. You can move or minimize the window but closing it will stop the model run. However, after getting the "Model Run Initiated Successfully" message box, it is okay to close the controller workbook.

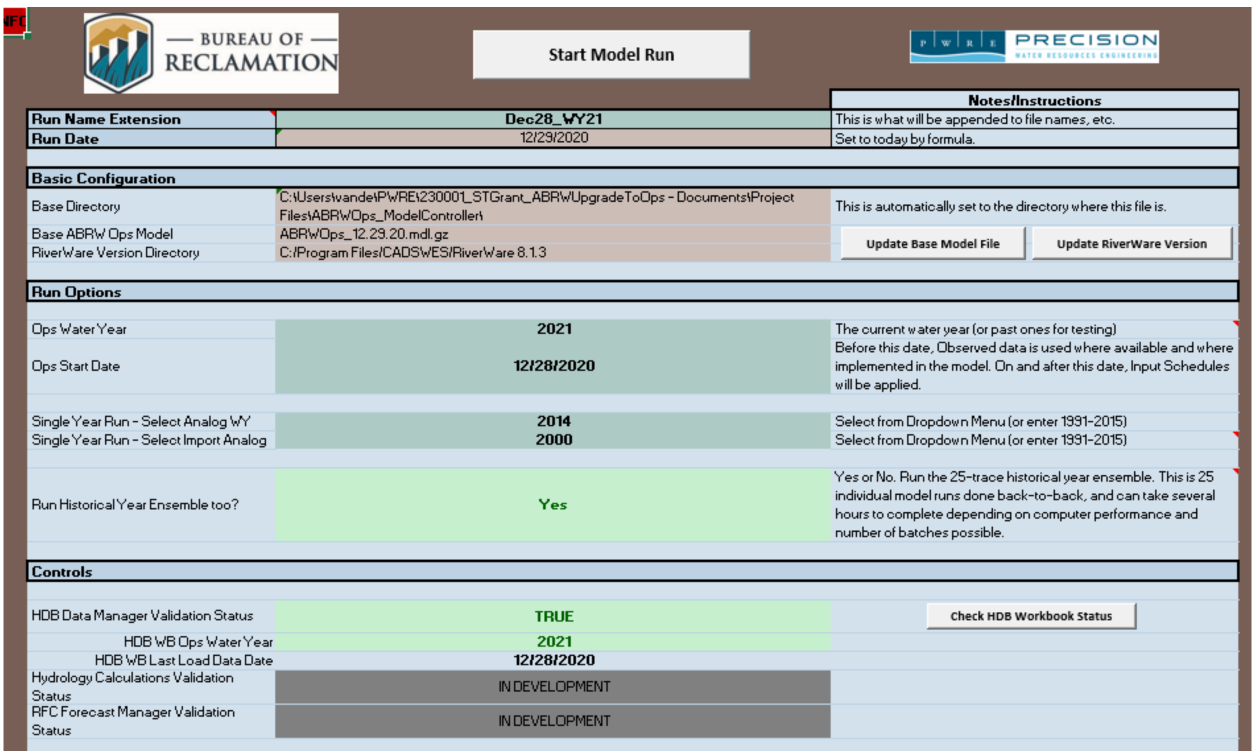



Figure 6-1. The primary Controller sheet.

### 6.2.2 EnsembleConfig Sheet

This sheet can be used to define alternative/smaller subsets of historical years if desired, by changing the "Year Step" and "Desired # Traces" cells. However, it is recommended that Historical Year Ensemble option be run with all 25 years.

This sheet is also where the user can control the number of run batches to be performed at once.

### 6.2.3 HydroAnalysis Sheet

This sheet contains a preliminary implementation of a "forecast"/future hydrology analysis. This is currently based only in historical years and the historical ensemble but should be expanded to include the RFC forecast information when it is implemented and integrated into the system. This analysis could also be further enhanced to support analog year selection and comparison based on the current estimated observed hydrology. This analysis is also helpful in identifying problematic areas and data errors/issues that should then be corrected. As the hydrology inputs are the model's most important inputs, significant care must be taken to review and QA/QC this data, and the raw data used in the calculations that generate it, to ensure that the model is being driven with the best data possible.

The dropdown menus in the bright blue, "Hydrology Analysis Controls" section are used to update or modify the currently displayed hydrology and import analysis. These allow the user to change the Hydrology Region and Import Aggregation displayed, as well as if the daily inflows or accumulated volumes are displayed. Note that the Accumulated Volume option can make it much easier to compare the overall conditions of various years and is generally recommended to be used first, although the daily inflow option can also be helpful for certain purposes. When any selection is updated, the data and plots will be updated accordingly. The "Load HDB WB Data into Controller" macro should be run whenever there has been a change/update to the HDB WB data (this can also be done through the "Check Status" macro on the Controller sheet). The "Generate Ensemble Hydrology Summary" macro can be run to rerun the analysis (a change selection via the dropdown menus will also cause the same macro to run).

The analysis plots display the current model input hydrology for the analog "single" run, and for all 25 historical ensemble years. The current estimated observed hydrology is shown for comparison. Additionally, the full historical period (1991-2015) range is also displayed with the shaded areas (shown as the 50% exceedance range and "outside" of the 50% exceedance range) to help with overall hydrology condition context. Near the beginning of an Ops WY, the range of the 25 historical ensemble traces will be nearly the same as the full historical range, and the range of the 25 traces should shrink as the year progresses.

It is important to note that because there is so much data that is not yet incorporated and/or not available in real-time, that the "current observed hydrology is calculated and ESTIMATED. It is therefore quite dependent on the selected analog years, which are used to fill input hydrology data wherever there is missing data (or other issues) that does not allow the hydrology calculations to be completed for any given node/date. This means that if different analog years are selected, the estimated observed hydrology will change, and can change significantly. The importance and implementation of this will continue to change as data issues are corrected and the hydrology and forecast calculations are further developed implemented.

As an example, to illustrate the hydrology analysis that this sheet performs and facilitates, the following plots are from the HydroAnalysis sheet for differently selected Ops Start Dates in WY 2020. There are three pairs of plots, displaying the Total Naturalized Model Input Inflow Above Pueblo Reservoir and the Total Imports for Ops Start Dates of 10/1/2019, 4/1/2020, and 12/31/2020, which represent the beginning, middle, and end of the year. Notice how the range of the historical ensemble collapses as the year progresses, which is what is expected.

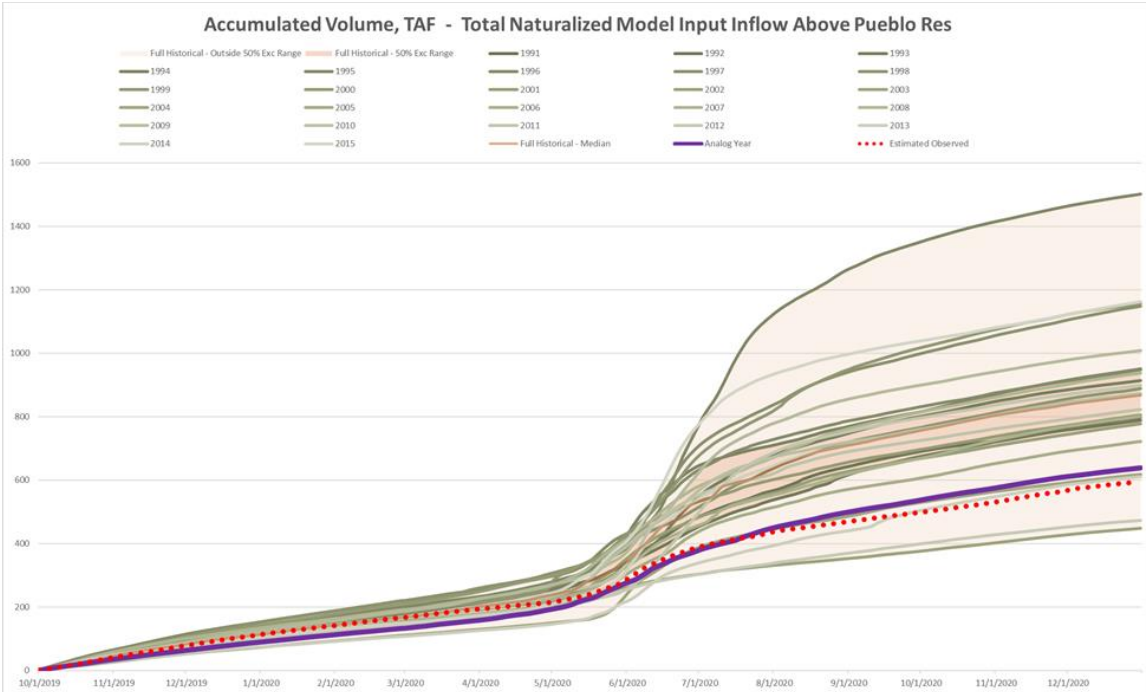



Figure 6-2. Total Naturalized Model Input Inflow Above Pueblo Res for WY 2020, Ops Start Date 10/1/2019.

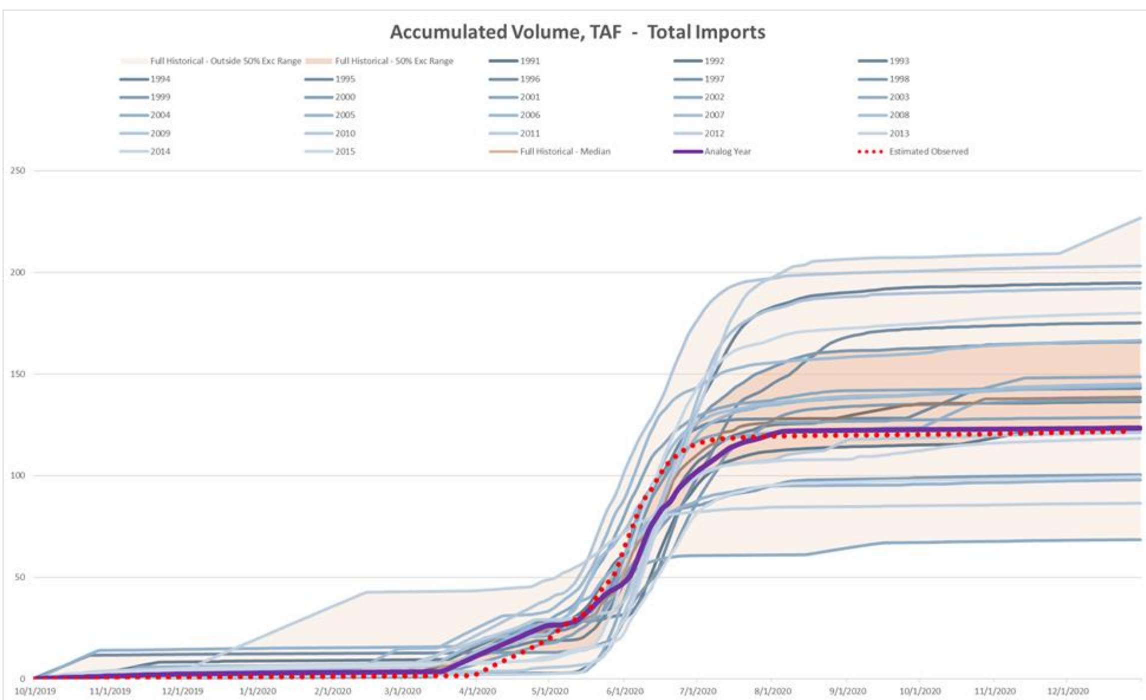



Figure 6-3. Total Model Input Imports for WY 2020, Ops Start Date 10/1/2019.

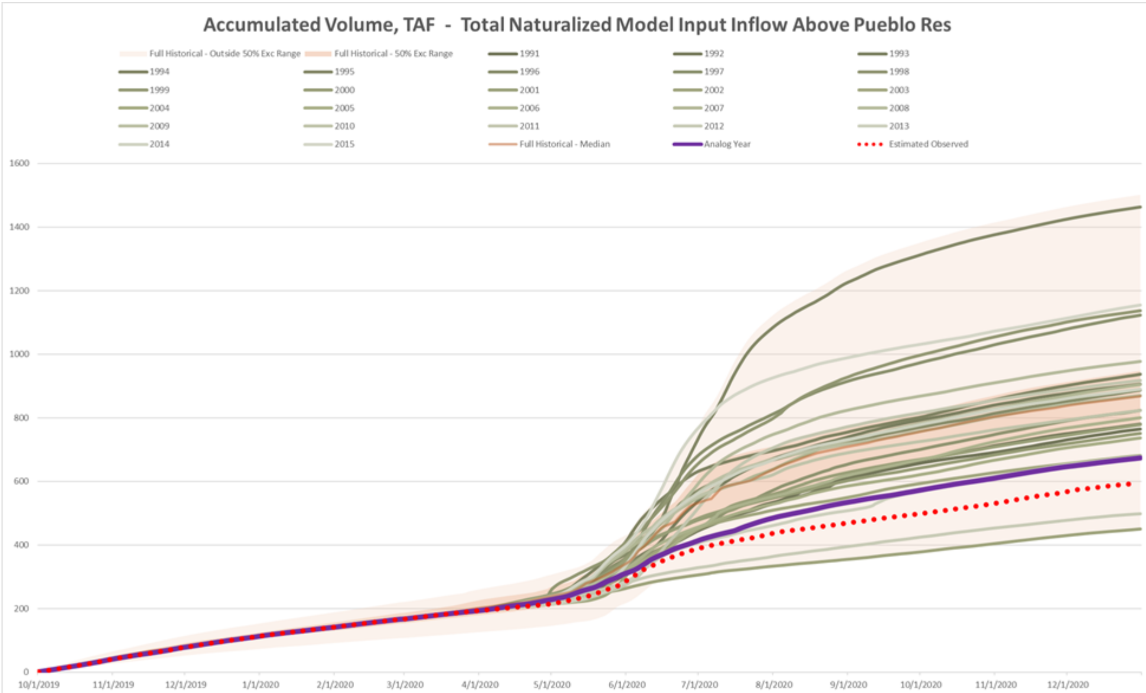


Figure 6-4. Total Naturalized Model Input Inflow Above Pueblo Res for WY 2020, Ops Start Date 4/1/2020.

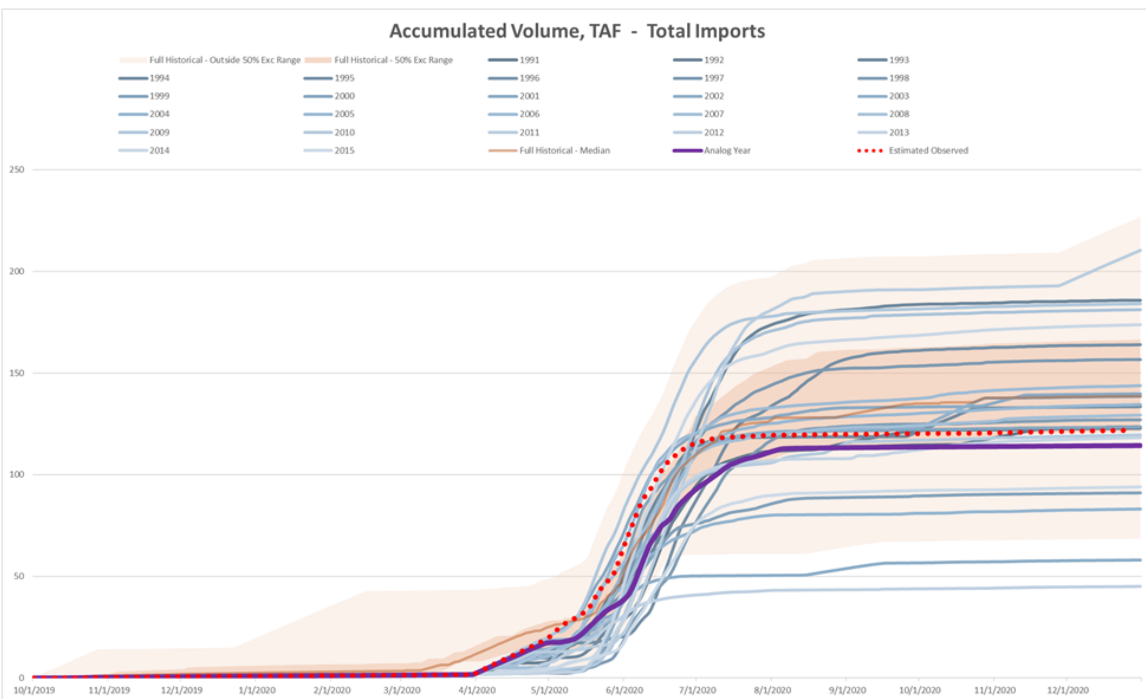


Figure 6-5. Total Model Input Imports for WY 2020, Ops Start Date 4/1/2020.

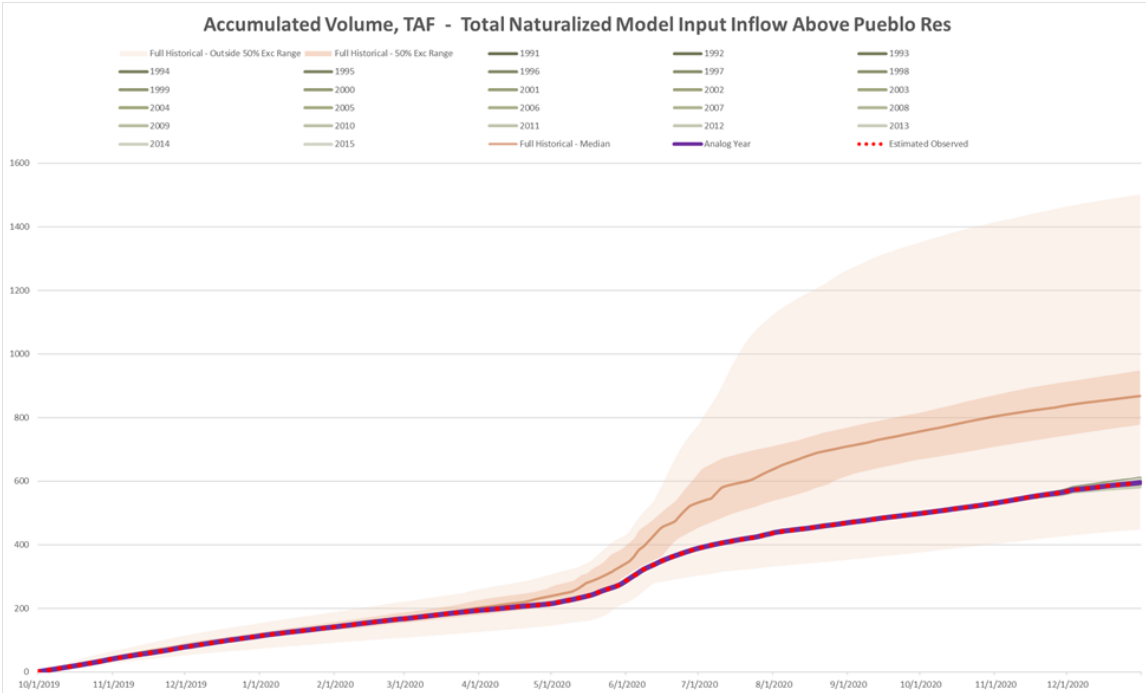



Figure 6-6. Total Naturalized Model Input Inflow Above Pueblo Res for WY 2020, Ops Start Date 12/31/2020.

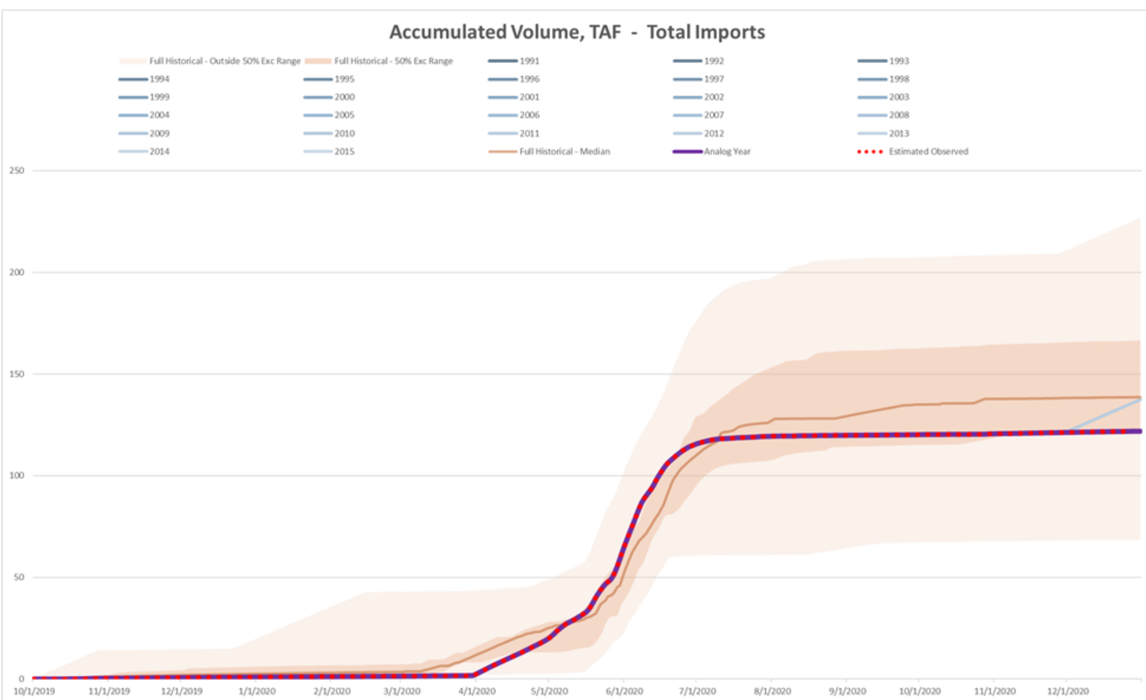



Figure 6-7. Total Model Input Imports for WY 2020, Ops Start Date 12/31/2020.

### 6.2.4 HistHydroSummary Sheet

This sheet summarizes the base model input hydrology (i.e., historical years based). This table is sortable by the different parameters.

BE CAREFUL! "Model Input" hydrology is not equivalent to natural flow or gage flow hydrology volumes, so it is not appropriate to base any comparison with these on any type of hydrology volumes from other data sources.

This is not the same for imports, where the volumes are historical. It should be noted that they are historical as realized, not total "potential" imports.

### 6.2.5 Hidden Sheets

These sheets are by default hidden in the workbook:

- ScriptParameters Sheet. This sheet contains various defined variables, names, and other supporting information used to support workbook function and RCL script creation.
- ScriptCommands Sheet. This sheet contains the base RCL script code lines, which are written by formulas and macro code, and used to create the RCL scripts used to execute model runs.
- HistoricalHydrologyData Sheet. This sheet contains the base historical developed model input hydrology data.
- HistoricalImportData Sheet. This sheet contains the base historical model input import data.
- RTHydroData. This sheet is a cloned version of the same sheet from the HDB workbook and is used to facilitate the hydrology analysis. This gets updated by macros as needed.
- ObservedData. This sheet is a cloned version of the same sheet from the HDB workbook and is used to facilitate the hydrology analysis. This gets updated by macros as needed.

# 7. Output Viewer Workbook

## 7.1 Purpose

This workbook is used to collect, organize, view, and plot model results. This workbook is very easy to use. Upon starting a model run, the Controller will have oriented the Output Viewer to the appropriate output directory, and thus it will be able to load data as soon as the run is finished. A copy of the previous Output Viewer will also be made into the archive folder and will still be oriented to the previous model output to facilitate comparison between model runs as desired.

## 7.2 Worksheets

### 7.2.1 TraceViewer Sheet

This sheet displays a plot of the model traces for the given run. It will also display the observed conditions if available for a given parameter.

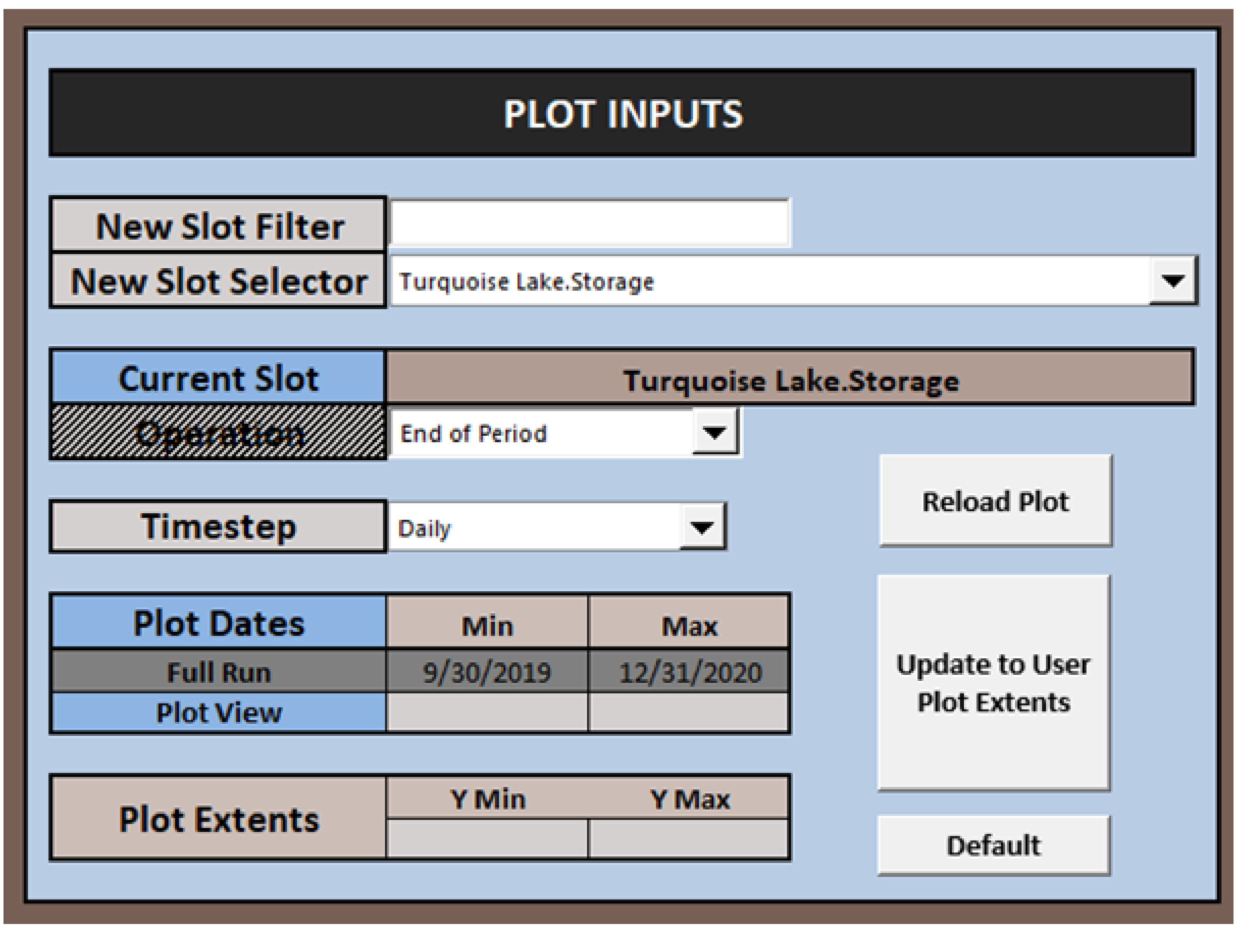



Figure 7-1. Plot Inputs screen in the Output Viewer workbook.

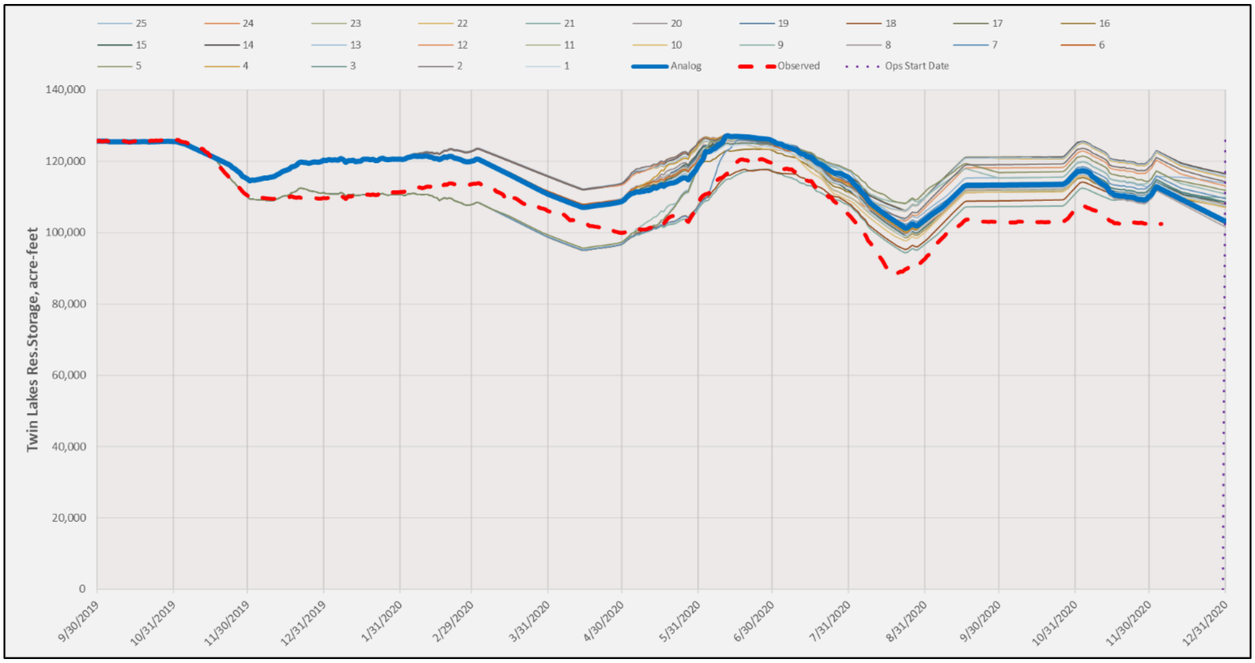


Figure 7-2. An example trace plot from the Output Viewer Workbook.

## 7.2.2 ExceedanceViewer Sheet

This sheet displays a plot of the exceedance statistics for the model traces for the given run. This is designed for analysis of ensemble model runs. It will also display the observed conditions if available for a given parameter.

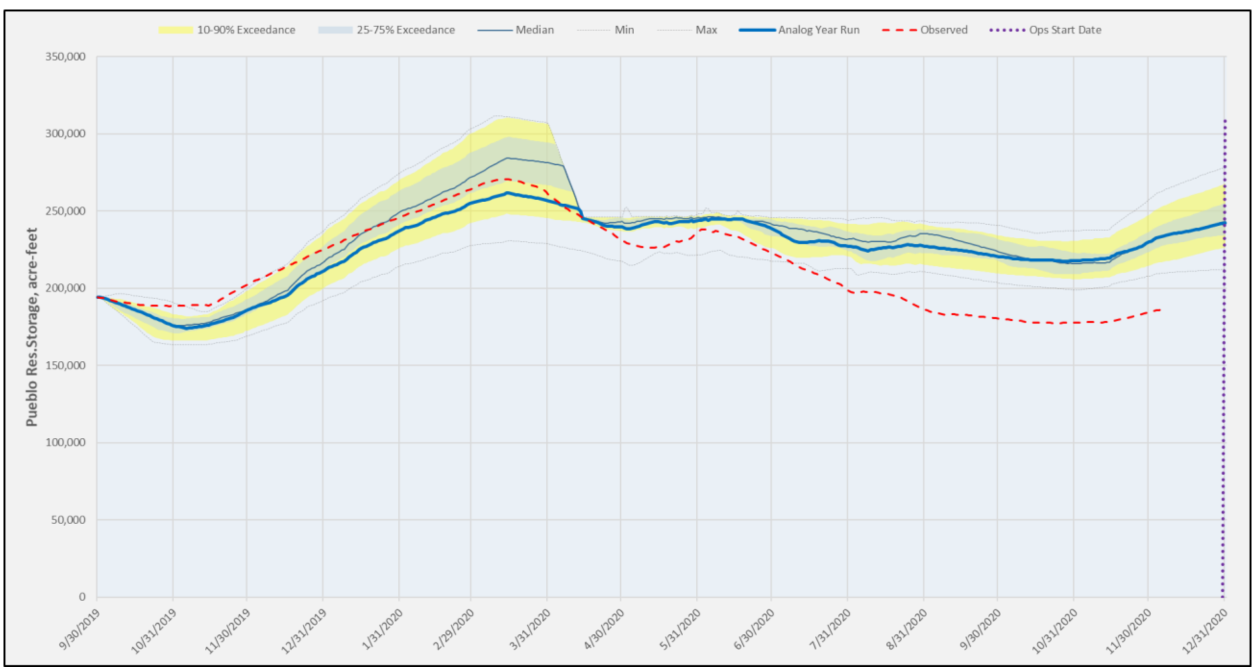
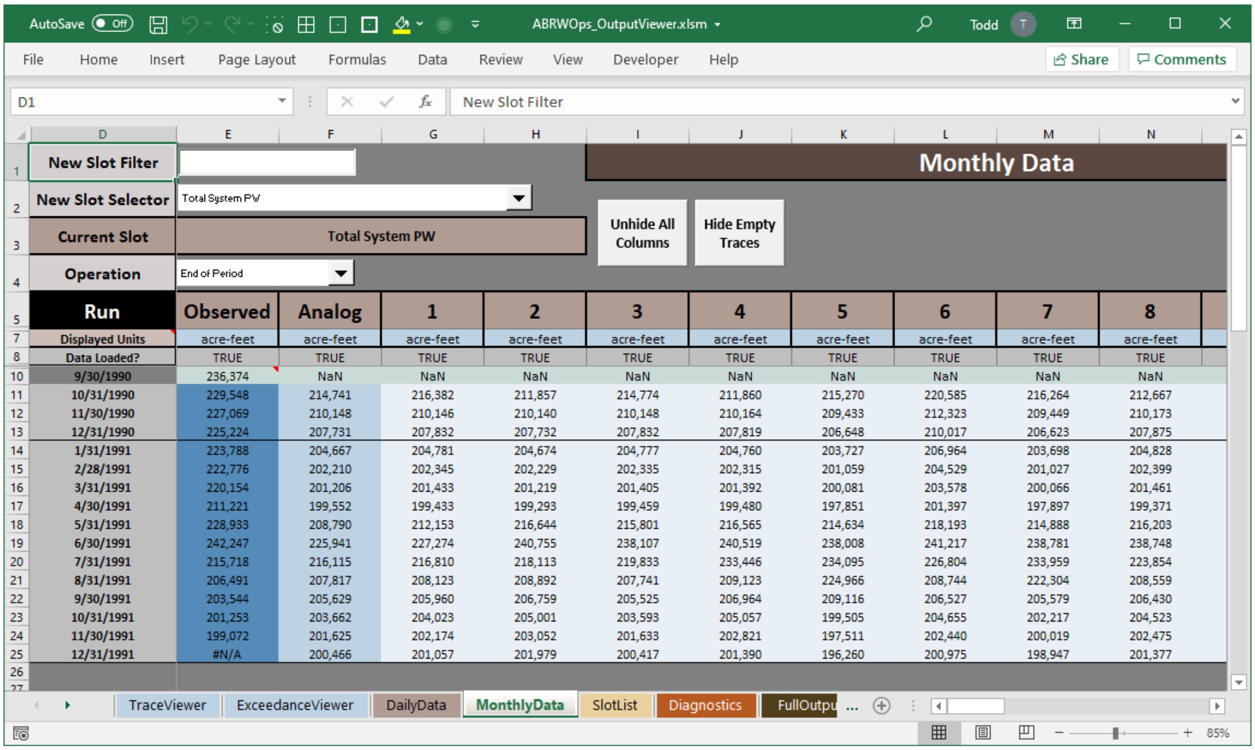


Figure 7-3. An example exceedance plot from the Output Viewer Workbook.

### 7.2.3 DailyData and MonthlyData Sheets

These sheets present the output for the currently selected slot. The Observed and Analog Year run are displayed on the left side and ensemble traces go to the right. Further to the right there are exceedance calculations done on the ensemble output if it exists.

The Daily sheet displays the daily timestep results, which is direct from the model. The Monthly sheet aggregates the results to a monthly timestep, and various operations can be selected such as "End of Period", "Sum to Volume", "Average", etc.




| | D | E | F | G | H | I | J | K | L | M | N |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 5 | Run | Observed | Analog | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 7 | Displayed Units | acre-feet | acre-feet | acre-feet | acre-feet | acre-feet | acre-feet | acre-feet | acre-feet | acre-feet | acre-feet |
| 8 | Data Loaded? | TRUE | TRUE | TRUE | TRUE | TRUE | TRUE | TRUE | TRUE | TRUE | TRUE |
| 10 | 9/30/1990 | 236,374 | NaN | NaN | NaN | NaN | NaN | NaN | NaN | NaN | NaN |
| 11 | 10/31/1990 | 229,548 | 214,741 | 216,382 | 211,857 | 214,774 | 211,860 | 215,270 | 220,585 | 216,264 | 212,667 |
| 12 | 11/30/1990 | 227,069 | 210,148 | 210,146 | 210,140 | 210,148 | 210,164 | 209,433 | 212,323 | 209,449 | 210,173 |
| 13 | 12/31/1990 | 225,224 | 207,731 | 207,832 | 207,732 | 207,832 | 207,819 | 206,648 | 210,017 | 206,623 | 207,875 |
| 14 | 1/31/1991 | 223,788 | 204,667 | 204,781 | 204,674 | 204,777 | 204,760 | 203,727 | 206,964 | 203,698 | 204,828 |
| 15 | 2/28/1991 | 222,776 | 202,210 | 202,345 | 202,229 | 202,335 | 202,315 | 201,059 | 204,529 | 201,027 | 202,399 |
| 16 | 3/31/1991 | 220,154 | 201,206 | 201,433 | 201,219 | 201,405 | 201,392 | 200,081 | 203,578 | 200,066 | 201,461 |
| 17 | 4/30/1991 | 211,221 | 199,552 | 199,433 | 199,293 | 199,459 | 199,480 | 197,851 | 201,397 | 197,897 | 199,371 |
| 18 | 5/31/1991 | 228,933 | 208,790 | 212,153 | 216,644 | 215,801 | 216,565 | 214,634 | 218,193 | 214,888 | 216,203 |
| 19 | 6/30/1991 | 242,247 | 225,941 | 227,274 | 240,755 | 238,107 | 240,519 | 238,008 | 241,217 | 238,781 | 238,748 |
| 20 | 7/31/1991 | 215,718 | 216,115 | 216,810 | 218,113 | 219,833 | 233,446 | 234,095 | 226,804 | 233,959 | 223,854 |
| 21 | 8/31/1991 | 206,491 | 207,817 | 208,123 | 208,892 | 207,741 | 209,123 | 224,966 | 208,744 | 222,304 | 208,559 |
| 22 | 9/30/1991 | 203,544 | 205,629 | 205,960 | 206,759 | 205,525 | 206,964 | 209,116 | 206,527 | 205,579 | 206,430 |
| 23 | 10/31/1991 | 201,253 | 203,662 | 204,023 | 205,001 | 203,593 | 205,057 | 199,505 | 204,655 | 202,217 | 204,523 |
| 24 | 11/30/1991 | 199,072 | 201,625 | 202,174 | 203,052 | 201,633 | 202,821 | 197,511 | 202,440 | 200,019 | 202,475 |
| 25 | 12/31/1991 | #N/A | 200,466 | 201,057 | 201,979 | 200,417 | 201,390 | 196,260 | 200,975 | 198,947 | 201,377 |

Figure 7-4 An example of the data available in the Output Viewer Workbook

### 7.2.4 SlotList Sheet

This sheet contains general run parameters and information to support data loading and viewing, as well as the list of slots that can currently be viewed in the Output Viewer. The Available Slot List currently contains a general selection of most of the main parameters in a relatively logical order.

This list can be adjusted or added to as desired. To do this, simply copy the appropriate column information from the Full Output Slot List into this list, being careful to not misalign anything in the current list. Entire groupings can be cut/pasted up or down to make space or reorganize, however DO NOT insert entire rows or grab and drag groups of cells as this may break references.

The Available Slot List table is hard-coded and is the same column order as the Full Output Slot List for ease of adding. It is manually controlled by the user.

The purpose of having this separate Available Slot List is to keep a reduced list of slots of interest that can be arranged in a logical order that makes it easier to navigate. The full output slot list contains many hundred slots and can be hard to navigate.

### 7.2.5 FullOutputSlotList Sheet

This sheet contains a full list of the slots available in the DMI output. The "Update Slot List" macro can be run to update this list when output slots are added or removed from the "ABRWOps_MasterDailyOutput" RiverWare DMI. This list can be used to find specific slots for adding to the "SlotList" sheet's slot list, which is the slots currently available for selection for plotting and displaying data. The column orientation in that list is the same here, which makes it easy to copy/paste the necessary slot information into the SlotList table (but don't copy the "Timestep" column).

There is potential to incorporate this full list into the Output Viewer's Available Slot List in more functional ways as well, including automating the adding of selected slots from this list to the Available Slot List.

### 7.2.6 Diagnostics Sheet

This is a run diagnostic loader tool that can be used to track ongoing model runs. This can be helpful for tracking progress and catching bugs or failed model runs without having to wait for the entire set of runs to finish, which can take a while depending on how many run batches can be run at once on your computer.

To update the diagnostics of the current set of runs, just click the "Load Diagnostics" button.

### 7.2.7 Hidden Sheets

These sheets are by default hidden in the workbook:

- "ObservedData" Sheet. This sheet is a copy of the DMI_ObservedData sheet from the HDB Data Manager workbook. This was copied into this workbook by the model controller at the beginning of the model run. This holds the observed data used to compare and evaluate results.

# 8. HDB Data Manager Workbook

## 8.1 Purpose and Status

The ABRW Ops HDB Manager workbook is used to organize, pull, view, and facilitate QA/QC (e.g., filling, replacing, extending, etc.) of the HDB dataset used by the ABRW Ops model. This workbook also performs calculations with the raw HDB data and translates and organizes it so it can be pulled into the ABRW model and other workbooks.

Use of the HDB data for operations modeling purposes will demand that the dataset be constantly QA/QC'd because missing data, errors, and inconsistencies will be apparent. The HDB Data Manager workbook will facilitate the QA/QC process by collecting and displaying all the relevant information needed to support operational modeling in a single place and with a logical organization scheme.

The entire workbook process is able to automatically (except for any additional manual filling or corrections needed and storage initialization) switch between Ops Water Years. This is designed to facilitate relative ease and efficiency in rolling the model over into future water years, as well as for running calibration/validation period traces (i.e., previous years) that may be useful in developing and testing enhanced model rules and methods. The Ops WY is selected on the CalcData sheet. This can also be automatically updated from the controller during the run process.

**Known Issue**

Occasionally a valid SDI with a good HDB dataset will fail to load during the HDB data pulling process. This seems to be caused by interruptions in internet connectivity or from other computer applications. If this happens, you should just need to rerun the HDB data loader.

## 8.2 Worksheets

### 8.2.1 Index Sheet

This sheet contains the index of the HDB SDI's that are currently used in the ABRW Ops modeling system. To make it into the model, any HDB data must be listed in this sheet and go through this workbook.

The columns across the top in row 5 are labeled with the information in that column. Cell comments are also used.

This list contains all SDI's that are used in the ABRW Ops model, some that are not directly used but that are used in supporting roles, and others that will or should be used in the future but use of them has not yet been implemented in the model. This list also contains placeholders for other data that needs to or should be maintained in HDB.

The "Read All HDB Data, Fill, Save, and Close WB" button at the top right is used to run the HDB loader and associated macros. This process does exactly what it says it will do. The HDB loading process can take a few minutes because of the number of SDI's involved. During this time Excel cannot be used. It is recommended to save and close other workbooks before this is done. The HDB load status is displayed in the bottom left corner on the status bar, however it may not always update smoothly. Also note that there are two sets of HDB SDIs that are loaded (the 2nd is the PW account storages only) and the status bar displays the progress of each group.

Note the "Overall HDB Data Validity Check" cell at the top near the center. If this cell is green, that means that all of the validity checks through this workbook are good and that the data is valid for the model. However, this does not necessary mean that all data is present or that the workbook has been updated with the most recent HDB data.

SDI's can be added to this list by copying an existing row and inserting it where you would like (it is helpful to logically group related things together). This will maintain the formulas in the appropriate cells. Then you can overwrite the inputs for the duplicated SDI. The necessary inputs are the deep green columns in row 5. The most important input is the new SDI. When this is entered the metadata for it will be displayed by formula in the "HDB SDI Information" columns, which can be used to ensure the entered SDI was the right one. See the cell comments in the other deep green column headers for their purposes. Note that when a row is entered, it will shift all of the columns of loaded HDB data in the "HDBData" sheets, which will cause the validity check to fail until the HDB data is reloaded, because the data mapping throughout the workbook will be incorrect.

### 8.2.2 FullHDBIndex Sheet

This is the full list of ECAO HDB SDI's. This is used to find SDI's of interest and view the various metadata to ensure that the correct SDI is being used. Excel's "Filter" functionality can be used on any column to help search.

The "HDB SDI Information" metadata on the "Index" sheet are looked up via formula to this sheet and thus this table should be updated as HDB nodes are added, corrected, or otherwise changed.

To update this table:

1) Clear all the values on this sheet by pressing Ctrl-A twice to select all, then use (Home>Clear>) "Clear Contents" to clear all the data without clearing this cell comment.
2) Copy/paste the updated SDI table into this sheet, making sure to start the paste in cell A1 and use Paste Values to avoid overwriting this comment.
3) Select Row 1 and click (Home>Sort&Filter>) "Filter" to reapply the filter abilities.
4) Ensure this has been done correctly by making sure the "HDB SDI Information" formulas on the "Index" sheet have not been broken, i.e., those cells should still be populating with the correct information unless a particular SDI or column/field still doesn't exist in the updated table.

### 8.2.3 Accounts2020 Sheet

This sheet contains a list of the Pueblo Reservoir accounts for WY 2020. The information for the EC accounts in this list has been implemented in the appropriate model setup tables so that the models accounts have the correct Max Content and Spill Priority.

This sheet MUST contain all of the current Pueblo Reservoir FryArk Project Water storage accounts to ensure that the totals are aggregated correctly where needed for the model. The PW account groups in column Q are looked up by formula into the Index sheet for the appropriate SDIs, the group totals of which are then summed on the "CalcData" sheet.

### 8.2.4 HDBData Sheet

ALL VALUES ON THIS SHEET ARE SET BY CODE OR FORMULA! DO NOT MODIFY!

This sheet contains the data pulled from HDB. This is the primary "HDBData" sheet and contains all non-PW subaccount data.

The "observed data period" for which HDB data is pulled, is currently set to be 10/1/2019 to "yesterday" (these are actually the only input parameters on this page; however, they should not yet be modified as the rest of the workbook will not adjust accordingly).

This sheet is used to efficiently review all of the data pulled from HDB. Missing data is colored light red by conditional formatting to make it easy to find. The rows across the top of the SDI metadata (names, etc.) are conditionally formatted to highlight which SDIs have missing data in the current data period.

The columns in this sheet are configured by formulas based on the SDI list in the "Index" sheet. The order and SDI's present are all configured in the "Index" sheet list, not here.

Each time HDB data is pulled, the entire HDB workbook dataset is cleared and then repopulated by the HDB data puller. This is to ensure data fidelity between HDB and this workbook and the modeling system.

The "Fill Missing" macro applies to SDIs that are on this sheet. When a value is filled or replaced by that macro, it colors it blue so that it stands out.

Note that when a row is entered in the "Index" sheet's SDI list, it will shift all of the header and metadata headers, and thus the data in the columns will no longer correspond to the stated SDI. When this happens, the "Mismatch Flag" will turn bright red, indicating that the entire workbooks data is invalid until the HDB data loading process is completed again.

The "Read HDB Data" button will run the HDB Loader macro (it can be selected to run only this sheet or the HDBData_PW sheet as well), but it will not automatically run the filling process as the "Read All HDB Data, Fill, Save, and Close WB" macro does. The Filling macro can then be run separately. When it is run, the macro searches the "HDBData_Filled" sheet for the associated SDI, and then uses that data to fill any missing HDB data if the "HDB First" filling process is selected for that SDI. If the Filled First is selected, any available filled data will be preferred over the HDB data. This is useful when there are known data issues in the HDB data that cannot be corrected right away.

### 8.2.5 HDBData_Filled Sheet

This sheet provides the ability to overwrite or fill the HDB data (outside of the HDB system) that will be used in the ABRW Ops model. The filling macro functionality is described in the overview for the HDBData sheet.

The columns in this sheet do not correspond with the columns in the HDBData sheet and are static. Thus, a column can be inserted at any location and the filling macro will find it by the SDI entered in row 24. Thus, this sheet also represents a place to add columns for important data that is not yet available in HDB. This is mapped to the HDBData sheet using a "fake" SDI (that is originally entered in the SDI column of the placeholder row in the "Index" sheet).

Additionally, "NaN OVERWRITE" can be used in "Filled First"-configured parameters to set a value to NaN, even if there is a value in HDB. This is useful when there is knowingly bad data in HDB. Preferably, the HDB data would just be corrected immediately.

### 8.2.6 HDBData_PW Sheet

ALL VALUES ON THIS SHEET ARE SET BY CODE OR FORMULA! DO NOT MODIFY!

This sheet contains data pulled from HDB. This is the secondary "HDBData_PW" sheet and contains all PW subaccount data. This is kept separate from the main "HDBData" sheet.

See the comment on the "HDBData" sheet regarding everything else about this sheet.

### 8.2.7 CalcData Sheet

This sheet provides a location to make "custom" calculations. It uses several different types of consistent columns to allow HDB SDI data to be pulled into this sheet (via the grey and green header columns, where a loaded SDI is entered into the green cell) and then be used combined with other data to make various calculations that are needed before the data is pulled to the DMI sheets and into the model.

"Calculation" columns are those with blue header cells under the word CALC (or otherwise called out). These are given a unique "Calc SDI", which is just a way to enable that data to subsequently be propagated by formula into the correct place in the DMI sheets. There is a "calc SDI" list on the left side in bright blue that ensures that all "calc SDI"s are unique and to easily find the calculated parameter needed. After these are defined and the calculation applied in the given column, these can now be "called"/utilized in other sheets and workbooks, in the same way that the SDIs are (but using a different mapping formula, which can be grabbed from another place using the same "type").

One of the major reasons for this sheet being designed in this manner is so that it is flexible enough for relatively complicated and custom calculations to be made with the other data used in the calculations being viewable right next to the calculated values, which helps ensure that the calculations are done correctly, and that the underlying data is also correct. Another major reason is so that the overall data dates can be changed in this workbook and all of the dependent data and calculations will change along with them.

The date rows and orientation on this sheet is the same as on the DMI data sheets, which helps maintain consistency.

**IMPORTANT NOTE ON PRELIMINARY HYDROLOGY CALCULATIONS:**

Many of these calculations are the preliminary implemented "hydrology calculations", which calculate the boundary inflows (those that aren't direct gages), and local inflows. These are calculated in a simplified manner and then adjusted to remove negatives.

There are many informal and developer comments.

### 8.2.8 DMI_RealtimeHydrology Sheet

This is the observed/realtime hydrology data organized with formulas and links for the RW DMI to pull in to use as the hydrology to drive the model for the "pre-Ops Start Date" period. The model pulls it in via the "ABRWOps_RealtimeHydrology" DMI. This is done at the beginning of every "batch mode" model run executed within the controller and can be done manually from the model open in the GUI.

The data from this sheet also gets pulled into the Controller workbook to facilitate the "forecast"/incoming hydrology analysis and plots.

### 8.2.9 DMI_ObservedData Sheet

This is the observed/current comparison data organized with formulas and links for the RW DMI to pull in for internal model comparisons and other uses. The model pulls it in via the "ABRWOps_ObservedData" DMI. This is done at the beginning of every "batch mode" model run executed within the controller and can be done manually from the model open in the GUI.

### 8.2.10 InitialStorageTables Sheet

This is the "Storage Initialization Setup" sheet where the model initial storages (9/30) for any desired model WY start date are set. It is currently configured adequately for the 2018, 2019, 2020, and 2021 water years, although some necessary data is roughly estimated.

There is some manual work to ensure all the model required initial storage data is filled in to match actual observed as well as possible. This means mapping the data we have and filling in where needed to account for account splits, aggregations, nuances, etc., in order to align the model's accounts with the real-world accounts. This is also where any infrequent or sparse data that we manage to obtain as far as "by entity" account breakdowns will come in handy.

This process is also necessary to ensure that storages are reconciled (total physical = sum of accounts). Since the model doesn't currently simulate with any admin/native accounts, any imbalance should be adjusted away using the override rows into an appropriate account (generally use the Proj West accounts where available or another large account). Generally, the imbalances seem to be minor enough that they aren't expected to make significant differences, however it is good practice to keep this as a somewhat manual process, especially since it is infrequent.

From here, the data is linked into the "DMI_InitStorages" that contains the specific (and picky because they are for table slots) formatting needed for the RiverWare DMI to work. The model then pulls it in via the "ABRWOps_StorageAndDemandInitialization" DMI. This is done at the beginning of every "batch mode" model run executed within the controller and can be done manually from the model open in the GUI.

### 8.2.11 Hidden Sheets

These sheets are by default hidden in the workbook:

- "DMI_AnnualDemands" sheet. This contains annual demand volume numbers for the major municipal water users. These can be changed here if better information is available and the RW DMI will import them.
- "DMI_InitStorages". This sheet contains the initial storage tables for all reservoirs and storage accounts in the model. The initial storages configured on the "InitialStorageTables" sheet are linked to the correct places in this sheet, and the RW DMI pulls them in from here.

- "HDBData_raw" and "HDBData_PW_raw". These sheets are copies of the HDBData sheets after the most recent data pull, but before the filling process has occurred. These are saved so that the raw HDB can be viewed and compared to the data after the filling process has taken place.
- HistoricalDivData. This is a temporary worksheet that contains the historical diversion datasets that are used to support the preliminary/tentative hydrology calculations. The use of data from this sheet will be reduced as actual observed diversion data is brought into HDB and the modeling system.

# 9. Hydrology Calculations Workbook

## 9.1 Purpose

This workbook will be used to perform the model input hydrology calculations that are used for the observed, pre-Ops Start Date period. This workbook will pull the necessary observed data from the HDB Manager Workbook and utilizes it together with data from the developed historical hydrology and diversion dataset.

This workbook is still in the concept phase. The model input hydrology calculations that are implemented are currently done in the HDB Data Manager workbook until the Hydrology Calculations workbook is functional. It is possible that the purpose of this workbook will be achieved through the development of a "naturalized" flow, physical network only RiverWare model which would take the place of this workbook. This model would be the same network as the ABRW Ops model but would be simplified to be physical only. It would benefit from RiverWare's strengths in terms of network and object methods and rules to achieve improved estimates of the actual observed hydrologic inflows. It is recommended that this possibility be given serious consideration.

# 10. RFC Forecast Manager Workbook

## 10.1 Purpose

This workbook will be used to collect and manage ABRFC water supply forecasts. It will apply the appropriate translations to facilitate comparison of the forecasts with available historical hydrology to facilitate analog year selection. Additionally, this workbook will need to extrapolate from the RFC forecast April-September volumes to be full WY, or other specific period, volumes. Conceptually, the forecasts can also be used to create forecast hydrology model input datasets for both "official" forecasts (single run) and forecast ensembles.

Appropriate calculations must be done to translate between the RFC forecast volumes and model input hydrology volumes. Although the mass balances used are not congruent, the components used in each are known and thus this translation can be made. If these translations are not made, the user CAN NOT AND SHOULD NOT compare the RFC forecast volumes directly to any model input hydrology year volumes, or any other volumes (gage flow volumes, etc.), as any of these types of comparisons would be "apples-to-oranges".

# 11. ABRW Ops RiverWare Model

## 11.1 Overview

The ABRW Ops model is the most recent advancement of the Fryingpan-Arkansas Project–Arkansas Basin RiverWare model. For the most part, the June 2018 "Fryingpan-Arkansas Project Riverware Model Documentation" remains applicable in describing what and how the model works.

A notable difference is that the downstream extent of the ABRW Ops model is now the Arkansas River at Las Animas gage, just upstream of the confluence with the Purgatoire River and John Martin Reservoir. The change in downstream model extent was made based on data and information availability and modeling feasibility. Additionally, operations downstream of the Las Animas gage can generally be expected to have relatively minor impacts on the upper basin and can be reasonably accounted for with appropriately modified downstream boundary conditions.

## 11.2 Adapting the Planning Model Ruleset

The ABRW Ops model's ruleset represents continued development and enhancement of the planning model ruleset. Throughout the adaptation process the objective has been to retain the functionality of planning model's ruleset wherever possible. In fact, the ABRW Ops model ruleset has been designed to utilize the planning model rules to nearly the same, full extent as they would be used in a planning model run.

The general process of adapting the ruleset and functions for ABRW Ops model usage is to find the appropriate place within the rules to incorporate the applicable observed, scheduled, or forecasted data. That data is integrated into the calculations being performed by the rules to attempt to get it to end up at a solution that matches the observed as best as possible. It is rarely, if ever, appropriate to directly replace a given result that was solved by the model's rules or methods, because doing so would often cause incompatibilities or unreconciled differences and "break" the model's solution.

## 11.3 Challenges with Utilizing Available Observed Data in the ABRW Ops Model

ABRW is an accounting-driven model, where overall system operations are less dictated in a top-down manner but, rather, are the result of aggregated accounting-level operations and administration in a bottom-up fashion. The "bottom" level in this case is the Colorado water rights system. Unfortunately, this also complicates simulation. This is even more true for operational modeling.

Take for example Twin Lakes Reservoir operations. If one were forecasting the conditions in Twin Lakes, they might expect to input a total release schedule and have the model apply that schedule exactly as given. Then, based on simulated inflows, diversions, and other factors, the model would forecast the future storage in Twin Lakes. However, in the ABRW model it isn't this straightforward. It is not possible to drive the model with an explicit release schedule because the complete accounting breakdown of that schedule is not known but is needed by the model to ensure overall mass balance. It is also not possible/feasible to input this breakdown because too many future conditions are unknown, most notably the amount of native water that will need to be released on a day-to-day basis, termed "native passthrough", which is not only dependent on future native inflows, Twin Lakes storage water right allocations, and downstream water right allocations, but also on various exchanges of water into Twin Lakes accounts from other sources (which are dependent on various Twin Lakes storage account conditions, downstream native and total river flows, and so on).

Thus, in the ABRW Ops model, we would need to input a "target" total release schedule rather than setting it explicitly. This way, the model can attempt to hold true to the input "target" schedule when it is possible but will be allowed to deviate from it as required. For example, if a very low Twin Lakes release schedule was entered, but the simulated native inflows and resulting water right allocations resulted in a higher native passthrough release from Twin Lakes, the model must be allowed to increase the releases accordingly to avoid breaking the model-wide native flow solution. There are other factors that further complicate this, which is why there is not yet an input schedule option for Twin Lakes total release.

Thus, integrating both observed data (in the pre-Ops Start Date) and input schedules (in the post-Ops Start Date period) into the model is not always as straightforward as one would think it would be. These types of parameters must therefore be input in a manner consistent with and that does not violate the model's requirements and solution processes. The parameters that have thus far been integrated are described below.

### 11.3.1 Use of Observed Data (Pre-Ops Start Date)

It is important to note that while obviously related to model input hydrology (system inflows), in this context we are referring to the use of observed data outside of that used for input hydrology. The use of model input hydrology is described above in Section 0.

The model must solve entirely for the pre-Ops Start Date period, and for model fidelity and for a model run not to break, that solution must be remain consistent with the solution throughout the rest of the model. For this reason, the fact that there is a relatively high likelihood that necessary data will be missing, errant, or otherwise inconsistent with other data presents an issue. To avoid letting these types of issues prevent the model from being used at all, the general rule is that wherever and however the use of observed data is implemented in the model, it will be used to the extent possible where and when it does exist, but it does not necessarily have to exist. Therefore, if the data doesn't exist, the model will essentially default to using the logic and solution process that it would use during a planning model run.

The use of observed data is in the process of beginning implemented and tested throughout the model. Much development potential remains in this arena given the observed data and parameters currently available. The addition of new data sources and parameters into HDB and the model will continue to present opportunities for development on this front.

The following observed data is currently used in the model to inform how it simulates ***during the pre-Ops Start Date period***:

- **Turquoise Total Storage**
    - The observed period Turquoise total storage is used to replace the model's guide curve that informs Turquoise Lake project water operations.

  - This occurs in the “Turquoise and Sugarloaf Conduit Operations” rule, within the “TurquoiseAndSugarloafOps” function.
- **Turquoise Lake Sugarloaf Conduit Releases**
  - Observed period SLC maximum capacity is set to the maximum of the observed release or 370 cfs (the otherwise model default max capacity).
  - Observed period SLC release “demand” is used in place of the otherwise model calculated demand. Note that the extent that this release demand is made is still limited by the project water volume available in Turquoise.
  - This occurs in the “Turquoise and Sugarloaf Conduit Operations” rule, within the “TurquoiseAndSugarloafOps” function.
  - This incorporation is still in development and testing and there is additional potential to further incorporate observed SLC (and Lake Fork Creek) Turquoise releases that have not yet been implemented.
- **Halfmoon Creek diversions into the Sugarloaf Conduit**
  - Observed diversions replace model determined demands.
  - Done in the “Set Up Halfmoon Creek to SLC Allowable Diversions” IR.
- **Otero Pump Diversions from Twin Lakes Res**
  - Observed diversions replace model determined demands. Note that because this replaces demands, the simulated diversions still may vary depending on diversion sources such as available storages.
  - Where only total Otero diversion is available, it is assumed to be split 50/50 between Aurora and CSU.
  - Where a better accounting breakdown is available, it is used to divide the total demand more accurately between them as follows. The current breakdown level of detail of observed data is: “Turq-AuroraCFI”, “Turq-CSUCFI”, “Turq-Homestake”, “Twin-TLCC”. Thus, when this breakdown exists, “total Aurora Otero demand” = “Turq-AuroraCFI” + “Turq-Homestake”/2 + “Twin-TLCC”/2. Similar for CSU.
  - This takes place using the “EstimateOteroPumpingBreakdownForEntity” function, and within the “Set CSU Daily Distributed Demands – Adjusted for Historic Demand Years” and “Setup Aurora Otero Pipeline Demands” IRs.
- **Twin Lakes Project Water Storage**
  - Observed Twin Lakes Project Water storage is used as a sort of guide curve for Twin Lakes operations to help inform Project Water releases from Twin Lakes.
  - This occurs in the “MaximumAccountStorageByReservoir” function, which is used by several rules.
  - This incorporation is still in development and testing and is associated with Turquoise and SLC operations.
- **Bessemer Ditch diversions** (and some other major ag diversions, see below)
  - Observed diversions are used to replace model diversion demands. Note that because this replaces demands, the simulated diversions still may vary depending on diversion sources such as simulated WR yields and available storages.

- This occurs in the "Verify Water Users and Accounts and Calculate and Verify Daily Demands" IR using the "DemandDataObjectAndObservedSlotNameMappingLists" fn.
- For "two-part" ag demands like Bessemer's, there is a "Max WR Diversion" component and a "Max Total Diversion when Delivering from Storage" component. The base demand levels are also dependent on hydrologic year type.
  - For the "Max WR Diversion" part, this demand is set to the *minimum* of the observed diversion or the model's Max WR Diversion.
  - For the "Max Total Diversion when Delivering from Storage" part, this demand is set to the *maximum* of the observed diversion or the model's base demand for this part.
- The same mechanism to utilize observed data has also been implemented for the following major ag users and will begin to function as observed data becomes available in HDB and is connected into the model:

### 11.3.2 Use of Input Schedules (Post-Ops Start Date)

"Input Schedules" are used to define known or expected future parameters and thus are applied to the post-Ops Start Date period in the model. Again, in this context, this is different than forecast period model input hydrology, which is described above in Section 0.

Input Schedules are utilized in the model much in the same way as observed data is, however, they apply to the **post**-Ops Start Date period only (not the **pre**-Ops Start Date period). The user configures these on the "InputSchedules" sheet in the Controller workbook.

The following Input Schedules are currently used in the model to inform how it simulates ***during the post-Ops Start Date period***:

(There are not yet any input schedules implemented in the model)

## 11.4 Other Elements in the Model

- Within RiverWare, it is recommended to usually peruse the model in Accounting View. Although it is busier with accounts and supplies, data objects and other items are better organized.
- A series of saved, preconfigured Output Plots are available in the Plot Page Dialog. These are located at the top of the plot list and compare simulated to observed data for many main parameters.

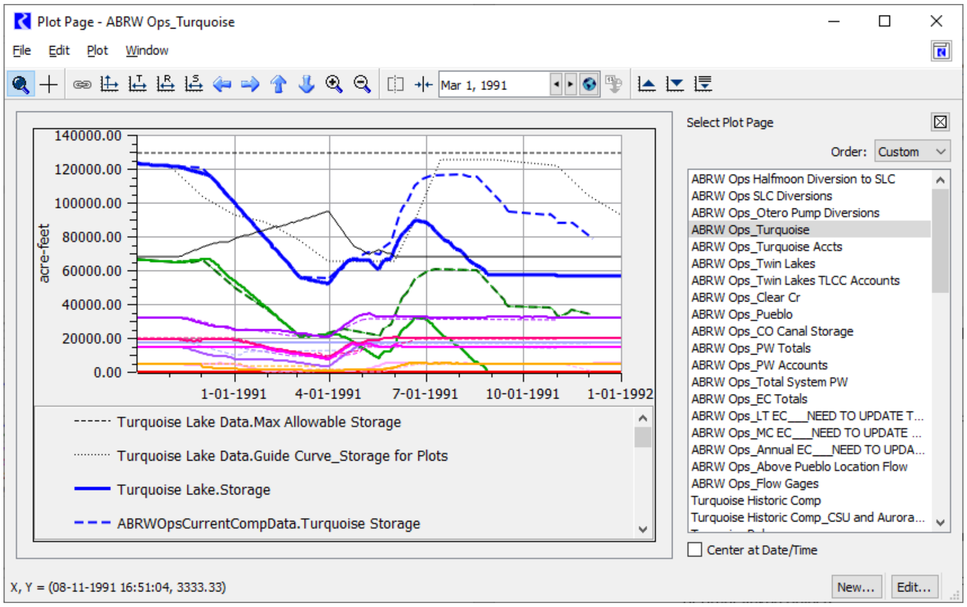



Figure 11-1. An example of a chart comparing actual and modeled storage

- The "ABRW Ops Functions" utility group in the model's Global Function Set contains functions that have been developed specifically for ABRW Ops modeling:

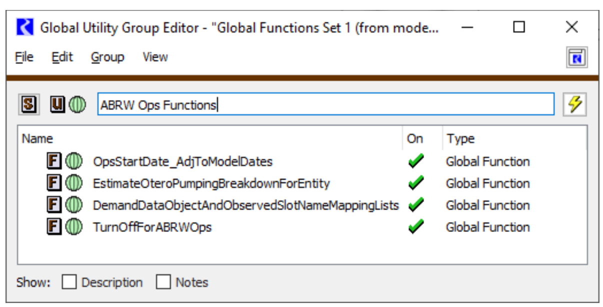



Figure 11-2. Function Sets in RiverWare

- The function "*OpsStartDate_AdjToModelDates*" is used throughout the rules to determine if the current timestep is before or after the Ops Start Date. It is called in every place that observed or input schedule data is applied in the rules. Using the RPL "Search and Replace" function is a very handy way to search for all places throughout the rule and function sets where something is being done specifically for operations modeling.
- Similar for "*TurnOffForABRWOps*" function.

## 11.5 Model Solution Process

This section contains a general rundown of how the ABRW model works. This will be most helpful for users without much RiverWare experience. Additionally, since RiverWare models can be designed to solve in very different manners, this should help even those with RiverWare backgrounds understand how the ABRW model works.

### 11.5.1 ABRW Model System Network and Rules Basics

**System Network –**

- Linked **OBJECTS** (e.g., reservoirs, reaches, water users) represent the system's mass balance
  - e.g. reservoir object outflow links to the downstream reach object's inflow, diversion to a water user object links to the diversion from a reach object
- **ACCOUNTS** on objects represent the accounting breakdown of that object's total "physical" water. Like object linking, accounts from one object can link to accounts on the same object or other linked objects.
  - e.g., outflow from a certain storage account on reservoir object links to the "passthrough" flow account(s) on the downstream reach object
  - Accounts also hold the model's **Water Rights**
- The entire network deterministically solves as possible given the knowns and unknowns.
  - e.g., for a simple reach (i.e., with no side inflows/outflows) if inflow is known, outflow will be calculated
  - Some things (generally those with relatively basic relationships) calculate dynamically within objects and accounts and automatically recalculate when associated parameters change, e.g., evaporation recalculates as reservoir surface area changes, transit losses recalculate as reach flow change, etc.
- **The model network, objects, and accounts will not solve if there's not enough information**
  - e.g., for a reservoir, even if previous storage and all inflows are known, it can't solve until the release is set.
- This is where **RULES** come in. e.g., rules are used to set the reservoir's release.
- This all happens on a daily timestep.

**Rules -**

- Rules are used to simulate the policy and operational decisions that drive the system.
- Rules calculate and set the unknowns to the model network.
- After each rule fires, the system network resolves as possible given the new or updated info.
- Rules are executed in a certain order that is designed to best simulate the system.
- Currently there are 168 rules in the ABRW model ruleset.
  - Most rules fire on every timestep. e.g., the rules that set reservoir releases or set diversions to water users
  - Some rules only fire when necessary. e.g., the rule that make deliveries from storage only fires when there are demands not fully met with native WR diversions.

- Some rules only need to fire on certain timesteps. e.g., the Winter Water storage rule only fires 11/15-3/14, the Winter Water distribution rule only fires on 3/15.
- The full system network initially solves early within each timestep (day) after enough rules have fired and enough of the unknown parameters have been set.
- The system network solution is then updated as various operations are layered on by rules
  - Native Flow Solution, Pre-Exchange Conditions, Between Exchange Solutions, etc.
- This facilitates very transparent, dissectible solutions ("clear box")
  - Can track exactly how a certain value was calculated, or how and why a simulated decision was made.
  - E.g., if a release was simulated from Twin Lakes Reservoir, can track the various calculations and conditions at that time that led to the release being made.

### 11.5.2 General ABRW Model Solution Order

On each day of the model run:
**Pre-Water Rights Solver (WRS),** before the initial native flow solution – Configure system for the WRS.

1. Configure that day's full system Water Right requests
   - Limit requests by **diversion demands**, water right limits such as annual/monthly volume limits, date limits, rate limits, available storage space, etc.
   - Turn off water rights that are out-of-season (e.g., WW canal WRs…), junior to WW fixed call
2. Adjust that day's full system native inflows
   - Base native inflows already set from input hydrology dataset
   - Add any simulated releases to native flow, e.g., augmentation/RF requirement releases, spills/evacuation, native admin account operations, etc.
3. **Solve Water Rights** – Allocates the system's native flow to WRs (requests) by priority date.
4. Based on water right allocations, set initial water user diversions, transfers into storage accounts, distribute storage yields between accounts, etc.
5. Make certain adjustments to the initial native solution
   - e.g., flood control holdback, some adjustments to WR allocations (e.g., move appropriate Pueblo Water native diversions from Pueblo to Comanche)
6. Set initial reservoir releases to native passthrough from WRS native flow solution.
   - This is the **"Native Flow Solution"**

**Post-Water Rights Solver** (after the initial native flow solution) - After this initial solution, operations and other processes are "layered" on, and the full system solution is continuously updated as rules fire.

7. Set preliminary operations of upstream reservoirs (Turquoise, Twin Lakes, Clear Creek), including:
   - FryArk Project Water operations
   - Sugarloaf Conduit operations, Otero pipeline diversions

- Import exchanges into reservoirs
- Contract exchanges/trades between entities (e.g., Pueblo to upstream reservoirs)
- Releases from owned accounts (Pueblo Water, CSU, Pueblo West) to Pueblo Reservoir

8. Make deliveries from storage to water users.
    - Deliveries based on **remaining diversion demands not met by direct flow WRs**.
        i. Different demands can be used when delivering from storage vs. WRs.
    - Made from various storage accounts/sources. Sources/order can vary by water user, e.g., Ag users generally use WW, then PW storage
    - Various types of delivery "mechanisms" are simulated, e.g. direct deliveries from Pueblo Res, river deliveries via reservoir releases, delivery exchanges
9. Make exchanges from Pueblo Res to upstream reservoirs, e.g., CSU/Aurora to Turquoise/Twin Lakes
10. Make exchanges from downstream sources to Pueblo Res
    - Each exchange is simulated one at a time. There is a full system **"Pre-Exchange Condition"** (and Post-Exchange Condition) solution for each.
    - Subject to various standard and unique limits, e.g., minimum flow criteria, season/rate limits
11. WWSP season only – Store WW in Pueblo Res, CO Canal, Fort Lyon Storage Canal, John Martin Res
    - Holdback/divert allowable native flow at each location

# 12. Calibration, Validation & Current Performance Status

## 12.1 General Calibration/Validation Process

The general calibration and validation process recommended for use during development and implementation of the ABRW Ops modeling system is as follows. This should be completed for Ops Water Years of 2018, 2019, and 2020. Additionally, these concepts should be kept in mind during 2021 modeling, and especially at the end of WY 2021.

1. Run with full historic ensemble. Observed should be reasonably within range. (i.e., OSD = 10/1/2019 for Ops WY = 2020)
2. Run with full historic ensemble but replaced with observed data where possible for full time period. Position of Observed should be improved within range. (i.e., OSD = 12/31/20 for Ops WY = 2020)
3. Run with Ops Start Date at various forecast dates with observed data only < OSD. Range should be limited <OSD, then expand >OSD. "Future" observed should be reasonably within range. (e.g., OSD = 5/1/20 for Ops WY = 2020)
4. Improve model logic/rules and application of data to improve relationship of range to observed.
5. Repeat for other recent historical years.
6. Continue to review and revisit all aspects as datasets are improved and more and new data is incorporated.

## 12.2 Discussion of Current Model Performance and Accuracy

This discussion focuses only on the broadest parameters in the system, storages in the primary and major reservoirs of Turquoise Lake, Twin Lakes, and Pueblo Reservoir. While the model simulates many more parameters (on the order of many thousand) down to minute details such as the individual water right yields of relatively small water users, the model cannot be claimed to be accurate if it does a poor job of simulating these primary parameters reflecting overall basin storage conditions. In a bottom-up type system like the Arkansas basin, the ultimate reasons for seemingly broad-scale inaccuracies can often be the collective impact of relatively minor components. Thus, identifying the actual reasons for inaccuracies, and subsequently correcting them to improve overall model performance, is generally complicated and requires a deep understanding of how the model works, thorough analysis of model results (over multiple scenarios), and thoughtful consideration of possible rectifications and implementation of a selected one.

It is important to understand that despite these significant hurdles remaining, there is no lack of evidence, clues, and leads regarding areas with a high potential for improvement as there is, for example, a large amount of observed data that has not yet been able to be incorporated, and many model rules and processes noted for improvement that have not yet been the focus of development given the current project resources and limitations.

As model performance is improved through the continued process of data review and incorporation and model enhancement, it can be expected that the performance of these broad parameters will improve. This will allow the focus of calibration and validation to move to other specific parameters of interest.

Finally, and as a precursor to the discussion below, the overall status of model performance in terms of accuracy in predicting or estimating various Arkansas basin or FryArk project conditions on a short-term operations level time frame (i.e., approximately weeks to months out and through the end of the current water year) is that model accuracy currently appears to be questionable. This is mentioned at the forefront to attempt to prevent current level-of-development model results from being taken out of context and/or used in an inappropriate manner during operational planning and decision-making. Several key reasons why the accuracy of the current model results is currently questionable, and potential steps to improve the performance, are discussed throughout the remainder of this section.

## 12.3 Current WY 2021 Lookaheads

The current lookaheads for WY 2021 are shown in plots below. Current in this sense means the most recent model runs at the time of this report, which use an Ops Start Date of 12/28/2020. This reflects a point nearly 3 full months into the water year, however this 3-month period represents on average only 16% of the WY total hydrology inflows, and just 4% of the average total basin imports. Thus, there is still significant uncertainty in terms of the years overall water supplies, as illustrated by the historical ensemble traces shown in the first two plots below. Note in these plots that the range of the projected inflows is just slightly smaller than the full period historical range (i.e., that corresponding with an Ops Start Date of 10/1/2020) which is shaded.

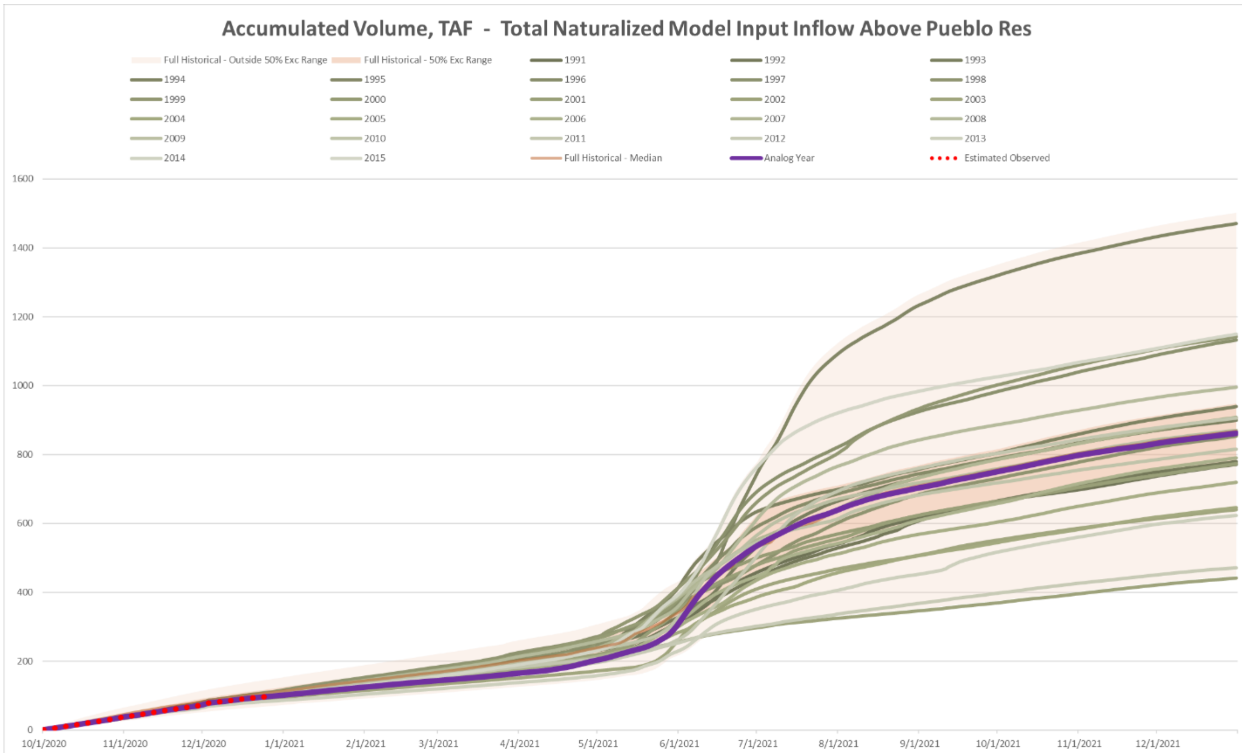



Figure 12-1. WY 2021 Historical Ensemble-Informed Total Naturalized Model Input Inflow Above Pueblo Reservoir as of December 28, 2020.

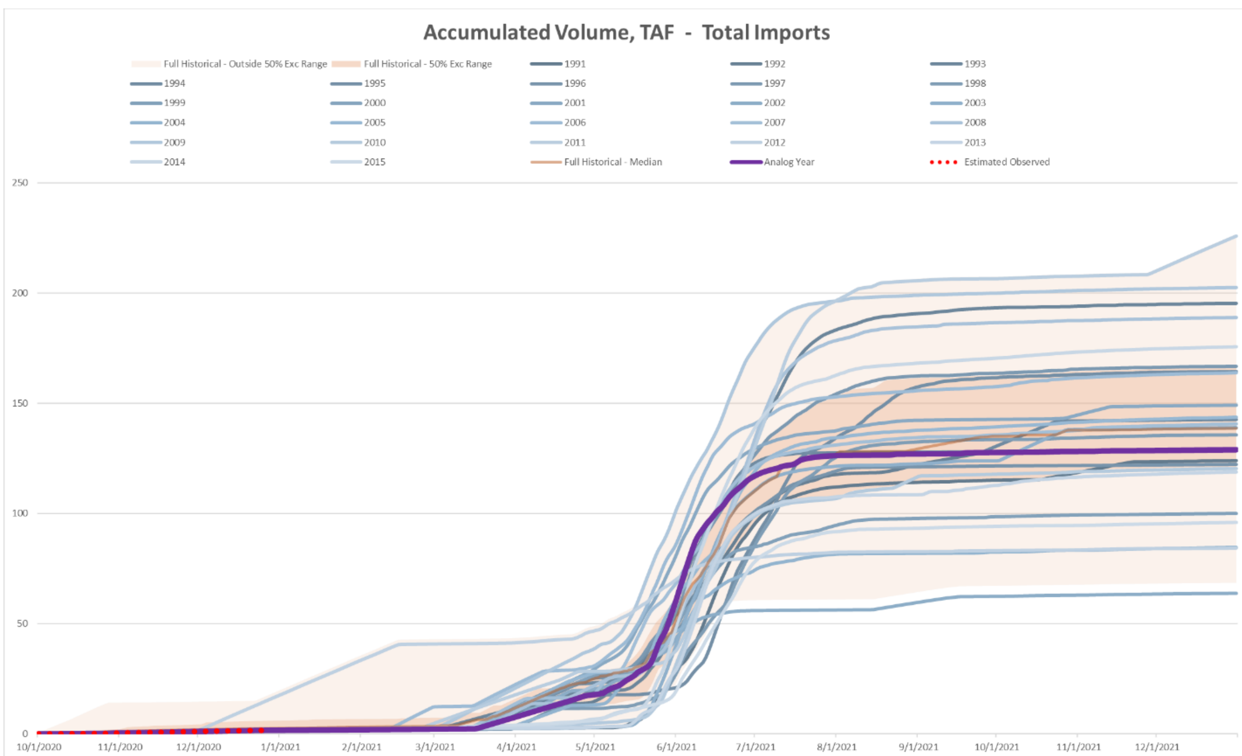



Figure 12-2. WY 2021 Historical Ensemble-Informed Total Imports as of December 28, 2020.

The next three plots below show the simulated total storages lookaheads for Turquoise Lake, Twin Lakes, and Pueblo Reservoir for WY 2021 with an Ops Start Date of 12/28/2020. Again, it is important to note that even though the model is providing results, these results are currently considered very questionable and should not be relied upon for operational decision-making purposes. This is because the performance of the model when applied at various points in recent historical years does not appear to be within a range that would be reasonably expected if it were performing accurately, as well as the fact that there are blatant biases observed within those results. Examples of these issues will be subsequently presented.

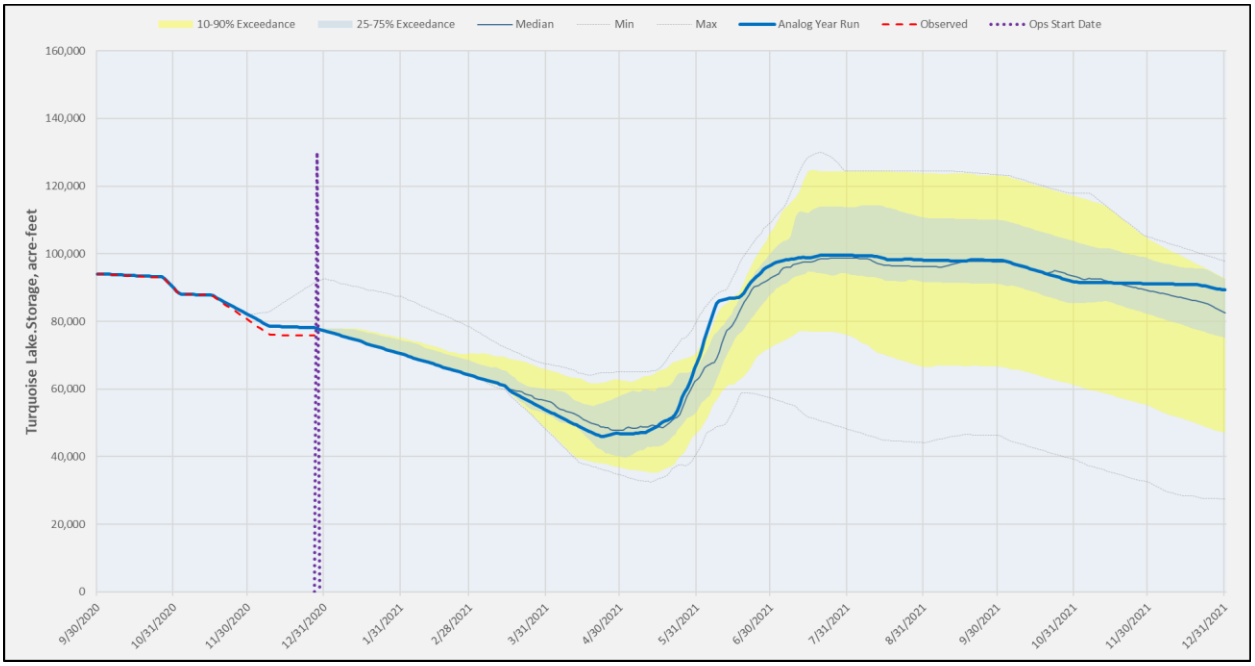


Figure 12-3. WY 2021 Historical Ensemble-Informed Turquoise Lake Storage Lookahead as of December 28, 2020.

For the above plot of Turquoise Lake Storage, this does look like it could be a relatively reasonable lookahead. However, we can use the model's performance on Turquoise Lake Storage in the previous years as a basis for determining whether or not to trust these results. Those results however, as displayed in the next section, show that model performance for Turquoise storage in previous years is poor, and this casts doubt on the accuracy of these results for the current WY. It can also be noted however, that simulated Turquoise storage in the observed period (pre-Ops Start Date), has done a pretty good job of tracking the actual observed storage.

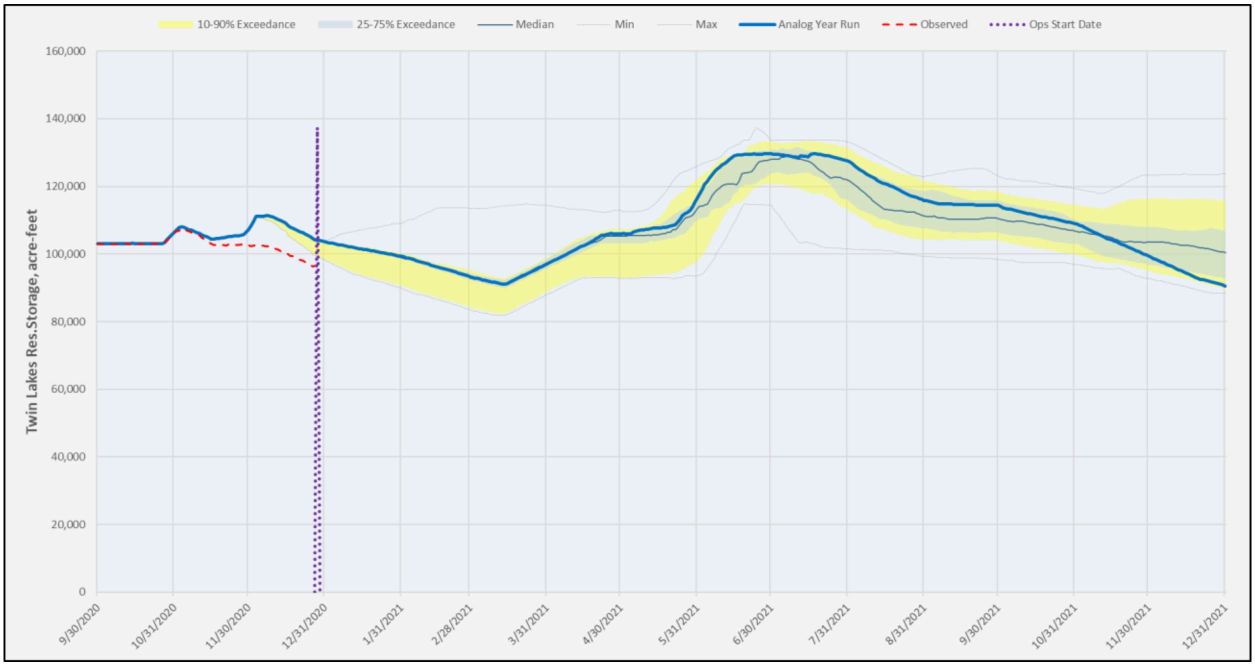



Figure 12-4. WY 2021 Historical Ensemble-Informed Twin Lakes Storage Lookahead as of December 28, 2020.

Generally, the same points made for Turquoise storage apply to Twin Lakes storage as well. However, it is observed here that simulated storage deviates from actual observed storage well before the Ops Start Date. Recall the discussion in the report section describing the model processes that explain that this means that the model is simulating something quite differently (and consistently in all model traces) than has actually occurred, which points to aspects of the model (those relating to Twin Lake operations) that need to be reviewed, diagnosed, and corrected or enhanced. To further obfuscate matters, it could also be data errors, missing periods, calculations or methods that require improvement, or other data issues driving this issue. It is very important to note that this is certainly a solvable issue.

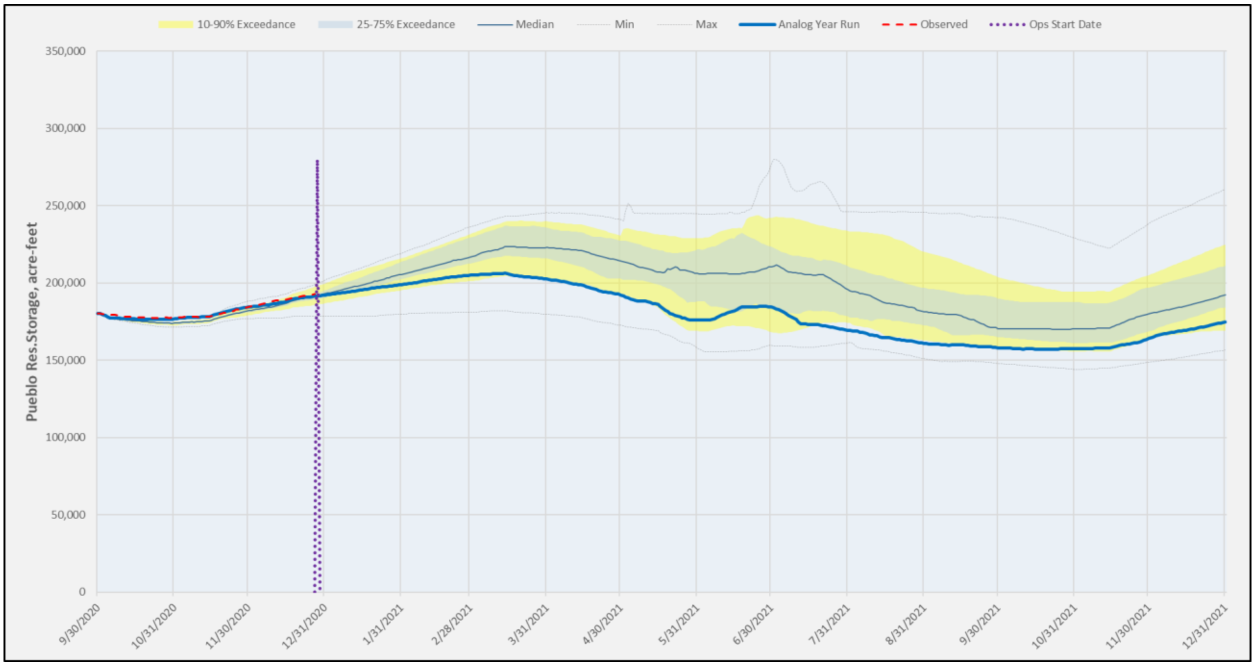


Figure 12-5. WY 2021 Historical Ensemble-Informed Pueblo Reservoir Storage Lookahead as of December 28, 2020.

The points made above for Turquoise also apply to the Pueblo Reservoir storage lookahead. Subsequent plots showing performance in previous years will point to some similar and some differing reasons for being skeptical of these lookaheads.

## 12.4 Previous Years Turquoise Lake Total Storage Performance

The following series of plots show simulated Turquoise Lake storages for WYs 2018, 2019, and 2020. Again, note that there are data issues that remain in the datasets for all years, and thus it is often difficult to determine if root causes of issues stem from model rules or data issues (which could impact driving hydrology data or observed data that is being used in another capacity to inform model simulation). Each series of plots contain three plots for each of the three water years. The top plot in each set is model results simulated with an Ops Start Date of the beginning of that water year (i.e., October 1). The middle plot is the same but simulated with an Ops Start Date of April 1, and the bottom plot is simulated with an Ops Start Date of Dec 31 (of the latter calendar year), which is the last day of the model runs. The bottom plots show how well the model (and datasets), at their current, preliminary level-of-development, is matching observed given all of the data that is currently incorporated into the modeling process. Again, just because observed data is available does not mean that it can be used to force the model to its exact values, as described previously in the report's section on the model.

The first thing to note in the series of plots for Turquoise storage is that end of year run (bottom plots, aka full/all observed period runs) simulated storage deviates quite significantly from actual observed. While the range of the model traces collapses to a (relatively) consistent result, this consistent result is not in-line with the actual observed beginning in approximately the early Spring period of each year.

Also, based on the Apr 1 runs (middle plots) and even the Oct 1 (top plots), in two out of the three years, the actual observed spring runoff period resulting filling storages are not within the simulated range resulting from the entire historical ensemble. Given that there is nothing known to be that significantly unique about these years compared to the 25 historical ensemble years, it should be expected that the actual observed should fall somewhere reasonably within that range.

A bit of investigation (the details of which are not included here, but can start to be uncovered by exploring some of the Turquoise-related parameters available in the Output Viewer), uncovers that even when simulated total Turquoise storages are matching observed in the pre-Ops Start Date periods, the model runs are already beginning to deviate from observed in other key Turquoise parameters, including account storages and the total release accounting breakdown and the release pathways (Lake Fork Creek to the Arkansas River vs. the Sugarloaf Conduit to Twin Lakes) used. This points to the fact that there is a good deal of data here that has not yet been incorporated to the extent possible. It is also apparent based on these results that the model's Turquoise Lake operations rules need to be enhanced further over their planning model form.

This example for Turquoise Lake also highlights where a model input schedule may be appropriate and useful, which would allow the user the ability to apply a planned drawdown schedule to the future/forecast period of the model run rather than use the generic, planning model drawdown guide curve. In the top (beginning of WY) plot for each of the three years, the simulated drawdown, which is driven largely by the model's guide curve in the case of Turquoise total storage, is observed to differ from the actual drawdown in all three of these historical years.

Overall, while there is significant direction and potential for improvement, it is seen that the current form of the model and datasets generally does a poor job of simulating Turquoise Lake storages in these recent historical years, and thus there is not much confidence in the current lookahead for WY2021. However, it is fully expected that with data QA/QC and pointed rule and method development and enhancement, the performance of Turquoise Lake total storage in the model can be greatly improved. The same is true for the dozens of other simulated Turquoise Lake physical and accounting parameters.

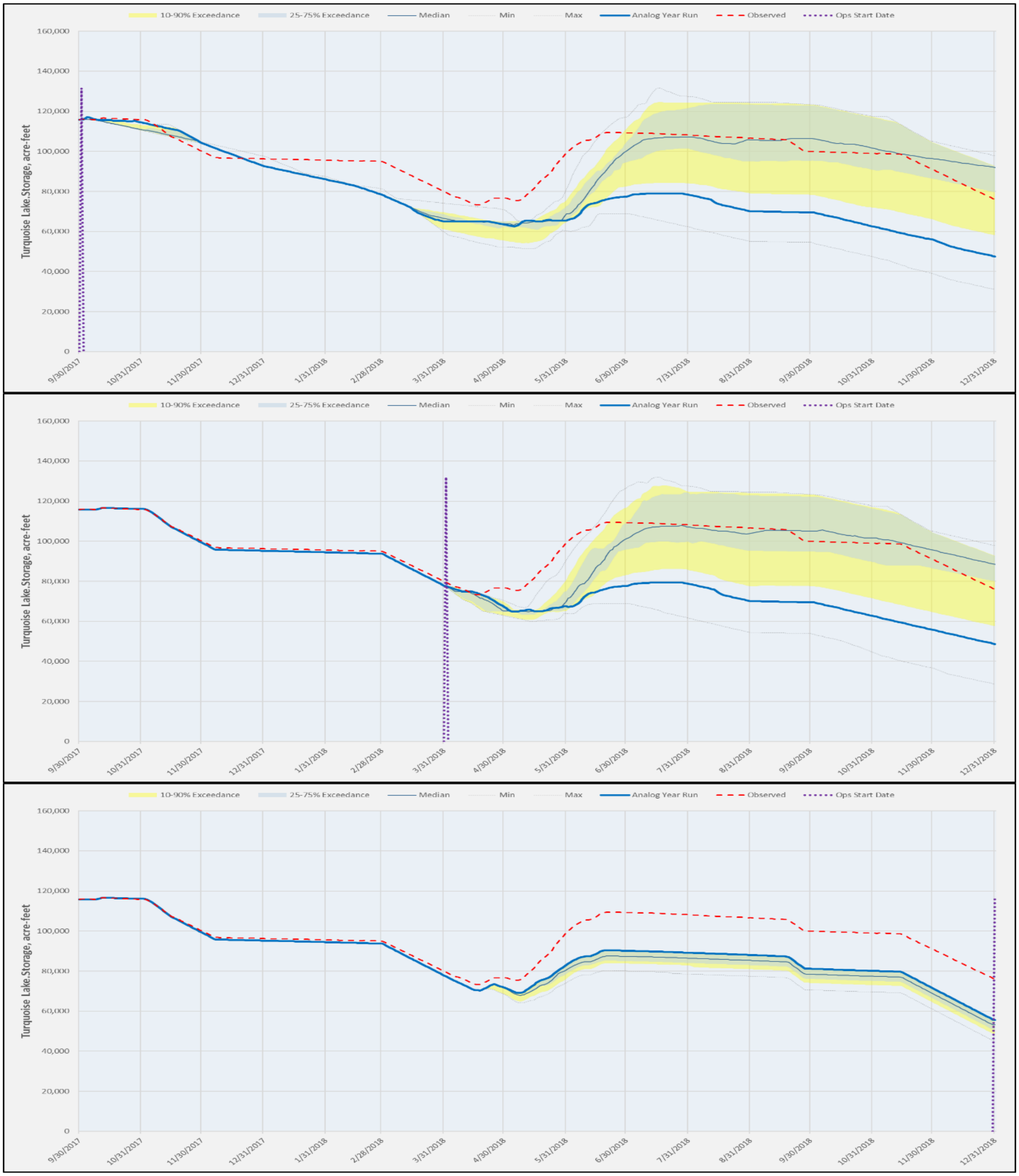


Figure 12-6. WY 2018 Historical Ensemble-Informed Turquoise Storage Lookahead as it would have been simulated from Oct 1, 2017 (TOP), Apr 1, 2018 (MIDDLE), and Dec 31, 2018 (BOTTOM).

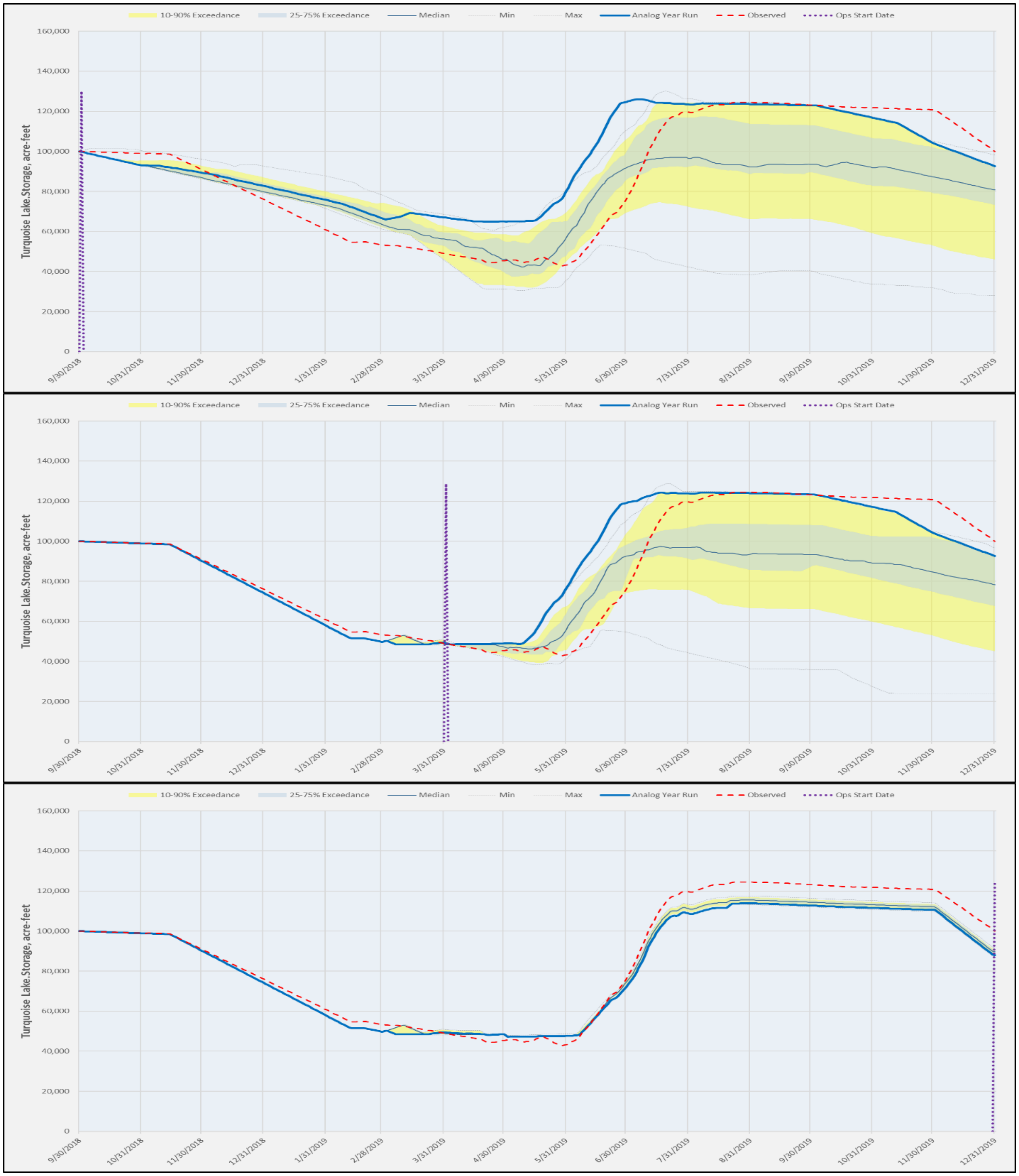



Figure 12-7. WY 2019 Historical Ensemble-Informed Turquoise Storage Lookahead as it would have been simulated from Oct 1, 2018 (TOP), Apr 1, 2019 (MIDDLE), and Dec 31, 2019. (BOTTOM).

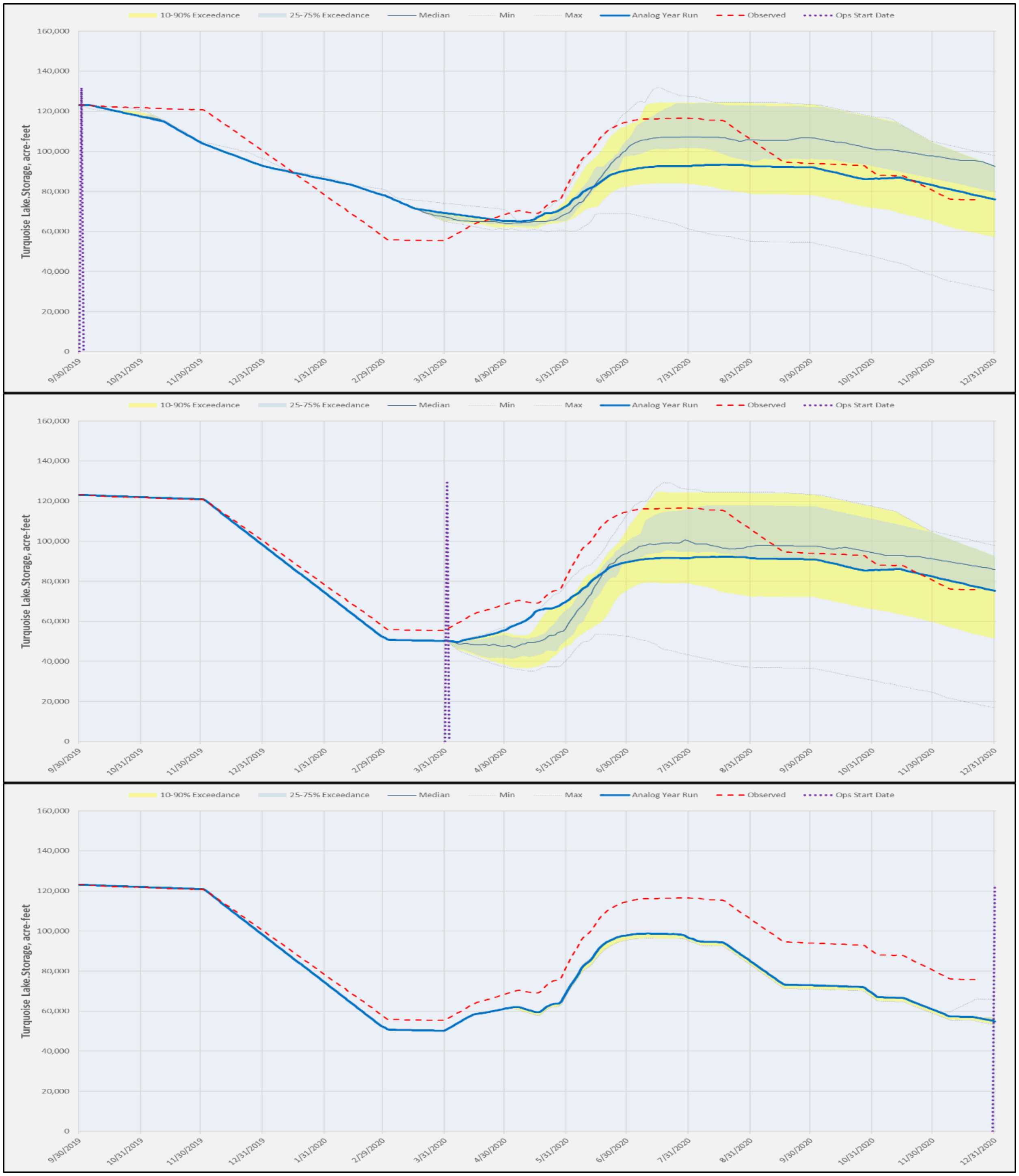



Figure 12-8. WY 2020 Historical Ensemble-Informed Turquoise Storage Lookahead as it would have been simulated from Oct 1, 2019 (TOP), Apr 1, 2020 (MIDDLE), and Dec 22, 2020 (BOTTOM).

## 12.5 Previous Years Twin Lakes Total Storage Performance

The model performance for Twin Lakes storage for WY 2020 is shown in the series of plots below. These are also available for 2018 and 2019 but have not been included in this report for brevity. Overall, many of the same types of issues (and potential solutions and paths forward) are observed in the Twin Lakes results as in the Turquoise Lake results.

An additional issue that is observed here is that the Twin Storage results do not seem to be collapsing across all model traces, even in the pre-Ops Start Date period and throughout the full observed period (bottom) run. There are several potential reasons for this, the most likely of which stem from uncertainty in hydrology inputs in the mainstem Arkansas River reaches, and that the uncertainty (or other variations elsewhere in the model, likely Pueblo Reservoir) is leading to varied simulation throughout the various simulated Twin Lakes operations. Those operations are complex and consistent of many independent and inter-dependent processes and objectives, including FryArk PW operations and various TLCC and TLCC-subaccount (such as CSU, Aurora, and PBWW) operations.

It is also expected that the modifications and enhancements that should be made to the Turquoise Lake (and other) operations and datasets could have a significant impact on the Twin Lakes results. Thus, a deep understanding of both how the Arkansas basin operates and how the model works to simulate those operations is crucial in determining the order of approaching or implementing various improvements.

On an overall basis for Twin Lakes total storage, as with Turquoise total storage, and while there is significant direction and potential for improvement, it is seen that the current form of the model and datasets generally does a poor job of simulating Twin Lakes storages in WY 2020, and thus there is not much confidence in the current lookahead for WY2021. However, it is fully expected that with, first, data corrections and QA/QC, and subsequently with pointed rule and method development and enhancement, the performance of Twin Lakes total storage in the model can be greatly improved. The same is true for the dozens of other simulated Twin Lakes physical and accounting parameters.

Figure 12-9. WY 2020 Historical Ensemble-Informed Twin Lakes Storage Lookahead as it would have been simulated from Oct 1, 2019 (TOP), Apr 1, 2020 (MIDDLE), and Dec 22, 2020 (BOTTOM).

## 12.6 Previous Years Pueblo Reservoir Storage Performance

The model performance for Pueblo Reservoir total storage for WY 2020 is shown in the series of plots below. Overall, many of the same types of issues (and potential solutions and paths forward) are observed here as in the Turquoise and Twin Lakes. Improvements to those factors will also change the Pueblo Reservoir results (and vice-versa), as model calibration and validation is an ongoing process.

As with the upstream reservoirs, there is ample reason to be skeptical of the WY 2021 lookaheads for Pueblo Reservoir based on the previous year performance. However, there is also evidence highlighting various factors that are likely to be driving inaccuracy and uncertainty.

Following the total storage plot series, the full observed period results are shown for total Project Water storage, total Excess Capacity account storage, and total Winter Water account storage within Pueblo Reservoir are also displayed. This is done to illustrate the general process through which the reasons for the model's results, be them accurate or inaccurate, can be further investigated by exploring the results for various components independently. Note that each of these are aggregated total account type results, each of which reflects several to many individually simulated accounts.

As illustrated in the plots, it is seen that while the model seems to currently be the most accurate for total Winter Water storage, each of the overall storage accounts seems to be simulated somewhat accurately by the model during some of the time period, but not consistently throughout the full model run period. For example, note that total Project Water seems to track relatively well through the beginning of July, but thereafter the actual observed drops significantly lower than the range of simulated traces. The reason for this particular difference is likely due to differences between the simulated and actual Project Water allocation to various basin entities, which could likely be rectified by a combination of enhancement to the model's Project Water allocation simulation methods and the incorporation of actual observed Project Water allocations as appropriate.

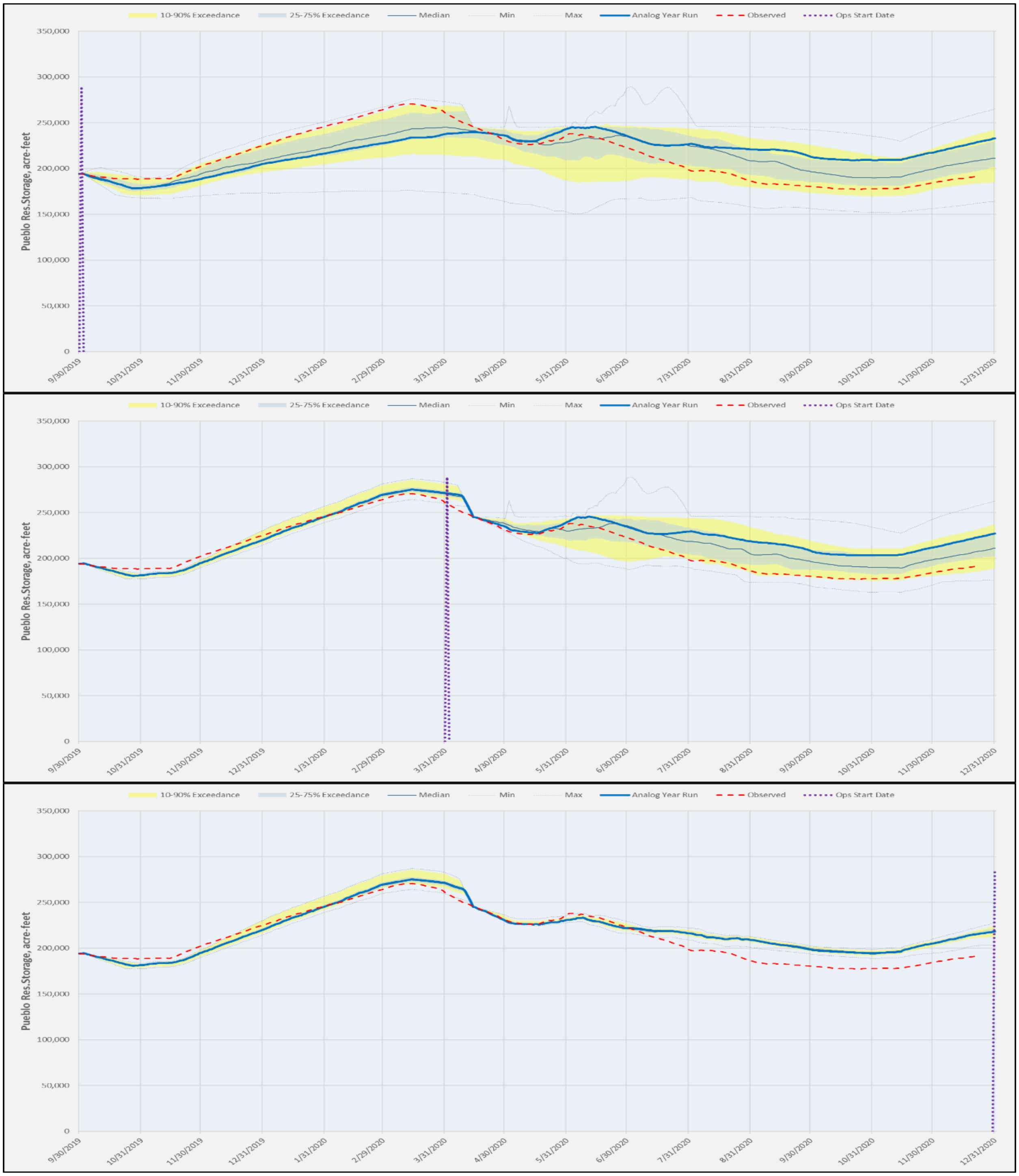


Figure 12-10. WY 2020 Historical Ensemble-Informed Pueblo Reservoir Storage Lookahead as it would have been simulated from Oct 1, 2019 (TOP), Apr 1, 2020 (MIDDLE), and Dec 22, 2020 (BOTTOM).

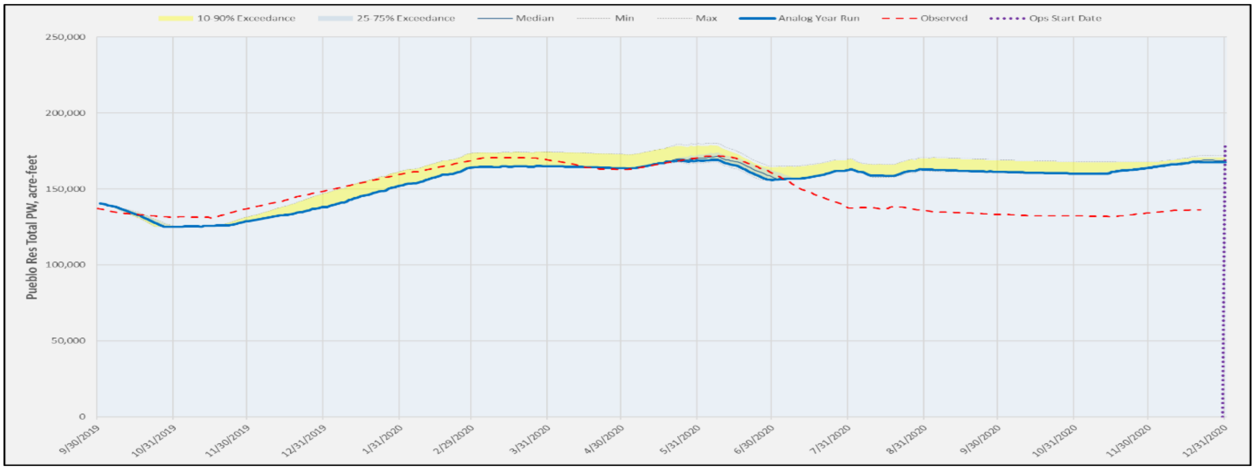


Figure 12-11. WY 2020 Historical Ensemble-Informed Total Project Water Storage in Pueblo Reservoir Lookahead for Ops Start Date of Dec 22, 2020.

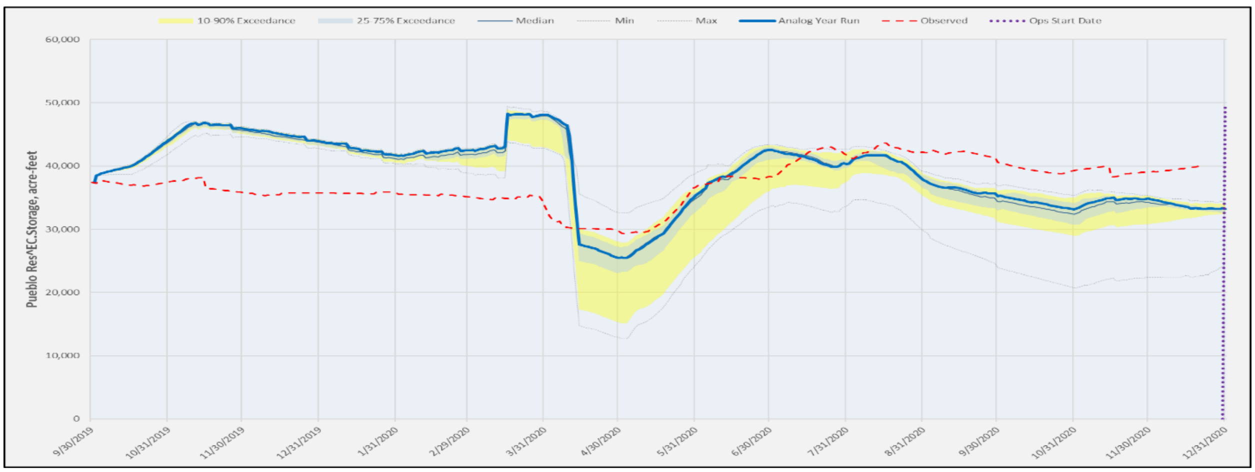


Figure 12-12. WY 2020 Historical Ensemble-Informed Total Excess Capacity Storage in Pueblo Reservoir Lookahead for Ops Start Date of Dec 22, 2020.

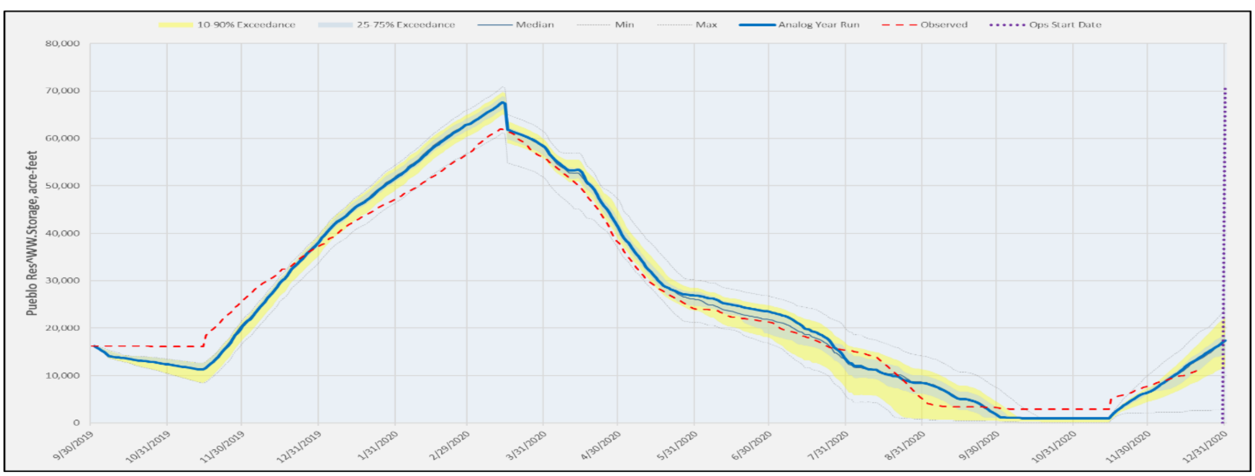


Figure 12-13. WY 2020 Historical Ensemble-Informed Total Winter Water Storage in Pueblo Reservoir Lookahead for Ops Start Date of Dec 22, 2020.