WATER ACCOUNTING AND ALLOCATION IN RIVERWARE

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Abstract: Managing water projects and allocating natural river flows are facilitated by modeling tools that track water ownership and model allocation according to various legal mandates and constraints. The laws and policies that regulate allocation and accounting of water vary greatly from state to state and in foreign countries. This paper describes the water accounting and water allocation features of RiverWare, a river and reservoir modeling framework that is used for planning, forecasting and scheduling operations of river systems. RiverWare's water accounting and water allocation capabilities are designed for maximum flexibility so as to be applicable in any river basin under any arbitrary water laws. Water ownership in RiverWare is modeled in a network of "paper water" accounts that is separate from the "physical water" simulation object network, but associated with it. For example, Reservoir Objects in the physical water modeling framework may contain Storage Accounts that keep track of the ownership of the stored water. Storage Accounts, along with Diversion Accounts and Instream Flow Accounts model the legal account entities. These are linked via "pass-through" accounts on Reaches and other connecting objects in order to track the ownership of the water as its flow is simulated through the network. Common accounting mechanisms such as accrual, carryover, transfers and exchanges are represented explicitly. RiverWare's Rulebased Simulation solver applies a set of prioritized logical operating rules to drive the simulation. These rules can access the information from the accounting network and also can drive the solution of the accounting network in concert with the simulation of physical water. In basins that are governed by the doctrine of Prior Appropriation, water allocation is determined by prioritized water rights, along with availability and requests. In RiverWare, the water rights solver allocates water in the accounting network to satisfy the requests in priority order. This paper describes RiverWare's water accounting and water allocation modeling features and shows how it is applied in three basins with very different water laws. On the Rio Grande, the Bureau of Reclamation manages allocation of water transferred from the Colorado River basin according to a set of highly specified legal constraints. The transbasin water must be tracked and managed separately from the native water. In the Truckee Carson Basin, Reclamation will manage a highly complex set of operating policies that maximize efficiency of the system by allowing (and tracking) water exchanges among the various owners. The allocations and accounting are overseen by the U.S. Federal Watermaster who shares the RiverWare models with Reclamation and stakeholders. In Texas, the Colorado River is managed by the Lower Colorado River Authority according to priority allocation. RiverWare accounting models assist LCRA with both long-term planning and daily operations. RiverWare is developed at the University of Colorado Center for Advanced Decision Support for Water and Environmental Systems with sponsorship of Reclamation, TVA and the U.S. Army Corps of Engineers.

INTRODUCTION

In many water-scarce areas such as the western United States, the right to store and divert water from rivers and lakes for beneficial use is controlled by a framework of water laws. These rights were originally intended for farming, mining, municipal and industrial uses. In recent decades, water rights and water ownership have also been extended to environmental, recreational and other uses. The management of water in river and reservoir systems with water rights can be complicated and water use must be accurately accounted for consistently with the water rights and laws. The traditional approach has been for water operators to keep a set of books with notations that record the water uses. In recent years, water modeling tools have been developed to support this activity. RiverWare®, a water modeling software for planning and operations, supports extensive and detailed water accounting activities, and integrates water accounting and water rights allocation with other operational objectives. This paper describes the RiverWare water accounting capabilities and three example applications.

Overview of RiverWare Modeling Approach: RiverWare is a general river and reservoir modeling tool for operational scheduling and forecasting, planning, policy evaluation, and other operational analysis and decision processes. RiverWare has the capability to model hydrology and hydrologic processes of reservoirs, river reaches, diversions, distribution canals, consumptive uses, shallow groundwater interaction and conjunctive use, hydropower production and energy uses. Its object-oriented, data-centered approach enables the modeler to represent site-specific conditions by creating a network of simulation objects, populating each with data, and selecting physical process algorithms on each object that are appropriate to the purposes of the object and its representation in the overall model. Data-driven simulations solve the hydrologic variables by propagating solutions of flows and stage through the network. The palette of objects, as shown in Figure 1, includes Reservoirs, River Reaches, Confluences, Diversions, Water Users, Stream Gages, Control Points and Data Objects, among others. A typical network representing a river system is shown in Figure 2.

Figure 1. Palette of Objects.

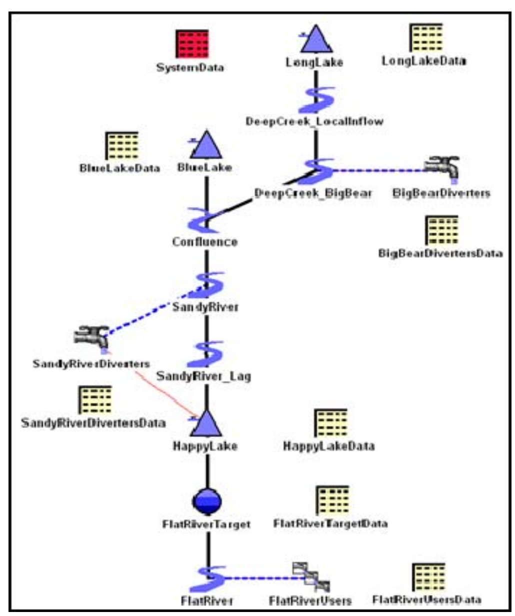

Figure 2. Typical RiverWare model network.

Rulebased Simulation: Rulebased simulation simulates based on a set of prioritized logical policy statements rather than explicitly specified input values for operations such as reservoir releases, storages, diversions, etc. In general, the operating policies, called *rules*, contain logic for operating the system based on hydrologic conditions, time of year, demands, and other operating criteria. The entire set of rules is executed at each timestep in priority order (lowest to highest). The higher priority rules can overwrite lower priorities. Each time a rule writes a value in an object, the results are simulated by the resulting solving of the objects.

Operational policy is expressed in the RiverWare Policy Language (RPL), an interpreted language developed for, and exclusive to, RiverWare. The language is rich enough to express the highly complex logic needed for many basins. The main elements of RPL are assignment statements, variables in the objects in the modeled network, mathematical and logical operators, including looping mechanisms, date/time expressions, a library of pre-defined functions, and user-defined functions. Rules are constructed in a syntax-directed editor that accesses a palette containing these elements. Figure 3 shows a rule with a single assignment. The result of the logical expression on the right is assigned to the variable name on the left.

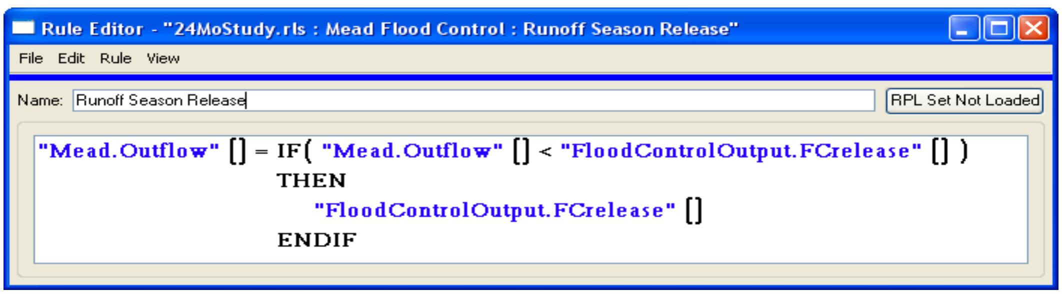

Figure 3. A simple rule assignment in the RiverWare Policy Language (RPL).

MODELING WATER OWNERSHIP AND ACCOUNTING

Water ownership is modeled in RiverWare via a network of account objects that are associated with the simulation objects on the workspace. The accounting network of objects keeps track of the "paper water" as distinct from the "wet water" modeled by the simulation objects. There are three types of legal accounts, each of which track the necessary aspects of the legal water right. In addition, Pass-through Accounts account for the paper water as it moves through the river network from one legal account to another.

Account Types: Descriptions of the four types of accounts follow.

Storage Accounts: Storage Accounts may exist on Reservoir objects to model storage rights. They compute storage and accrual at each timestep, given inflow from upstream accounts, outflow (release from the storage account through reservoir release), and transfers to and from other storage accounts on the same reservoir. Storage also considers transfers to diversion accounts on linked Water User objects, and transfers from these as return flows. Gains and losses including local inflows and evaporative losses can be distributed to the storage accounts according to any arbitrary logic. The accrual is tracked as the total inflow into the account during the accounting period, typically a year, and maximum accrual may be specified for the period.

The account is allocated a specified amount at the beginning of the period, and carryover methods specify how much, if any, storage can be retained at the end of the accounting period and carried over into the following period. Storage Accounts may also have priority dates used to allocate water in a priority allocation scheme. (See section below on Water Rights.)

Diversion Accounts: Diversion Accounts may exist on Water User objects to model the right to divert water from a stream or river. The Water User object is linked to a Reach object via diversion and return flow links. Similarly, the Diversion Account is linked to a Pass-through Account on the Reach (see below). Given diversion, the account computes depletion and return flow, using the various available methods which are similar to the methods on the Water User object, i.e., the account mirrors the physical water process for consumptive use. However, the account also tracks accrual (the cumulative depletion or consumptive use over the accounting period). In addition, the Diversion account can split the return flows and lag the returns according to step-response coefficients. Diversion Accounts may also have priority dates used to allocate water in a priority allocation scheme. (See section below on Water Rights.)

Instream Flow Accounts: Instream Flow Accounts represent legal flow rights in a river and may exist on Control Point objects. They have an inflow from water transfers from upstream accounts, and an outflow which transfers water downstream. Inflow = Outflow since there is no storage. Accrual is the cumulative sum of the inflows over the accounting period. Instream Flow Accounts are different than the above in that they do not remove water from the system or reserve it for a use. Because flow rights can consider all flow that is passing a point, regardless of the ownership of the water, Instream Flow Accounts have a unique feature – a variable “Flow” which is the sum of all the inflows into all the accounts on the Control Point object, i.e., the sum of the flows passing through at each timestep. This can be used to determine if additional water must be released upstream to satisfy the flow right. Instream Flow Accounts may also have priority dates used to allocate water in a priority allocation scheme.

Pass-through Accounts: Pass-through Accounts on simulation objects such as Reaches, Confluences, Gages, etc., keep track of the water as it is transferred between legal accounts, typically flowing through objects such as Reaches, Confluences and River Gages. These accounts apply legal time lags and transit losses that are simpler than the physical process routing and gains/losses calculated by the object methods. Pass-through accounts may be linked to Diversion Accounts on an adjacent Water User object through Diversion and Return Flow links. New water is introduced into the Pass-through Accounts on Reach objects via methods that distribute local inflows into the accounts on that object and also distribute physical losses due to evaporation, seepage, etc. to the accounts. Pass-through accounts solve for outflow given inflow. Reconciliation methods may be used to calculate gains or losses such that the sum of account inflows and outflows match the inflow and outflow of the physical water object.

Attributes of Accounts and Their Links: Accounts have two optional attributes that can be used for tracking water and managing the transfers: *Water Type* and *Water Owner*. The Water Type attribute allows categories of water that have management implications. For example, type *Allocatable Flow* could identify the water that is available for priority allocation, distinguishing it from water released from project storage. In the Upper Rio Grande Water Operations Model, the San Juan Chama *Transbasin* water is distinguished from the *Native* Rio Grande water; the two types of water have separate management policies. The Water Owner attribute is more specific, identifying the entity who has rights to the water, or perhaps a specific use, such as the Recreation Pool in a reservoir, or Fish Water dedicated to ESA purposes.

The links between accounts represent the transfer of paper water from one account to another, either from a legal account to a Pass-through Account on a downstream object, or between Pass-through Accounts. Links also may exist within an object to transfer water from one account to another. For modeling convenience, these links have attributes of *Destination* and *Release Type*. The attributes allow categorization of the transfers between accounts to be used by rules that determine the releases. Also, the type attributes provide descriptive information about the results for modelers and interested parties.

Display of Accounting: An alternate view of the model network shows the accounts on the object along with their links. Color coding can be used to display water types and water owners as well as link types as in Figure 4 below on the right.

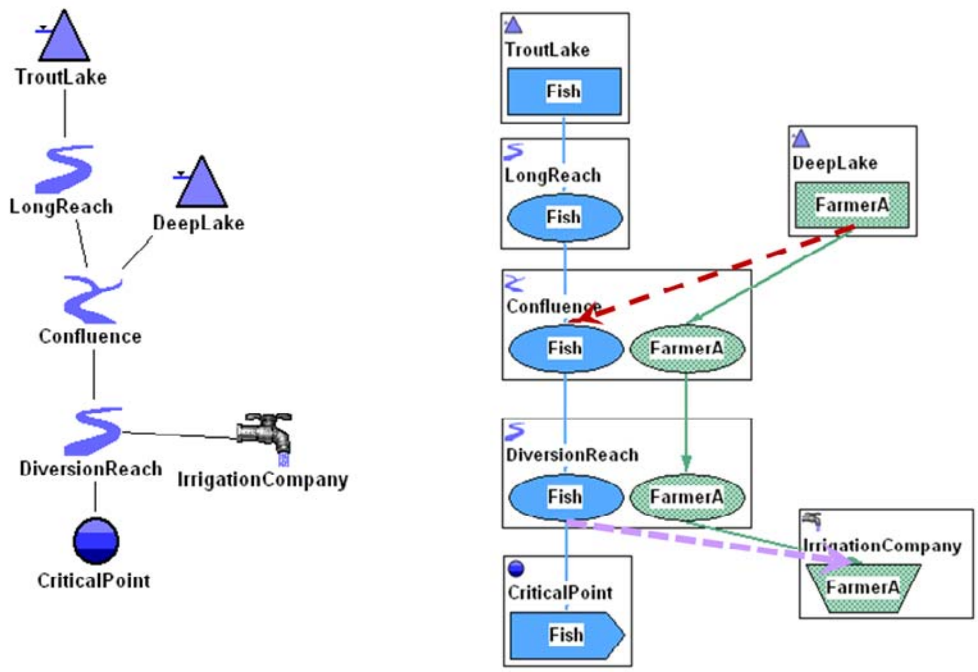

Figure 4. An exchange is an association of links: the Borrow (red arrow) is from Deep Lake for fish, and the payback (purple arrow) from Trout Lake is to the Irrigation Company.

Exchanges: It is common for water owners to exchange water for convenience. A simple exchange is illustrated in Figures 4 below. The large Deep Lake stores water for Irrigation Company, whereas the smaller Trout Lake stores water for fish flows at the downstream control point. When Trout Lake is short of water, it borrows from Deep Lake for the fish; it is later paid back when Trout Lake is full by releasing for Irrigation. The exchange is modeled as a simple association between two accounting links, designated as a *borrow* and a *payback*. The association is tracked on an Exchange Object with a user-specified name. The object maintains the link values as well as the debt balance information. The rules have access to the exchange information so exchanges can be included in operating policy.

WATER ACCOUNTING AND RULEBASED SIMULATION

For multi-objective operational analysis and decision-making, RiverWare provides an interface for expression of operational policies as well as both descriptive and prescription solution algorithms driven by these policies. In addition to operating the physical water (simulation objects), the rules have access to the information in the accounting network, and can make transfers among the accounts by setting the values of the links between accounts. Rules control the transfer of paper water through the accounting network based on criteria such as:

- executing release from storage or diversion from a river in response to demand;
- meeting other operational criteria such as environmental flows and interstate compacts;
- reconciling the accounting system with the physical system, e.g., a flood control release in the physical system needs to be reconciled in the accounting system so the total storages of accounts match the final reservoir storage;
- executing exchanges;
- allocating for a set of prioritized water rights.

Interaction of RPL with the accounting system is facilitated by a number of predefined functions in RPL that are designed to quickly and efficiently access and accounting information.

Prioritized Allocations: Many western U.S. states have adjudicated water rights that specify priority access to supply based on the adjudication date, i.e., “first in time, first in right.” To allocate water based on this logic, the model must determine how much each user can have at each timestep, limited by legal rights, requests, physical constraints, and protection of the higher rights of more senior users. The problem becomes more complex when travel time of water is greater than the computational timestep, and when water in transit suffers losses.

The problem requires a global solution, that is, a solution that considers the entire network simultaneously. There are in general two possible approaches to solving the problem – the first is to use an optimization algorithm. This approach is efficient, but requires that the modeler provide weights to the rights. The challenge of correctly weighting not only the water rights, but other operational objectives, is a drawback of this approach. An alternate approach is an “iterative” solution, that is less efficient computationally, but easier to formulate. RiverWare uses the iterative approach in which the solver sequentially allocates water to each right in priority order, checking for possible shorting of senior rights and adjusting when needed.

The water rights solver is invoked through a RPL function “Solve Water Rights” that references a chain of water accounts that represent the allocatable flow in the system, as distinct from other water such as project water. The solver visits all water rights (storage, diversion and instream flow rights) that are linked to that supply chain in priority order as described above. The solver finds the allocation and returns the entire set of values to the rule. In doing so, the solver considers legal constraints such as annual accrual limits and daily maximum diversion rates, as well as physical constraints such as size of conservation pool and size of diversion structure.

Figure 5 shows a network of accounts with two types of water: Allocatable Flow, the water that is to be allocated based on priorities, and Project water. The allocatable flow is identified as the blue pass-through accounts. The water is allocated in order to the 1908 Water User, the 1922 Storage in Reservoir B, the 1933 Instream Flow right on the Control Point, and the 1980 Storage in Reservoir A. When the water is released from storage, it is no longer available for priority allocation, but is dedicated to use by downstream diverters who have rights to the project water. The downstream Diversions have rights only to project water, both the 1922 Project water released from Reservoir B and the 1980 “Bartlett” water released from Reservoir A. Note that Reservoir A does not allow storage of 1922 Project water which must pass through.

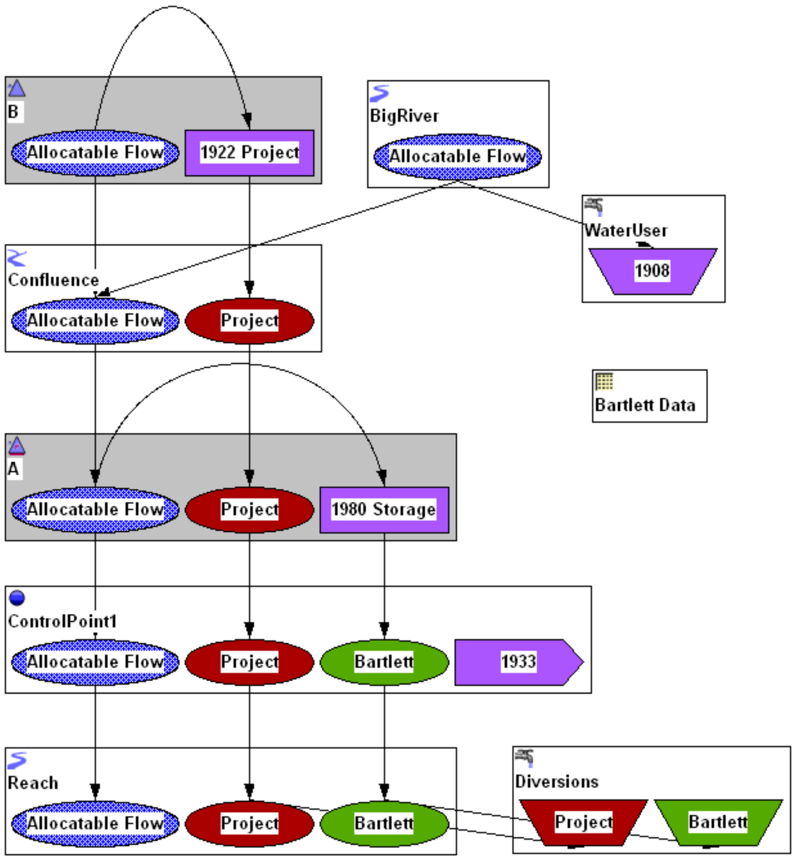

Figure 5. Example of a water rights allocation model setup. The water that can be allocated to prioritized rights (purple accounts) is shown in the blue chain of pass-through accounts. Project water is stored as part of priority allocation, and released from storage and delivered to downstream users separate from the priority allocation process.

<u>Allocation with Other Operating Policies:</u> An advantage to this approach to water allocation and accounting is the ability to separate the priority allocation rule from other operating rules such as flood control and delivery of project water, and execute all the rules in a priority order. Further, some water users have rights to both allocatable flow and water in storage, but prefer to take allocatable flow to the extent possible before using their stored water. This is easy to execute and track.

Instream flow rights can be satisfied by both allocatable flow and any other water that is passing the control point for other objectives. A special type of iteration of rules can be applied in which the amount of water that can be reserved for the instream flow right is noted and saved, then the junior rights are allocated without concern for the instream flow right. Next, other operating policies are executed. Then the water rights allocation rule is executed again, this time allocating to the instream flow as needed, considering other water that is passing the control point. An example rule set is shown in Figure 6.

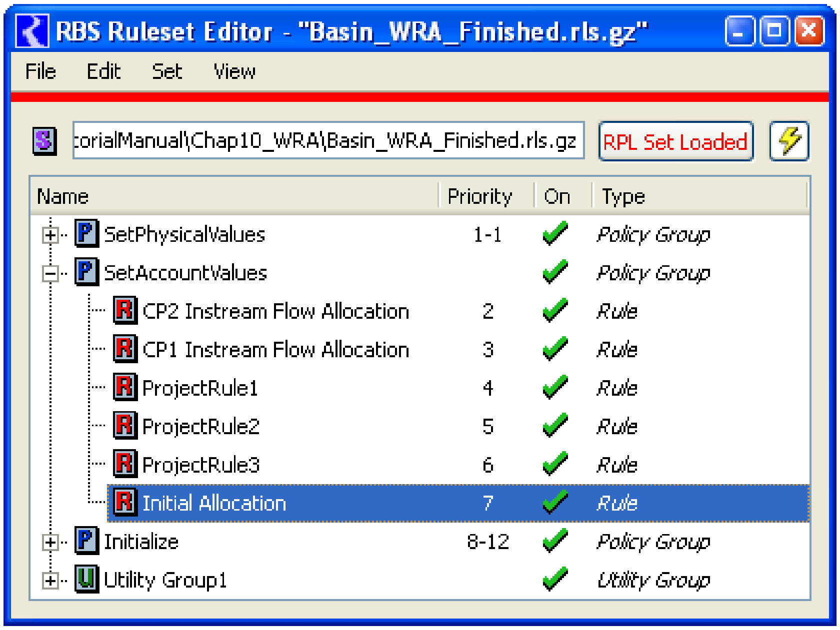

Figure 6. Example ruleset with initial allocation (rule 7), other operating rules (6, 5 and 4) and iterations of priority alloction for the instream flow (rules 3 and 2).

EXAMPLE APPLICATIONS

RiverWare has been applied to a number of basins for water accounting and water rights allocation for planning and operations. The main uses of RiverWare models with water accounting are for:

- Long term planning studies, for example to determine the reliability of supplying a new water right, or the effect of change in operating policies on other uses. Also can be used to study the effects of climate change on future reliability of supplies or analyzing alternatives for NEPA processes.
- Annual operating plans or seasonal forecasting in which water users and management agencies forecast allocations given current conditions and type of hydrologic year anticipated, with attention to specific known operating criteria or constraints.
- Daily operations models assist water operators in scheduling operations on a daily basis to meet water rights as well as operational criteria.
- After-the-fact Accounting models take as input the actual operations (releases, diversions, etc.,) and calculate document the actual accounting for recording purposes. This is necessary because daily operations and water use do not always end up as scheduled for various reasons. The accounting also keeps track of exchange balances.

In the following examples, we present models that have been developed and are used for all of these types of applications.

<u>Upper Rio Grande Water Operations Model (URGWOM)</u>: The Upper Rio Grande includes the portion of the Rio Grande from the headwaters in Colorado, through the state of New Mexico, to El Paso, Texas (Figure 7). The river is operated for water supply, flood control, interstate compact (with Texas), Native American water rights, Endangered Species Act compliance and recreation. Developed through an interagency effort including the Bureau of Reclamation, the U.S. Army Corps of Engineers, the U.S. Geological Service, the New Mexico Interstate Stream Commission, the Bureau of Indian Affairs, the URGWOM simulates physical processes, operational rules and water accounting transactions; its purpose is "to facilitate more efficient and effective accounting and management of water." (http: www.spa.usace.army.mil/urgwom/needfor.asp). The Rio Grande receives about 110,000 ac-ft of water per year from the San Juan Basin through the San Juan-Chama Project, primarily for municipal, industrial and domestic use, as well as for supplemental irrigation in the middle Rio Grande Valley, and for incidental recreation and fish and wildlife benefits. This trans-basin water must be managed and accounted for separately from the native water. Thus, the model must distinguish these two water types, specify operational rules for each water type, and support system operators in making timely and accurate deliveries and tracking leases and exchanges. Figure 8 shows the accounting view of the San Juan-Chama diversion to the downstream gauge above Heron Reservoir with the two water types.

Figure 7. Location of Upper Rio Grande.

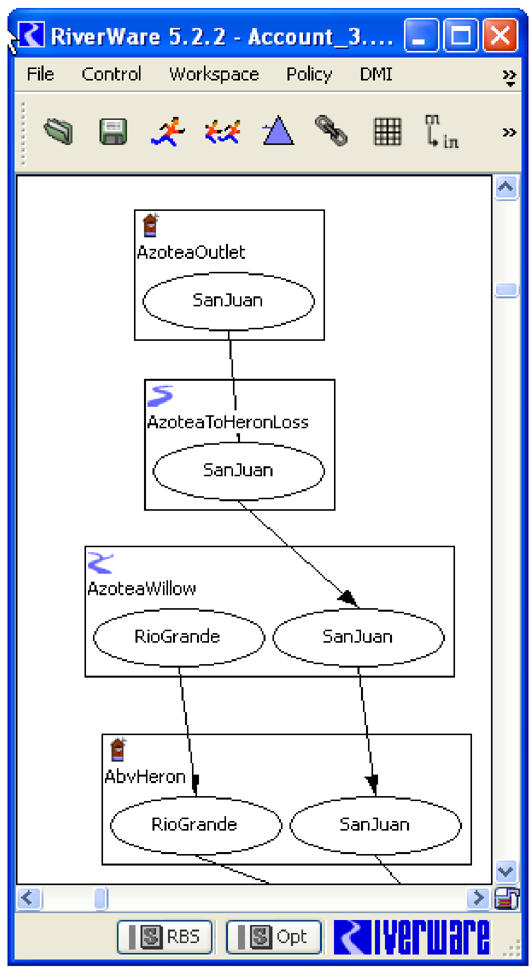

Figure 8. Accounting View of San Juan Chana Project water above Hereon Reservoir.

Four different RiverWare daily timestep models are used for decision support by the Corps of Engineers and the Bureau of Reclamation in managing the river:

A special version of the Operations Model, called the Forecast Model, is used with a given hydrologic forecast, to forecast annual supply, and that information is used in the regular Operations Model to predict available storage, meet demands and predict system conditions for the coming year, including end of year storage. Detailed accounting track storage and delivery of allocated water for individual users. Separate storage accounts are established for each of the contractors for San Juan-Chama Project water at Heron Reservoir with additional storage accounts at El Vado, Abiquiu and Elephant Butte reservoirs, if they have allocated storage space. Separate pass-through accounts are used to track the delivery of the allocated water for each contractor to allocated downstream storage locations and other delivery locations. Accounting is required in URGWOM to appropriately identify the available supply and demands for individual water users and to ultimately set reservoir releases in rulebased simulations. Native Rio Grande water is designated for different uses from San Juan-Chama Project water. Water users include the city of Albuquerque that has allocated San Juan-Chama Project water that is delivered to their new surface water diversion and drinking water plant and the Middle Rio Grande Conservancy District which uses both native Rio Grande water and allocated San Juan-Chama Project water to meet demands for irrigation. Many contractors pump groundwater to meet demands and deliver allocated San Juan-Chama Project downstream to effectively payback the river for depletions. The exchanges manager in RiverWare is used to track these debts to the river as contractors cause depletions from pumping. Water needs for ESA interest are also tracked separately in URGWOM. Representing all the individual uses of water correctly with accounting is important for developing accurate forecasts of total river flows and reservoir storage for an upcoming year to present in an Annual Operating Plan.

The After-the-fact Accounting Model tracks and documents actual storage and deliveries of water for individual users and generates an up-to-date report on the status of accounts that is reconciled with system conditions in the basin. Actual deliveries made, based on requests from contractors and actual operations, are input daily to the corresponding accounts in the Accounting Model. Accounting losses are included to represent the distribution of physical transit losses between passthrough accounts, and resulting storage conditions for individual accounts are computed with consideration for the distribution of physical losses at a reservoir. Specific accounting methods were developed in RiverWare specifically for URGWOM such that losses are distributed appropriately to reflect the impacts of San Juan-Chama Project water on depletions of native Rio Grande water. Results from the simulations are used to provide water users with updated information on the status of their accounts, and annual accounting reports are prepared at the end of each calendar year for the Rio Grande Compact Commission.

The Planning Model simulates the basin for 40 or more years at a daily timestep, using historical hydrology or synthetic stochastic data. The model is used to evaluate policy alternatives or the impacts of a proposed action on important system indicators such as water deliveries, environmental flows or Compact deliveries. A simplified accounting set up is used for individual contractors for San Juan-Chama Project water. Accounting is specifically useful in the Planning Model for simulating proposed transfers that would result from potential water agreements that have been evaluated as potential solutions for meeting the growing demands for water in the basin. Such transfers that have been analyzed include Reclamation leases of San Juan-Chama

Project water from contractors to then be used for ESA purposes and relinquished Compact credits to subsequently allow storage of native Rio Grande water for meeting different needs in the basin. Separate accounts are needed to track the storage of native Rio Grande water resulting from relinquished Compact credits.

<u>The Lower Colorado River Authority's Daily River Operations Model</u>: The Lower Colorado River Authority (LCRA) is a raw water and power provider headquartered in Austin, Texas. LCRA owns and operates several reservoirs just upstream from Austin that comprise the Highland Lakes system, with a combined conservation storage of approximately 2 million acre-feet. LCRA manages these reservoirs to provide water to municipal, agricultural, industrial, and environmental interests, as well as for flood control and hydropower generation.

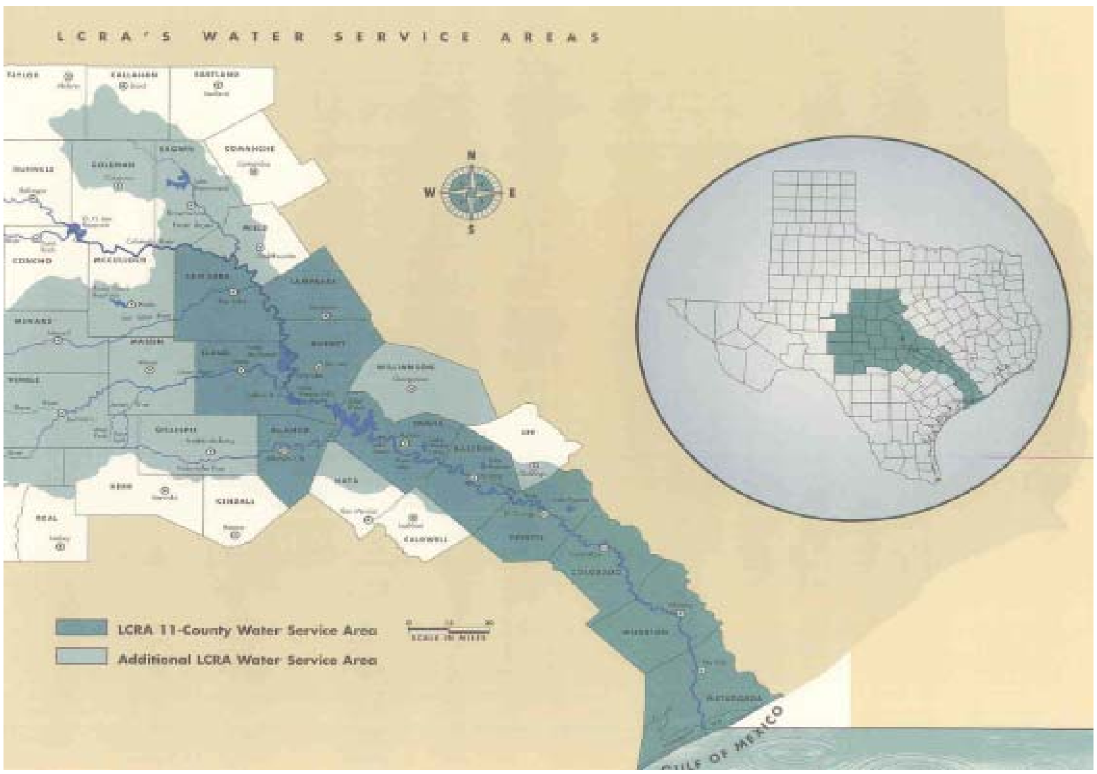

Figure 9. LCRA's water service area.

In 2008 LCRA's River Operations Center (ROC) began developing a new set of modeling tools to assist them in their daily operational decision-making process. The LCRA Daily River Operations Model (DROM) project was undertaken to replace or upgrade many of the modeling and software tools currently used by the ROC. Three RiverWare models form the core of the DROM tool. They include a Daily Release Model, a Routing Model, and an Accouting Model. Both the Daily Release and Accounting Models take advantage of RiverWare's accounting and water rights solver capabilities. These capabilities were key determining factors in selecting RiverWare when examining LCRA's needs, which included:

- The need to have a more robust decision-making foundation for reservoir and river operations. Much of this need centers on a desire to more accurately reflect water rights and operational policies *a priori* in the decision-making process. As demands for water increase and excess supply disappears, it becomes increasingly important to operate the system more efficiently and to ensure that operational decisions appropriately reflect rules and policies.

- Commonality of modeling tools. Having an "apples-to-apples" comparison of decision-making logic (Daily Release Model) to after-the-fact water accounting (Accounting Model) provided the ROC with insight as to sources of inefficiency in the system. Comparisons of water orders to actual diversions, forecast inflows to actual river gains, and environmental target operations to actual deliveries are now possible within a common modeling environment.

The two accounting-based models simulate the allocation of natural inflows (run-of-river) water based on the legal doctrine of prior appropriation. In addition, LCRA delivers stored water to a variety of contract holders, and also ensures environmental flow deliveries to several instream flow monitoring locations plus freshwater inflows to Matagorda Bay in the Gulf of Mexico. The models represent approximately 25 permitted water rights, including both direct flow and storage rights. Many of these water rights holders have their supplies augmented by contractual water stored in LCRA reservoirs during periods of low natural inflows.

Figure 10 illustrates the accounting structure in the lower sections of the river, including the Garwood diversion, which is an agricultural water user. Garwood receives run-of-river water allocated based on priority administration, and is supplemented by interruptible contract water purchased from LCRA.

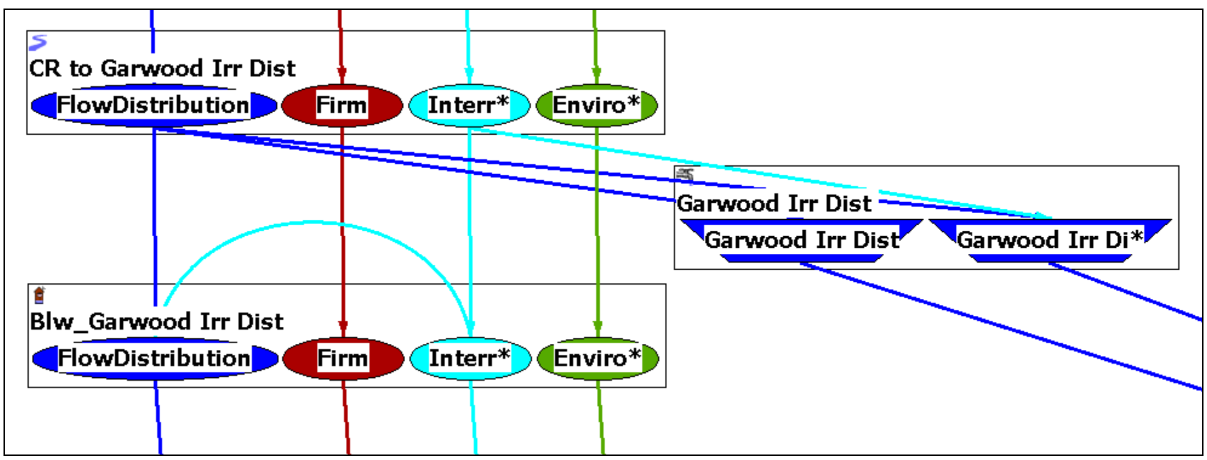

Figure 10. Water Accounts in LCRA's Daily Release Model.

The Daily Release Model utilizes forecasts of inflows and water demands as requested by users in the basin, and provides an estimate of the daily volumetric release requirement to the ROC staff. The model output includes estimates of contractual releases from storage as well as estimates of required run-of-river bypasses in order to satisfy downstream senior water rights. The Accounting model is an after-the-fact model run at the end of each month. It utilizes much of the same logic as the Daily Release Model, but as inputs utilizes the actual reported diversions and hydrologic inflows. Outputs from the Accounting model are used for customer billing, internal water auditing, and for regulatory reporting to the Texas TCEQ and other regulatory agencies.

The DROM tools were completed in the summer of 2009, underwent testing through the remainder of the year, and as of January 1, 2010 are being used operationally by the ROC.