EVALUATING RIVERWARE'S ABILITY TO SIMULATE COLORADO'S WATER RIGHT SYSTEMS

A Side-By-Side Comparison of River Ware and StateMod's Simulation of Water Right Allocation and Related Operations

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Executive Summary

Accurately simulating water rights is of utmost importance in water resource system models of Colorado's basins; however, the complexity of their water right system presents challenges for many modeling platforms. A primary strength of the Colorado Decision Support System's (CDSS) surface water model, StateMod, lies in its ability to simulate these systems, which has become trusted after years of development and use. While StateMod fits its current application within CDSS well, it has several limitations that reduce its ability to assume new and enhanced roles, such as limited flexibility, transparency, and minimal user-friendliness and support. RiverWare is a state-of-the-art, powerful, and widely used modeling platform that excels in many of the areas where StateMod is limited. However, RiverWare's ability to simulate water rights remain largely untested in Colorado water rights systems.

The primary objective of this study was to evaluate RiverWare's ability to simulate components of Colorado's complex water right systems. This was accomplished by developing a RiverWare model that simulates the water rights system of Colorado's White River basin, and by analyzing and comparing its simulation process and results against the existing StateMod model of the same basin. While this study compares the water right simulation procedures and results between RiverWare and StateMod in detail, the overall findings and conclusions can be summarized in these main points:

- Overall, RiverWare was found to be able to simulate the allocation of available flow by water rights and other associated operations, in a very similar, if not identical, manner to StateMod.
- RiverWare's and StateMod's water right solution algorithms are very similar and were shown to produce identical results when simulating allocation to direct diversion and storage water rights, instream flow rights at points, and several associated water right operations.
- RiverWare's water right solver has two notable shortcomings relative to StateMod's capabilities:
    - It does not innately incorporate same-timestep return flows for subsequent allocation, although a workaround was identified and enhancement to incorporate this is feasible. (Note this would likely not be a significant limitation in a daily timestep model.)
    - Instream flow water rights can only be represented as points, rather than as reaches.
- RiverWare was found to simulate offstream reservoir system operations, exchanges, and changed water rights including reusable return flows and return flow replacement obligations in at minimum a comparable, and often an equivalent manner to StateMod. RiverWare also provides considerable additional flexibility in representation of complex or specific operations.
- Well water rights and augmentation plans were adequately implemented in RiverWare, albeit in a less robust way that would make large scale inclusion difficult. Potential improvements to the RiverWare platform are suggested to facilitate of well simulation comparable to StateMod.
- StateMod's direct integration within the CDSS system allows for efficient model and input dataset development, management, and updates, and is certainly a key strength compared to RiverWare for CDSS applications. Simulation speed and efficiency is also a strength of StateMod.

Many effective and important RiverWare models are already being utilized in various basins of Colorado, several of which include simulation of water rights as a fundamental component. This study's findings provide additional credibility regarding the ability of these and new RiverWare models to simulate Colorado's water rights systems and administration processes.

1 INTRODUCTION

1.1 BACKGROUND AND PURPOSE

Water resource system models are used by water managers to support purposes ranging from long-term planning to short-term operational decision-making. Utilization of these models provides countless benefits to their users, such as effective risk-management, improved system efficiencies, and reduced operating costs. To the benefit of Colorado as a whole, the CWCB has been instrumental in supporting the development, accessibility, and usefulness of decision-making tools to entities and stakeholders throughout Colorado. These efforts center on Colorado's Decision Support Systems (CDSS) developed by CWCB, DWR, and partners.

Accurately simulating water rights is of utmost importance in models of Colorado's basins; however, the complex nature of Colorado's water right system presents a challenge. A major strength of CDSS's surface water model, StateMod, lies in its ability to simulate these water right systems, which is trusted after years of development and use.

However, the StateMod platform has several significant limitations that reduce its usefulness, limited flexibility and transparency, minimal user-friendliness and support, and difficulties simulating complicated reservoir operations and water accounting.

RiverWare is a state-of-the-art, powerful, and widely used modeling platform that excels in many areas where StateMod is limited. Its strengths include its flexibility, transparency, and ability to model complex reservoir operations. Its core features include a user-friendly workspace GUI that captures the physical representation of a basin, user-constructed rules to simulate river basin policy, basin operations and decision-making processes, and a mature infrastructure to perform complex water accounting.

A relatively recent enhancement to RiverWare is its Water Rights Solver, which can be integrated within its powerful rulesets. Since its development, several models have utilized the Water Rights Solver, including the Lower Colorado River Authority's Daily River Operations Model and the Arkansas Basin RiverWare model. Still, its water right simulation ability remains largely untested within Colorado's water rights systems, and uncertainty remains surrounding its ability to simulate these complex systems.

The primary objective of this study was to evaluate RiverWare's ability to simulate Colorado's complex water right system. This was accomplished by developing a RiverWare model simulating a Colorado basin's water right system, and by analyzing and comparing its simulation process and results against the existing StateMod model of the same basin.

1.2 DESCRIPTIONS OF COMPARED MODELING PLATFORMS

1.2.1 RiverWare Modeling Platform

RiverWare is a well-established and state-of-the-art generalized hydrologic water resource system modeling platform that allows a user to develop customized models of specific river basin systems. Its core features include a user-friendly workspace GUI that allows users to represent the physical layout of a basin's water resource system by linking objects and accounts into an intuitive visual network.

RiverWare contains an extensive library of built-in methods that can be used to simulate many typical and standard processes on objects throughout the network, the ability for users to write custom "rules" to simulate specific river basin policy, operations, and decision-making processes, and a mature infrastructure to perform complex water accounting. RiverWare models are highly transparent and results can be traced to the specific and step-by-step calculations used to simulate the decisions and processes that drive system operations.

RiverWare is actively developed and supported by the Center for Advanced Decision Support for Water and Environmental Systems (CADSWES) at the University of Colorado in partnership with the Bureau of Reclamation, the Tennessee Valley Authority, and the United States Army Corps of Engineers. In addition to supporting and continuously enhancing and updating the software to meet the needs of its users and sponsors, CADSWES offers expert-led training classes and direct support for RiverWare users.

RiverWare models are utilized by water managers, engineers, and operators throughout numerous river basins and complex water resource systems across the United States and the world and range in size from large-scale federal projects to local municipal systems. Uses range from near-future hourly timestep hydropower optimization to short-term operational forecasting and scheduling to long-term planning, policy development, and water supply evaluations. RiverWare models have been used to support numerous court cases, negotiations, and other high-level governmental studies and assessments such as National Environmental Policy Act (NEPA) Environmental Impact Statements (EIS's) and Environmental Assessments (EAs). Notable applications of RiverWare models include the Truckee River Operating Agreement (TROA) models, the Colorado River Simulation System (CRSS) and Mid-Term Operations Model (MTOM), and the Upper Rio Grande Water Operations Model (URGWOM).

Further information and documentation are available for the RiverWare software at http://www.riverware.org/.

1.2.2 StateMod Modeling Platform

StateMod is the surface water model component of the Colorado Water Conservation Board's (CWCB) Colorado Decision Support System (CDSS). Although generally utilized in Colorado, StateMod is a generalized hydrological modeling tool that can be applied to any river basin through appropriate input data preparation. It is a monthly and daily timestep surface water allocation and accounting modeling platform capable of simulating various water management policies in a river basin. It can be configured to compute naturalized flows and to allocate natural flow to water rights following the prior appropriation doctrine used in Colorado, which is its primary strength.

StateMod is well established and trusted by Colorado's water managers and decision-makers given its decades of use and relatively uniform implementation throughout the state. StateMod models have been developed and implemented in the CDSS framework (or are nearing completion) for all of Colorado's major river basins. The CDSS program began in 1993 and supports three areas: Interstate Compact policy analysis, water resources management and planning, and water rights administration. The StateMod models primarily support the first two areas and have served as the technical foundation for Interstate Compact, statewide, and basin planning (including Colorado's Water Plan and its Technical Update, Basin Implementation Plans, Statewide Water Supply Initiatives, and Colorado River Water Availability Study). The models have allowed the state to assess water supply availability, consumptive uses, shortages, climate change impacts, and Interstate Compact scenarios. Additionally, many water users and researchers have used the StateMod models to conduct their own studies (including Colorado River Water Conservation District's Risk Study and Cornell/NCAR Robustness/Vulnerability Study).

StateMod models typically rely heavily upon the use of standardized modeling methods and procedures within the platform. Despite the relatively limited ability for customization outside of the standard methods, StateMod's methods have been developed alongside and to be consistent and effective within the CDSS framework and are reflective of methods generally accepted by Colorado's water resource water managers, engineers, and decision-makers. StateMod's integration in CDSS allows for relatively efficient model development, data management, and joint utilization with CDSS's other components such as StateCU and HydroBase.

Further information and documentation are available for the StateMod software at https://www.colorado.gov/cdss/.

1.3 Acknowledgements

This study was funded by the Colorado Water Conservation Board (CWCB) through a 2019-2020 Colorado Severance Tax Operational Fund grant and was performed by Precision Water Resources Engineering, LLC. CWCB and CDWR staff provided input and guidance on the study's purpose and objectives in terms of the specific operations and processes viewed as being most important to evaluate RiverWare's ability to simulate in contrast to StateMod.

Wilson Water Group was subcontracted by Precision Water Resources Engineering to provide an updated White River basin StateMod model with adjustments made to facilitate the comparison of specific simulation aspects. Wilson Water Group also provided valuable support in further configuring and using the StateMod model and dissecting results, as well as greatly assisting in the understanding of how StateMod works.

Additionally, CADSWES staff and RiverWare developers provided detailed answers and explanations regarding RiverWare's technical simulation methods and valuable insight through the course of the study.

2 Development of RiverWare Model for Comparison with StateMod

2.1 Overview

In order to compare and contrast RiverWare and StateMod's simulation of water rights and related operations, models of the same basin that were similar enough to be appropriate for detailed, technical comparison were needed. This was accomplished by first selecting an appropriate existing StateMod model of a Colorado river basin, and then by developing a comparable RiverWare model.

The White River basin in northwestern Colorado was selected for this study for several key reasons. First, the White Basin StateMod model is complete and straightforward compared to others. Second, the White Basin does not contain complex reservoir and system operations and accounting found in other basins, which would make the evaluation and comparison of how water right allocation and related operations and transactions are simulated more difficult to isolate. Finally, the White Basin StateMod model is trusted and has been used successfully by basin stakeholders. For these reasons, the White Basin StateMod model represents an effective basis for comparison.

Appropriately comparing and contrasting the simulation methods and results of the different modeling platforms is complicated by the fact that often the specific procedures to be compared are multiple steps into the simulation process. As such, the simulation of these aspects is inherently dependent on preceding steps and relatively minor differences there can propagate through the simulation and make like comparison very difficult. Thus, with the objective of being able to compare the desired aspects on an "apples-to-apples" basis without the trouble of weeding out differences ultimately originating from previous steps, much care was taken to develop the RiverWare model to follow the same simulation process, data, and methods used by StateMod to the extent possible.

It is important to note that for these reasons, the manner in which this specific RiverWare model was developed, and the end model product itself, is very likely not the same as it would have been if the objective was to develop a RiverWare model of the same river basin, operations, and policy, but using the more typical RiverWare methods and simulation processes. Put another way, a RiverWare model developed following more typical RiverWare modeling procedures would almost certainly be set up differently than the model developed during this study. That being said, due to the wealth of user options and customizability, two RiverWare models developed by two different modelers would potentially look quite different. Thus, it would take a concerted and coordinated effort with consistent methods put in place to standardize models across varying basins, which is no doubt a strength of the StateMod platform as it is currently used in Colorado.

The remainder of this section describes the White Basin StateMod model used as a starting point and the process used to develop a comparable RiverWare model.

2.2 Starting Point White Basin StateMod Model

Wilson Water Group (WWG), a partner in this study, is the CWCB contractor most recently responsible for development and enhancement of the White Basin StateMod model and several other Colorado basin StateMod models. At the beginning of the study, WWG provided Precision with an updated White Basin StateMod model (commonly referred to as simply the StateMod model through this report) to be used as the point of reference for development of a comparable White River basin RiverWare model (commonly referred to as the RiverWare model through this report).

WWG also made specific adjustments to the provided model to facilitate the comparison of the simulation ability of various water right system aspects that do not actually exist in the White Basin and thus had not been included in the StateMod model originally. WWG's original starting model and the adjustments made are described below, per WWG:

1. WWG started with the wm2015 model from the State of Colorado
2. The model was updated for the Yampa/White/Green Basin Roundtable Phase 3 Modeling Project.
3. The specific scenario selected is the largest Wolf Creek Reservoir configuration. This includes:
    a. Historical Hydrology
    b. Future Demands
    c. Wolf Creek Reservoir is off-channel and has a 90,000 acre-feet capacity.
    d. Wolf Creek Reservoir can only store in excess of 300 cfs bypassing the reservoir pump station and 300 cfs at the Watson gage.
    e. Pump Station Capacity is 400 cfs
    f. Wolf Creek Reservoir releases to:
        i. Oil and Gas and Oil Shale demand nodes
        ii. Town of Rangely
        iii. 300 cfs flow target at the Watson gage.
4. This scenario was further modified to include an exchange, a changed water right, and well augmentation.
    a. Exchange - release from off-channel Wolf Creek Reservoir to the gas demands on the Piceance - This operation is senior to the release via pipeline.
    b. Changed water right used to meet municipal demand.
        i. Increased Meeker's demand. Moved the demand to an off-channel demand node. Added operating rules to use the direct diversion rights first. Only two of Meeker's water rights are included in the operating rule file so the changed ditch shares would be needed.
        ii. To represent a typical change case decree, WWG calculated the HCU credits for a change of 5% of the water rights under WDID 4300848 (Oak Ridge Park Ditch) and calculated the maximum allowable diversions and limited the water rights that are stored in an accounting plan. Note these calculations were performed outside of the model and are input to the model.

iii. Moved remaining irrigation demand to an off-channel demand structure (4300848_I).
iv. Adding operating rules to put each water right into the accounting plan.
v. Adding operating rule to split the accounting plan into 5% of the available water to the municipal plan and 95% to the irrigation plan.
vi. The irrigation plan releases to the irrigation demand.
vii. The municipal plan releases to the Meeker demand (direct) and then to Lake Avery (exchange). Releases from the municipal plan are limited to the historical percent of consumptive use. This generates terms and conditions in the form of a return flow obligation. Return flow obligations can be met either in priority, by reusable effluent, or by releases from Lake Avery.

c. Well Augmentation - switched the 43_FutGlf (future golf course) node from a surface water diversion to a well diversion. Set up augmentation plan to release water from Lake Avery if depletions are out of priority.

Additionally, throughout the study, many different StateMod runs were configured and utilized by Precision with assistance by WWG as needed. These configurations were used in order to isolate specific operations and processes and facilitate technical, piece-by-piece comparison of the model components of interest. These various configurations and additional modifications made to the StateMod model are described throughout the report.

2.3 Model Timestep and Run Period

The White Basin StateMod model provided has a monthly timestep, generally consistent standard within CDSS, and a full run period of October 1974 to September 2015, or 41 full water years. The StateMod platform can also perform simulation at a daily timestep simulation with preparation of appropriate input data, which was accomplished for the White Basin StateMod model in 2018. While certainly useful in some circumstances, StateMod's daily simulation is generally achieved by relatively basic disaggregation of the standard monthly datasets and utilizing the same simulation processes and procedures that are used on a monthly timestep.

While there is no standard RiverWare timestep, and the platform allows models to be developed on timesteps ranging from 5 minutes up to 1 year, RiverWare models on similar scales as the StateMod models tend to be run at daily or monthly timesteps. However, unlike StateMod, daily timestep RiverWare models are generally developed to simulate basin policy and operations at a more detailed level than StateMod, utilizing RiverWare's powerful, customizable rule-based simulation abilities to represent highly specific and complex basin operations and decision-making processes.

For these reasons, it was determined early on during the study that it would be substantially more difficult to (1) develop a daily timestep RiverWare model that still simulates the system following the same methods and processes as StateMod, and (2) directly compare daily timestep results between the two models in an "apples-to-apples" manner that would meet the study's objectives of specifically comparing RiverWare's and StateMod's water right allocation and associated simulation methods.

Therefore, the White Basin RiverWare model was also developed to operate on a monthly timestep and the same run period. Additionally, the model is run with RiverWare's "Inline Rulebased Simulation and Accounting" controller mode, which is necessary for accounting and water right allocation simulation.

2.4 Developing the Model Network in the RiverWare Workspace

2.4.1 Overview of Workspace and Node/Object Types

RiverWare has a user-friendly and aesthetic graphical user interface (GUI) workspace that is used to develop, configure, and execute model runs. Additionally, the RiverWare GUI provides easy and intuitive access to the various model data and results. Its GUI and workspace greatly enhance the transparency and understandability of RiverWare models, especially with new modelers and less technically oriented users who can use RiverWare to make runs and access results in models set up for that purpose by more advanced developers.

An initial step in building the RiverWare model from the StateMod model was to parse the network node (often also referred to as stations in StateMod/CDSS terminology) information defined in StateMod model's river network file (.rin). This text file includes, among other things, the station IDs, names, and "downstream nodes" for each node in the StateMod network. This "downstream node" information is ultimately what defines the node order and connections, or "links" in RiverWare terminology, that make up the model network.

The White Basin StateMod model has approximately 10 "types" of nodes that represent different processes that can take place at the node. It may be helpful to note at this point that the RiverWare platform uses a much more "object-oriented" modeling approach than StateMod does. This means that within RiverWare, distinct "objects" of different types are used to represent various basin features and contain their own data and calculation methods that are used to simulate various processes on that object.

In contrast, StateMod does not distinguish between distinct node "types" in the same way that distinct RiverWare "object" types are used to represent specific features, such as "reach", "confluence", and "water user" objects. Rather, StateMod's nodes essentially represent various features and multiple simulation aspects within a single node. An illustrating example of this is a StateMod node, identified by a single station ID, represents both a river reach and a water user that diverts from the reach. In RiverWare, this same node would be represented by two distinct objects, a "reach" object and a "water user" object, that are connected by a "link" representing the diversion from the reach to the water user. For these reasons, translating StateMod nodes to the appropriate RiverWare objects can be more nuanced than it would initially seem, and proper object selection can be critical to the model function. It is, of course, simple to change an object originally represented by one object type with another.

2.4.2 Physical River Network

In total, the White Basin StateMod model has 203 nodes, which translated to 394 objects in the RiverWare network. It should be noted that, in order to facilitate comparison of model results, effort was made to keep the RiverWare network as similar as possible to the StateMod network. Had direct model-to-model comparison not been the main objective of this study, the RiverWare model network would likely differ somewhat from its current configuration. This is especially true with respect to the inclusion of the many additional reach objects that was necessary to maintain the precise return flow locations used by StateMod, which are of course simply one approximation of reality, but where subtle variations can cause significant differences in river flows available to downstream water users or instream flow reaches. This important nuance is discussed further below.

Table 1, below, provides a high-level description of how each type of StateMod node was represented within RiverWare. Subsequently, Figure 1 and Figure 2 show small sections of the model network schematics representing the same basin features. Note that RiverWare water user objects and their associated return flows are described in the following report section.

To create the RiverWare network, each of the objects was placed into the RiverWare workspace and then linked with its neighboring objects appropriately. Once the network was built, the appropriate RiverWare object methods, as denoted in Table 1, were selected. It should be noted that, while translating the network from StateMod to RiverWare is straightforward, building the RiverWare network itself is a relatively tedious process with so many objects and links involved. This is especially true for the corresponding accounting and supply network that is described further below. However, while it can be tedious, manually building the RiverWare network is a relatively minor task that can be easily accomplished in a few hours and can be quite helpful in orienting a modeler to a new basin. Furthermore, it is plausible that the process of transforming a StateMod node network into a RiverWare workspace could be standardized and automated given the active development of RiverWare by CADSWES's engineers and software developers.

The representation of reservoirs in StateMod is very basic and thus RiverWare's extensive reservoir configuration options were not utilized. The reservoir representation was easy to replicate in RiverWare with the same Elevation-Storage and Elevation-Area tables and maximum storage constraints. The White Basin StateMod model does not include maximum release constraints or representation of any spillway flows, so these were not configured in RiverWare.

In StateMod, reservoir evaporation losses are calculated as the last simulation step on each timestep based on monthly evaporation rates and the average storage through the month, which is calculated using the "pre-evaporation loss end-of-month storage", and thus the calculated evaporation is simply set once rather than iterating to a solution based on those evaporation losses and resulting reduction in surface area. Additionally, StateMod does not account for the "upcoming" evaporation losses in its monthly fill limits, which often results in the reservoirs appearing to never completely fill, as the end-of-month storages will be with the resulting evaporation loss. This simple representation actually required a rule being written to replicate in RiverWare, as none of the numerous available reservoir object methods were that basic.

Table 1: General description of how StateMod node types are represented within RiverWare.

StateMod Node Type	RiverWare Object(s)	RiverWare Representation Description
Diversion	Reach object with a linked Water User object	These Reach objects do not have Local Inflows (“gains”), and thus the object methods use "No Local Inflow, Solve Outflow" and "Available Flow Based Diversion". Water User object methods differ depending on the type of use. The Water User’s “Incoming Available Water”, “Diversion”, and “Return Flow” slots are linked to the appropriate reaches (note that the specific RF slot linked varies by RF splitting/routing method).
Diversion/Natural Flow	Reach object with a linked Water User object	These Reach objects have Local Inflows (“gains”), and thus the object methods use "Specify Local Inflow, Solve Outflow", which allows them to be set by Initialization Rule (IR), and "Available Flow Based Diversion". Water User object methods differ depending on type of use.
Well	Water User object	Water User objects do not have a built-in method to lag the surface water depletions associated with well pumping, and thus the Water User object’s diversion slots were not directly linked to a reach but instead set directly to the appropriate nodes via a rule. The return flow slots are linked in the same manner as a surface water user.
Instream (Minimum Flow)	Control Point object	Control Point objects must be used in RiverWare here to allow for Instream Flow water rights accounts.
Instream / Natural Flow	Control Point object	Control Point objects must be used in RiverWare here to allow for Instream Flow water rights accounts. These are generally upstream ends of reach sections that include “Boundary Inflows” set by IR at the start of run.
Other	Reach/Stream Gage object as appropriate	The reach object methods include "No Routing" and "No Local Inflow, Solve Outflow". “Other” nodes are generally used to define downstream ends of instream flow reaches in StateMod.
Plan	Data object or slots on associated network objects	This type of node is modeled in RiverWare using rules that set slot values to Data objects or custom slots on the associated network objects.
Reservoir	Reservoir object	The Reservoir Object methods include "Input Evaporation” which allows evaporation to be calculated and set by rule using the same calculation as StateMod.
Reservoir / Natural Flow	Reservoir object	If the reservoir is the upstream end of a river section, “Boundary Inflows” are set by Initialization Rules. If the reservoir is within a river reach, the "Input Hydrologic Inflow" method is used so the “Local Inflows” can be set by IR.
Streamflow Gage	Stream Gage object	No methods needed.
Streamflow Gage / Natural Flow	Stream Gage object	These have “Boundary Inflows” that are set by IR.
n/a	Confluence object	RiverWare can use a Confluence objects to represent the confluence of two rivers/streams. StateMod does not use a distinct node type for this purpose. Rather, two upstream nodes will be defined to have the same downstream node, and this will combine the upstream flows.

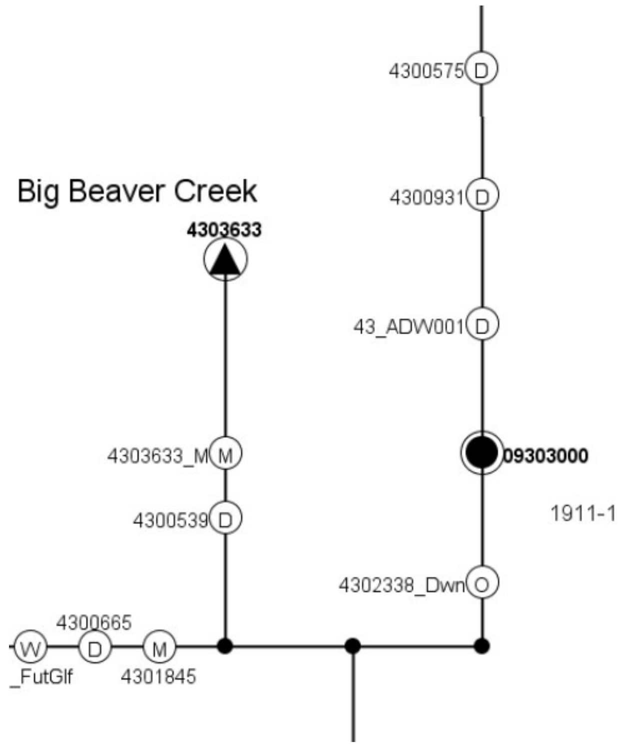

Figure 1: Clipped section of StateMod model schematic.

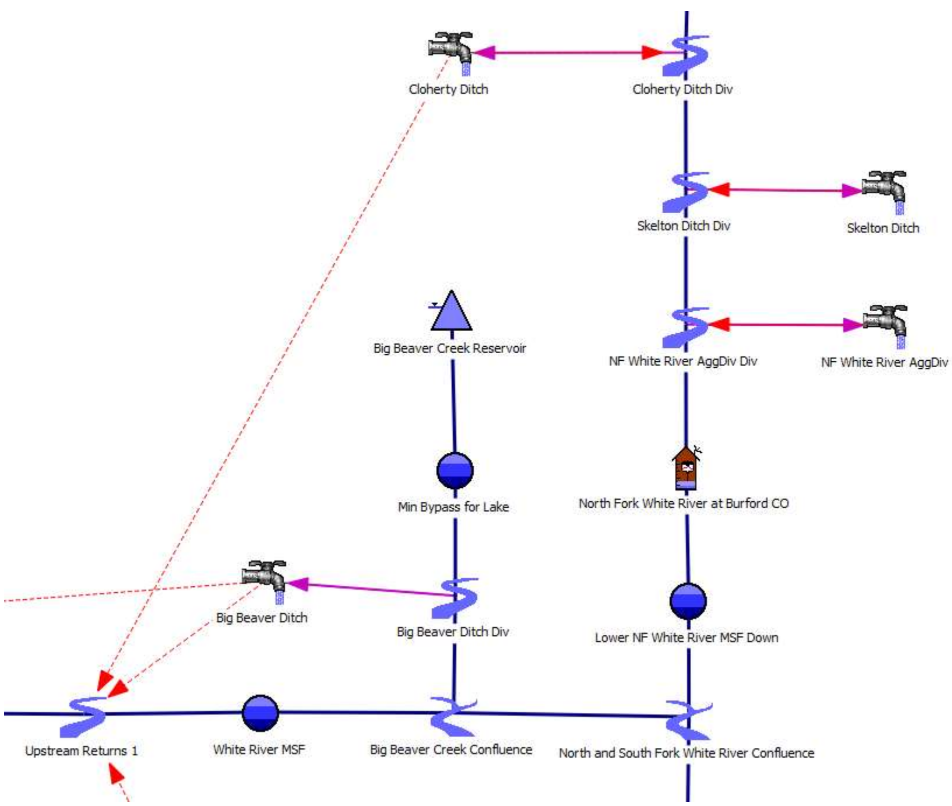

Figure 2: Clipped section of RiverWare model schematic.

2.4.3 Accounting Network

For a RiverWare model to be used to simulate accounting and water rights allocation, an accounting network also had to be developed corresponding with the physical network. The accounting network is essentially an additional layer to the "physical" simulation object network that uses "accounts" to track water of different types, uses, and/or owners throughout the network. Whereas physical objects are connected by "links", accounts are connected by "supplies".

To create the accounting network, "accounts" of various types are created on the objects corresponding to the level of detail of the breakdown required at that location for the desired or required level of detail for simulation. For the White Basin RiverWare model, the accounting network consists of "Native" accounts that flow through nearly all of the networks objects and define the "allocatable flow chain", which is discussed later in the report.

RiverWare has four distinct account types for use on the appropriate object types, which are described below, including how they are used in the White Basin RiverWare model.

- **Passthrough accounts** are used to track the breakdown of different flow account chains through the network.
    - Passthrough accounts generally exist on all of the object types that make up the actual river network, so reach, reservoir, stream gage, confluence, and control point objects.
    - The "Native" chain previous referred to is necessarily made of passthrough accounts that reflect the continuous nature of the river flow. This chain also can have inflow sources along the way that originate from other accounts, such as releases from a reservoir "storage" account into the appropriate native account to represent, for example, a well augmentation release.
    - Passthrough account chains can also hold deliveries of water in order to keep them distinct from the native, allocatable flow. For example, a "Deliveries" passthrough account chain is used in the White RiverWare model to transmit deliveries from the Wolf Creek Reservoir storage accounts to the appropriate water users.
- **Storage accounts** are used to track the breakdown of total storage on reservoir objects.
    - For this study, the RiverWare model was developed at the same level of detail as the StateMod model, where 6 of the 7 reservoirs are simulated with just a single, generally named "Storage" account, and Wolf Creek Reservoir has two storage accounts: "Fish" and "Energy".
    - Additionally, in RiverWare models with water right allocation simulation, storage accounts are used to define and hold ***storage water rights***. RiverWare only allows a single water right per account, and thus when a reservoir has multiple storage water rights multiple storage accounts must be used. While there are multiple ways to handle this situation, a convenient manner in which to treat the storage water rights accounts is to not to allow them to actually store water, but to simply use them only in the water right allocation simulation process and set them up to immediately transfer any allocation into the appropriate "operable" storage account, or split by ownership percentages into multiple storage accounts. This configuration streamlines the process as allocations from multiple rights are combined into the appropriate accounts to be used during subsequent simulation.
- **Diversion accounts** are used on water user objects to track the breakdown of water sources as they are diverted from the passthrough accounts on reach objects.

- Diversion accounts are also used to define and hold diversion water rights, which also require distinct accounts for each water right and thus necessitates many water user objects to have numerous diversion accounts corresponding with their water right portfolios. It is important to note, however, that each of these diversion water right accounts are used to hold the detailed simulation results including the specific appropriation requests and resulting allocations, as well as the controlling reasons behind the results, and thus this information exists and is easily accessible for each individual water right on every timestep through a whole model run.
- Diversion accounts are also used to represent other (i.e., non-water right) deliveries of water, such as from reservoir storage. Thus, in the White Basin RiverWare model, there are several water users that have additional diversion accounts beyond just their water right accounts.

- **Instream Flow accounts** can only be placed on control point objects and are used for the sole purpose of defining and simulating instream flow water rights. Instream flow accounts are unique in that they contain a slot that continuously and automatically represents the sum of all of the passthrough accounts that exist on the object since the instream flow rights are not concerned with the water types meeting their demand, just the overall flow.

It should be noted that while RiverWare does contain functionality and various tricks to eases some of the process, the creation of the accounting and supply network can be a somewhat tedious process. However, as with the physical network, this effort is a relatively minor nuisance in overall model development.

Although accounting networks can quickly become quite complex, RiverWare's GUI and workspace are very helpful in keeping track of these network layers and allows the user to easily toggle between "Simulation View" and "Accounting View". Various figures throughout this report show these different views, and the overall model schematics for both views are included as Appendices.

2.5 RiverWare's Water User and Return Flow Methods

2.5.1 Water User Methods

There are 146 diversion nodes in the StateMod model. In StateMod, a diversion node represents a location along the river where water is diverted (and/or otherwise supplied) and consumed, and where any applicable return flows are generated. In StateMod, however, return flows generated at a node cannot return to the same node, as discussed further below. To represent these diversion nodes in RiverWare it requires both a reach object and a water user object.

In RiverWare, a reach object is used to represent the river location from where water is diverted. However, it is on water user objects that the various diversion, depletion, and return flow calculations occur. The diversion accounts that hold the diversion water rights are also held on the water user objects. During simulation, the reach and water user objects communicate through their links, which triggers them to solve together when sufficient information is present. In this model, the water user and reach objects are linked by their "Available for Diversion" (reach object) and "Incoming Available Water" (water user object) slots, and their "Diversion" slots (on both objects).

RiverWare contains many built-in water user object methods that can be selected and configured to perform various calculations such as generating water user demands (i.e., diversion and depletion requests), consumptive use, and return flows. These range from simple input or periodic demand and fractional return flows options to advanced options like “Head Gate Sprinkler Requests”. It is also possible to use various custom slots, rules, and functions to implement different methods as desired by the user.

For this study, RiverWare’s various water user object methods were reviewed and compared to how StateMod simulates these processes. The methods ultimately implemented in the RiverWare model are summarized below in Table 2, and subsequently discussed. The return flow split and routing methods are described in a following subsection.

Table 2: RiverWare Water User object methods for demands and return flows.

	Irrigation Nodes	Non-Irrigation Nodes
Method Category	**Method Name**	
Diversion and Depletion Request	Irrigation Requests with Soil Moisture	Input Requests
Irrigation Acreage and Evapotranspiration Rates	Input Acreage and Rates	N/A
Return Flow	Variable Efficiency with Soil Moisture	Variable Efficiency
Return Flow Split	Nodes with multiple return flow locations (21 total) use the "Multi Return Fractional Split" Method, otherwise no method was used.	
Return Flow Routing	Nodes with multiple return flow locations (21 total) use the "Multi Split Impulse Response" method. All other nodes use the "Impulse Response" method.	

In the White Basin StateMod model, the diversion nodes can essentially be divided into two types of water users for this purpose, irrigation and non-irrigation. For the 16 non-irrigation nodes, the “Input Requests” diversion/depletion request method and “Variable Efficiency” return flow method were determined to be able to replicate StateMod’s calculations given the appropriate input data. The input data used for the non-irrigation water users is as follows:

- StateMod’s “Total Demand” is input as RiverWare’s “Diversion Requested”
- StateMod’s “CU Demand” is input as RiverWare’s “Depletion Requested”
- Also used: Maximum Efficiency, Maximum Flow Capacity (i.e., ditch capacity)

In the White Basin StateMod model, the 130 irrigation water users use the “Variable Efficiency of Irrigation Use” method, which allows a user’s efficiency to vary up to a maximum efficiency depending on water availability, with “Soil Moisture Accounting” that accounts for the impacts of flows both from soil moisture to the crops when needed, and to soil moisture when the water supply is higher than consumptive use. These methods are described in the StateMod platform documentation, (accessible at: http://opencdss.state.co.us/statemod/15.00.14dev/doc-user/Model%20Description/35/), as well as in the various StateMod basin model documentation. The ability to simulate these methods within the water right solution framework is considered a key feature of the StateMod platform.

Upon review and testing of RiverWare's available methods, it was determined that the "Irrigation Requests with Soil Moisture" diversion/depletion request method with "Input Acreage and Rates" sub-method, paired with the "Variable Efficiency with Soil Moisture" return flow method, allow for a very similar representation of StateMod's irrigation water uses, with only a couple of caveats discussed in the next subsection. Figure 3, below, shows a RiverWare water user object configured with these methods.

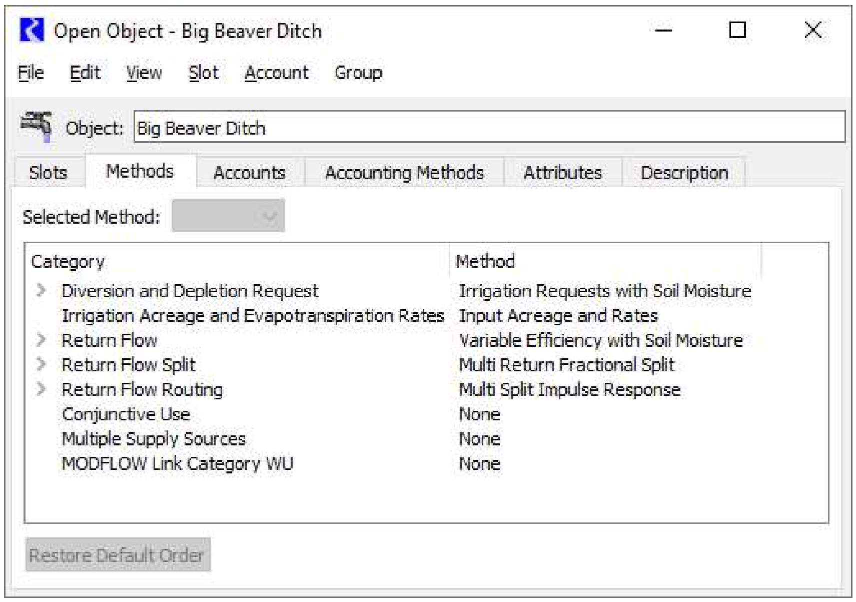

Figure 3: Example of RiverWare's Water User object method configuration found to be comparable to StateMod's methods.

The complete potential mass balance of the paired "Irrigation Requests with Soil Moisture" and "Variable Efficiency with Soil Moisture" user methods is shown in the schematic in Figure 4 below, from the RiverWare documentation. It should be noted that not all of the components were used to replicate the StateMod methods for this study, however some may in fact be applicable in certain circumstances. The RiverWare documentation describes the full details of this method and can be accessed at: https://riverware.org/HelpSystem/index.html#page/Objects/waterUser.29.08.html#ww1152704.

When appropriately configured and populated with the input data listed below, these RiverWare user methods for irrigation water users were found to be able to exactly replicate StateMod's simulation of irrigation water uses, complete with soil moisture accounting and variable efficiency, but only ***for water users with a single irrigation type***, as explained further in the following subsection.

The input data used for the irrigation water users is as follows:

- StateMod's "Total Demand" is input as "Diversion Requested"
- The user's Total Irrigated Acres is input to "Irrigated Area" through all run dates
- StateMod's "CU Demand" is used to back calculate and set the water user's "Evapotranspiration Rate", using "ET Rate = CU Demand/Irrigated Area" (done in RiverWare by an Initialization Rule)

- The RiverWare water user's "Minimum Efficiency" slot is set to be equal to the "Maximum Efficiency" through all run dates. It is important to note that this ***DOES NOT*** result in constant efficiency, as this only reflects the delivery efficiency between the headgate and the field.
- Also used: Maximum Efficiency, Maximum Flow Capacity (i.e., ditch capacity)
- For soil moisture: Maximum Soil Moisture (ft, = AWC * soil depth), Maximum Infiltration Rate (set to a very high number to reflect no limit)
- Initialization Timestep "Soil Moisture" is set to 50% of the maximum soil storage (= 0.5 * Irrigated Area * Maximum Soil Moisture)

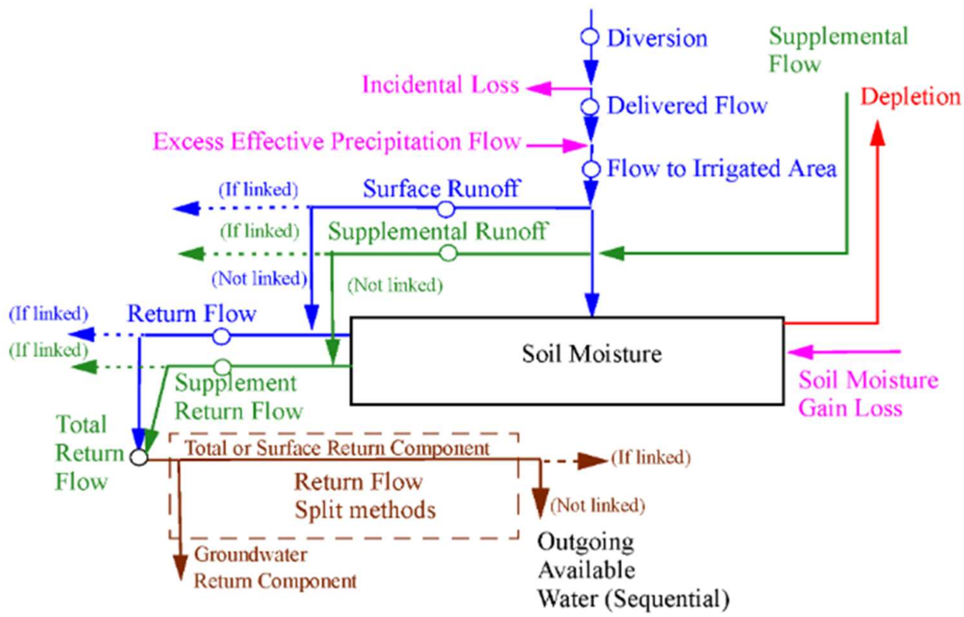

Figure 4: Schematic of RiverWare's paired "Irrigation Requests with Soil Moisture" and "Variable Efficiency with Soil Moisture" user methods. (From RiverWare Documentation, Figure 28.1, revised Dec 2019.)

It should be noted that this RiverWare method uses slightly different terminology than StateMod's methods. For example, the "incidental loss" in RiverWare (although currently not used) would refer to losses between the diversion headgate and the field, whereas in StateMod they refer to subsequent losses to the generated return flow prior to it returning to the river (which are captured in RiverWare by other means).

Additionally, and as mentioned above, there are different uses of the term "efficiency" that can be confusing. In RiverWare, both the Maximum Efficiency (which is a single value) and the Minimum Efficiency (which is a series slot) are set to the same StateMod Maximum Efficiency value. However, this ***DOES NOT*** result in the use of constant efficiency, as this "Minimum Efficiency" in RiverWare only reflects the delivery efficiency between the headgate and the field, not the overall realized efficiency, which is calculated and reported in the "Efficiency including Soil Moisture" slot. This is the appropriate value to be compared to StateMod's "Actual Efficiency".

2.5.2 Caveats with Variable Efficiency and Soil Moisture Accounting in RiverWare

As described above, RiverWare's paired "Irrigation Requests with Soil Moisture" and "Variable Efficiency with Soil Moisture" water user object methods can be used to exactly replicate StateMod's simulation of irrigation water uses, complete with soil moisture accounting and variable efficiency, but only ***for water users with a single irrigation type***. It is important to note, however, the RiverWare methods still work with water users with multiple irrigation types but they require lumping the irrigated areas together and using the area averaged efficiency. Doing this results in a very similar representation to StateMod, however it does not obtain the same exact results.

The reason that these methods do not exactly replicate the method for users with multiple irrigation types is because StateMod internally considers the acres of different irrigation types, with differing efficiencies, separately during its "farm headgate delivery" and subsequent soil moisture calculations. However, the total "ditch headgate delivery" is prorated between the areas of different irrigation types strictly by their areas, rather than their consumptive use needs. This fact can result in two oddities that are not captured when considering the irrigated area in a lumped fashion with area averaged efficiency:

1. In StateMod, a water user can have both "To Soil" and "From Soil" flows in the same timestep. This indicates that the irrigated area of the less efficient irrigation type has been under-supplied and is therefore drawing from soil storage, while the more efficient one has been over-supplied and is therefore giving to soil storage. Despite this separate treatment within a timestep, StateMod does not track the soil storages of each irrigation type independently.
2. In StateMod, a water user can appear to be fully supplied, i.e., the "total diversion" = "total CU demand" / "combined efficiency" and yet a portion of the area will experience a shortage while a portion experiences an over-supply, which results in a different total return flow. This can occur without soil moisture accounting, thus leading to the second necessary change below.

While this does seem like a trivial difference considering the aggregation of various crop, field, and irrigation type data that generally happens during the data preparation process, it does result in slightly different results. These differences then can propagate into the water users return flows and soil storages and further throughout the system. Although this certainly causes negligible differences for overall modeling purposes, especially considering overall model and input data uncertainty, the impacts on available allocatable flow through return flows does complicate direct model-to-model comparison of water right allocation simulation.

For these reasons, when these differences were tracked down, the following two adjustments were made to both models and thus exist in all of the comparison runs through the rest of the report.

1. ***Soil Moisture Accounting is turned off***
2. ***All Irrigated Areas are set to the flood irrigation type, and thus have a 54% efficiency.***

It is worth noting here that given that only minor modifications from an existing user method would be needed, adding another built-in user method to RiverWare to replicate StateMod's methods here seems like it would be a feasible task. Additionally, there were also ideas for various other workarounds here that were identified, however they were not pursued given that the main purpose of this study was simulation of water rights.

While Soil Moisture Accounting is not used for the model runs through the rest of the study, for the purposes of illustrating the RiverWare method's applicability, an example of the RiverWare methods getting results identical to StateMod's for a water user with a single irrigation type is provided in Appendix C. This was taken from the "CompBase_SMAOn" corresponding model runs that is provided in the collection of model results alongside this report for review and comparison along with the others, as described in Section 4 of the report.

2.5.3 Return Flow Methods and Locations

The "Return Flow Split" and "Return Flow Routing" methods used in the RiverWare water user objects is shown above in Table 2. These methods allow RiverWare to exactly replicate the manner in which StateMod may spatially split the return flows between multiple locations by percentages (using "Multi Return Fractional Split"), as well as lag those return flows temporally by lag coefficients (using "Impulse Response" or "Multi Split Impulse Response"). These methods can be used in any combination necessary. Thus, using these methods, the StateMod split ratios and delay tables were used to configure the water user objects appropriately in the RiverWare model. Additionally, StateMod's "incidental losses", that are built into the delay tables, function in the same manner in RiverWare.

Regarding return flow locations, a subtle but important difference was identified during this study pertaining to the way that return flows are structured within the general node mass balance. While it is straightforward within RiverWare to mimic StateMod's return flow model, careful thought had to be put towards choosing the appropriate return flow locations within RiverWare. Specifically, within StateMod, when return flows return to the river at a diversion node, those return flows are immediately available for diversion at that node. In RiverWare, this is not the case; return flows that return to a reach are not available for diversion by the water user linked to that reach. Rather, that return flow would need to be linked to the reach immediately upstream of the reach where they should be available for diversion. Take, for example, the pair of diversion locations within the RiverWare model shown below in Figure 5.

This section of the river is on the South Fork of the White River, and the water flows from the bottom of the image to the top along the black line. Purple arrows represent links between a reach where water is diverted from the river to the water user. The dashed red arrows represent return flows. Figure 5 shows return flows from the Sweede Ditch returning to two locations. The first is the "Sweede Ditch RF" reach. The return flows that occur at this reach are not available for diversion until these flows reach the "Charlie Smith Ditch Div" reach. The second return flow link is between the Sweede Ditch water user and the "Charlie Smith Ditch Div" reach. The return flows propagated through this link are not available for diversion until they reach the downstream "Marcott Ditch Div" reach. This differs from the StateMod structure in that the first return flow could return directly to the Charlie Smith diversion node and be available for diversion by the Charlie Smith Ditch diversion. The second return flow could return directly to the Marcott Ditch diversion node and be available for diversion by Marcott Ditch. While this is a subtle difference, it is a difference worth noting because if not properly accounted for, it could have significant impacts on model results through impacts to the availability of allocatable return flows.

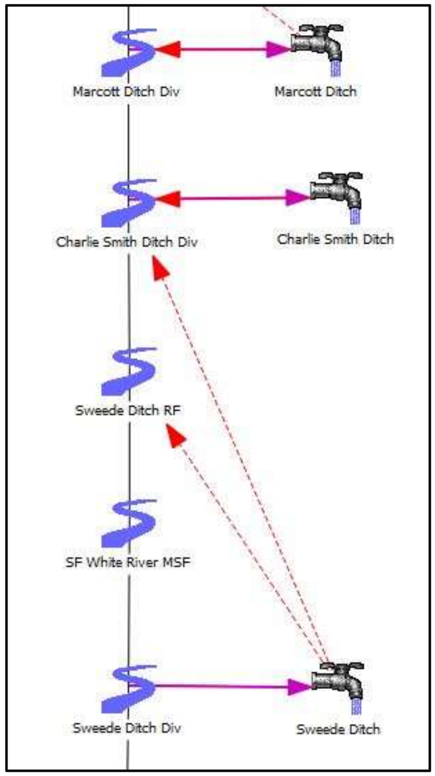

Figure 5: Schematic showing three diversion locations of the South Fork of the White River in RiverWare.

To further clarify, the water balance for StateMod nodes and RiverWare reaches are shown in Figure 6 and Figure 7 below. The overall water balance for StateMod nodes is given by the following equations:

$$River\ Inflow = Upstream\ Inflow + Reach\ Gain^{*} + Return\ Flow^{*} - Well\ Deplete^{*} + From/To\ GW\ Storage^{*} \quad (1)$$

$$River\ Outflow = River\ Inflow - River\ Divert^{*} - River\ by\ Well^{*} \quad (2)$$

The overall water balance for the RiverWare reach is given by:

$$Outflow = Inflow + Local\ Inflow^{*} - Diversion^{*} + Return\ Flow^{*} \quad (3)$$

** Water balance terms may or may not be used on a given node depending on what the node is modeling*

It is worth noting that while the water balances do represent the same overall things, these nuances between StateMod and RiverWare do require careful attention when configuring one model based on the network of another. They also complicate direct comparisons between models, requiring the use of various “StateMod equivalent” calculations during comparisons. Fortunately, it is easy to create generalized expression slots that can efficiently be copied through the applicable objects in RiverWare. Several of these “StateMod equivalent” calculated parameters are used in the model “Comparison Workbook” to facilitate apples-to-apples comparison of results. For example, due to the return flow location difference discussed above, a RiverWare “Reach.Outflow” cannot be directly compared to the StateMod “River_Outflow”, rather the “SM_River_Outflow” expression slot is used, which is equal to the “Reach.Outflow” minus “Reach.Return Flow”, since in StateMod, that return flow wouldn’t show up until the next downstream reach.

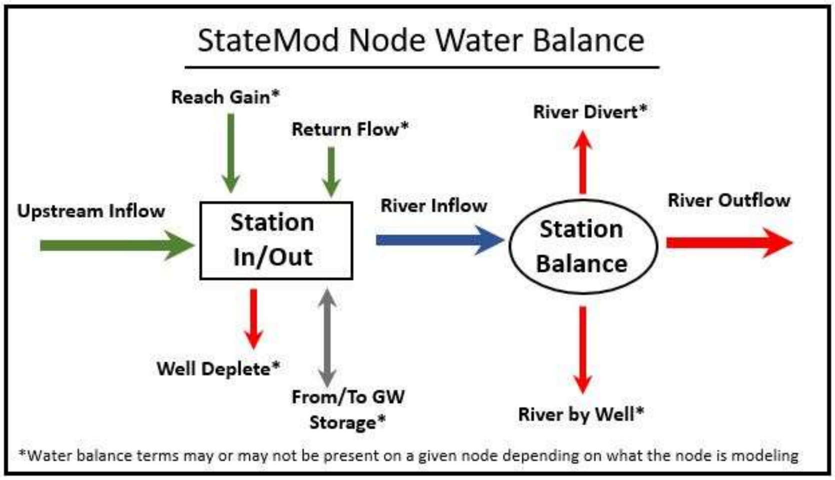

Figure 6: Schematic representing the water balance of StateMod Nodes

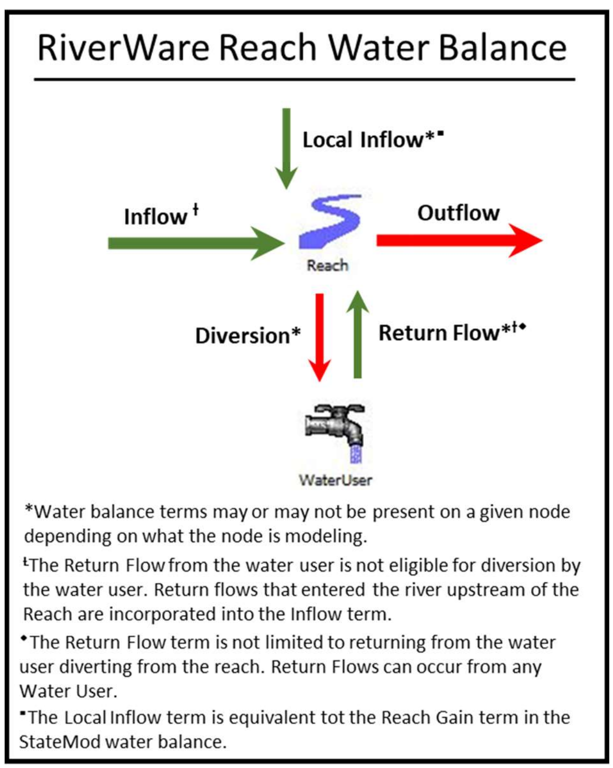

Figure 7: Schematic representing the water balance of RiverWare reaches.

2.6 MODEL INPUT DATA

While comparison of the model input dataset development processes between StateMod and RiverWare was not a primary focus of this study, there are some important differences that are worth noting.

StateMod's direct integration within the CDSS system allows for efficient model and input dataset development and management, and this is certainly a key strength compared to RiverWare for CDSS applications. Within the CDSS system, StateMod input files can be generated in a largely automated manner through the use of TSTool and StateDMI scripts and drawing data directly from the Hydrobase database. Thus, the model files can be efficiently maintained and updated so that they represent the most up-to-date datasets available from the State of Colorado.

While RiverWare has established data management interface (DMI) connections to various databases to facilitate data transfer to and from models, it is not inherently connected to any given database or modeling system. RiverWare DMIs also tend to focus on input timeseries and specific scenario/alternative data and are less functional in terms of actively managing and configuring model network, object, and account configuration aspects (e.g., managing the collection of waters rights on a water user) that generally end up needing to be maintained manually by the model developer or user utilizing RiverWare's GUI. Thus, RiverWare does not currently offer the sort of automated model and input file development and management that StateMod offers within CDSS, although it is conceivable that a similar model and data management system could be developed and utilized for specific applications of RiverWare models.

Another notable difference is that the CDSS integration and specific design of StateMod models allows them to be run in Baseflow mode to generate natural flows based on the appropriate historical/observed data accessible within CDSS. While it is possible to develop RiverWare models with similar functionality, the calculation of natural flows (or other model input hydrology datasets) is often done outside of RiverWare because of complications stemming from the varying data needs and different RiverWare solution processes that generally need to be used for "natural flow calculation" or "simulation" runs.

For the purpose of this study, and in order to be as consistent as possible, the RiverWare model was developed to use the same input data as the StateMod model. To do this, the necessary data was obtained directly from the StateMod input and output files as required. For convenience for RiverWare model review and experimentation by interested parties, this required input data is all stored within the RiverWare model file creating a standalone model file that does not require any DMI's or other data handling to run and view results. Some data, like physical reservoir configuration information, is stored directly on the appropriate simulation objects. Other input data is generally stored in series slots (for timeseries data) and table slots (for various other data) on data objects, and Initialization Rules that fire at the beginning of a model run are used to set the necessary data to the appropriate objects and slots throughout the model's simulation network.

3 Simulation of Water Right Allocation and Associated Operations

3.1 Colorado's Prior Appropriation System

The use of the natural surface water supply (i.e., native flow) in Colorado's river basins is administered by the "1st in time, 1st in right" Prior Appropriation Doctrine, also referred to as the Colorado "water rights" system. Water users own water rights that grant them a legal right to use the system's native flow according to availability. When native flow is insufficient to meet all of the water rights, the demands are met in priority order based on the date of the water right appropriation ("priority date"), or the corresponding administration number. This is achieved through the use of "calls" placed on the river that dictate which water rights are allowed to divert. The natural water supplies in many of Colorado's basins are highly appropriated and only in very wet periods is there enough native flow to satisfy all of its water rights. When this happens, there is no river call and it is considered a "free river".

Complicating matters further, it is common for single diversion locations (often referred to within models as water users) to contain several unique water rights each with their own priority date, maximum native flow diversion rate, and other potential limits and rules defining their allowable uses. These multiple water rights often represent the adjudication of additional water rights as ditch coverage expanded or the collective water rights of many unique water users that divert water from a single river diversion location into a shared canal. This means that the total water right diversion at a single location can be made up of individual allocations to multiple distinct water rights. Furthermore, due to changing ownership, further subdivision, and legal to changes in water uses and the rules associated with specific water rights ("changed water rights"), the ultimate ownership, types of uses, and even actual use locations of the water allocated at a single diversion point can vary widely.

Consequently, the administration and tracking of these systems, even in relatively simple ones, readily becomes very complicated. The simulation of these systems, which is used to provide useful and valuable management and decision-making and management tools, also presents a significant challenge.

3.2 General and Configuration Differences

The RiverWare and StateMod platforms both have the ability to simulate allocation by water rights. At a fundamental level, the StateMod platform was built with specific simulation of Colorado water rights as its core functionality and solution process, while the addition of water right simulation functionality was a subsequent enhancement to the established RiverWare platform, albeit more than a decade ago.

While not entirely accurate, it is helpful to think of StateMod as a "water right-centric" model that incorporates other operations and processes into its framework, while RiverWare is a "water resource system and operations-centric" model that incorporates water rights into its framework.

At a high level, a few notable differences in how the platforms handle the general water right information of a basin stand out. First, StateMod prioritizes water rights using "administration numbers" that correspond to the water rights appropriation and adjudication priority dates, and potentially other aspects that factor into the senior to junior priority rankings. However, RiverWare currently only assigns water right priorities through the use of datetimes (dates, hours, and minutes), and therefore the “administration numbers” used by StateMod cannot be directly used. While this is a superficial difference, as only the relative priority ranking matters, it does present an additional model translation step. However, this could be eliminated by an option in RiverWare that would allow for the use of administration numbers in place of priority dates (and/or an automated conversion utility), which presumably would be relatively easy to implement if desired by sponsors.

For use in the RiverWare model developed for this study, the StateMod administration numbers were converted into their date equivalents for use in the RiverWare model. This followed the process in the Administration Guideline document shown on the following page. Although the RiverWare Water Rights Solver allows for shared priority water rights, this functionality was not utilized because StateMod does not. As such, in addition to the priority dates, times (hours and minutes) were used to distinguish between water rights of the same dates to reflect an identical priority order to that used by StateMod. When the water rights in StateMod have identical administration numbers, they are simply prioritized in the order they are read into the program at the beginning of a model run and between data files as follows: instream flows, reservoirs, diversions, operating rights, and wells. Since other operations are simulated by StateMod through the use of “operational rights” within this same priority system, the administration numbers given to these rights have to be carefully prioritized in order to ensure they operate as intended. In the RiverWare model, operations are not simulated in the same priority system as the water rights, as described later in this section.

Another notable difference is the way that the water right information is organized and configured in the models. In StateMod, water right information is defined in lists in various text files (“.ddr”, “.rer”, etc.) along with the various water right information including max rates, volumes, and the corresponding model nodes that they are owned by. Additionally, there is a full, priority sorted list of the water rights simulated for a given run in the “.xwr” output text file. While this is not the most user-friendly or transparent organizational scheme it does make for efficient initial model configuration. Figure 8, below, shows a screenshot of a StateMod “.ddr” text file defining direct diversion water rights.

In RiverWare, consistent with its object-oriented modeling approach, water rights exist and are configured in accounts that exist on the simulation objects. Direct flow diversion water rights, storage rights, and instream rights are defined on diversion, storage, and instream flow accounts respectively, on the corresponding object types. As previously discussed, initially constructing the water right accounts can be tedious, although the process can be automated to some extent and could potentially be further automated by enhancements to RiverWare if desired by sponsors. After the water right accounts are created, appropriately named, and their priority dates set, it is easy to write rules to check, set, and otherwise access and use with the various information that reside on them. For example, in the White Basin RiverWare model, Initialization Rules are used to check each water right’s priority date and name to ensure that they have been all configured properly, and to set data such as the “Initial Request” (i.e., for allocation of natural flow) that are used during simulation. Figure 9, below, shows several screenshots highlighting the visual way water rights are configured in RiverWare.

ADMINISTRATION GUIDELINE
Administration Number (aka Holt Number)
Division One – South Platte River

The "Admin Number" was developed by the Division of Water Resources (Ken Holt, Division 6 hydrographer) to provide a simple ranking of water rights' priorities. The number references the number of days since December 31, 1849, an entirely arbitrary date except for the fact that it is prior to the most senior Colorado water right.

The Admin Number requires the following data:

- Adjudication Date of the subject water right[i]
- Previous Adjudication Date[i]
- Appropriation Date of the subject water right

The Admin Number is in the form: XXXXX.YYYYY

The left side of the number (XXXXX) is the number of days between December 31, 1849 and the latter of the Previous Adjudication Date and the Appropriation Date.

- If the Appropriation Date is <u>later</u> than the Previous Adjudication Date, then the left side of the Admin Number (XXXXX) is the number representing the Appropriation Date and the right side (YYYYY) is five zeroes ("00000").
- If the Appropriation Date is <u>earlier</u> than the Previous Adjudication Date, then the left side of the Admin Number (XXXXX) is the number representing the Previous Adjudication Date and the right side (YYYYY) is the number that represents the Appropriation Date.

Once the left and right sides of the Admin Number are determined, the Admin Number should be viewed as a single number with 10 significant digits; the smaller the Admin Number, the more senior the water right. There are basically three categories of Admin Numbers.

1. Original[ii] adjudications (no Previous Adjudication Date exists):

Lower Boulder Ditch		Admin No
Adj Date	06/02/1882	3561.00000
Previous Adj Date	None	↑
Appropriation Date	10/01/1859 →	

2. Supplemental adjudications (a previous adjudication exists) with an Appropriation Date later than the Previous Adjudication Date:

Beaver Brook Pipeline		Admin No
Adj Date	05/13/1936	24745.00000
Previous Adj Date	10/09/1895	↑
Appropriation Date	10/01/1917 →	

3. Supplemental adjudications with an Appropriation Date earlier than the Previous Adjudication Date:

Barnes Meadow Reservoir		Admin No
Adj Date	12/18/1945	26409.26135
Previous Adj Date	04/22/1922 →	↑
Appropriation Date	07/22/1921 →	

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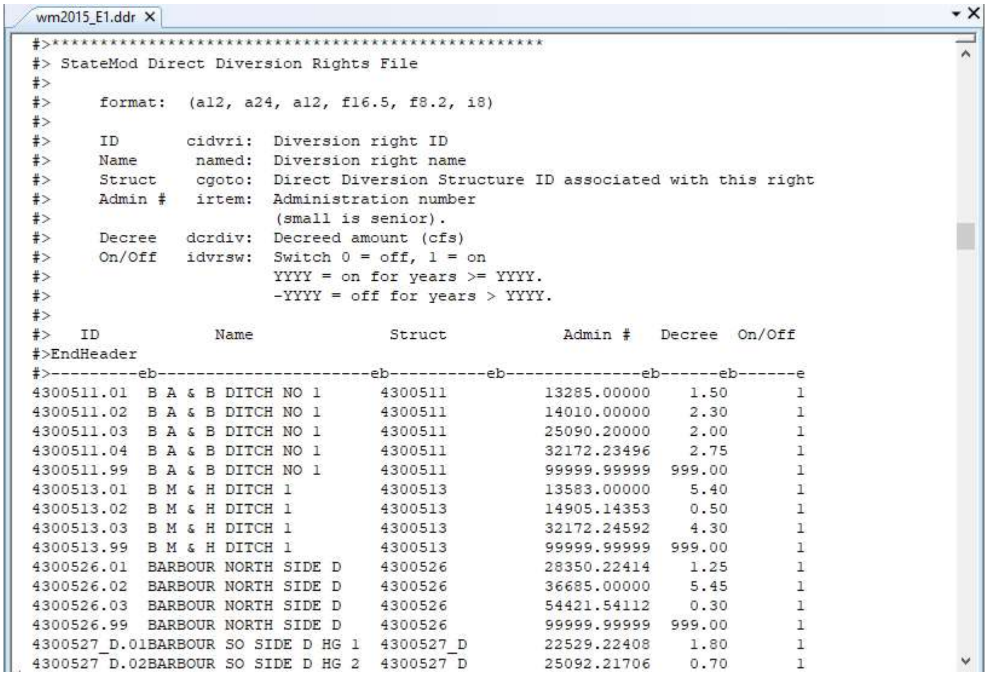
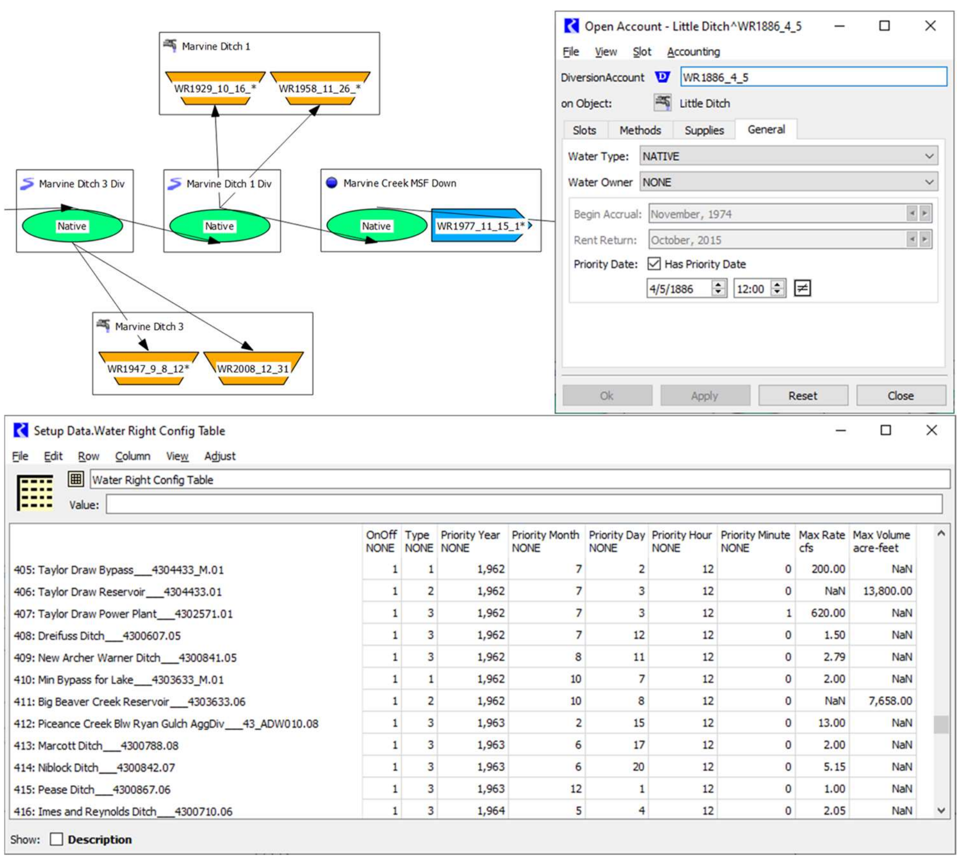
[i] Prior to the creation of a standing water court by the 1969 Water Rights Determination and Administration Act, the Adjudication Date is the date of the respective district court adjudication. Since the 1969 Act, for the purpose of the Admin Number, the Adjudication Date is December 31 of the year the application for a water right was filed. Likewise, since 1969, the Previous Adjudication Date is December 31 of the year before the subject water right application.

[ii] In addition to the first water right adjudications in each of the district courts, the following water rights are tabulated as having no Previous Adjudication Date: non-exempt alluvial well water rights with applications filed no later than July 1, 1972 (CRS 37-92-306); most exchanges (37-92-305(10); nontributary water rights (37-92-305(11)); exempt wells (CRS 37-92-602(4)); and, certain court ordered decrees (such as the North Fork decrees, CA1678 & 84CW566).



```
wm2015_E1.ddr
#>*****************************************************
#> StateMod Direct Diversion Rights File
#>
#>     format:  (a12, a24, a12, f16.5, f8.2, i8)
#>
#>     ID        cidvri:  Diversion right ID
#>     Name       named:  Diversion right name
#>     Struct     cgoto:  Direct Diversion Structure ID associated with this right
#>     Admin #    irtem:  Administration number
#>                        (small is senior).
#>     Decree    dcrdiv:  Decreed amount (cfs)
#>     On/Off    idvrsw:  Switch 0 = off, 1 = on
#>                        YYYY = on for years >= YYYY.
#>                        -YYYY = off for years > YYYY.
#>
#>   ID            Name                 Struct            Admin #   Decree  On/Off
#>EndHeader
#>---------eb----------------------eb----------eb--------------eb------eb------e
4300511.01  B A & B DITCH NO 1      4300511         13285.00000    1.50       1
4300511.02  B A & B DITCH NO 1      4300511         14010.00000    2.30       1
4300511.03  B A & B DITCH NO 1      4300511         25090.20000    2.00       1
4300511.04  B A & B DITCH NO 1      4300511         32172.23496    2.75       1
4300511.99  B A & B DITCH NO 1      4300511         99999.99999  999.00       1
4300513.01  B M & H DITCH 1         4300513         13583.00000    5.40       1
4300513.02  B M & H DITCH 1         4300513         14905.14353    0.50       1
4300513.03  B M & H DITCH 1         4300513         32172.24592    4.30       1
4300513.99  B M & H DITCH 1         4300513         99999.99999  999.00       1
4300526.01  BARBOUR NORTH SIDE D    4300526         28350.22414    1.25       1
4300526.02  BARBOUR NORTH SIDE D    4300526         36685.00000    5.45       1
4300526.03  BARBOUR NORTH SIDE D    4300526         54421.54112    0.30       1
4300526.99  BARBOUR NORTH SIDE D    4300526         99999.99999  999.00       1
4300527_D.01BARBOUR SO SIDE D HG 1  4300527_D       22529.22408    1.80       1
4300527_D.02BARBOUR SO SIDE D HG 2  4300527_D       25092.21706    0.70       1
```

Figure 8: Screenshot of the StateMod Direct Diversion Rights, ".ddr", text file, used to define water rights.



	OnOff NONE	Type NONE	Priority Year NONE	Priority Month NONE	Priority Day NONE	Priority Hour NONE	Priority Minute NONE	Max Rate cfs	Max Volume acre-feet
405: Taylor Draw Bypass___4304433_M.01	1	1	1,962	7	2	12	0	200.00	NaN
406: Taylor Draw Reservoir___4304433.01	1	2	1,962	7	3	12	0	NaN	13,800.00
407: Taylor Draw Power Plant___4302571.01	1	3	1,962	7	3	12	1	620.00	NaN
408: Dreifuss Ditch___4300607.05	1	3	1,962	7	12	12	0	1.50	NaN
409: New Archer Warner Ditch___4300841.05	1	3	1,962	8	11	12	0	2.79	NaN
410: Min Bypass for Lake___4303633_M.01	1	1	1,962	10	7	12	0	2.00	NaN
411: Big Beaver Creek Reservoir___4303633.06	1	2	1,962	10	8	12	0	NaN	7,658.00
412: Piceance Creek Blw Ryan Gulch AggDiv___43_ADW010.08	1	3	1,963	2	15	12	0	13.00	NaN
413: Marcott Ditch___4300788.08	1	3	1,963	6	17	12	0	2.00	NaN
414: Niblock Ditch___4300842.07	1	3	1,963	6	20	12	0	5.15	NaN
415: Pease Ditch___4300867.06	1	3	1,963	12	1	12	0	1.00	NaN
416: Imes and Reynolds Ditch___4300710.06	1	3	1,964	5	4	12	0	2.05	NaN

Figure 9: Screenshots of RiverWare's configuration of water rights, displayed visually on their objects in the accounting network and configured via its account dialog and a data table set up water right appropriation requests according to specified limits.

3.3 Distinction between Allocatable and Non-Allocatable Flows and Accounting Chains

Allocatable flow, often referred to as “native” flow, is stream flow that originates naturally within the basin and is therefore eligible for allocation to and use by the owners of water rights. This also includes the subsequent return flows that are generated by the use of native flow or other water sources (e.g., stored native water) where ownership of return flows is not retained. In contrast, non-allocatable flow is other flow through the river system that is not eligible for water right allocation and use. Examples of non-allocatable flow, often referred to as different “water types”, may include various “project water” classifications, imported transbasin water, and direct deliveries from storage sources to specific water users. Using the latter as an illustrative example, a delivery of stored water from a reservoir to a downstream user would not be allowed to be diverted and/or consumed by another user in the intervening reach (even a senior water right holding user) and thus would be distinctly tracked as non-allocatable flow through that reach. In more complicated systems with many different water types, further mechanisms (such as exchanges, trades, augmentation, and replacement) have been developed that further complicate the tracking of various allocatable and non-allocatable flow chains.

In complex water rights systems, effective management and administration is often aided and achieved through explicit tracking and accounting of the various types of water moving through the system. As would be expected, modern technological improvements are greatly expanding the accuracy, level of detail, and transparency to which these water resource systems are being administered, driven by increasing demands and competition for a highly uncertain and variable resource. Administration systems through Colorado and the western United States, are developing and utilizing advanced administration and informational tools, such as the publicly accessible “Colors of Water Tool” within the “Arkansas Basin Water Operations Dashboard” in Colorado’s Arkansas Basin (“Division 2”), shown in Figure 10, below.

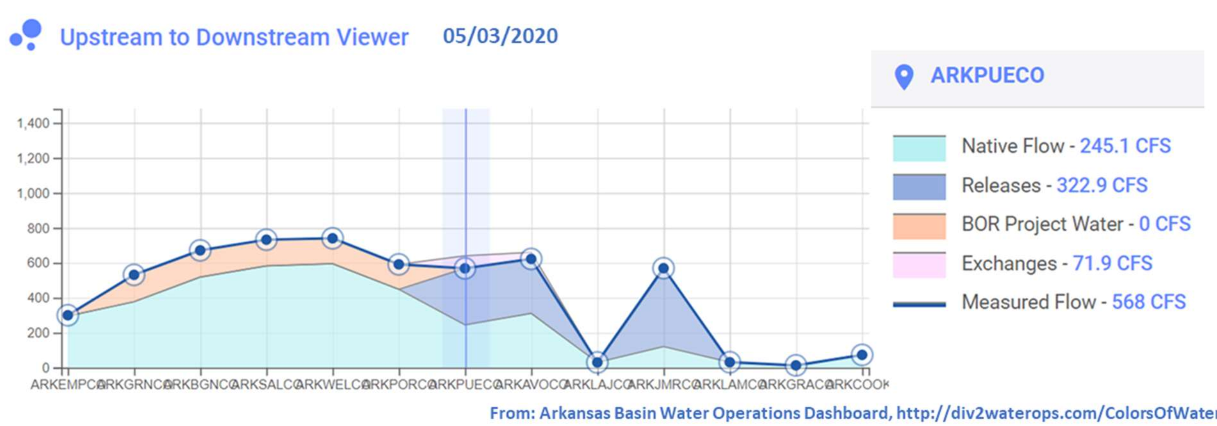


Figure 10: The Arkansas Basin Water Operations Dashboard’s “Colors of Water” Tool, used to illustrate and administer the river flow accounting of various water types through the basin’s reaches on a single day.

Along these lines, a significant difference in model representation relating to water right simulation is the different levels of detail to which RiverWare and StateMod allow for explicit representation of distinct account flow chains. To this end, StateMod does not explicitly track or differentiate between “allocatable” and various “non-allocatable” flows throughout the river system, but rather calculates and tracks just the total flow and allocatable flow at each node throughout its simulation process. When “non-allocatable” flows are present in the system, they are not explicitly accounted for and tracked, but rather they are accounted for so as to not be included in the “available flow” calculations. This is essentially equivalent to StateMod lumping all non-allocatable flow together through intervening nodes.

Although it has certain limitations, StateMod’s simplified representation of flow accounting chains is convenient, computationally efficient, and does not necessarily impact the ability of StateMod to accurately simulate the water right allocation process. It does, however, limit the transparency of the simulation process (i.e., how and why the model came to the answer that it did) and the level of detail of the model results. Additionally, and as just alluded to, there are cases where this simplification can limit StateMod’s ability to simulate the impacts of specific administration rules. For example, in the Arkansas River basin, some significant exchanges are specifically not allowed to occur on the imported “Fryingpan-Arkansas Project Water” that can at times represent major portions of the river’s flow, a limit that would be very difficult to appropriately represent in StateMod. Furthermore, this lack of detail can also limit the applicability of the model to help answer specific questions that may be of interest to various basin stakeholders.

In contrast, RiverWare allows for a much more detailed, explicitly tracked accounting system that can better resemble the level of detail to which even the most complex water resources systems are managed and administered. RiverWare views the “allocatable flow” as a distinct flow accounting chain (often termed “Native”, as in the White Basin RiverWare model) that is tracked explicitly throughout its network, incorporating its various inflows and outflows throughout the system. Then, in addition to the Native flow accounting chain, RiverWare allows for the tracking and “layering on” of various other flow chains that can represent different “non-allocatable flow” water types. The total flow throughout the network is then the sum of all of the individual flow accounting chains. During its simulation of water rights, however, RiverWare will only allocate the water available in the specified allocatable flow chain, although instream flow rights may be met by the reaches total flow and therefore satisfied by flow through other accounts.

Thus, in a RiverWare model, a delivery of reservoir storage to a downstream water user can be tracked explicitly in a “Deliveries” flow account chain, with the release from a specific storage account shown as an inflow to the “Deliveries” account chain at the upper end and the diversion shown removing the flow at the lower end. Moreover, these abilities substantially aid in the representation of complex mechanisms such as various types of deliveries, shepherding, exchanges, and replacement and augmentation releases, where they can be implemented as explicit transactions or interactions between distinct accounting flow chains. Figure 11, below, shows how multiple account chains are used to distinctly track various specific water types and transactions in the White Basin RiverWare model.

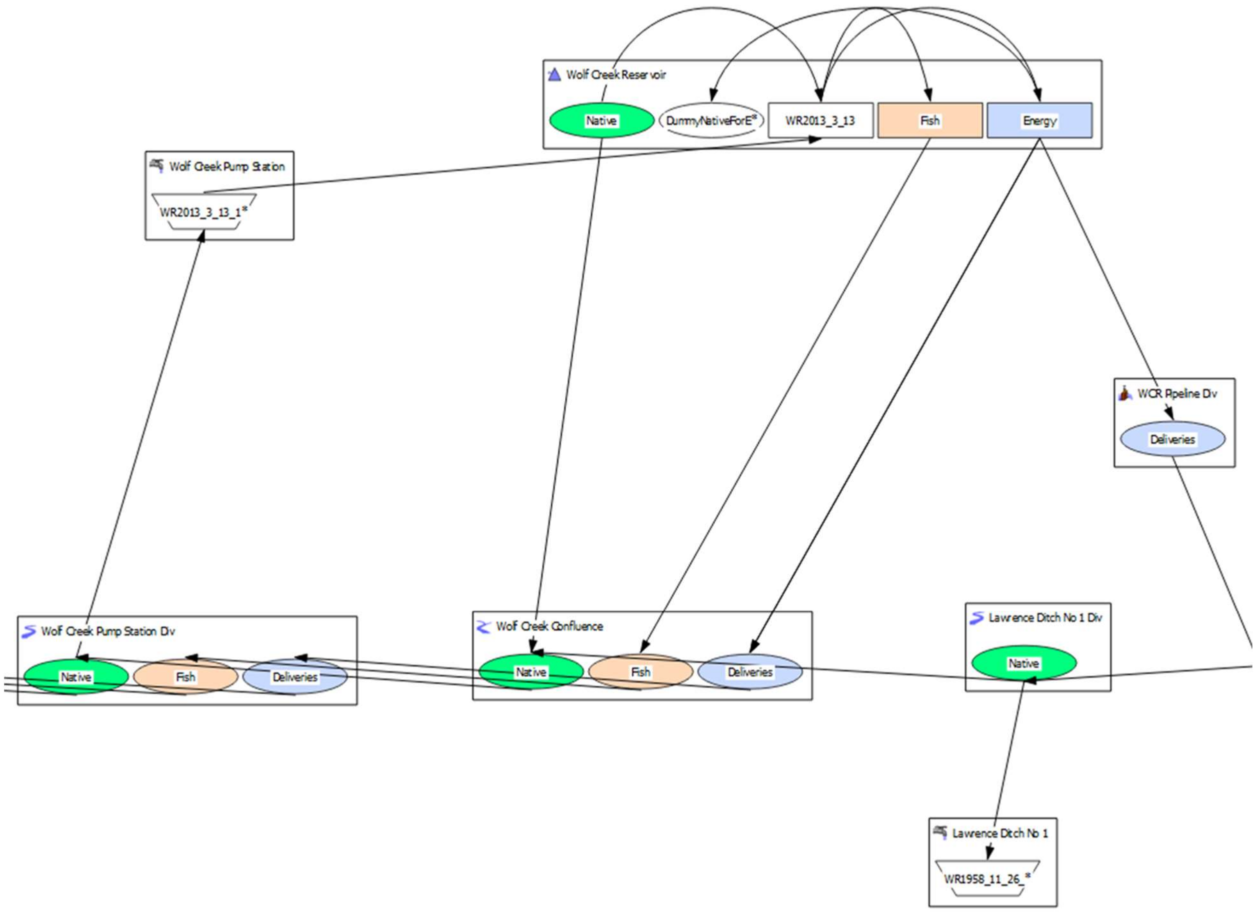


Figure 11: RiverWare accounting network schematic showing accounts and supplies used to track distinct water types.

3.4 General Model Solving Processes

3.4.1 Overview

Both the RiverWare and StateMod model platforms generally follow physically based, algorithmic, or "direct", solution processes. This generally means that the simulation process consists of calculations where one calculation leads to another, which leads to another, and so on until the overall result is reached. This also generally means that the meaningfulness, purpose, and order of each of the individual calculations can actually be interpreted and understood. This places their solving processes in the same category and generally distinguishes them from other types of "black box" modeling platforms (e.g. MODSIM, WRIMs, etc.) that use linear programming solvers or other optimization schemes, to find solutions to giant systems of interdependent equations set up with ambiguous weight terms.

Both platforms also generally use an iterative solution approach, especially when it comes to the simulation of water rights. Thus, they can both iterate through appropriate interdependent processes until a specified tolerance or convergence criteria is met. For example, RiverWare's base nature will iterate back through previously fired rules (described below) as the rule's dependencies are altered due to other simulation processes. This process is very analogous to the manner in which StateMod's solution algorithm (also described below) will "re-operate" through its previously simulated water rights to account for the impacts of later simulated rights.

It is worth noting, however, that RiverWare will inherently iterate to a much higher degree than StateMod does due to the manner by which RiverWare tracks and senses changes to dependences throughout the model. However, given the platform's flexibility the magnitude to which it iterates can be controlled by the user. Recall the reservoir evaporation simulation process described at the end of Section 2.4.2 as an illustrative example.

3.4.2 RiverWare's Simulation Process

At a basic level, a RiverWare model is a network of connected, physically based objects that share and propagate their results with their connected objects. Thus, RiverWare's network solves in an object-oriented manner, which can be helpful to think of as "modular", where its objects "dispatch", or solve internally based on the object's user methods and mass balance calculations, when given the necessary information.

For example, when a RiverWare water user object first solves for its diversion requests from a reach, that information propagates to the corresponding reach object, which can then solve for the actual diversion that can be made based on the flow it has available. This then propagates back to the water user object, which can then solve for the resulting consumptive use and return flows created by that diversion, which are then propagated to the returning reach locations, increasing the flow available in those and downstream reaches. This solution process results in a simulation network that will initially solve all the way through based on the information available relatively early in the solution process of any given timestep. Then, as various other information is modified or updated on objects throughout the network, the entire networks solution will continuously re-solve.

RiverWare's main controller mode options, "Simulation" and "Rulebased Simulation", represent different manners in which input data and other information is given to the object network. In "Simulation" mode, all of the input data is set to objects at the beginning of the run and then timestep-by-timestep throughout the run the network solves based only on the object's methods and relationships. "Rulebased Simulation" mode is an extension of the base Simulation mode, in which some of the data used to solve is provided by a set of user-defined rules that fire in priority order on each model timestep. During simulation, rule execution then alternates with object dispatching to incorporate the effects of the rules in the model. RiverWare's accounting modes generally just add accounting capabilities to these main controller modes. RiverWare also contains an Optimization mode that operates using a fundamentally different solution approach that, instead of solving a model on a timestep-by-timestep basis, provides a single global solution over all objects and all timesteps. However, RiverWare's Optimization mode is only used in highly specific situations and is not applicable or related to water right simulation.

The White Basin RiverWare model developed for this study uses the "Inline Rulebased Simulation and Accounting" controller mode. This mode allows for a high level of flexibility in terms of defining the methods and process by which the model ultimately solves. This also results in an extremely high level of transparency as the "current" results throughout the whole network can be accessed and reviewed at nearly any point during the simulation process. During a model run, a user can pause the process at desired points and actually step through the simulation process to review the results of individual calculations and their impact on the overall solution.

3.4.3 StateMod's Simulation Process

One of the primary differences between the solution processes used by RiverWare and StateMod is that while RiverWare incorporates the simulation of water rights into its existing "Rulebased Simulation" and object network framework, StateMod's simulation process is fundamentally intertwined with its water right simulation. Thus, this solution process, termed the "Modified Direct Solution Algorithm", or "MDSA", is described in the following section.

Consequently, StateMod effectively cannot be separated from its simulation of water rights by priority, although it would not make much sense to do so given that water rights represent the basic operational structure of the basins represented by StateMod models. That being said however, it could be an interesting experiment to attempt to modify a StateMod model to simulate a system in an upstream-to-downstream fashion where hydrologic availability, rather than water right priority, was used to distribute water throughout a basin.

3.5 StateMod's Modified Direct Solution Algorithm (MDSA)

As mentioned above, StateMod's solution process is termed the "Modified Direct Solution Algorithm", or "MDSA" (Bennett, Ray R., December 2000). The MDSA represents an enhanced version of StateMod's previous "Direct Solution Algorithm", that allows for the incorporation of same-timestep return flows into the available flow, as well as allowing for the simulation of variable water use efficiencies and soil moisture accounting. The MDSA algorithm generally follows the following, abbreviated allocation process, as presented in the StateMod platform documentation:

1. Water availability is determined at each river node to include both native inflows and return flows accruing from a prior time step.
2. The most senior direct, instream, storage, well or operational water right is identified.
3. Diversions are estimated to be the minimum of the decreed water right, structure capacity, demand, and available flow in the river. For a direct flow or reservoir right, the available flow in the river is the minimum of the diverting or downstream node plus any of the diverting right's return flow to that node at the current time step. For an instream right, the available flow in the river is the flow at each river node within the instream reach. For a well, pumping is not constrained by the available flow in the river since pumping may deplete ground water storage.
4. Downstream flows are adjusted to reflect the senior diversion and its return flows.
5. Return flows for future time periods are determined and stored.
6. Well depletions for future time periods are determined and stored.
7. The process is repeated by priority for each successive direct, instream, storage, well and operational water right.

8. If new water is introduced to the system from a reservoir's operation or return flows accrue to a non-downstream node, the model reoperates the current time step and the process is repeated beginning with the most senior direct, instream, storage or operational right.
9. The process is repeated for each month or day of the study period.

Various other basin operations, such as reservoir releases and deliveries, are simulated within the MDSA framework through the use of “operational rights” (or “OPRs”), which are defined in the “.opr” text file. OPRs are incorporated into the overall water right simulation order by being given appropriate priorities (using the same “administration number” ranking system) to achieve the intended effects. Consequently, the function of OPRs can be very dependent on the relative priority they are given, making proper ordering essential. While this is not dissimilar from the importance of appropriately ordering RiverWare’s rules, the need to incorporate the OPRs into a prioritized list of hundreds or more rights can make this even more of a challenge. Even in the White Basin StateMod model, which represents the most basic of Colorado’s StateMod models, this list has over 500 individual water rights. Furthermore, there are some limitations of the MDSA process regarding operations that could potentially have undesirable impacts on StateMod model results. One such limitation that was discovered during comparison with RiverWare model results is that during its re-operation process, StateMod will not reduce a previously determined value. This means that while StateMod will re-operate “unsatisfied” OPR rights during simulation, and thus will, for example add to a previously “shorted” OPR right defining a delivery from storage to a water right, it will not reduce that OPR storage delivery if other operations have resulted in increased available flow and therefore would have potentially increased the base diversion water right allocations and reduced the need for storage deliveries in the first place.

3.6 Implementing StateMod’s MDSA “Directly” Using RiverWare’s Rules?

In a fundamental way, StateMod’s MDSA solution algorithm is very similar to developing a RiverWare ruleset that consists of an individual rule for each water right, that fire in senior to junior water right priority order, where each rule solves for and sets its single water right’s present allocation. Once each rule is fired and its assignments made, the associated objects would then dispatch, solve as possible, and the interim results would be propagated appropriately through the network. Then, following RiverWare’s solution approach, any changes to the dependencies of the previous rules (e.g., increased allocatable flow available to previously “fired” more-senior water rights) would trigger those rules to re-fire, or “re-operate” in StateMod terminology.

If a RiverWare ruleset were created in this manner, then it might make sense to place the various other operating rules (i.e., non-water right rules) within the water right priority system. An example of how a ruleset developed in this manner may work is shown below in Figure 12.

In reality, this type of implementation is likely not a feasible option in a RiverWare model, primarily due to the fact that this would require managing over 500 individual rules. However, this conceptualization may help users who are familiar with either platform understand how the other works. It is important to note that this example ***IS NOT*** the process used by RiverWare’s water rights solver function.

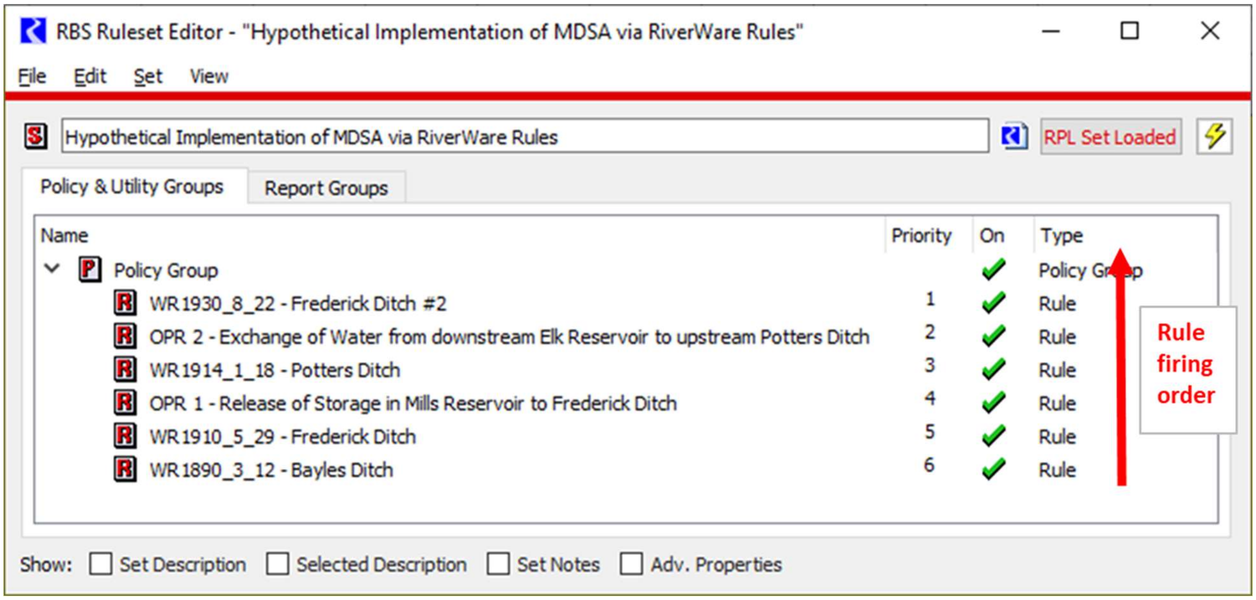


Figure 12: Hypothetical example showing how a "direct" implementation of MDSA may look as a RiverWare Ruleset.

3.7 RiverWare's Water Right Solver

3.7.1 The SolveWaterRights Function and Process

RiverWare's Water Rights Solver algorithm exists as a function, called "SolveWaterRights", that is called within a rule during simulation. When called, the function uses a "computational subbasin" object to internally clone the entire accounting network and the allocation algorithm is then applied on this cloned network. This allows for various other things that have been simulated and set on the actual model network to remain unchanged during the simulation of water rights.

RiverWare's SolveWaterRights method works by the following process, as described in the RiverWare documentation. Further details of the process can be found in the documentation if desired.

1. Determine local timestep of the accounts representing the rights. (Note, this step does not apply to networks in which lags are not simulated, which they are not in the White Basin RiverWare model.)
2. Clone the accounting network. The solver works on this cloned system to solve the problem.
3. Clear values on supplies that represent allocations from the allocatable flow supply chain.

Then, for each water right in priority order:

4. Compute the appropriation request.
5. Compute allocation that meets the request, constrained by not violating senior rights.
6. Create a list of {slot name, value} pairs or a list of {slot name, date-time, value} triplets of allocations that are returned by rule function.

After its execution, the SolveWaterRights function returns its results in the form of a list of assignments that are then made to the accounting network. Subsequently, the RiverWare rules resume firing in the same Rulebased Simulation manner. In this manner, the simulation of water rights can be "layered on" to other processes that may be simulated by the model, such as the operations of “project water” and other non-allocatable flows, or conversely, those processes can be “layered on” to the water right solution.

It should be noted that the SolveWaterRights function can be called multiple times per timestep, and in fact, it must be by design during the simulation of instream flow water rights, as discussed below. Because the previous water rights solver results are internally cleared at the beginning of each call, the solver will return updated simulation results each time based upon any changes to the available allocatable flow chain and to the water right’s appropriation requests.

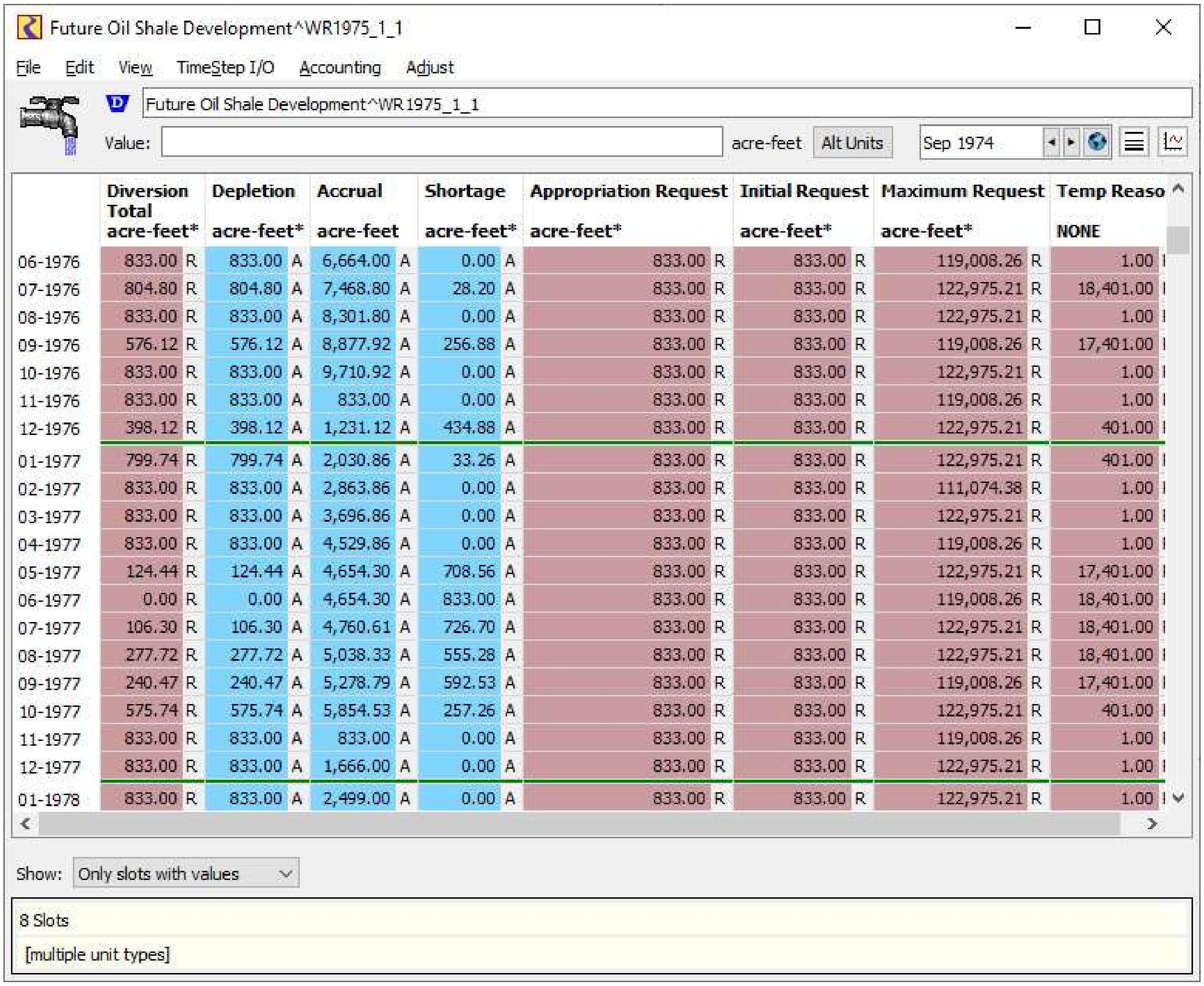
Because it is relatively computationally expensive, it is generally good practice to design the model and ruleset in a manner that limits the number of times that the SolveWaterRights function. Thus, the methods through which the water rights solver was implemented for this study do not represent a recommended practice. Rather, it was implemented in this manner in an attempt to replicate the manner by which StateMod simulates water right allocation.

While the way the model platforms work may appear quite different on the surface, due to the differences in the platform’s handling of the object network and the fact that the RiverWare water rights solver is implemented within its traditional Rulebased Simulation, the water right allocation simulation algorithms themselves are in fact very similar. At a base level, these methods simply step through the water rights in priority order, allocate the available flow to them, correspondingly update the available allocatable flow through the network, and repeat.

It should be noted that RiverWare’s water right solver has additional functionalities that were not utilized during this study, but may be applicable to simulation of specific water rights situations in Colorado’s basins, including water right subordination, in which a senior right can give up their water right allocation to reduce a junior’s shortage. Additionally, the “SolveWaterRightsWithLags” version of the function can be used to simulate water right allocation in a model that simulates lags throughout the basin, provided that these lags are whole timesteps, typically days. This method has been successfully implemented in the daily timestep Arkansas Basin RiverWare model (ABRW), which uses the results of water right allocation simulation as a base solution upon which a vast assortment of other, non-allocatable flow, operations are layered.

3.7.2 RiverWare Water Rights Solver Results

True to its strengths, a key feature of RiverWare’s water rights solver is the transparency with which water rights allocation results are provided. During and following simulation, a user is able to access the results of individual water rights, describing its appropriation request and how it was determined, the corresponding allocation, the current shortage if applicable, and the “reason” returned by the SolveWaterRights function describing why the right received the allocation that it did. A screenshot of the simulation results for a specific water right is shown below in Figure 13.



	Diversion Total acre-feet*	Depletion acre-feet*	Accrual acre-feet	Shortage acre-feet*	Appropriation Request acre-feet*	Initial Request acre-feet*	Maximum Request acre-feet*	Temp Reaso NONE
06-1976	833.00 R	833.00 A	6,664.00 A	0.00 A	833.00 R	833.00 R	119,008.26 R	1.00
07-1976	804.80 R	804.80 A	7,468.80 A	28.20 A	833.00 R	833.00 R	122,975.21 R	18,401.00
08-1976	833.00 R	833.00 A	8,301.80 A	0.00 A	833.00 R	833.00 R	122,975.21 R	1.00
09-1976	576.12 R	576.12 A	8,877.92 A	256.88 A	833.00 R	833.00 R	119,008.26 R	17,401.00
10-1976	833.00 R	833.00 A	9,710.92 A	0.00 A	833.00 R	833.00 R	122,975.21 R	1.00
11-1976	833.00 R	833.00 A	833.00 A	0.00 A	833.00 R	833.00 R	119,008.26 R	1.00
12-1976	398.12 R	398.12 A	1,231.12 A	434.88 A	833.00 R	833.00 R	122,975.21 R	401.00
01-1977	799.74 R	799.74 A	2,030.86 A	33.26 A	833.00 R	833.00 R	122,975.21 R	401.00
02-1977	833.00 R	833.00 A	2,863.86 A	0.00 A	833.00 R	833.00 R	111,074.38 R	1.00
03-1977	833.00 R	833.00 A	3,696.86 A	0.00 A	833.00 R	833.00 R	122,975.21 R	1.00
04-1977	833.00 R	833.00 A	4,529.86 A	0.00 A	833.00 R	833.00 R	119,008.26 R	1.00
05-1977	124.44 R	124.44 A	4,654.30 A	708.56 A	833.00 R	833.00 R	122,975.21 R	17,401.00
06-1977	0.00 R	0.00 A	4,654.30 A	833.00 A	833.00 R	833.00 R	119,008.26 R	18,401.00
07-1977	106.30 R	106.30 A	4,760.61 A	726.70 A	833.00 R	833.00 R	122,975.21 R	18,401.00
08-1977	277.72 R	277.72 A	5,038.33 A	555.28 A	833.00 R	833.00 R	122,975.21 R	18,401.00
09-1977	240.47 R	240.47 A	5,278.79 A	592.53 A	833.00 R	833.00 R	119,008.26 R	17,401.00
10-1977	575.74 R	575.74 A	5,854.53 A	257.26 A	833.00 R	833.00 R	122,975.21 R	401.00
11-1977	833.00 R	833.00 A	833.00 A	0.00 A	833.00 R	833.00 R	119,008.26 R	1.00
12-1977	833.00 R	833.00 A	1,666.00 A	0.00 A	833.00 R	833.00 R	122,975.21 R	1.00
01-1978	833.00 R	833.00 A	2,499.00 A	0.00 A	833.00 R	833.00 R	122,975.21 R	1.00

Figure 13: Screenshot of the detailed results available for each individual water right in RiverWare.

3.7.3 Same-Timestep Return Flow Water Right Solver Limitation and Workaround

A significant shortcoming of RiverWare's Water Rights Solver was identified during this study in that currently, the SolveWaterRights simulation method ***does not internally account for the impacts of return flows that are generated by water right allocations and that accrue back to system the on the same timestep***. By *internally*, this means within a single call of the SolveWaterRights function. Fortunately, this caveat ultimately allows for a workaround that leverages RiverWare's flexibility, and the fact that the water rights solver is integrated within Rulebased Simulation abilities, that allows for these same-timestep return flows to be incorporated into the water right simulation.

It is important to note that this shortcoming would likely not be a significant issue in daily timestep models where all return flows can reasonably be assumed to begin accruing on the next day. However, in a monthly model these same-timestep return flows represent significant additions to the allocatable flow chain.

It should also be noted that the RiverWare diversion account methods do include a “Split and Route” method that is the accounting-side equivalent to the physical water user object’s split and impulse lag response methods that achieve the same return flow representation as StateMod, as was described in Section 2.5. Unfortunately, this diversion account return flow method has not yet been implemented to work within RiverWare’s water rights solver. According to CADSWES, these methods could be enhanced to work together, however it has not been a priority of their current sponsors.

Nevertheless, a workaround was developed during this study that results in the inclusion of these same-timestep return flows in the flow allocated by the water rights solver, and thus allows for exact matching of the water right allocations simulated by StateMod, as will be discussed later in Section 4.

The concept for this workaround is simple, because the physical-side water user objects perform the necessary return flow splitting and routing, those results can be directly used to re-set the return flows accruing in accounting network. Thus, the water rights solver can be iterated over until some tolerance or convergence criteria is met, each time seeing additional allocatable flow from return flows in its native flow chain. In the White Basin RiverWare model developed for this study, the overall change in allocation was used as an indication of convergence, and a change tolerance value of 0.002 cfs (~0.12 af/month) was found to perform very well.

In fact, this iteration method is quite similar to how the StateMod MDSA will re-operate through its water rights to incorporate the impacts of same-timestep return flows. Of course, StateMod only re-operates through its previously “unsatisfied” water rights each time, while RiverWare must iterate over its entire water rights network. While the re-firing of rules as triggered by changing dependencies is actually a standard and often-utilized RiverWare functionality, in this case it represents a significant inefficiency and leads to relatively long run times relative to StateMod (see Section 4.9 for a comparison of model run times). This inefficiency is further and significantly compounded with the inclusion of instream flow rights, discussed in the next section.

Additionally, this workaround does somewhat complicate the RiverWare ruleset and solution process by requiring that a subset of the model’s rules be iterated over in a uniform fashion. However, because of the high level of control that can be built into a ruleset relating to the manner in which rules fire, this is achievable. This process is explained later in this section in the description of how the White Basin RiverWare model’s ruleset works.

3.7.4 Inclusion of Instream Flow Water Rights

A second significant shortcoming of RiverWare’s water rights solver relative to StateMod was identified pertaining to the manner in which it allows instream flow water rights to be simulated. Currently, ***RiverWare only allows instream flow rights to be implemented as points***. In contrast, in addition to point locations, ***StateMod allows instream flow rights to be defined for stretches of river designated by an upstream and a downstream node***.

While a couple of potential workarounds were experimented with during the course of this study, a viable one was not found. These potential workarounds included using two or more control point objects configured with water right priority dates spaced a minute apart as RiverWare does not allow equal priority dates for instream flow rights. For instream flow reaches that only spanned a single intervening node, this method was tested and did in fact result in the same results as StateMod.

However, due to the potential for excessive run times discussed below, these methods were not considered viable workarounds for true implementation.

Thus, for most of the comparison runs presented in the next section that contain instream flow water rights, the applicable instream flow rights in StateMod were converted from reaches to points, applied at their upstream point. It should be noted that RiverWare was found to be able to replicate the representation of these point instream flow rights, although for the reasons discussed below this should be considered more of a proof of concept than a feasible solution.

The potential for practical workarounds here was complicated by the fact that RiverWare's innate method of simulation of instream flow water rights requires that the water right solver be called multiple times per timestep, stepping through each applicable "instream flow right controlling date". This results in a requirement that the water rights solver be called as many times as the number of instream flow rights that there are, following an initial call in which none of the rights are allowed to call out upstream junior water rights. Ultimately, this need for iteration stems from the fact that RiverWare's water right simulation generally represents just one operational tier upon which various other basin operations are layered, but that the various "non-allocatable" flows of these other operations can actually help to meet these instream flows and thus must be accounted for.

However, due to the previously discussed, iterative workaround used to incorporate same-timestep return flows, this multiple water rights solver call requirement for instream flow water rights becomes a significant burden and can result in a very high number of water right solver function calls per timestep. Given the 16 instream flow rights in the White Basin models, this was found to result in a maximum of 528, and an average of 68, calls of the water right solver rule in a single timestep, which unsurprisingly required increasing various maximum iteration criteria throughout RiverWare to allow it to solve.

However, and as a testament to RiverWare's flexibility and evidence that the underlying water right solver method is sound, the comparison model run with all 16 instream flow rights turned on as point locations came to the exact same results as StateMod does, albeit taking around 1.5 hours to run.

3.8 THE WHITE BASIN RIVERWARE MODEL RULESET

The RiverWare ruleset developed in the White Basin RiverWare model is shown below in Figure 14. It is important to note that this ruleset was developed in this manner for the purpose of replicating the manner in which StateMod solves. This required that it be developed to operate in a specific manner to control the order in which the rules and rule groups are fired, especially during iterations.

The ruleset is broken down into 5 policy groups, described here in the order upon which they fire, which is from the bottom of the ruleset to the top according to RiverWare's rule priority scheme.

- Start Timestep Only Rules – This group contains just a single rule, fired only on the run start date, that sets up the Well water user object (if turned on) so it will solve through the entire run.
- Fire Once Rules – This group contains rules that fire just once per timestep and that calculate and set the appropriation requests for each water right through the model, accounting for the applicable demands, accrual limits, and maximum storage capacities, etc. This also sets incoming lagged return flows to the accounting network prior to the water right solver firing, which can help reduce the need for iterations.
- Main WRS Iterating Rules – This group contains the main rules used to call the water rights solver and then set its current solution to the object and account networks. The last rule in this group will then evaluate the change in total allocation made in the last iteration and trigger the whole group to re-fire appropriately if necessary.
- Operations Iterating Rules (i.e., OPRs) – This group contains the rules used to simulate the basin's non-water right allocation operations. The individual rules will only fire if the corresponding operations are turned on.
- End of Timestep Rules – This group contains the reservoir evaporation rule, which forces RiverWare to simulate reservoir evaporation in the basic manner done by StateMod, and a verification rule for debugging purposes to ensure that the water right solver rules are firing appropriately.

It should also be noted that the various options to control which operations are turned on or off are located on the "Setup Data" data object. Thus, all of the rules in the ruleset should remain turned on (i.e., the green checkmarks) regardless of the particular run configuration.

Following the ruleset, one of the model's rules is shown in Figure 15. This rule uses a custom-written generalized RiverWare function to make a delivery from storage to a downstream water user as needed if the user's direct diversion water rights are not sufficiently in priority. This generalized function is quite analogous how StateMod uses standard "OPR" types, in that it is given a set of input arguments for which it executes a consistent process to simulate operations. The RiverWare RPL code for the function is shown in Figure 16, and logically and intuitively shows the calculation process through which the operation is simulated. A user can actually pause and step through these calculations as they occur during a model run to understand exactly how an operation is simulated and why the result ended up as it did. This allows for a very high degree of model transparency.

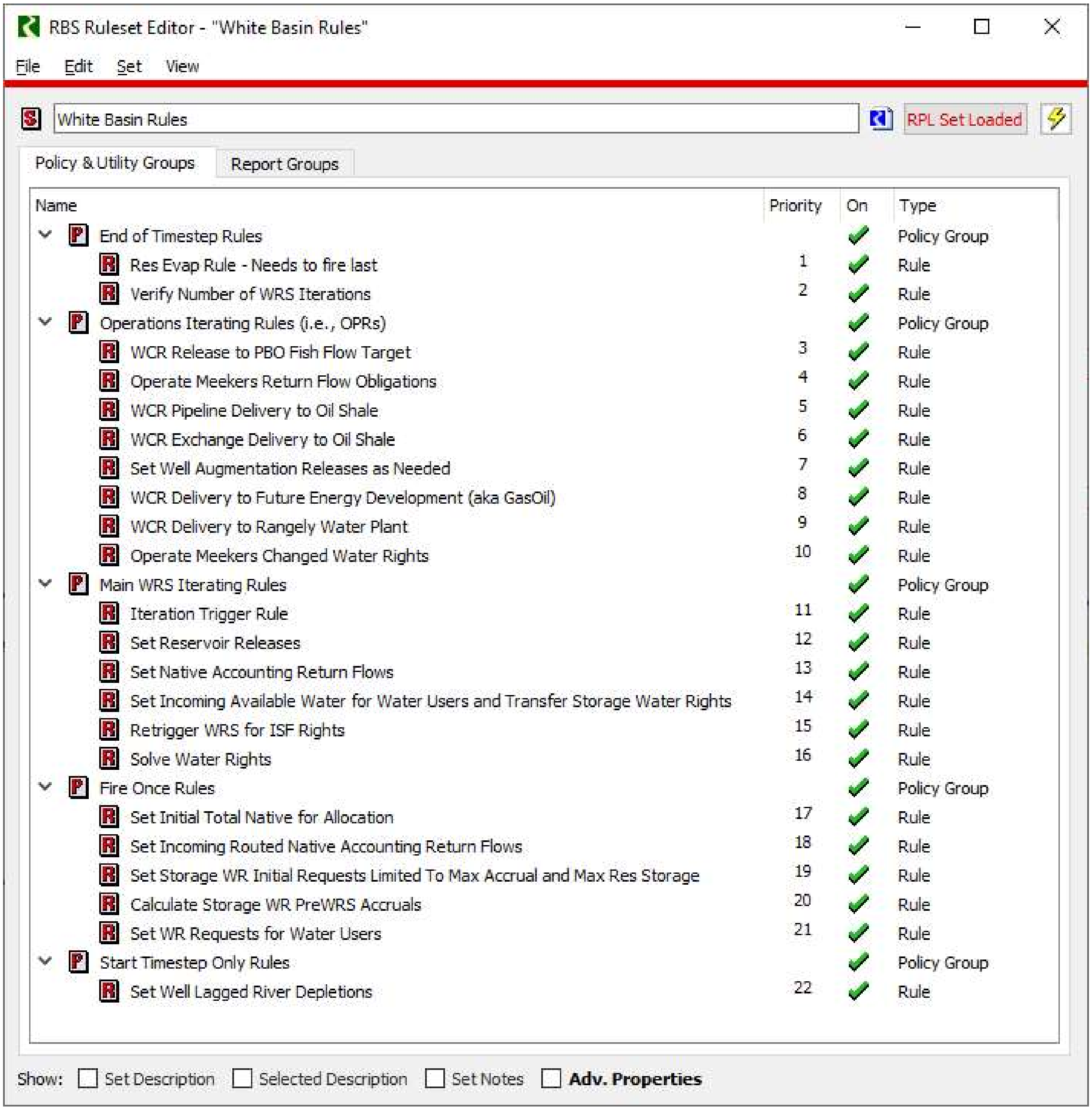


Figure 14: White Basin RiverWare Model's Ruleset.

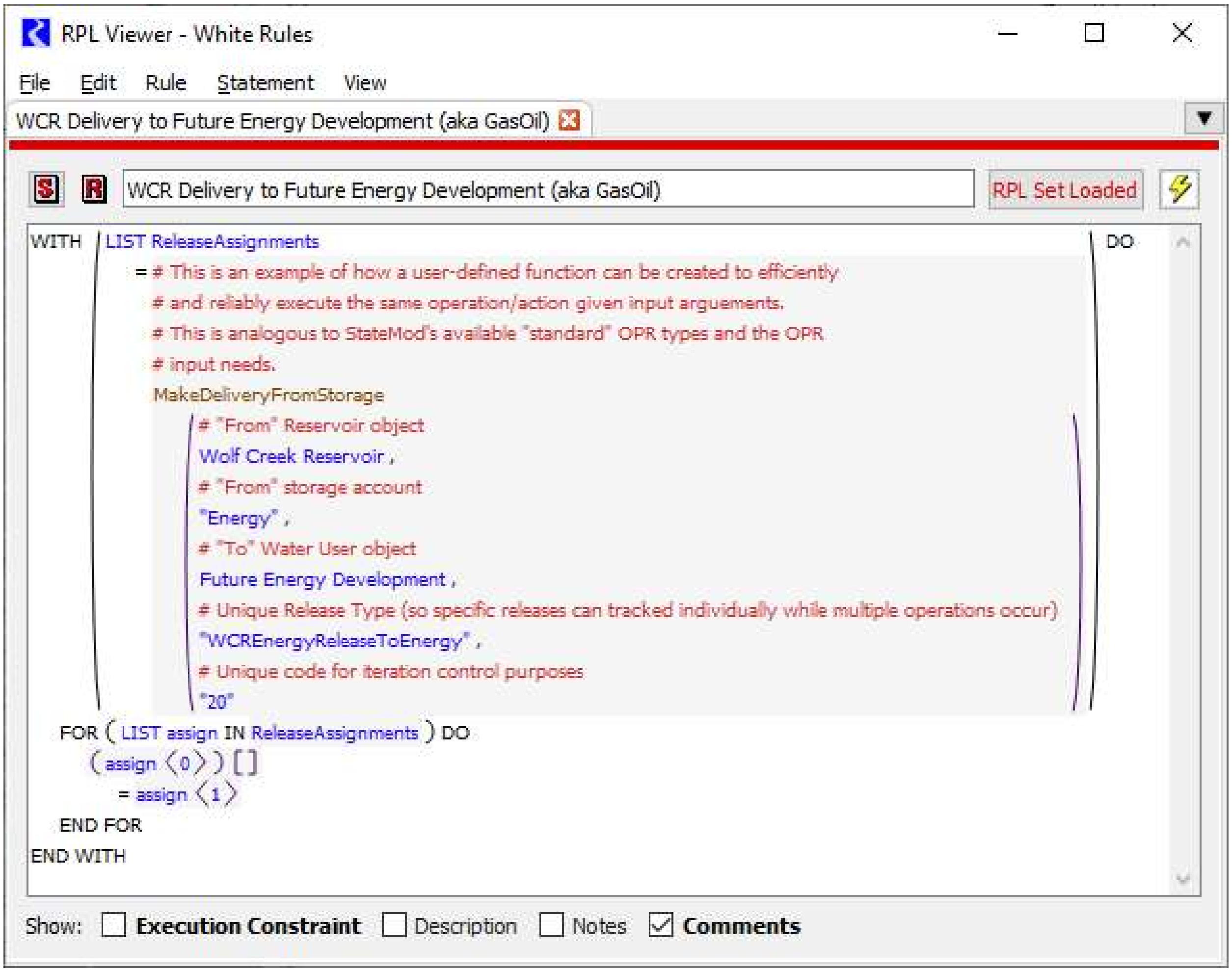


Figure 15: Example RiverWare operation rule using the generalized "MakeDeliveryFromStorage" function.

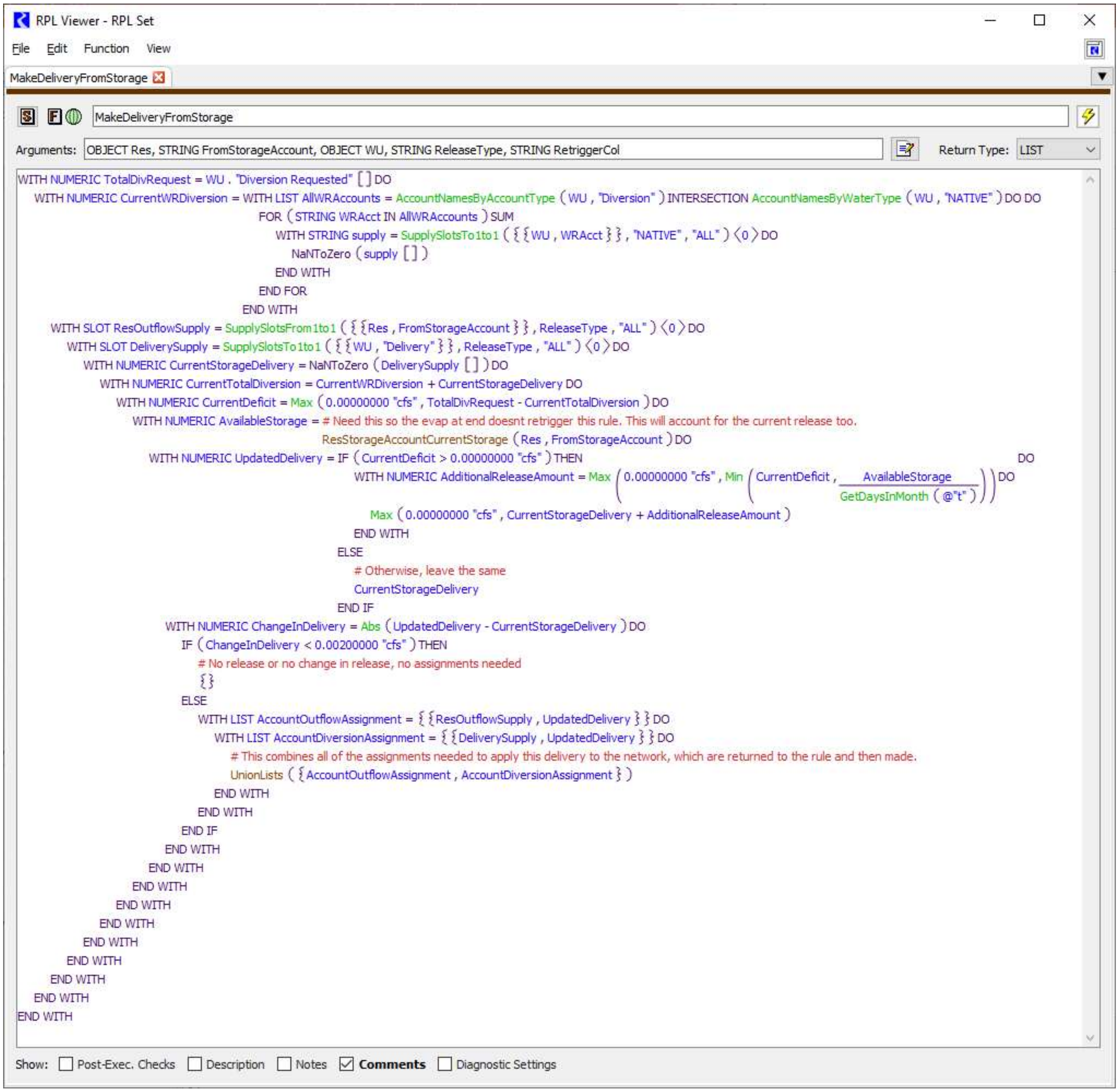


Figure 16: RiverWare RPL code for the generalized "MakeDeliveryFromStorage" function, showing the calculation process used.

4 Comparison of Model Results of Simulated Water Right Allocations and Operations

4.1 Overview and Comparison Workbook Tool

In order to compare how the RiverWare and StateMod platforms simulate various aspects of the water rights system, comparisons were made across a series of different model configurations. Most of these configurations were designed to isolate individual simulation components of interest so they could be directly compared. Additionally, some of these configurations were designed to evaluate how well various components were able to be simulated concurrently. The main model configurations and comparison run matching status are summarized below in Table 3. The results of these comparisons are then discussed through the rest of this section.

A “Comparison Workbook” tool was created during this study to facilitate efficient comparison of model results across various the various run configurations. This tool and the various comparison run result workbooks are delivered along with this report. It is recommended that interested readers should use the Comparison Workbook tool alongside the report while reading through the rest of this section. This way, the reader can load the specific runs being discussed to peruse the model results in a side by side basis.

The Comparison Workbook tool allows a user to select a set of paired model result workbooks corresponding to the comparison run configurations shown in Table 3 above, or alternatively select individual result workbooks to compare various other model runs. The user can then select an object type (Reservoir, Water User, or Reach/Gage) and a specific parameter to compare. The available parameters differ by object type and are as follows:

- Reservoir:
    - SM_River_Inflow
    - SM_Res_Outflow
    - Storage
    - Evaporation
    - TotalWRInPriority
    - SM_BOM_Fill_Limit
- Water User:
    - SM_River_Divert
    - SM_Total_Supply
    - SM_Total_Return
    - TotalWRInPriority
    - Soil Moisture
- Reach/Gage:
    - SM_River_Inflow
    - SM_River_Outflow
- *Note: Parameters beginning with “SM_” are calculated “equivalent” parameters to ensure apples-to-apples comparisons. These are necessary due to the fact that many output terms have*

slightly different meanings or are reported in slightly different ways from one platform to the other.

Once a set of model runs and desired object type and parameter is selected, the “Load Data” macro is used to load those results into the workbook from the raw output workbooks for comparison. The workbook facilitates side-by-side viewing of the results from both platforms as well as the difference between them, organized in a convenient upstream to downstream order.

Within the “Comparison Workbook” workbook and throughout comparisons, a differential tolerance of 0.5 acre-feet/month (~.008 cfs), was applied. Difference values within this tolerance were attributed to differing model convergence and precision, and thus were considered to be equal for the purposes of this study.

Table 3: Main Model Configurations Used to Compare of RiverWare's and StateMod's Simulation of Water Rights and Associated Operations.

Report Section	Run Configuration Name	Div. WRs	Storage WRs	ISF WRs[1]	Well + Aug	Wolf Creek Offstream Res Ops			Meeker Changed WRs		Model-To-Model Comparison Matching Status
						Base Ops[2]	Exchange[3]	Fish Target Release[4]	Base Ops[6]	Exchange[7]	
4.2	Comparison Base	On	On	Off	Off	Off	Off	Off	Off	Off	Full match
4.3	ISF On, All as Upstream Points	On	On	On	Off	Off	Off	Off	Off	Off	Full match
4.4	Well & Augmentation On	On	On	Off	On	Off	Off	Off	Off	Off	Full match, except for 2 months due to SM's "auto" To/From GW Storage, see Section 4.4.
4.5	WCR Base Ops	On	On	Off	Off	On	Off	Off	Off	Off	Full match
	WCR Base Ops + Exchange	On	On	Off	Off	On	On	Off	Off	Off	Full match
	WCR PumpTo + Fish Release Only	On	On	Part[4]	Off	Part[5]	Off	On	Off	Off	Full match
	WCR All Ops On	On	On	Part[4]	Off	On	On	On	Off	Off	Full match
4.6	Meeker Changed WRs Base Ops	On	On	Off	Off	Off	Off	Off	On	Off	Single minor difference observed stemming from operation simulation order, see Section 4.6 for discussion.
	Meeker Changed WRs Base Ops + Exchange	On	On	Off	Off	Off	Off	Off	On	On	Minor differences observed stemming from operation simulation order and related impacts on exchange limits, see Section 4.6 for discussion.
4.7	All WCR + Meeker Changed WRs Ops	On	On	Part[4]	Off	On	On	On	On	On	Minor differences observed stemming from operation simulation order, see Section 4.7 for discussion.

1: All 16 ISFs as point locations at upstream node (SM ISF file modified to apply only to upstream nodes)
2: WCR Base Ops include: WCR Pump To, Rangely Release, Energy (GasOil) Release, Piceance OilShale via Pipeline
3: Exchange from WCR to Piceance "OilShale"
4: To simulate the WCR Fish Target Release in StateMod, the associated ISF right must be turned on. It was found that otherwise SM will deliver 300 cfs from WCR regardless of the other flow in the river at the target node.
5: "Pump To" Wolf Creek Res is On
6: Meeker Changed Oak Ridge Park (OakRP) WR's Base Ops include: (1) Split OakRP Yield by ownership to Meeker (5%) and OakRP-Irrigation (95%), subject to monthly and annual volume limits. (2) Deliver OakRP-Irrigation yield to OPR-Irrigation. (3) Deliver OakRP-Meeker yield to meet remaining Meeker Demand not met by its own In-Priority WRs. (4) Track reusable RFs from Meeker-OakRP deliveries. (5) Meeker OakRP RF Requirements met (i) In-Priority, (ii) By Reusable RRFs. (Met by Avery release only if Exchange is on)
7: Exchange of excess Meeker OakRP yield to Lake Avery. Also allows OakRP RF Requirements to be met by Lake Avery releases if needed (after they are met by in-priority and reusable RFs)

4.2 Diversion and Storage Water Rights – "Comparison Base Run"

The simulated allocations to diversion and storage water rights were found to be identical between the RiverWare and StateMod models in the base configuration comparison run (termed "Comparison Base"). This configuration only includes the diversion and storage water rights (numbering 502 and 14 individual rights, respectively), and thus does not include any instream flow rights or other operations.

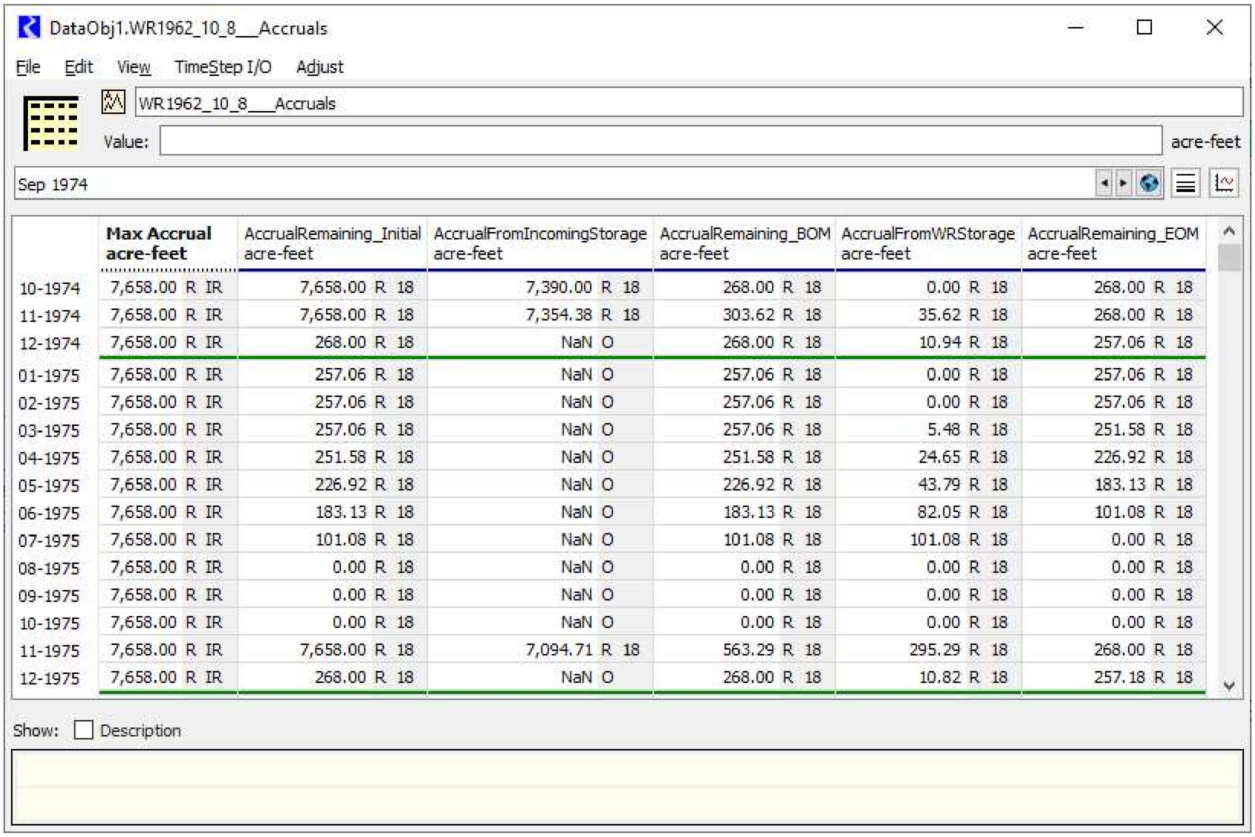
At a fundamental level, this significant finding shows that the RiverWare and StateMod water right allocation simulation algorithms found the same results for all allocations to all water rights throughout the whole model network. Furthermore, this result can be interpreted as evidence to support the hypothesis, based on examination of the underlying solution algorithms, that these simulation processes are essentially equivalent.

It should be noted, however, that in order to do this a computationally expensive workaround was necessary that required iterating RiverWare's water right solver to allow for the incorporation of same-timestep return flows. The need for this workaround, described more fully in Section 3.7.3, does represent a shortcoming in that the water right solver doesn't yet account for these return flows internally. However, an enhancement to RiverWare to incorporate this ability is certainly plausible given a need, and ultimately the workaround implemented served its purpose during this study.

Irrespective to the model results, but regarding the steps necessary prior to water right simulation, it was observed that StateMod "automatically" determines the appropriation requests of the individual diversion and storage water rights based on their priority order and other respective limits. In RiverWare, this did require an additional step, however this was easily accomplished by a generalized rule fired at the beginning of each timestep before any water right simulation. This rule simply loops over all the water users and reservoirs and distributes the total demand to the associated water rights in senior to junior order, accounting for any individual water right volumetric or other specific limits.

This seemingly additional step is, of course, due to the fact that this task is simply a built-in process in StateMod process and thus done behind the scenes. While the generalized rule necessary to do this is easy and efficient, an additional object and/or account method implemented on the RiverWare platform could be helpful for this purpose.

It is also worth pointing out, however, that because StateMod does these calculations behind the scenes, the detailed results showing how the overall answer was found are not available. For example, StateMod reports the overall reservoir "BOM Decree Limit"(/"Fill_Limit"), which depends on the various accruals and limits of the individual storage rights, however it can require post-processing to figure out how that answer was found. In RiverWare, the rule implemented for the same purpose can easily set and track the various individual parameters leading to the overall result, as shown below in Figure 17. This leads to a very understandable and traceable simulation process with a high level of transparency.



DataObj1.WR1962_10_8___Accruals

File Edit View TimeStep I/O Adjust

WR1962_10_8___Accruals

Value: acre-feet

Sep 1974

	Max Accrual acre-feet	AccrualRemaining_Initial acre-feet	AccrualFromIncomingStorage acre-feet	AccrualRemaining_BOM acre-feet	AccrualFromWRStorage acre-feet	AccrualRemaining_EOM acre-feet
10-1974	7,658.00 R IR	7,658.00 R 18	7,390.00 R 18	268.00 R 18	0.00 R 18	268.00 R 18
11-1974	7,658.00 R IR	7,658.00 R 18	7,354.38 R 18	303.62 R 18	35.62 R 18	268.00 R 18
12-1974	7,658.00 R IR	268.00 R 18	NaN O	268.00 R 18	10.94 R 18	257.06 R 18
01-1975	7,658.00 R IR	257.06 R 18	NaN O	257.06 R 18	0.00 R 18	257.06 R 18
02-1975	7,658.00 R IR	257.06 R 18	NaN O	257.06 R 18	0.00 R 18	257.06 R 18
03-1975	7,658.00 R IR	257.06 R 18	NaN O	257.06 R 18	5.48 R 18	251.58 R 18
04-1975	7,658.00 R IR	251.58 R 18	NaN O	251.58 R 18	24.65 R 18	226.92 R 18
05-1975	7,658.00 R IR	226.92 R 18	NaN O	226.92 R 18	43.79 R 18	183.13 R 18
06-1975	7,658.00 R IR	183.13 R 18	NaN O	183.13 R 18	82.05 R 18	101.08 R 18
07-1975	7,658.00 R IR	101.08 R 18	NaN O	101.08 R 18	101.08 R 18	0.00 R 18
08-1975	7,658.00 R IR	0.00 R 18	NaN O	0.00 R 18	0.00 R 18	0.00 R 18
09-1975	7,658.00 R IR	0.00 R 18	NaN O	0.00 R 18	0.00 R 18	0.00 R 18
10-1975	7,658.00 R IR	0.00 R 18	NaN O	0.00 R 18	0.00 R 18	0.00 R 18
11-1975	7,658.00 R IR	7,658.00 R 18	7,094.71 R 18	563.29 R 18	295.29 R 18	268.00 R 18
12-1975	7,658.00 R IR	268.00 R 18	NaN O	268.00 R 18	10.82 R 18	257.18 R 18

Show: Description

Figure 17: Example of Individual Storage Water Rights Accrual results implemented in RiverWare.

4.3 Instream Flow Rights

The shortcomings of RiverWare's ability to simulate instream flow water rights relative to StateMod was previously described in detail in Section 3.7.4. In summary:

- RiverWare only allows instream flow rights to be implemented as points.
- StateMod allows instream flow rights to be defined for stretches of river designated by an upstream and a downstream node, in addition to point locations.

This shortcoming limited the extent to which the simulation of instream flow water rights could be compared. This was compounded due to the fact that RiverWare requires multiple calls of the water right solver to simulate instream flow rights, which when combined with the iterative same-timestep return flow workaround, further complicated the ability to compare instream flow right simulation. Thus, for most of the other comparison runs discussed in this section, instream flow rights were turned off in both models.

However, in an effort to evaluate RiverWare's simulation process for instream flow rights on a conceptual basis, even if full implementation on the level of StateMod is currently infeasible, a paired model run was configured for comparison. For this run the 11 reach instream flow rights in StateMod were converted to points at their upstream node location and represented in both models. This configuration was called "ISF On, All as Upstream Points". This comparison run also had all of the diversion and storage rights on, but no additional operations. Through this comparison run, it was found that RiverWare's water right solver was, in fact, able to come to the same solution as StateMod for the instream flow point rights and all other water rights in the models. However, this RiverWare model run did take approximately 1.5 hours to run and therefore should be considered more of a proof of concept than a feasible solution.

On an overall basis, the fact that RiverWare is not currently able to simulate instream flow water rights as reaches presents a considerable limitation relative to StateMod.

4.4 Wells, Well Water Rights, and Augmentation

4.4.1 Overview and Representation in RiverWare

The ability of RiverWare to simulate well depletions to surface water, well water rights, and associated augmentation requirements was evaluated by the inclusion of a single well node and augmentation demand in the model. Ultimately, a satisfactory representation in RiverWare was achieved for the purposes of this study. However, it was not as neat or repeatable as desired and the implementation of many wells would represent a challenge.

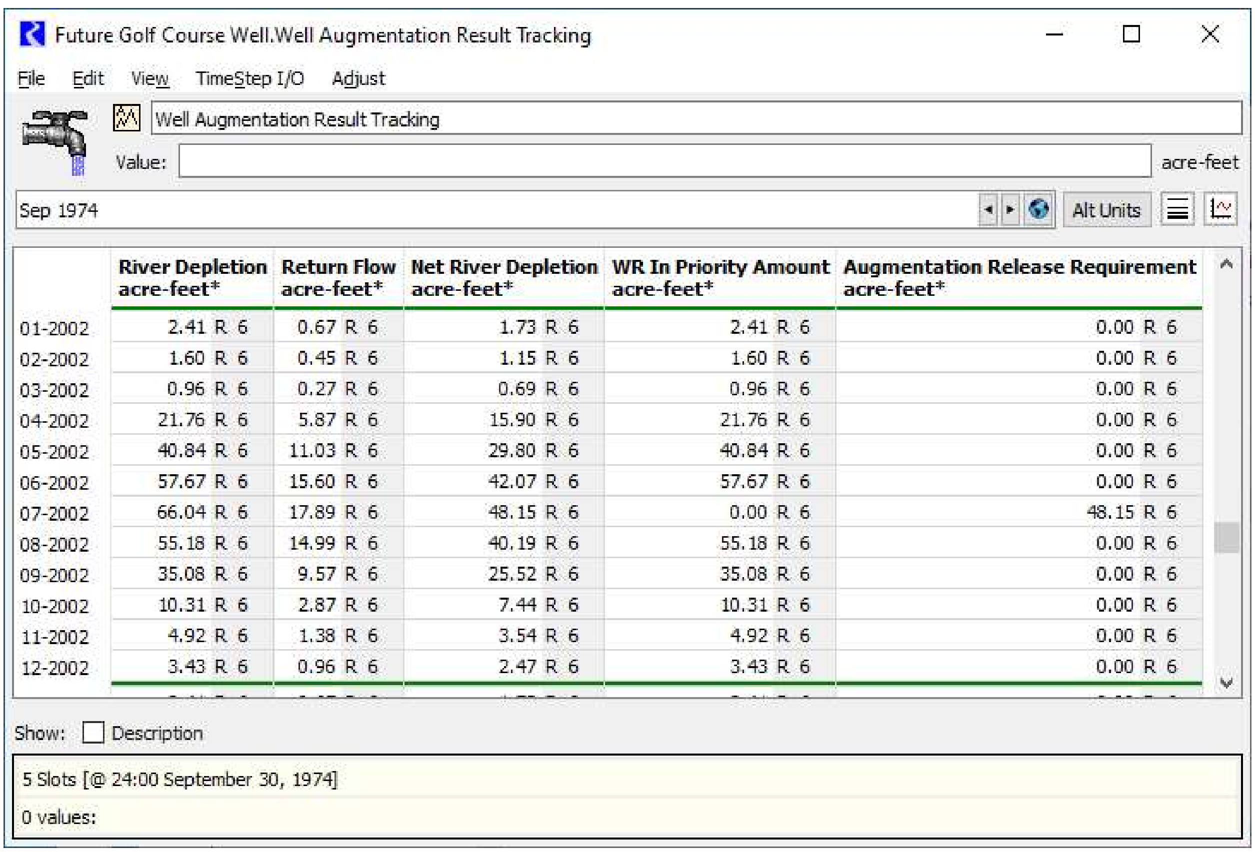
In StateMod, well stations are defined within the ".wes" file and the corresponding well water rights in the ".wer" file. Additionally, a corresponding plan node is used to keep track of the well augmentation plan and sources, and corresponding OPR rights are used to check the well water right's priority status and release water from augmentation sources when the rights are out of priority.

In RiverWare, the well water user (named "Future Golf Course Well"), was implemented as a Water User object only linked to the network by its return flow, but with no other physical links or accounting supplies. In StateMod, "you can't stop the wells", which means that they are simulated as pumping and depleting the river before their in-priority status is determined. This is necessary because surface water depletions from wells are lagged and therefore the current timestep's depletions are dependent on previous timestep pumping. This representation was also implemented in RiverWare. To do this, when turned on, the well object is configured appropriately by an Initialization Rule and a first-timestep only rule (called "Well Setup Rule" and "Set Well Lagged River Depletions", respectively) which allow the object to dispatch and solve for the entire run period at the beginning of the very first timestep, which allows its return flows to be seen in the network.

Then, since there was not an appropriate object method to represent a lagged river depletion, these depletions were calculated and set to the network by rule, which could also be done all at once on the start timestep. Conceivably, an additional water user method(s) could be developed by CADSWES that would facilitate the representation of temporally lagged river depletions associated with well uses.

A further nuance that also complicated matters slightly is that within StateMod, the river node that sees the surface water depletion from the well actually has that depletion split into two parts that impact the river in slightly different locations. The part that represents the river depletion corresponding to the same timestep depletion (termed "River by Well" in StateMod output), comes out of a reach *below* a surface water diversion from that reach. However, the part that represents the lagged depletions from previous months (termed "Well Depletion"), comes out of a reach *above* a surface water diversion. StateMod separates these impacts because the impact of a previous months pumping on the river influences the water supply available to all users before any diversions occur while the impact of the current months pumping impacts water rights that are junior to the well only. This separated representation was replicated in the RiverWare model. However, this did necessitate the inclusion of an additional reach object below the reach being depleted, so that the mass balance for the native flow available to the water user diverting from the reach was determined in the exact same order as in StateMod.

Due to the fact that the well pumping and depletion occurs regardless of in-priority status, the well water user's water right account was not linked to the native allocatable flow chain in the accounting network. This is because the native flow depletion is already included, and therefore an allocation diversion to that water right account would in fact be double counting the impact on the native flow chain. Thus, a rule was written to evaluate the well water right's priority status against all downstream water rights to determine whether the well's depletion was in-priority or not. If not, the same rule (named "Set Well Augmentation Releases as Needed") sets the appropriate augmentation release from the corresponding reservoir to make up for the out of priority depletion. This rule also sets the results of its calculation to a tracking slot to facilitate review of results and understand of how the process works, which is shown in Figure 18 below. A more efficient, internal method by which to evaluate the priority status of well water rights could conceivable be developed and implemented to RiverWare.



	River Depletion acre-feet*	Return Flow acre-feet*	Net River Depletion acre-feet*	WR In Priority Amount acre-feet*	Augmentation Release Requirement acre-feet*
01-2002	2.41 R 6	0.67 R 6	1.73 R 6	2.41 R 6	0.00 R 6
02-2002	1.60 R 6	0.45 R 6	1.15 R 6	1.60 R 6	0.00 R 6
03-2002	0.96 R 6	0.27 R 6	0.69 R 6	0.96 R 6	0.00 R 6
04-2002	21.76 R 6	5.87 R 6	15.90 R 6	21.76 R 6	0.00 R 6
05-2002	40.84 R 6	11.03 R 6	29.80 R 6	40.84 R 6	0.00 R 6
06-2002	57.67 R 6	15.60 R 6	42.07 R 6	57.67 R 6	0.00 R 6
07-2002	66.04 R 6	17.89 R 6	48.15 R 6	0.00 R 6	48.15 R 6
08-2002	55.18 R 6	14.99 R 6	40.19 R 6	55.18 R 6	0.00 R 6
09-2002	35.08 R 6	9.57 R 6	25.52 R 6	35.08 R 6	0.00 R 6
10-2002	10.31 R 6	2.87 R 6	7.44 R 6	10.31 R 6	0.00 R 6
11-2002	4.92 R 6	1.38 R 6	3.54 R 6	4.92 R 6	0.00 R 6
12-2002	3.43 R 6	0.96 R 6	2.47 R 6	3.43 R 6	0.00 R 6

Figure 18: RiverWare Well Depletion and Augmentation Requirement Tracking Slot as implemented.

4.4.2 Comparison of Model Results and Discussion

To evaluate the representation of the well in RiverWare, a comparison model run was made in each model with the well depletion and augmentation turned on, and the model results were compared. This model configuration was simply called "Well & Augmentation On".

It was found that RiverWare's representation matched StateMod's nearly identically, with one caveat that stems from a nuance within StateMod. Through this comparison, it was discovered that StateMod will use a "To/From GW Storage" parameter to balance its available flow chain when there is a well depletion that would cause the available flow to go below 0 at any point through the system, as described in the StateMod documentation on page 266. In these situations, StateMod will add the required flow amount to one timestep, and then remove it from the next, which thus has impacts on the available flow chain on both timesteps. This occurs in July and August of 2002 in the comparison run.

Additionally, StateMod seemingly allows this "To/From GW Storage" balancing to occur anywhere along the length of the river and thus it can occur nowhere in proximity to the actual well depletion. This impact was also observed to occur at the same level whether the augmentation requirement was turned on or off, from which it can be deduced that StateMod applies this term sometime at or near the beginning of its solution process, and then does not re-evaluate its need once an augmentation release is applied. If it were re-evaluated, the augmentation release would essentially eliminate the need for the balancing term. While this method could certainly be replicated by various means in RiverWare if desired, it was not during this study.

4.5 Offstream Reservoir Storage and Operations

4.5.1 Overview and Specific Model Configurations

The ability of RiverWare to simulate operations associated with offstream reservoir storage and operations was evaluated using the various operations of the offstream Wolf Creek Reservoir (WCR). Ultimately, the RiverWare simulation of these operations was found to fully match the StateMod solution, which is discussed further below.

As summarized above in Table 3 and described below, four specific model configurations were used to compare the simulation of these operations in an individual manner, as well on an all-together combined basis.

1. **WCR Base Ops**. Includes below items a-d.
2. **WCR Base Ops + Exchange**. Includes below items a-d & e.
3. **WCR PumpTo + Fish Release Only**. Includes below items a & e only.
4. **WCR All Ops On**. Includes all below items, a-f.

The six associated individual operations are summarized as follows:

a. Pump to WCR from mainstem White River when WRs are in-priority *(StateMod OPR type 11)*.
b. River release to downstream Rangely demand as needed when direct flow WRs are out-of-priority *(StateMod OPR type 2)*.
c. River release to downstream Future Energy ("GasOil") demand as needed when direct flow water rights are out-of-priority *(StateMod OPR type 2)*.

d. Pipeline release to upstream tributary Piceance Creek "OilShale" demand as needed when direct flow water rights are out-of-priority *(StateMod OPR type 3)*.
e. River exchange release to upstream tributary Piceance Creek "OilShale" demand as needed when direct flow water rights are out-of-priority *(StateMod OPR type 4)*. When turned on, the exchange demand is senior to the pipeline release.
f. River release to downstream Fish Flow Target ("Target PBO Flow") of 300 cfs when instream flow right is out-of-priority and target is not fully met *(StateMod OPR type 1)*. It should be noted that to simulate the WCR Fish Target Release in StateMod, the associated ISF right must also be turned on as it was found that otherwise StateMod would deliver 300 cfs from WCR regardless of the other flow in the river at the target node, and thus this individual point ISF right was turned on in both models when this operation is present.

4.5.2 Representation in RiverWare

In StateMod, six different operational rights (OPRs) of 5 different OPR types are used to simulate these operations as shown above. In RiverWare, these operations were implemented in 5 distinct rules, while the "Pump To WCR" was implemented to occur automatically within the existing water right rules and thus did not require its own rule.

As part of the incorporation of the WCR operations in the RiverWare model, custom generalized RiverWare rule functions were developed to efficiently simulate the various storage deliveries to water users, either by direct river delivery or by exchange. These rules were previously discussed in Section 3.8 and portions were shown in Figure 15 and Figure 16.

4.5.3 Comparison of Model Results and Discussion

As mentioned above, the RiverWare simulation of these operations was found to fully match the StateMod solution for each specific configuration as well as for all of the operations combined. Accordingly, the complete model results for the rest of the system were also found to be identical. Notably, this was found to be true even considering that StateMod simulates these operations within the water right priority system, while the associated RiverWare rules are executed outside of the RiverWare water rights solver process. In order to replicate the StateMod operations, it was found that the 5 individual operational rules simply had to be ordered to fire in the same order, relative to each other, as the StateMod OPRs. In the implemented RiverWare solution process, the water rights solver is re-fired after each individual operation to incorporate any potential impacts on the water right system solution (e.g., allocating any additional return flows generated by the delivery).

Although it obtains the exact same results, a notable difference in the manner in which some these operations are simulated in RiverWare is that explicit supply flow chains and delivery accounts are used to distinguish storage deliveries from direct flow water right deliveries. In addition to keeping the deliveries separate from the allocatable flow supply chain, and thus preventing the water right solver from potentially allocating this water to other users, this allows for the explicit tracking of the individual flow components through the river nodes in between the release and the delivery. As illustrated with the following example, this representation provides easier access to detailed results and allows for various enhanced analysis over the StateMod representation.

To highlight this explicit representation an example of a 10-month mid-run time period is provided below in Figure 19. In April 1977 in this example, there are two distinct deliveries from Wolf Creek Reservoir, one from the “Energy” storage account to the “Future Energy Development” water user just downstream of the reservoir, and one from the “Fish” storage account to the Fish Target ISF node located well downstream of the shown nodes. In the schematic, dark blue arrows and boxes are used to highlight various “Energy” items, orange for “Fish” items, and green for “Native” items.

As shown in Figure 19, it is easy to track the distinct release amounts all the way through the network from their sources to their uses. Walking through on the April 1977 timestep and following the order they are simulated by the model:

1. The *Future Energy Development* diversion water right was found to not be in-priority by the water rights solver, as shown in the bottom center account. Thus, there is no diversion from the *Future Energy Development Div* reach’s *Native* account, shown in the middle left account.

2. Thus, a delivery of 2,983 AF is made to meet the full demand from *Wolf Creek Reservoir*’s *Energy* storage account. This amount in then highlighted in dark blue boxes along the right side and originating from the storage account, passing through the intermediate *Wolf Creek Pump Station Div*’s, and into the *Future Energy Development Div* reach where it is diverted to *Future Energy Development*’s *Delivery* account (distinguishing it from any in-priority native diversions). The *Deliveries* flow account chain below the diversion reach node is also then seen to have 0 outflow reflecting that it is the only delivery currently using that flow supply chain.

3. Subsequently, at the downstream Fish target node, there was no Native flow in the river, as shown in bottom left, and the ISF right was found to be out-of-priority (not shown). Thus, a release of 17,852 AF (300 cfs) was made from *Wolf Creek Reservoir*’s *Fish* storage account. This amount in then highlighted in the various orange boxes, originating from the storage account, passing through the intermediate reaches, including the *Wolf Creek Pump Station Div* and *Future Energy Development Div* reaches shown and many more not shown downstream reaches, until it reaches the Fish target node where it is shown to be the only flow currently existing in the river at that point, thus meeting the Fish target it was released for exactly.

Furthermore, as highlighted in red, the total flow breakdown at the in-between “Wolf Creek Pump Station Div” reach node is readily available and shows the explicit flow components that make up that node’s total outflow. Here, it is easy to trace the specific Fish and Energy delivery amounts that are passing through the node, which combine with the Native passthrough flow to equal the total node outflow.

While helpful even in this simple situation with just two concurrent reservoir releases, this type of explicit representation becomes even more advantageous when attempting to decipher much more complicated operations present in many Colorado basins that can include numerous simultaneous releases, exchanges, and other transactions to and from many different basin locations.

It should also be noted, that the various “mid-solution” values for all of these parameters are readily available during the simulation process. Thus, if on the April 1977 timestep the run was paused after the Energy release rule but before the Fish release rule, the “Wolf Creek Pump Station Div” would show the current total node outflow made up of only the Native passthrough and Energy delivery, as the yet-to-be-set Fish release would be 0 at that point. Combined with the explicit representation of all of the various individual components, this ability leads to an incredibly transparent and traceable simulation process, as well as being indispensable for model debugging.

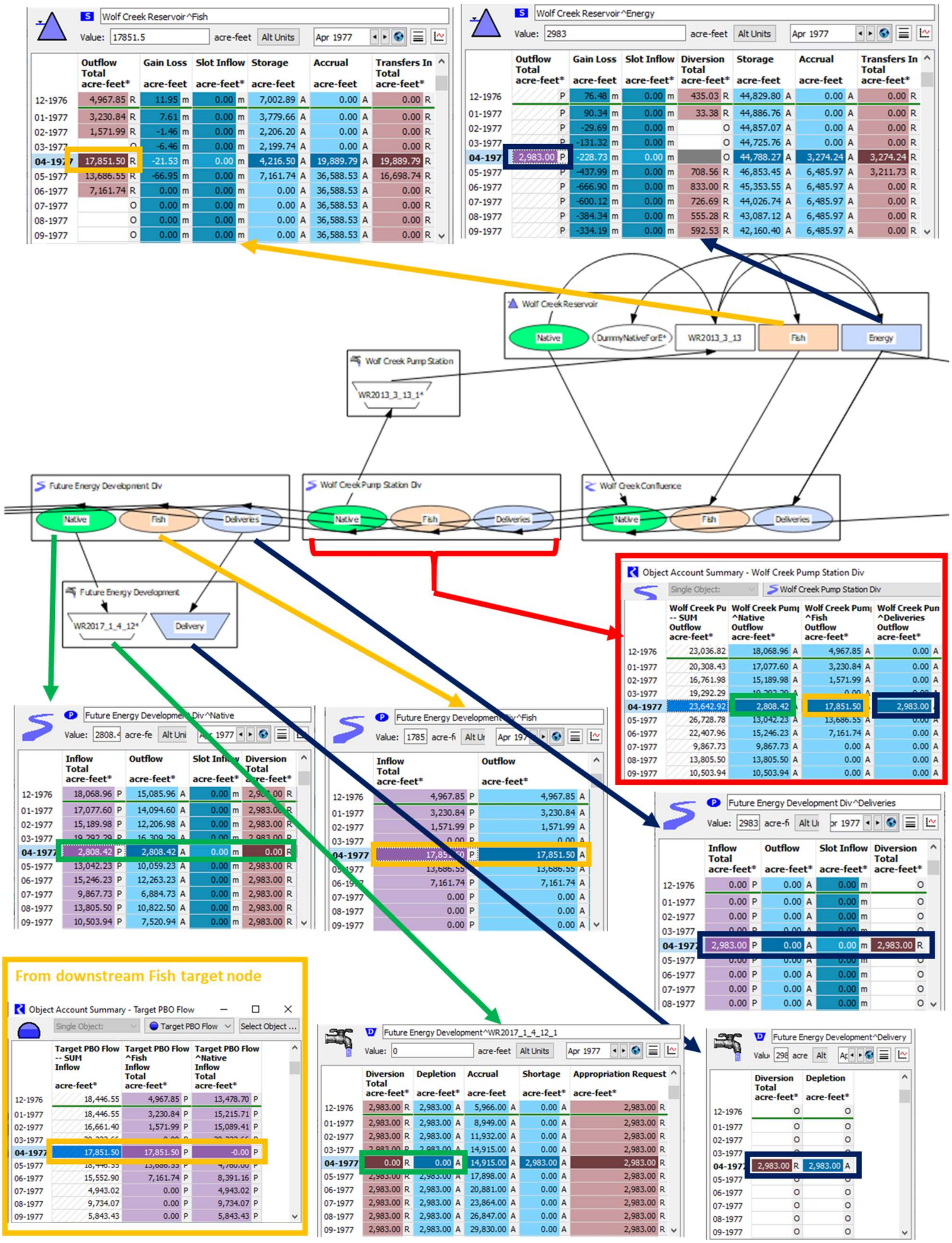


Figure 19: RiverWare screenshot schematic illustrating detailed results of river flow components with individual deliveries. See detailed description in text.

4.6 Changed Water Rights

4.6.1 Overview and Specific Model Configurations

The ability of RiverWare to simulate changed water rights was evaluated through the inclusion of a changed water right and associated operations in both models and comparison of the simulation results. Since the original White Basin StateMod model does not include any changed water rights, the model was modified to include the operations associated with a typical water rights change case where a municipality (*Meeker Demand*) has partial ownership of water rights from an irrigation ditch (*Oak Ridge Park Ditch*), as previous described in Section 2.2.

As summarized above in Table 3 and described below, two model configurations were used to specifically compare the simulation of changed water right operations.

1. **Meeker Changed WRs Base Ops**. This configuration includes:
    a. Split yield of Oak Ridge Park (OakRP) direct flow water rights (7 individual WRs) by ownership to Meeker Demand (5%) and OakRP-Irrigation (95%) water users, subject to monthly and annual volume limits on each of the individual WRs.
    b. Deliver OakRP-Irrigation yield to remaining OPR-Irrigation demand (on *Oak Ridge Park Off Channel Ditch* water user in model).
    c. Deliver OakRP-Meeker yield to meet remaining Meeker Demand not met by its other in-priority direct flow WRs, which are located on the *Meeker Diversion* water user object (note that this node/water user is actually named *Meeker Wells Diversion* although it is not modeled as a well structure in either model*)* which diverts from the river and delivers to the "offstream" *Meeker Demand* water user object. The supplemental delivery of the changed WR yield is also made through the *Meeker Diversion* water user object, but through a distinct Changed WRs diversion
    d. Calculate and track the reusable return flows from the *Meeker Demand* water user generated from the OakRP changed WR yield portion of the delivery.
    e. Calculate and track the return flow (RF) requirements due to the OakRP changed WR yield based on historical consumptive use factors. RF requirements are met by:
        i. RF requirements are "In-Priority".
        ii. Reusable RFs from (d).
2. **Meeker Changed WRs Base Ops + Exchange**. This configuration includes:
    a. All of the operations in (1) above.
    b. Meeker-OakRP yield in excess of current need is attempted to be exchanged into Lake Avery (*Big Bear Creek Reservoir*). Note, this use also generates RF requirements.
    c. Additionally, any RF requirement not met by the first two sources above can also be met by releases from Lake Avery.

4.6.2 Representation in RiverWare

In StateMod, 20 different operational rights of 10 different OPR types are used to simulate these operations. In RiverWare, these operations were implemented in two rules. The first rule, "Operate Meeker's Changed Water Rights", makes all of the necessary calculations and assignments for all of the operations described above in 1a-1d and 2b. The second rule, "Operate Meeker's Return Flow Obligations", does the same for 1e and 2c. The controls that allow a user to easily turn these operations on or off for a given run are located in the “Setup Data.Meeker Changed WRs Ops Controls” table slot. Additionally, the input data and detailed results associated with these operations are contained in the “Meeker OakRP Changed WRs” data object, shown below in Figure 20. Subsequently, Figure 21 shows the “OakRP WR Allocation Breakdown” slot that is used to track each individual part of the OakRP WR allocations, highlighting RiverWare’s ability to tailor the ways in which detailed results are saved and displayed. In StateMod, the same results displayed in this single RiverWare slot are spread throughout the “.xop” and “.xpl” text output files in values rounded to integers as full precision results are not available for OPR and PLN results.

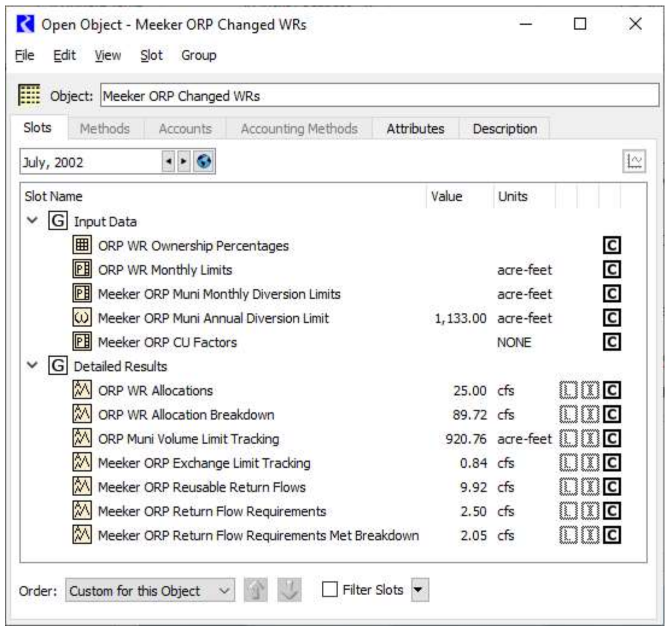
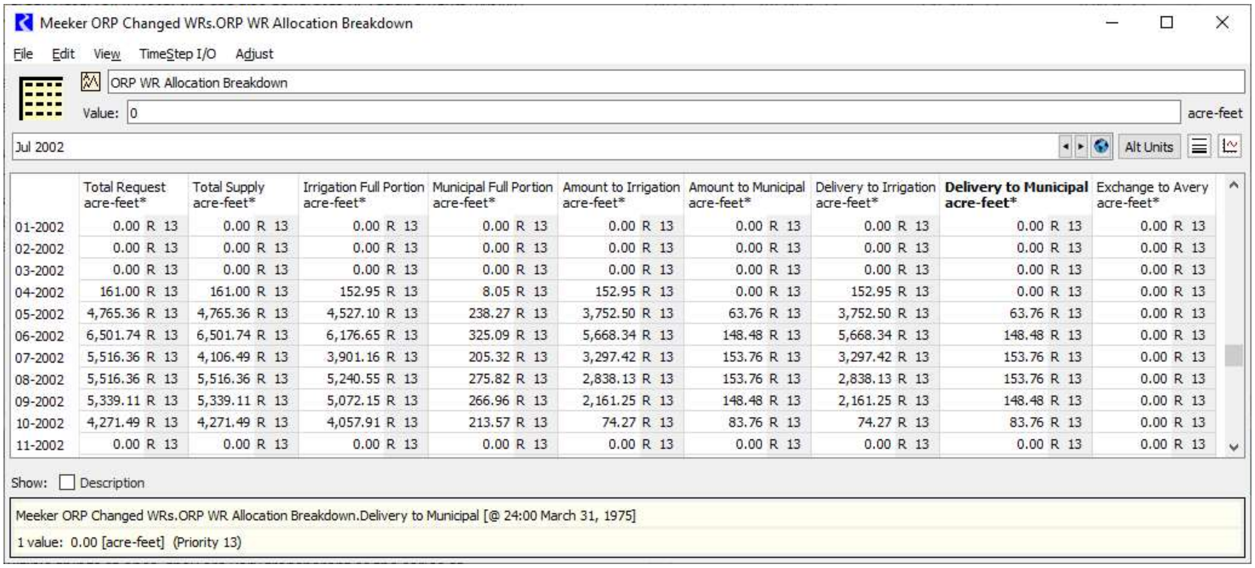


Figure 20: Meeker OakRP Changed WRs data object, which holds the necessary input data and detailed simulation results.



	Total Request acre-feet*	Total Supply acre-feet*	Irrigation Full Portion acre-feet*	Municipal Full Portion acre-feet*	Amount to Irrigation acre-feet*	Amount to Municipal acre-feet*	Delivery to Irrigation acre-feet*	**Delivery to Municipal acre-feet***	Exchange to Avery acre-feet*
01-2002	0.00 R 13	0.00 R 13	0.00 R 13	0.00 R 13	0.00 R 13	0.00 R 13	0.00 R 13	0.00 R 13	0.00 R 13
02-2002	0.00 R 13	0.00 R 13	0.00 R 13	0.00 R 13	0.00 R 13	0.00 R 13	0.00 R 13	0.00 R 13	0.00 R 13
03-2002	0.00 R 13	0.00 R 13	0.00 R 13	0.00 R 13	0.00 R 13	0.00 R 13	0.00 R 13	0.00 R 13	0.00 R 13
04-2002	161.00 R 13	161.00 R 13	152.95 R 13	8.05 R 13	152.95 R 13	0.00 R 13	152.95 R 13	0.00 R 13	0.00 R 13
05-2002	4,765.36 R 13	4,765.36 R 13	4,527.10 R 13	238.27 R 13	3,752.50 R 13	63.76 R 13	3,752.50 R 13	63.76 R 13	0.00 R 13
06-2002	6,501.74 R 13	6,501.74 R 13	6,176.65 R 13	325.09 R 13	5,668.34 R 13	148.48 R 13	5,668.34 R 13	148.48 R 13	0.00 R 13
07-2002	5,516.36 R 13	4,106.49 R 13	3,901.16 R 13	205.32 R 13	3,297.42 R 13	153.76 R 13	3,297.42 R 13	153.76 R 13	0.00 R 13
08-2002	5,516.36 R 13	5,516.36 R 13	5,240.55 R 13	275.82 R 13	2,838.13 R 13	153.76 R 13	2,838.13 R 13	153.76 R 13	0.00 R 13
09-2002	5,339.11 R 13	5,339.11 R 13	5,072.15 R 13	266.96 R 13	2,161.25 R 13	148.48 R 13	2,161.25 R 13	148.48 R 13	0.00 R 13
10-2002	4,271.49 R 13	4,271.49 R 13	4,057.91 R 13	213.57 R 13	74.27 R 13	83.76 R 13	74.27 R 13	83.76 R 13	0.00 R 13
11-2002	0.00 R 13	0.00 R 13	0.00 R 13	0.00 R 13	0.00 R 13	0.00 R 13	0.00 R 13	0.00 R 13	0.00 R 13

Figure 21: RiverWare "Meeker ORP Changed WRs.ORP WR Allocation Breakdown" slot displaying detailed results for the changed WR allocation and its various portions.

While the two RiverWare rules used to simulate these changed water right operations are advanced RiverWare rules that each do multiple things at once, they are very transparent as the series of calculations and slot assignments they make is displayed within the rule, as shown in the clipped rule section in Figure 22 below, which shows how the reusable return flow is calculated. This allows for model users, even those who are not advanced RiverWare developers, to understand the exact simulation process used in a logical manner. It also allows for particular results to be traced down to their individual calculations and variables, especially considering that it is possible to pause simulation at any given point and work through the process in a step-by-step manner.

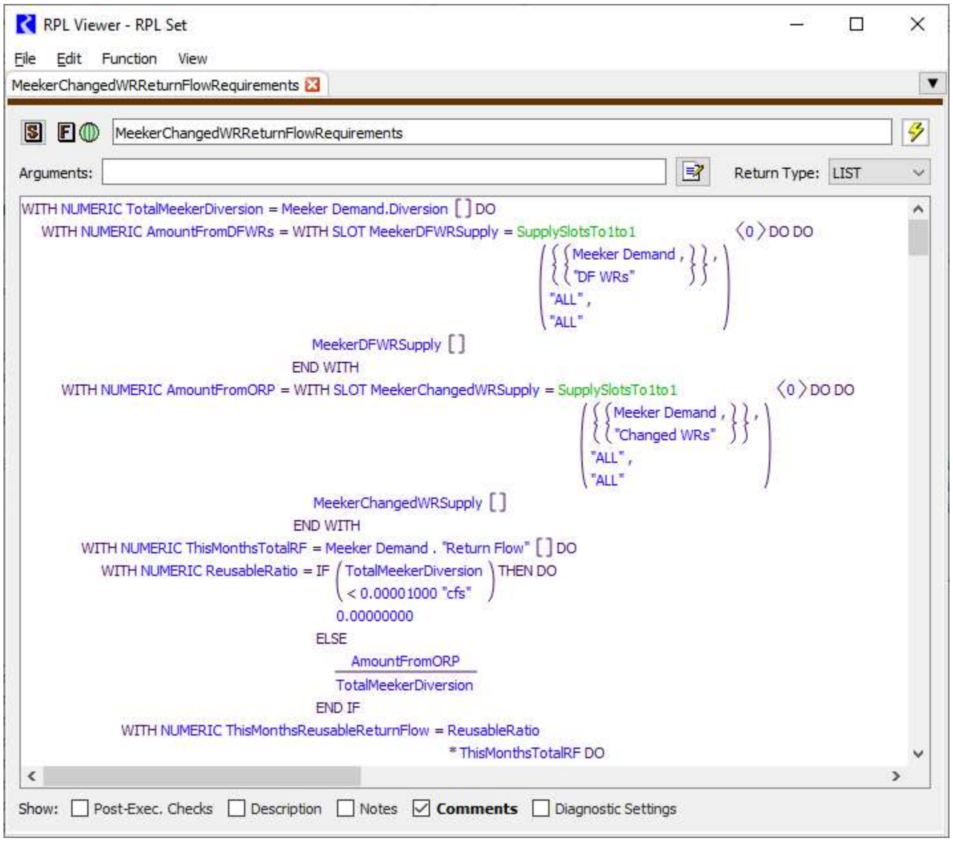


Figure 22: Section of RiverWare rule showing the calculation process used to determine Meeker's reusable return flows generated from use of its OakRP changed WR yields.

4.6.3 Comparison of Model Results and Discussion

For the first model comparison configuration, "Meeker Changed WRs Base Ops" (without the exchange), the models were found to come to identical results aside from just a single difference. This difference was that on one timestep, July 2002, the RiverWare model found a higher allocation for the direct flow water rights for the *Meeker Diversion* than that solved by StateMod (RiverWare found 456 AF in-priority, while StateMod found 405 AF). Because the changed OakRP WRs were sufficiently in-priority, the total diversion to the Meeker Demand remained identical, as the StateMod model simply delivered a higher amount of the Meeker-OakRP water (RiverWare delivered 154 AF, while StateMod delivered 205 AF).

Interestingly, the reason for this difference was traced to the manner in which StateMod simulates the changed water right operations. In the StateMod simulation process, the full supply of the changed diversion water rights are "diverted" from the river at their individual priorities and held temporarily in a "plan" structure until StateMod reaches the priority of the changed water right OPRs defining the uses of this water. Any associated OPRs then have access to this water and can "release" it from the plan for a delivery or other operation. Following the OPRs that are able to use this water, any unused supply is then "spilled" back to the river through the use of "type 29" OPRs. Similarly, reusable return flows generated from deliveries of changed water rights or other reusable sources are also held in plan structures until they are "spilled" back into the river system.

However, it is the fact that this water supply is temporarily held in the plan structure outside of the rest of the river system that ultimately caused this result difference. The water rights and OPRs that are simulated during the time after this water gets placed in the plan and before it gets spilled back into the river do not have access to the excess supply that will eventually get returned to the river. While previously shorted water rights can get re-operated and be able to take advantage of the increased river flow, any OPR operations that were already simulated in the intervening period will not be re-evaluated. Thus, when the originally solved Meeker Demand partial shortage is made up for with the delivery of yield from the changed OakRP WRs, StateMod will not re-evaluate how much supply it receives from its direct diversion water rights and its need for supplemental sources.

The manner in which these changed WR operations were implemented in the RiverWare model does require that the full OakRP WR supply ever be held outside of the river network and spilled back into the system later during simulation. Because the RiverWare model is continuously re-evaluating all of the water right allocations and operations and adjusting everything accordingly, its results are able to incorporate the increased direct diversion water right supply, and therefore reduce the use of the changed OakRP WR yields.

This single, minor difference was discussed above in some detail because it is essentially due to the same reason that the second model comparison configuration here, the “Meeker Changed WRs Base Ops + Exchange”, was found to have more numerous differences in model results. This configuration adds the potential for exchange of excess Meeker-OakRP yield upstream into Lake Avery. Although the observed differences in this case are minor and would almost certainly have a negligible impact on overall results for all but the most detailed studies, many of them were traced to their root causes for the purposes of this study.

In this configuration, in addition to some differences stemming from the mechanism described above, many of the observed simulation differences were due to another similar reason. In StateMod, this exchange operation is simulated within the water right priority system, and it happens to be implemented senior to some of the Lake Avery storage water rights. This causes the exchange of water into the reservoir to be made prior to the determination of the allocations to those junior storage rights, effectively reducing the yields of those storage water rights and increasing the exchange use of the Meeker-OakRP yields. This can also lead to some cascading effects, such as due to the accrual/volumetric limits associated with both the storage rights and the Meeker-OakRP changed WRs, although in this case, the overall reservoir storages are observed to quickly reconverge.

In contrast, the implementation of this exchange in RiverWare does not inherently put its priority above those of the Lake Avery storage water rights, although it could be made to do so if that were the way the real world operation would be made. In addition to this priority difference, the exchange potential through the intervening reaches between the upstream reservoir and downstream water source may also be calculated differently between the models. This, again, is because this operation is determined in StateMod before there is an entire network water right allocation solution, whereas in RiverWare it can be continuously re-evaluated to incorporate any other potential impacts, such as those due to junior water right supply and return flows or other basin operations.

4.7 ADDITIONAL COMPARISON RUN WITH MULTIPLE OPERATIONS

The previously discussed model comparisons were designed chiefly to evaluate the ability of RiverWare to replicate StateMod's simulation of water rights and associated operations on a piece-by-piece basis. In order to be useful in complex systems, however, a water resource system model must be able to appropriately simulate many different operations occurring simultaneously. Here, due to the fundamental differences in how other operations are integrated with water right simulation between platforms (as has been previously discussed), it was not expected that RiverWare and StateMod would always come to the same exact model results when multiple operations were considered together. However, it was expected and found to be true that the model results would still be very similar, as discussed further below.

As a precursor, however, it is also important to note that there is not a right answer here and it is not appropriate to state that either platform simulates operations in better manner than the other based on this comparison. It seems likely that some types of operations are more suited to being simulated directly during the simulation of water right allocation, while some are better represented by layering them onto the water right solution outside of the water right simulation process. It can be stated, however, that while StateMod's simulation of operations is limited to only its preexisting "OPR types", the flexibility RiverWare's simulation process, and especially its customizable rules, functions, and methods, allows for the simulation of a nearly limitless range of operation types.

Still, paired model runs were made to compare how the RiverWare and StateMod models performed when simulating multiple, concurrent operations. This final comparison run, termed "All WCR + Meeker Changed WRs Ops" in Table 3, was configured to simulate both the full set of Wolf Creek Reservoir operations and the full set of Meeker changed water right operations. Recall that the primary difference in operational simulation here is that while StateMod simulates its operations within the same process as its simulation of water right allocation, RiverWare simulates its water right allocation separately and then layers various operations onto that solution. However, in order to maintain as much similarity as possible in these runs, the RiverWare operational rules were ordered to reflect the same relative StateMod OPR priority order.

As expected, various minor differences are observed between the model results from this configuration of multiple operations. However, as shown in Figure 23 and Figure 24 below, the impacts of the various differences on the overall results were very limited in both spatial and temporal scope before results came back together, and thus the broad model results were found to be exceedingly similar. Interested parties are encouraged to use the provided Comparison Workbook to explore the various simulation differences under this configuration, as well as others of interest.

One typical finding during this comparison is that often, these observed differences can be traced to instances where, for some water user or reservoir associated with additional operations, the RiverWare simulated total WR amount in priority is higher than that found by StateMod. This also typically results in differences in the associated operations, and is also due to essentially the same mechanism described above in Section 4.6.3. These differences can be traced back to the fact that although StateMod simulates operations (including reservoir releases to meet demands) within its water right priority system, StateMod will not reduce already made releases or diversions, including those relating to exchanges. This means that even when a subsequent operation (including supply and return flow from a junior water right) would potentially result in a higher allocation to a senior water right, the already made OPR delivery to that water user will not be reduced. Thus, the water user would not be able to take advantage of the increased in-priority supply and, essentially, results in an unnecessary use of storage or other supplies. Although the fact that the operations compared here do not actually exist in the basin precludes the ability to evaluate which platform matches real world operations in a more accurate manner, this essentially means that the RiverWare model was able to simulate a more efficient manner of basin operations than was simulated by StateMod.

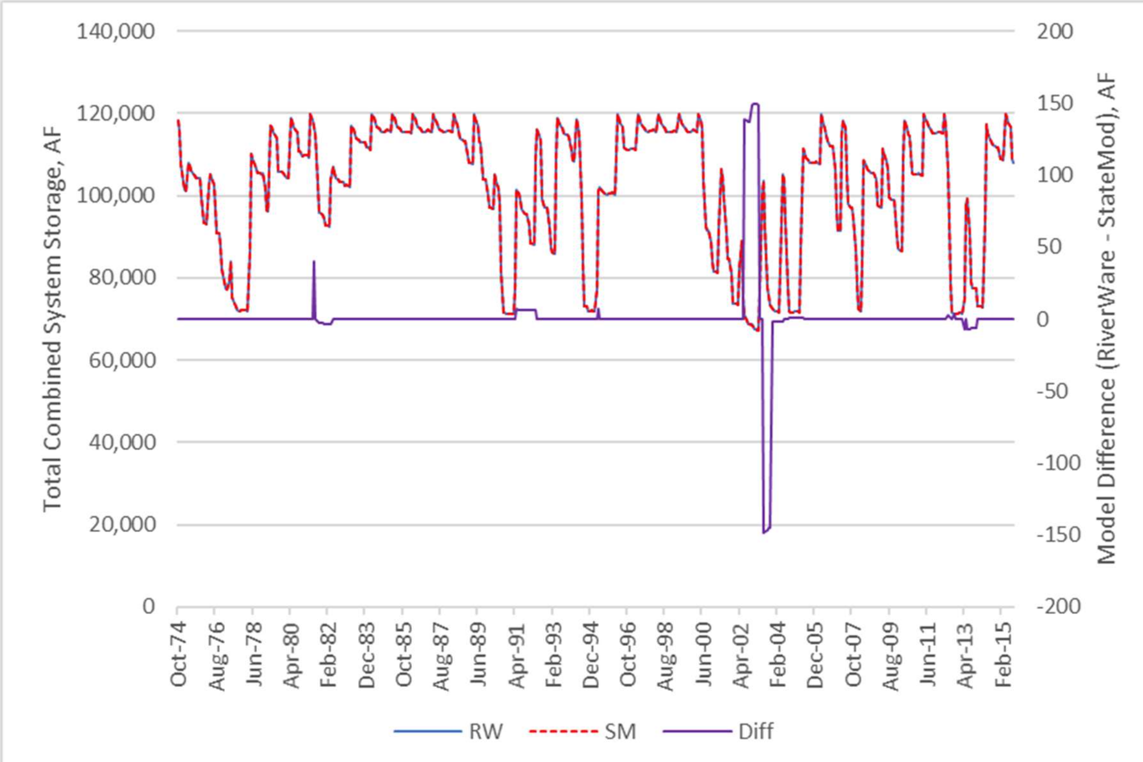


Figure 23: RiverWare and StateMod Results for Total Combined System Storage. NOTE LEFT/RIGHT AXIS SCALE DIFFERENCES.

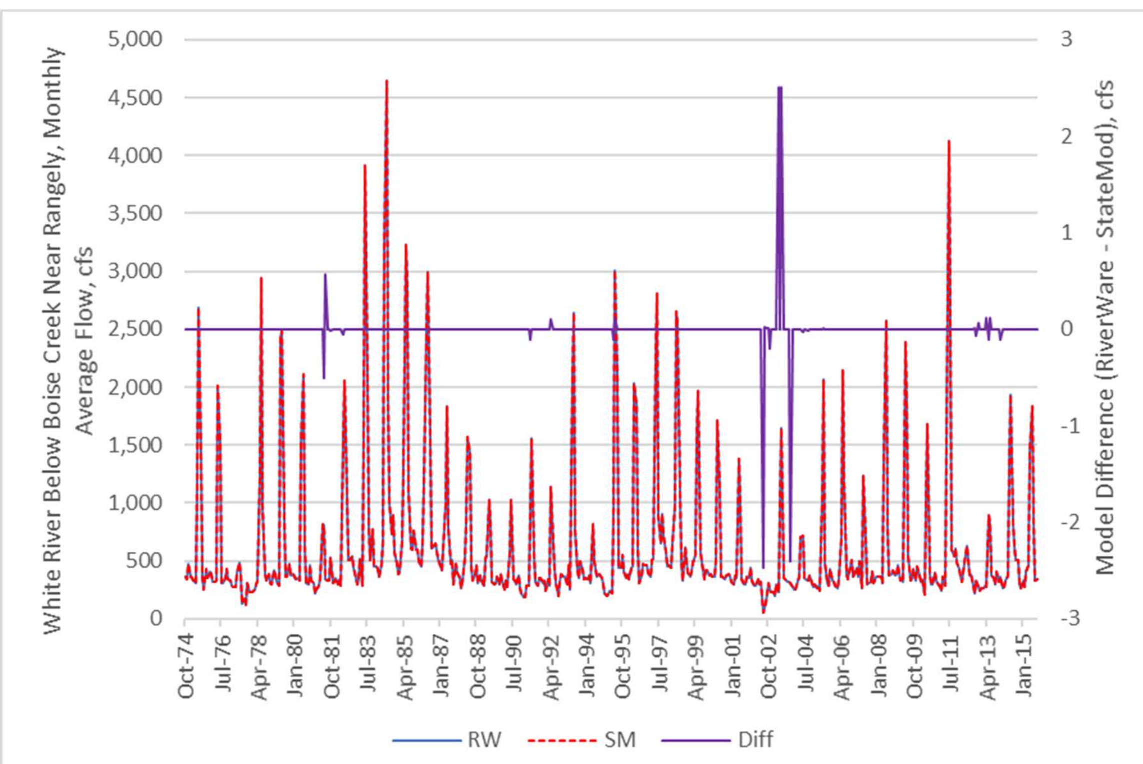


Figure 24: RiverWare and StateMod Results for White River near Rangely. NOTE LEFT/RIGHT AXIS SCALE DIFFERENCES.

4.8 Water Rights Call and Control Location Reporting

Prior to this discussion, it is important to note that, while it is a convenient manner in which to explain water supply allocation by water rights, and is often applicable to real-world administration procedures, the determination and applicability of a river's calling water right is generally not as clear cut or imperative as it seems. The water right allocation algorithms used by both platforms do not work by "calling out" upstream junior rights in the manner typically thought of in real world administration, but rather allocate the available water supply throughout network in a senior to junior fashion until the available supply is exhausted. For this reason, the determined "calling water rights" are model results and are not descriptive of the manner in which the models actually work. Thus, in general, a model's resulting calling rights are most useful and applicable for model calibration and validation purposes.

It should also be noted that it can be misleading to expect or define a single calling water right or call priority. In fact, due to the way that water enters river networks in a variable and spatially distributed manner, and the way that water rights of varying priorities are also distributed throughout the basin (including on tributaries), there can often be multiple water right calls occurring simultaneously throughout the basin. Both the StateMod and RiverWare platforms are able to account for this and can be used to report multiple calling rights and locations when applicable.

StateMod's standard output includes the ".xca" text file, which is used to report the estimated water right calls through the model run. Additionally, the ".xdd" text file reports the *control location* and *control right* that was found to limit the water right supply for each diversion structure (when applicable). While the identification and reporting of calling water rights is not a standard output of the RiverWare SolveWaterRights function, it can be achieved through rules based on the results that are provided. The RiverWare water right solver does report a "Temp Reason" parameter for each individual water right simulated that identifies a downstream calling water right, if one exists. This is analogous in functionality to StateMod's *Control Location* and C*ontrol Right* ".xdd" file results, except that RiverWare natively reports this on a "per water right" basis rather than a "per water user" basis. Nevertheless, this information can be processed with rules and/or functions to obtain the "per water user" result. These results can then be used to estimate the overall water right calls present in the basin for each timestep to report the same information provided in the StateMod ".xca" file.

Thus, in order to demonstrate that RiverWare can replicate the water right call and location report, rules and functions were developed in the RiverWare model to provide the same water right call output as StateMod. First, slots were created on each object with water rights (water users, reservoirs, and instream flow control points) to report its *Control Location* and *Control Right* results set by a rule, which are equivalent to the results provided in the StateMod ".xdd" file. One item of note here is that StateMod often reports control locations for structures even when the structures have no demand and are therefore not shorted, and this reporting was not implemented in RiverWare.

Finally, an end-of-timestep rule was written to determine and report the overall basin water right call results, which are equivalent to the ".xca" results, as shown in Figure 25 below. Of note here is that StateMod is inconsistent in its reporting of "headgate limits" in the ".xca" file, and thus the RiverWare overall call output was set to not report these limits, although they are shown in the individual object output. As shown in the figures, it was found that RiverWare was able to replicate the same water right call results as StateMod when other simulation differences (i.e. due to operations) were not present.

Diagnostics Output Window - RiverWare 8.0.6 - WhiteBasinRiverWareModel_WRCalls.mdl.gz

File | Edit | Settings | Search: | Filter: | Ignore Case | RegEx | Auto Scroll

Diagnostics Message
1976-Jun : No calls
1976-Jul : Call Location = Hill Creek Ditch No 2 @ WR Priority Date = 12:48 January 31, 1938. Impacted structures: {"Hill Creek Ditch No 3"}
1976-Jul : Call Location = Square S Cons Ditch Sys @ WR Priority Date = 12:02 May 1, 1886. Impacted structures: {"Future Oil Shale Development", "Morgan
1976-Aug : No calls
1976-Sep : Call Location = Metz Ditch @ WR Priority Date = 12:00 July 15, 1888. Impacted structures: {"Future Oil Shale Development", "Morgan Ditch 2"}
1976-Oct : No calls
1976-Nov : No calls
1976-Dec : No calls
1977-Jan : No calls
1977-Feb : No calls
1977-Mar : No calls
1977-Apr : No calls
1977-May : Call Location = B A and B Ditch No 1 @ WR Priority Date = 13:02 January 31, 1938. Impacted structures: {"Bruce Baker Ditch", "Lagrange Ditch",
1977-May : Call Location = Dreyfuss Ditch @ WR Priority Date = 12:15 November 26, 1958. Impacted structures: {"Johnson Ditch"}
1977-May : Call Location = Metz Ditch @ WR Priority Date = 12:36 October 15, 2123. Impacted structures: {"Future Oil Shale Development", "Morgan Ditch 2
1977-May : Call Location = Piceance Creek Blw Ryan Gulch AggDiv @ WR Priority Date = 12:01 April 15, 1887. Impacted structures: {"Belot Moffat Ditch", "Bl
1977-Jun : Call Location = B A and B Ditch No 1 @ WR Priority Date = 12:01 October 15, 2123. Impacted structures: {"Bruce Baker Ditch", "Lagrange Ditch",
1977-Jun : Call Location = Hill Creek Ditch No 2 @ WR Priority Date = 12:48 January 31, 1938. Impacted structures: {"Hill Creek Ditch No 3"}
1977-Jun : Call Location = Square S Cons Ditch Sys @ WR Priority Date = 12:00 December 26, 1886. Impacted structures: {"Belot Moffat Ditch", "Black Eagle
1977-Jul : Call Location = B A and B Ditch No 1 @ WR Priority Date = 13:02 January 31, 1938. Impacted structures: {"Bruce Baker Ditch", "Lagrange Ditch", "
1977-Jul : Call Location = Piceance Creek Blw Ryan Gulch AggDiv @ WR Priority Date = 12:01 April 15, 1887. Impacted structures: {"Belot Moffat Ditch", "Blac
1977-Jul : Call Location = Square S Cons Ditch Sys @ WR Priority Date = 12:00 May 5, 1886. Impacted structures: {"Future Oil Shale Development", "Morgan
1977-Aug : Call Location = Square S Cons Ditch Sys @ WR Priority Date = 12:02 May 1, 1886. Impacted structures: {"Future Oil Shale Development"}
1977-Sep : Call Location = B A and B Ditch No 1 @ WR Priority Date = 13:02 January 31, 1938. Impacted structures: {"Lagrange Ditch", "Sprod Ditch 1"}
1977-Sep : Call Location = Metz Ditch @ WR Priority Date = 12:36 October 15, 2123. Impacted structures: {"Future Oil Shale Development"}
1977-Sep : Call Location = Piceance Creek Blw Rio Blanco AggDiv @ WR Priority Date = 12:00 April 2, 1883. Impacted structures: {"Gordon Ditch", "Hanrahan

```
 OutCallR    Year Mon   Day Imcd Call Location   Call Right Call Location Name
___________ ____ ____  ____ ____ ____________   __________ ______________________
OutCallR    1976 JUN     1   -1 NA               -1.0000 NA
 OutCallR    1976 JUL     1   41 4300696          999.0000 HILL CREEK NO 2 DITC_DIV
 OutCallR    1976 JUL     1  146 4300948          999.0000 SQUARE S CONS D SYS _DIV
 OutCallR    1976 AUG     1   -1 NA                -1.0000 NA
 OutCallR    1976 SEP     1  148 4300816          999.0000 METZ DITCH          _DIV
 OutCallR    1976 OCT     1   -1 NA                -1.0000 NA
 OutCallR    1976 NOV     1   -1 NA                -1.0000 NA
 OutCallR    1976 DEC     1  145 43_OilShl       2000.0000 Future Oil Shale Dev_DIV
 OutCallR    1977 JAN     1  145 43_OilShl       2000.0000 Future Oil Shale Dev_DIV
 OutCallR    1977 FEB     1   -1 NA                -1.0000 NA
 OutCallR    1977 MAR     1   -1 NA                -1.0000 NA
 OutCallR    1977 APR     1   -1 NA                -1.0000 NA
 OutCallR    1977 MAY     1   65 4300608          999.0000 DREYFUSS DITCH      _DIV
 OutCallR    1977 MAY     1   87 4300511          999.0000 B A & B DITCH NO 1  _DIV
 OutCallR    1977 MAY     1  143 43_ADW010        999.0000 PICE_ADW PicCrBlRyan_DIV
 OutCallR    1977 MAY     1  148 4300816          999.0000 METZ DITCH          _DIV
 OutCallR    1977 JUN     1   41 4300696          999.0000 HILL CREEK NO 2 DITC_DIV
 OutCallR    1977 JUN     1   87 4300511          999.0000 B A & B DITCH NO 1  _DIV
 OutCallR    1977 JUN     1  146 4300948          999.0000 SQUARE S CONS D SYS _DIV
 OutCallR    1977 JUL     1   87 4300511          999.0000 B A & B DITCH NO 1  _DIV
 OutCallR    1977 JUL     1  143 43_ADW010        999.0000 PICE_ADW PicCrBlRyan_DIV
 OutCallR    1977 JUL     1  146 4300948          999.0000 SQUARE S CONS D SYS _DIV
 OutCallR    1977 AUG     1  146 4300948          999.0000 SQUARE S CONS D SYS _DIV
 OutCallR    1977 SEP     1   87 4300511          999.0000 B A & B DITCH NO 1  _DIV
 OutCallR    1977 SEP     1  132 43_ADW008        999.0000 PICE_ADW PicCrBlRioB_DIV
 OutCallR    1977 SEP     1  148 4300816          999.0000 METZ DITCH          _DIV
```

Figure 25: Sample RiverWare (top) and StateMod (bottom) overall basin water right call results (".xca" results).

4.9 Comparison of Model Run Times

A supplementary result confirmed by this study, although already known to many users, is that there is no doubt that StateMod is a very efficient program in terms of run times and calculation and solution process efficiency. With monthly StateMod models, even with all options enabled, run times can still be tallied in seconds.

The RiverWare model runs do have a significantly longer run time, which seems to be directly related to the number of iterations of the water rights solver required. Recall that these iterations were necessary primarily to incorporate the same-timestep return flow workaround discussed in Section 3.7.3. Thus, if that were incorporated into the water right solver function itself, the run times could be expected to decrease. Additional water rights solver iterations are triggered when the simulation of operations is incorporated into the water rights solver process. This was done to replicate StateMod's simulation process and would not be required for appropriate simulation, which would further decrease run times. For comparison purposes, selected approximate run times are shown below.

- "Base Comparison" run time = ~7 minutes
- "Base + WCR Res Operations and Exchange (no ISFs)" run time = ~8 minutes
- "Base + WCR Res Operations and Exchange (with single, point ISF right)" run time = ~16 minutes
- "Single WRS Call" run time = ~3 minutes

Shown last above, a run was also made where the water rights solver was limited to being called once per timestep. It is notable that this run time of ~3 minutes (for a 41-year run at a monthly timestep), while significantly decreased from the iterative run times, is still much longer than StateMod's run time. It is believed that this is primarily due to the computational overhead due to RiverWare's GUI and continuous object dispatching and network solving characteristics, however this was not investigated in detail. It should also be noted that all model run times are dependent on computer performance.

One potentially equalizing factor in terms of run times that was observed is the efficiency of access to model results. Here, the time comparisons were reversed, as the RiverWare output to Excel DMI took only a few seconds to export a vast amount of results, while the TSTool script used to export StateMod results from the binary output file to Excel for just 13 parameters took approximately 3 minutes.

5 CONCLUSIONS

The primary objective of this study was to evaluate RiverWare's ability to simulate Colorado's complex water right system. This was accomplished by developing a RiverWare model simulating a Colorado basin's water right system, and by comparing its simulation process and results against the existing StateMod model of the same basin.

To support the study's purpose, the White Basin RiverWare model built as part of this study was designed to replicate the StateMod simulation methods as much as possible. This is because the methods used by StateMod have been implemented in a standardized and structured fashion by Colorado's water management agencies for well over a decade and are generally considered to be trustworthy and valid by industry experts. Thus, it was desired to evaluate the extent to which RiverWare can replicate those methods, while also identifying potential areas of issue or incompatibility. Of course, while StateMod's methods are convenient, functional, and trusted, other methods also provide appropriate or enhanced functionality and applicability over a range of model uses, although thoroughly reviewing them was not a part of this study.

This study compared the simulation procedures and results between the RiverWare and StateMod modeling platforms representation of water rights and associated operations in a detailed and technical manner. However, the overall findings and conclusions can be summarized in these main points:

- On an overall basis, RiverWare was found to be able to simulate the allocation of available flow by water rights, as well as other associated water right operations, in a manner very similar, if not identical, to that used by StateMod.
- RiverWare's and StateMod's water right solution algorithms are very similar and were shown to produce identical results when simulating allocation to direct diversion and storage water rights, instream flow rights at points, and several associated water right operations.
- RiverWare's water right solver in its present form has two notable shortcomings relating to StateMod's capabilities. These would likely need to be addressed to remain fully consistent with StateMod's methods, although alternatively, other simulation methods could provide comparable and equally valid results. These shortcomings are:
    - It does not inherently allow for subsequent allocation of same-timestep return flows. However, a workaround was identified and enhancement to incorporate this is feasible. Note that this would likely not be a significant limitation in a daily timestep model.
    - Instream flow water rights can only be represented as points, rather than as reaches.
- RiverWare was also found to have other potential advantages that are currently lacking in StateMod. These include simulation process transparency, accessibility to input data and results, and flexibility to allow for representation of complex operations and specific situations.
- StateMod's direct integration within the CDSS system allows for efficient model and input dataset development, management, and updates, and is certainly a key strength compared to RiverWare for CDSS applications.
- Simulation speed and efficiency is certainly a key strength of StateMod compared to RiverWare, which it achieves through a very efficient and lightweight solution process with thoughtful assumptions and simplifications.

Some more detailed, but noteworthy, findings of this study with respect to other specific water right operations of interest include:

- Well water rights and augmentation – An adequate implementation of these operations was achieved in RiverWare to essentially replicate StateMod's representation. However, it would be less than ideal if numerous wells were to be simulated and, thus, enhancement to the RiverWare in the form of additional water user methods could be very advantageous here.
- Offstream reservoir operations – RiverWare was able to simulate various types of these operations, including in-priority diversion to, and subsequent river, carrier, and exchange deliveries from, in an equivalent manner to StateMod. A strength of the platform, RiverWare can also provide considerable additional flexibility in representation of complex or specific operations.
- Changed water rights – RiverWare was able to simulate these operations, including division of water right yields, differing use locations such as downstream delivery or upstream exchange, reusable return flow accounting, and return flow obligations, in a comparable manner to StateMod.
- Variable water use efficiency and soil moisture accounting – While not identical to StateMod's simulation process, RiverWare's "Irrigation Requests with Soil Moisture" and "Variable Efficiency with Soil Moisture" internal water user methods were found to allow for a very similar representation of these processes as StateMod.

Many effective and important RiverWare models are currently being utilized in various basins of Colorado, several of which include simulation of water rights as a fundamental component. This study's findings provide additional credibility regarding their ability to simulate the Colorado's water rights systems and administration processes. Continued implementation of RiverWare models through the Colorado basins could allow for further innovation and application of highly informative and integral decision support systems and tools.

Finally, this study provides several examples of how RiverWare's user-defined rules and functions can be used to implement StateMod's standardized and familiar methods, such as its specific "OPR" types, in a consistent and repeatable manner. Presuming that the fidelity of these methods remains a top priority to the State's water management agencies, it is conceivable that these could be internally added to the RiverWare platform as predefined functions and methods to ensure reliable application. This would also facilitate consistency between related models. A partnership between Colorado and CADSWES could be highly beneficial to continued and successful application of the RiverWare platform in Colorado's water resource systems.

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APPENDIX A: WHITE BASIN RIVERWARE MODEL SCHEMATICS

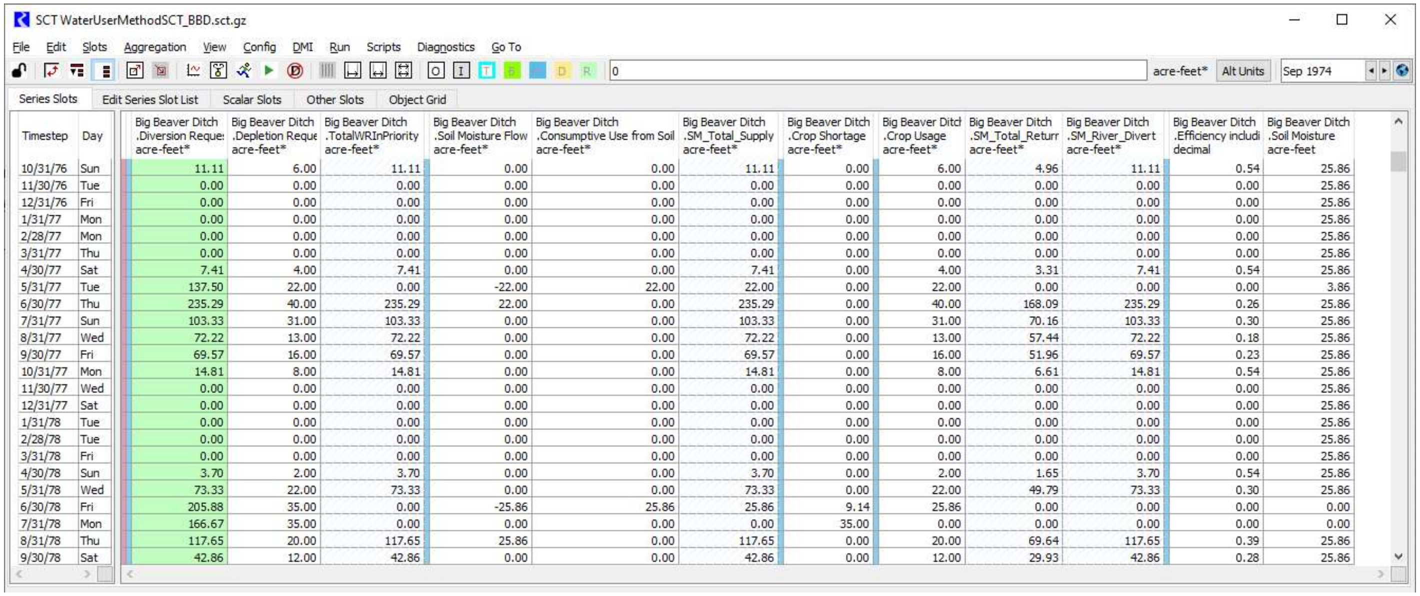
Both simulation (physical) and accounting network schematics included separately.

APPENDIX B: WHITE BASIN STATEMOD MODEL SCHEMATIC

Included separately.

APPENDIX C: EXAMPLE OF RIVERWARE REPLICATING STATEMOD'S REPRESENTATION OF VARIABLE EFFICIENCY AND SOIL MOISTURE ACCOUNTING

See comparable tables on following page.



Timestep	Day	Big Beaver Ditch .Diversion Reque: acre-feet*	Big Beaver Ditch .Depletion Reque acre-feet*	Big Beaver Ditch .TotalWRInPriority acre-feet*	Big Beaver Ditch .Soil Moisture Flow acre-feet*	Big Beaver Ditch .Consumptive Use from Soil acre-feet*	Big Beaver Ditch .SM_Total_Supply acre-feet*	Big Beaver Ditch .Crop Shortage acre-feet*	Big Beaver Ditcl .Crop Usage acre-feet*	Big Beaver Ditch .SM_Total_Returr acre-feet*	Big Beaver Ditch .SM_River_Divert acre-feet*	Big Beaver Ditch .Efficiency includi decimal	Big Beaver Ditch .Soil Moisture acre-feet
10/31/76	Sun	11.11	6.00	11.11	0.00	0.00	11.11	0.00	6.00	4.96	11.11	0.54	25.86
11/30/76	Tue	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	25.86
12/31/76	Fri	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	25.86
1/31/77	Mon	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	25.86
2/28/77	Mon	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	25.86
3/31/77	Thu	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	25.86
4/30/77	Sat	7.41	4.00	7.41	0.00	0.00	7.41	0.00	4.00	3.31	7.41	0.54	25.86
5/31/77	Tue	137.50	22.00	0.00	-22.00	22.00	22.00	0.00	22.00	0.00	0.00	0.00	3.86
6/30/77	Thu	235.29	40.00	235.29	22.00	0.00	235.29	0.00	40.00	168.09	235.29	0.26	25.86
7/31/77	Sun	103.33	31.00	103.33	0.00	0.00	103.33	0.00	31.00	70.16	103.33	0.30	25.86
8/31/77	Wed	72.22	13.00	72.22	0.00	0.00	72.22	0.00	13.00	57.44	72.22	0.18	25.86
9/30/77	Fri	69.57	16.00	69.57	0.00	0.00	69.57	0.00	16.00	51.96	69.57	0.23	25.86
10/31/77	Mon	14.81	8.00	14.81	0.00	0.00	14.81	0.00	8.00	6.61	14.81	0.54	25.86
11/30/77	Wed	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	25.86
12/31/77	Sat	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	25.86
1/31/78	Tue	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	25.86
2/28/78	Tue	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	25.86
3/31/78	Fri	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	25.86
4/30/78	Sun	3.70	2.00	3.70	0.00	0.00	3.70	0.00	2.00	1.65	3.70	0.54	25.86
5/31/78	Wed	73.33	22.00	73.33	0.00	0.00	73.33	0.00	22.00	49.79	73.33	0.30	25.86
6/30/78	Fri	205.88	35.00	0.00	-25.86	25.86	25.86	9.14	25.86	0.00	0.00	0.00	0.00
7/31/78	Mon	166.67	35.00	0.00	0.00	0.00	0.00	35.00	0.00	0.00	0.00	0.00	0.00
8/31/78	Thu	117.65	20.00	117.65	25.86	0.00	117.65	0.00	20.00	69.64	117.65	0.39	25.86
9/30/78	Sat	42.86	12.00	42.86	0.00	0.00	42.86	0.00	12.00	29.93	42.86	0.28	25.86

Structure ID 4300539
Structure Name BIG BEAVER DITCH

	Demand		From River By			Shortage		Water Use					
	Total	CU	Priority	From SoilM	Total Supply	Total Short	CU Short	CU	To SoilM	Total Return	River Divert	Efficiency	Soil Storage
1976-10	11.11	6.00	11.11	0	11.11	0	0	6.00	0	4.96	11.11	0.54	25.86
1976-11	0	0	0	0	0	0	0	0	0	0	0	0	25.86
1976-12	0	0	0	0	0	0	0	0	0	0	0	0	25.86
1977-01	0	0	0	0	0	0	0	0	0	0	0	0	25.86
1977-02	0	0	0	0	0	0	0	0	0	0	0	0	25.86
1977-03	0	0	0	0	0	0	0	0	0	0	0	0	25.86
1977-04	7.41	4.00	7.41	0	7.41	0	0	4.00	0	3.31	7.41	0.54	25.86
1977-05	137.50	22.00	0	22.00	22.00	115.50	0	22.00	0	0	0	0	3.86
1977-06	235.29	40.00	235.29	0	235.29	0	0	40.00	22.00	168.09	235.29	0.26	25.86
1977-07	103.33	31.00	103.33	0	103.33	0	0	31.00	0	70.16	103.33	0.30	25.86
1977-08	72.22	13.00	72.22	0	72.22	0	0	13.00	0	57.44	72.22	0.18	25.86
1977-09	69.57	16.00	69.57	0	69.57	0	0	16.00	0	51.96	69.57	0.23	25.86
1977-10	14.81	8.00	14.81	0	14.81	0	0	8.00	0	6.61	14.81	0.54	25.86
1977-11	0	0	0	0	0	0	0	0	0	0	0	0	25.86
1977-12	0	0	0	0	0	0	0	0	0	0	0	0	25.86
1978-01	0	0	0	0	0	0	0	0	0	0	0	0	25.86
1978-02	0	0	0	0	0	0	0	0	0	0	0	0	25.86
1978-03	0	0	0	0	0	0	0	0	0	0	0	0	25.86
1978-04	3.70	2.00	3.70	0	3.70	0	0	2.00	0	1.65	3.70	0.54	25.86
1978-05	73.33	22.00	73.33	0	73.33	0	0	22.00	0	49.79	73.33	0.30	25.86
1978-06	205.88	35.00	0	25.86	25.86	180.02	9.14	25.86	0	0	0	0	0
1978-07	166.67	35.00	0	0	0	166.67	35.00	0	0	0	0	0	0
1978-08	117.65	20.00	117.65	0	117.65	0	0	20.00	25.86	69.64	117.65	0.39	25.86
1978-09	42.86	12.00	42.86	0	42.86	0	0	12.00	0	29.93	42.86	0.28	25.86