RiverWare Model and Analysis Tools for River System Planning and Management

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Abstract

Reliable fresh water supplies, energy and environmental sustainability are three of the most pressing challenges facing humanity and are the primary objectives of river system planning and management. Maximizing overall river system benefits is complicated by competing objectives such as hydropower, agricultural production, flood risks and environmental protection, and by the need to make plans robust across a range of uncertain future hydrologic and demand conditions. Managing across state and national borders may add further challenges. Advanced modeling and analysis tools can be used to explore the benefits and tradeoffs of a range of management plans and serve as the basis for decision-making for both specific operational decisions and for long term infrastructure and policy decisions. This paper and presentation describes the RiverWare suite of models and analysis tools that have been applied to the planning and management of a variety of river systems with different hydrologic conditions and operational objectives. RiverWare is a unique modeling platform that supports the expression of detailed and flexible logic for operational criteria and performance metrics and automates the simulation and analysis of ensembles of hydrologic scenarios. Analysis tools include the RiverSMART utility for creating and managing large studies that analyze many alternatives. As examples, we present several models that demonstrate a range of types of applications. RiverWare is developed, maintained and distributed by the University of Colorado Center for Advanced Decision Support for Water and Environmental Systems (CADSWES).

Key Words: rivers, models, decision support, hydropower, hydrology, uncertainty, Nile

1. Introduction

Effective planning and management of river systems for maximum water and energy benefits, social and national equity, and environmental sustainability is increasingly critical as fresh water supplies dwindle, populations increase, and future hydrologic conditions are more uncertain. Long term plans should be made with consideration of a wide range of possible future scenarios and must be adaptable and resilient to adjust to unanticipated future conditions. In shorter timeframes within which risks and probabilities are quantifiable, the river systems should be managed to optimize benefits to the extent possible. In both planning and short term management, decisions must be made that resolve conflicting objectives by informed tradeoff analysis. These planning and management capabilities require simulation and optimization models that can adequately represent the physical and operational aspects of the systems in appropriate detail, and can be implemented in a framework that provides performance metrics, quantification of risk and probability, and detailed tradeoff information.

This paper describes the RiverWare® modeling system [1] and associated utilities that are used by water management agencies and others for planning, forecasting and operational decision making on river basins. RiverWare is developed and maintained at the University of Colorado Center for Advanced Decision Support for Water and Environmental Systems (CADSWES) under sponsorship of the United States Bureau of Reclamation, the Tennessee Valley Authority and the United States Army Corps of Engineers. The purpose of the paper is both to describe the RiverWare model and analysis tools, and to provide guidance for the use of these in effective planning and management activities, especially those that are relevant to the river systems in Sudan. Several example models are presented that demonstrate a range of types of applications.

The paper has the following sections: Modeling Physical Features and Processes, Multi-objective Operational Rules and Optimization, Risk Based Analysis, Scenario Studies with RiverSMART, Example Applications, and Conclusions.

2. Modeling Physical Features and Processes

RiverWare can model the physical (hydrologic) processes associated with reservoirs, river reaches, gains and losses, distribution canals, agricultural consumptive uses, shallow groundwater interaction and conjunctive use. It can model some water quality constituents such as total dissolved solids, temperature and dissolved oxygen. Man-made infrastructure such as spillways and outlet works, hydropower plants at dams, inline power and pumping plants, diversion structures, wells and distribution canals and associated energy generated or consumed are also represented. To develop a model, the modeler drags objects off the Palette onto the Workspace, names them, links them together, selects desired physical process algorithms, and populates them with data. Figure 1 shows the Workspace, the Palette, and a model of objects linked together. The arrow indicates the action of creating a Stream Gage object on the Workspace by dragging it from the Palette.

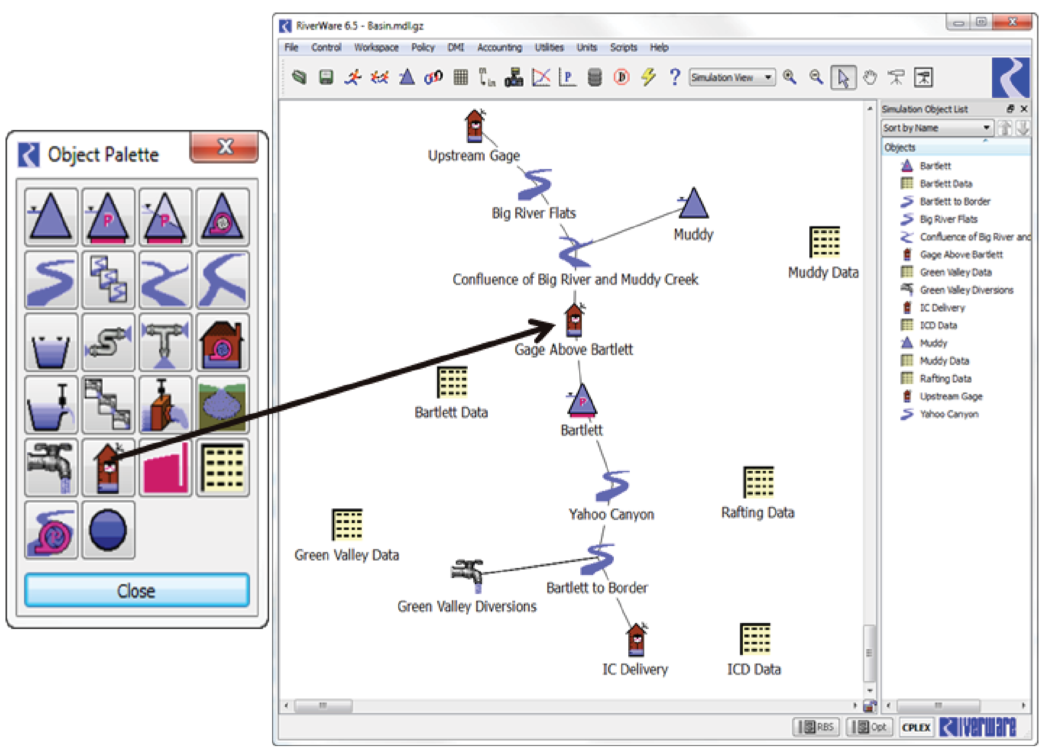

Figure 1. RiverWare workspace with objects named and linked, and Palette of Objects

Each object has Method Categories that contain methods for physical process algorithms. The modeler selects the desired algorithm, or *method*, based on timestep size, resolution of data, institutional preferences, or other modeling needs. For example, every Reach object has a Routing Category that contains about a dozen routing methods from which the modeler may make a selection. All Reservoirs have Evaporation and Bank Storage methods, and all Power Reservoirs have Power Calculation methods. The methods allow each object to be modeled independently as needed.

Inflows are the primary input into the model. These may be forecasted inflows for a short term operations model, period of record hydrology or stochastically generated flow sequences for planning models, or flows generated by a rainfall runoff model. The model simulates by solving the governing equations on each object and propagating values via links. Additional input values are needed, e.g., reservoirs solve for storage if inflow and release are specified. Each object has various combinations of knowns and unknows that allow the object to solve, e.g., reservoirs also can solve for release if inflow and storage a specified. The many combinations allow for the model to be flexibly specified depending on operating criteria. The solution of the objects resulting from user input values is called Simulation, or "Pure Simulation" and is used often for model calibration or for 'what-if' scenarios.

3. Multi-objective Operational Rules and Optimization

Operations of river and reservoir systems are based on specific objectives like providing water for irrigation, producing hydropower, generating hydropower, minimizing flood damage and maintaining environmental flows, to name a few. RiverWare's multi-objective solvers are driven by user specified operating policies. Rulebased Simulation is driven by a set of prioritized logical rules; whereas the goal programming optimization is driven by prioritized objectives and constraints.

Rulebased Simulation solves as rules fire and set values in the model such as reservoir releases storages, diversions, etc., then simulation proceeds similar to pure simulation The rules contain logic for operating the system based on hydrologic conditions, time of year, demands, and numerous other considerations. The rules expressed in the RiverWare Policy Language (RPL), an interpreted language developed for, and exclusive to, RiverWare. A rule is constructed in a syntax-directed editor that accesses a palette containing these elements. The rule set is a collection of prioritized rules that as a whole, define the operating policy of the river system. The entire rule set is applied at each timestep in the model. Rulebased Simulation is the most widely used solution technique among RiverWare users, mainly because most reservoir operating policies are based on procedural type of logic, i.e., IF (state of system, date, etc.) THEN (operate as X release, etc.). RPL, a functional language, includes hundreds of functions and allows user-defined functions as well, for ease of use. The language is structured to allow almost any possible logic as operating policies, which is useful in basins with highly complex policies.

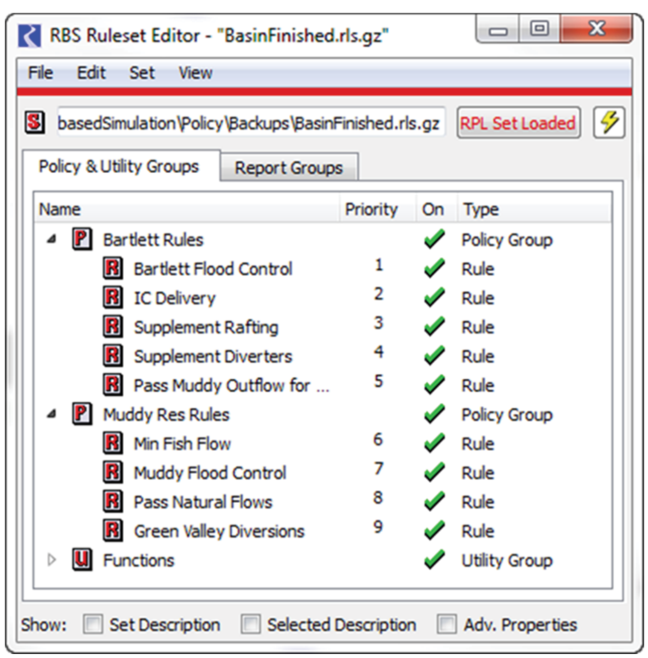

Figure 2. A prioritized rule set.

RiverWare's optimization solution is a linear, pre-emptive goal programming algorithm that optimizes reservoir releases for a prioritized set of user-specified objectives [2]. It solves simultaneously over multiple time steps and all objects rather than simulating one time step at a time. The prioritized goals can be either specific objectives, e.g., maximize the value of hydropower, or constraints that are treated as objectives, e.g., maintain target forebay elevations and minimize the violation of this (soft) constraint. This approach to optimization avoids the difficulty of needing to specify weights on multiple objectives, and also avoids problems of infeasibility.

4. Risk Based Analysis

Modeling studies for which risk-based or probabilistic outcomes are desired can be driven by an ensemble of inputs that represent a statistical distribution. Commonly risk based river system analysis is conducted by simulating many model runs driven by an ensemble of hydrologic scenarios that represent possible hydrologic sequences. If the ensemble represents the hydrologic variability, then the results of the runs can be expressed as probabilities or risks. RiverWare's Multiple Run Manager (MRM) utility automates the process of making many runs [3]. The results can be analyzed using an Excel based tool, the Graphical Policy Analysis Tool (GPAT), developed for this purpose. Figure 3 shows one of many types of plots possible with GPAT.

5. Scenario Studies with RiverSMART

Scenarios are combinations of possible events and options that provide information about possible future states. In river basin management, these could include different demand projections, different water availability projections, different operating policies, and different future infrastructures. Scenario based analysis is used in particular when the likelihoods of various future conditions are not known, and the

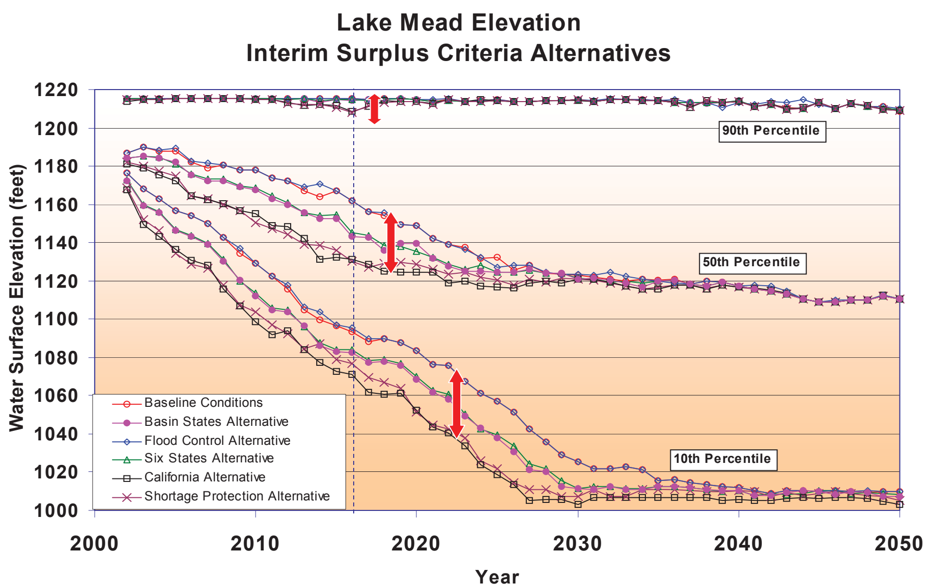

Figure 3. One of many types of probabalistic plots that can be generated using RiverWare's Multiple Run Manager with a hydrologic ensemble, and the Graphical Policy Analysis Tool.

analysis aims to cover a wide range of possible futures. The RiverWare Study Manager and Research Tool (RiverSMART) [4] is a set of analysis tools that facilitates the creation, execution and archiving of planning studies that compare the results of many scenarios. RiverSMART provides a user interface as shown in Figure 4 that provides a graphical representation to help conceptualize all the components and their interactions.

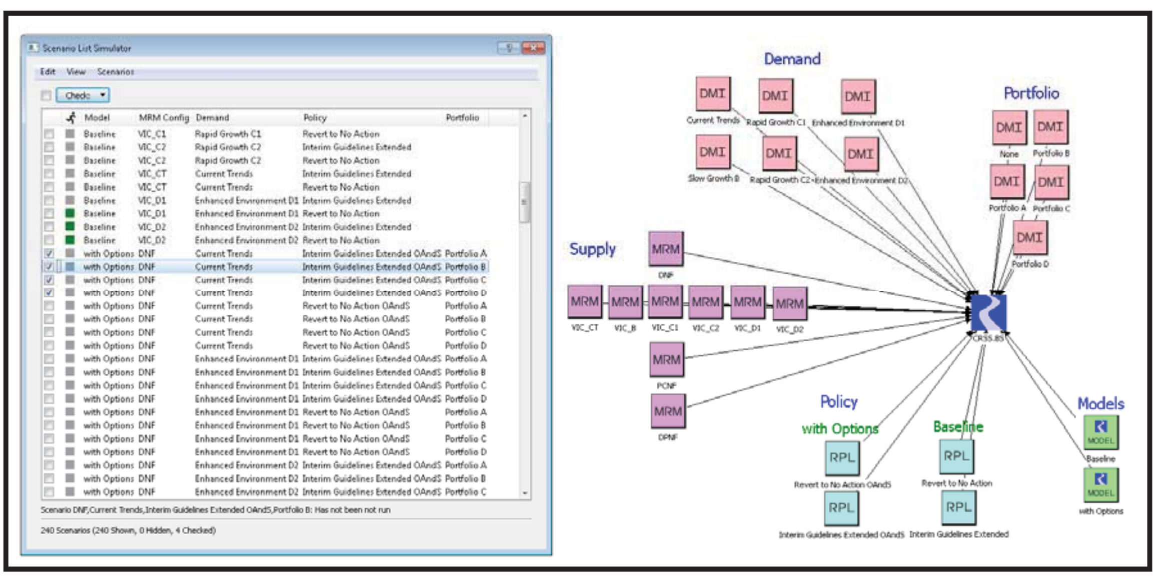

Figure 4. Screen shot of RiverSMART showing various input components of the scenarios.

RiverSMART is built on a plugin architecture and provides the framework for communication amongst the various plugins. In general, the plugins generate hydrologic ensembles, specify alternative input data to the RiverWare model, define alternative model configurations and policy, and post process desired outputs. Following is a description of some of the plugins available in RiverSMART:

- Hydrology Simulator and Disaggregation Plugins synthesizes an ensemble of streamflows from reference values, usually observed historical or paleo reconstructed values using selectable methodologies including K Nearest Neighbor resampling, Paleo Conditioned Homogenous Markov Chains, and Paleo Conditioned Non-homogenous Markov Chains. There is also a Spatial Disaggregation plugin to disaggregate the flows from one site to a number of sites according to correlations of the reference data. The Temporal Disaggregation plugin disaggregates annual data to a monthly timestep.
- RiverWare Model: The RiverWare Model plugin instructs which RiverWare model to use. This allows the user to develop alternative facilities or model configuration as a component in the study.
- RiverWare DMI (Data Management Interface) plugin instructs which RiverWare DMIs in the model should be run to bring in alternative data.
- Demand Input Tool (DIT) is an Excel based tool to develop alternative demands, allowing users to enter baseline demand data, create and enter alternative demand scenarios and plot the baseline and scenario data to visualize changes. Water can easily be moved between sectors, e.g., agriculture to M&I.
- RiverWare Policy: The RiverWare Policy plugin specifies the RiverWare ruleset to use. This allows the user to develop alternative operations as one of the scenario components.

- Output options include GPAT, netCDF, Tableau or other tailored tools that can be specified through the R Plugin.

Once the components are added to the RiverSMART workspace, a list of all possible scenarios is generated and the user can select the ones to be included in the study. The user then runs the specified scenarios with RiverSMART managing the data archiving, importing data for new scenarios, and starting the next scenario. The runs utilize RiverWare's distributed Multiple Run Management where individual runs are spread over available computer processors. The output devices are also selected and executed. All information is archived and can be sent to others as a package.

6. Example Applications

RiverWare is used as a planning and management tool on a number of river basins. The following is a selection of these to illustrate the variety of applications.

6.1 Colorado River Basin

The Colorado River Basin in the arid southwestern US (Figure 5) is shared by 7 states and another country, Mexico. The Bureau of Reclamation has various RiverWare models for operations and planning. The Colorado River Simulation System (CRSS) is used for annual operating plans and long term planning. Recently is was used along with the RiverSMART tools for the Colorado River Basin Water Supply and Demand Study [4] [5], an extensive analysis of future supply demand imbalances and options to address these. It was conducted with the basin states and a large number of basin stakeholders. Performance indicators included agricultural supplies, environmental flows and hydropower generation among others. CRSS has also been used for negotiation of Minute 319 to the International Treaty with Mexico that addresses shortage sharing.

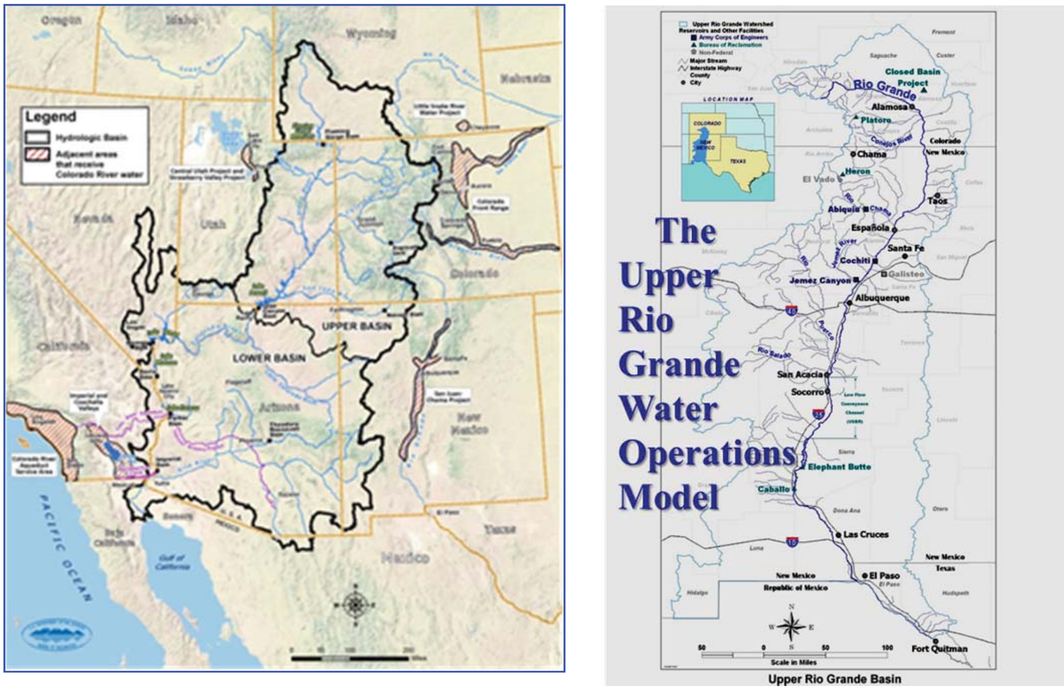

Fig. 5. RiverWare is applied by US Bureau of Reclamation on the Colorado Basin (left) and by a consortium of agencies on the Upper Rio Grande Basin (right)

6.2 Upper Rio Grande

The Upper Rio Grande Basin in the southwest US (Figure 5) is managed jointly by the Bureau of Reclamation, the US Army Corps of Engineers, the US Geological Survey and the New Mexico Interstate Stream Commission. RiverWare is used for long term planning, annual operating plans, daily scheduling and official water accounting [6]. Of special note in this model are the extensive deliveries to irrigated lands with distribution canals and return flows, and the complex surface – groundwater interaction that is modeled with RiverWare's groundwater objects.

6.3 Tennessee Valley Authority

The Tennessee Valley Authority in the eastern US manages 46 reservoirs including 29 hydroelectric projects and a large pump storage facility using RiverWare's optimization solver [7]. In addition to maximizing the value of hydropower, TVA operates their system for flood control, navigation, recreation and water quality.

6.4 Nile Basin

A Nile Basin model has been developed by Kevin Wheeler (Oxford University) and is presented in this conference proceeding.

7. Conclusions

Analysis for future planning or for collaborative decision making requires tool that allow detailed representation of physical systems and their operational policies. Futhre, the framework for developing risk based studies and scenario studies is greatly facilitated by utilities that organize, execute and archive the data, models and output. The RiverWare and associated tools have been developed over many year specifically in resonse to the need for a variety of management applications and continue to be enhanced to meet evolving integrated water resources management requirements.

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