RIVERWARE DECISION SUPPORT TOOLS FOR PLANNING SUSTAINABLE RIVER DEVELOPMENT WITH HYDROPOWER

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Abstract: Fresh water supplies, energy and environmental preservation are three of the most pressing issues facing humanity. Planning for development of reservoir and hydropower on the rivers of the world can be improved by the use of powerful tools to analyze the natural hydrologic supply of water and determine the most effective management that balances human and ecosystem needs. Simulation and optimization modeling tools must be flexible to analyze structural and mult-objective operational alternatives under the varying and changing hydrology. Hydropower operations should additionally consider potential variations and trends in the value of energy. Environmental effects including water quality and riparian habitats are also operating objectives. Results of planning studies include risk-based predictions of the benefits and effects of a proposed project. Trade-off and sensitivity analysis provide additional input to the decision-making process. The University of Colorado Center for Advanced Decision Support for Water and Environmental Systems develops tools for planning studies with these capabilities. The RiverWare suite of tools includes: 1) generation of synthetic hydrologic sequences that capture natural variability and trends due to climate change; 2) long-lead forecasting capabilities based on climate signals; 3) mulit-objective river and reservoir modeling tools including hydropower with value of energy; and 4) statistical analysis tools for representation of the outcomes of the analysis. These tools are used by major water management agencies in the US such as Bureau of Reclamation, Corps of Engineers and Tennessee Valley Authority, and also numerous smaller water management agencies. This paper and presentation describe these tools and two application by AMEC Earth and Environmental for the El Dorado Irrigation District in California, and the Tarrent County Regional Water District in Ft. Worth, Texas.

Key words: reservoir operations, stochastic hydrology, optimization, water resources management.

1 Understanding Hydrologic Variability and Climate Change

Critical to planning is a thorough understanding of the hydrologic variability and trends introduced by climate variability and change. Essential in this effort a streamflow simulation tool that is simple, robust and can generate a variety of plausible streamflow scenarios for risk-based planning studies. To this end, a non-parametric approach based on K-nearest neighbor (K-NN) time series bootstrapping [1] has been shown to be successful for this purpose. This approach has been recently expanded to generate streamflow scenarios based on flow variability observed in the long paleo reconstructed flows [2] from tree ring data going back about 800 years. This integration of the paleo flows generate a rich variety of wet and dry flow sequences that help provide a realistic estimate of water resources system risk. These techniques have been demonstrated on basins in the Western U.S. to generate stochastic streamflow ensembles with a rich variety and that compare well with the statistical properties of the historical sequences. Decadal variability induced by climate features such as ENSO, PDO, AMO and climate change can also be incorporated in the above technique to generate conditional flow scenarios on decadal to multi-decadal time scales.

At the seasonal time scale skillful long lead ensemble streamflow forecasts can contribute to improved system planning and performance; forecasts can feed into operating plans and operating policies can be structured in an "adaptive" fashion according to the forecast. Large scale climate features have been known to impact seasonal streamflow variability in the Western US and especially in Colorado River Basin, which is well demonstrated [3; 4; 5; 6]. Grantz et al. [4] and Regonda et al. [5] developed a methodology for identifying potential predictors of spring runoff volumes by correlating historical runoff data with large-scale land-ocean-atmosphere system variables such as atmospheric pressure, surface air temperature, sea surface temperature, zonal and meridional winds over the Pacific and North American regions, as well as more traditional predictors such as the Palmer Drought Index and the basin snow water equivalent. These predictors were used in a multi-model ensemble forecasting technique to provide skilful seasonal streamflow forecasts in the Colorado River basin [6]

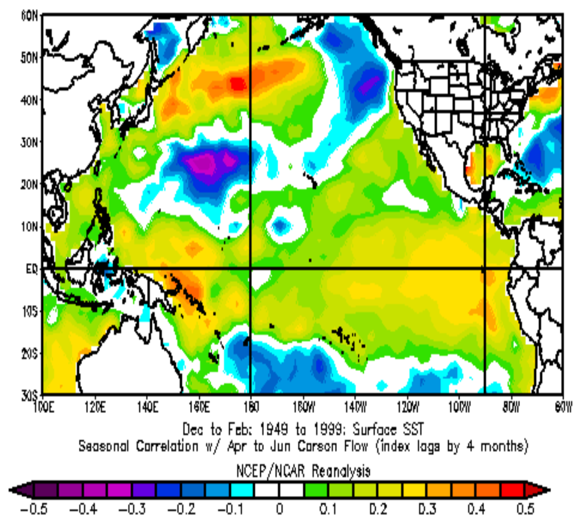

Figure 1. Sea surface temperatures in February correlated with April to July runoff volume in the Truckee River Basin

Although these techniques have been validated and demonstrated in the western United States, they are applicable globally as they do not depend on any particular climate index such as ENSO, but rather consider many variables in every part of the globe in search for correlations. A further advantage of these techniques is versatility in providing risk and reliability envelopes for water resources systems management under climate change and variability. They offer a simple and effective tool for this purpose without running elaborate models that require specific parametric assumptions.

In this suite of decision support tools, the stochastic hydrology traces are input into the river/reservoir model for simulation or optimization in a Monte-Carlo like set of runs.

2 Simulation and Optimization with RiverWare

RiverWare® is a general river and reservoir modeling tool widely used in the US due to its interpreted language for expression of multi-objective operating policies. RiverWare applications include operational scheduling and forecasting, planning, policy evaluation, and other operational analysis and decision processes [7,8] The wide range of applications is made possible by a choice of computational timestep ranging from 1 hour to 1 year. RiverWare has the capability to model:

Hydrology and hydrologic processes of reservoirs, river reaches, diversions,
distribution canals, consumptive uses, groundwater interaction and conjunctive use;
Hydropower production and energy uses; and
Water rights, water ownership, and water accounting transactions.

RiverWare's object-oriented, data-centered approach enables the modeler to represent site-specific conditions by creating a network of simulation objects, linking them together to form the river/reservoir network, 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. For example there are numerous methods for routing flow in river reaches, for evaporation calculations and for computing the hydropower generated. Figure 1 shows the RiverWare workspace and the palette of objects from which models are constructed.

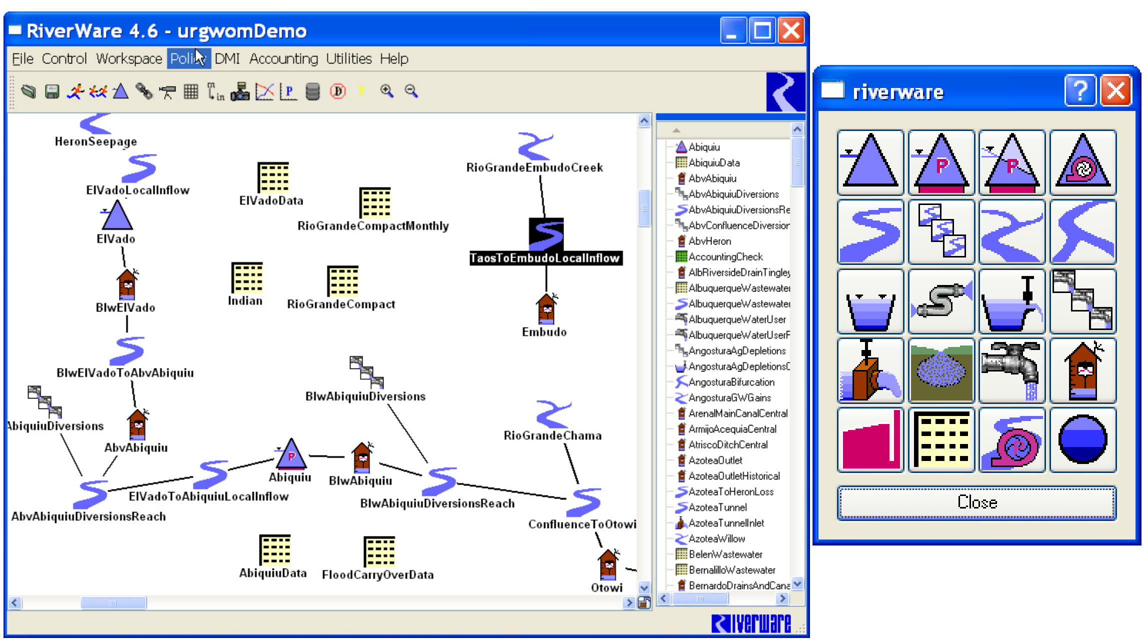

Figure 2. The RiverWare workspace and the Object Palette.

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.

Rulebased simulation provides a means for simulation based on 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 numerous other considerations. Operational policy is expressed in the RiverWare Policy Language (RPL), an interpreted language developed for, and exclusive to, RiverWare. RPL is a functional language in which assignments (to slots) are made only at the highest level of the rules. 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.

RiverWare's optimization solution [9] is a linear, pre-emptive goal programming algorithm that optimizes reservoir outflows for a prioritized set of user-specified objectives, solving simultaneously over multiple time steps rather than simulating one time step at a time. Preemptive linear goal programming successively applies prioritized objectives. Each objective is optimized in order and then constrained to its optimal value. Thus, a high priority objective is never sacrificed for a lower. Sets of constraints are converted to a single objective to minimize the deviation from the constraints. This approach avoids inconvenient infeasibilities. RiverWare provides linearizations for nonlinear variables. The objectives and constraints are formulated in the RPL syntax-directed editor. The software formulates the optimization problem (one for each prioritized goal) and sends it to the solver. RiverWare employs CPLEX, a robust third-party solver.

The Tennessee Valley Authority (TVA) is the primary user of RiverWare's optimization; their river operations schedulers use it for hydropower optimization on a daily and hourly basis. [10] The economics of hydropower optimization are represented by the implicit variable "Net Avoided Cost." The net avoided cost represents both the short-term value of hydropower in avoiding cost from thermal generation (or purchases to meet the power demand), and the long-term value of water used. The power plants can be modeled at the plant level, and currently under development is an integer programming solution that will solve the unit commitment problem on an hourly basis, considering all constraints and costs of unit operations.

3 Planning models for risk and reliability

For planning studies that consider risk and reliability, it is necessary to make many runs and use the aggregated results from all the runs to get probabilistic output, much like a Monte Carlo simulation. RiverWare includes a utility called Multiple Run Management (MRM) that sets up and executes multiple runs automatically and sends the results to output files that can be analyzed by post-processing programs. Using MRM, the user can make many runs over a planning horizon, using many traces of stochastically generated hydrologic inputs. MRM exports the results of the runs to one or more files in RiverWare Data Format (rdf). Then, post-processing analysis programs can import the rdf files and generate probabilistic information about the occurrence of certain events or the effectiveness of proposed operating policies. The hydrologic traces can be generated externally as described in Section 1.

With the use of the Graphical Policy Analysis Tool (GPAT) [11], an Excel-based tool developed jointly by CADSWES and Reclamation, the output of stochastic MRM can be used to compare two or more proposed operating policies in terms of their probabilistic effects on specified basin measurement criteria. In environmental impact studies, the measurement criteria may include a stream flow or lake elevation that is expected to comply with biological recommendations. To use GPAT for policy comparison, the multi-trace runs are performed for each policy alternative, and the results imported into GPAT. GPAT can provide statistical information in various ways over time, hydrologic trace, and policies. Figure 3 shows and application of GPAT on the Colorado River for the Interim Surplus EIS. The plot shows how six different operating policies compare with respect to the long term elevation of Lake Mead and different confidence levels. Each policy was modeled with the stochastic hydrologic traces, all starting with the same initial conditions in January 2000.

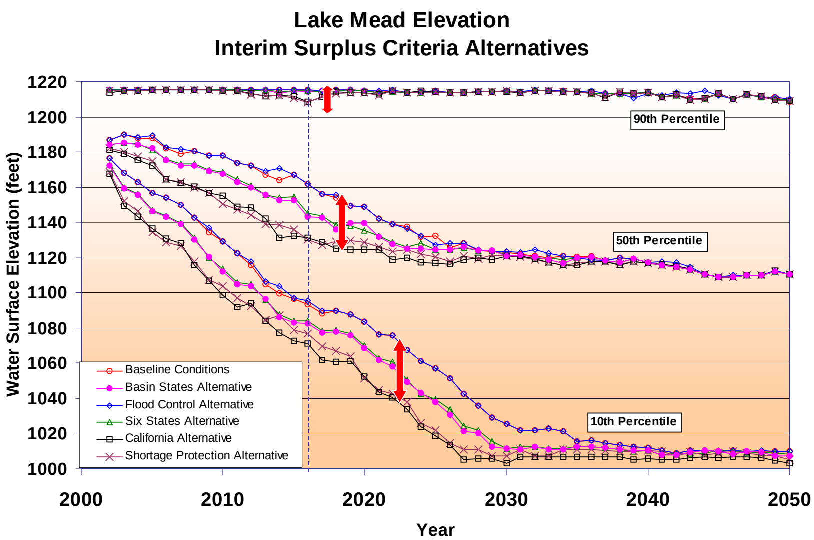

Figure 3. Application of the Graphical Policy Analysis Tool for comparing alternative operating policies on the Colorado River.

4 Applications

RiverWare has been applied to numerous river systems in the U.S. and elsewhere and descriptions of these applications can be found in the literature. The K-NN stochastic streamflow generator has been applied on the Colorado River, the Truckee-Carson Basin and the Gunnison River in concert with multiple trace RiverWare runs. A couple of recent applications that use the stochastic streamflow generation, RiverWare and GPAT – are two applications developed by Hydrosphere Resource Consultants (now AMEC) in Boulder, Colorado.

4.1 El Dorado Irrigation District (California) Hydroelectric Project Daily Operations Model

In late 2006 AMEC was retained by El Dorado Irrigation District (EID) to develop and implement a daily operations model for EID's Hydroelectric Project 184. Project 184 lies in the South Fork American River basin and consists of four large reservoirs, diversion, pipeline, and canal structures, a forebay, and a 20 mW power plant. It also is a primary source of water for EID's treated water customers. Project 184 received a new FERC license in October 2006. This license includes operating criteria and constraints on instream flow levels and reservoir pool elevations.

These constraints vary by month and year depending on the type of year (e.g., wet, normal, dry, very dry, etc.) AMEC developed a daily RiverWare model of Project 184. It includes all the pertinent infrastructure components (reservoirs, diversions, power plant, canals, forebay), and includes a ruleset that reflects EID's operating criteria and the constraints imposed by the new FERC license. The model allows operators to examine “what-if” scenarios when making daily operating decisions.

In early 2008, AMEC developed a tool to forecast the April through July runoff volume at Kyburz gage, a key location in the Project 184 system crucial to meeting minimum stream flows. The forecasting tool uses large scale climate data (i.e. sea surface temperature, 500mb geopotential height, meridonal wind and zonal wind) from areas of the pacific ocean that are highly correlated with snowfall and weather patterns contributing to snowmelt in the Project 184 watershed.

The Forecasting Tool is used with RiverWare as follows: At the beginning of January, February and March, the forecasting tool is used to assign a weight to each of the historical water years on record based on the similarity between the forecasted water year and the historical water year. These weights are used to determine the forecasted water year type (e.g., wet, normal, dry, very dry, etc.). The daily RiverWare model can then be run with the Multiple Run Manager to simulate the inflows associated with each of the historical water years within the framework of the current water year and the associated operations. The GPAT tool is then used to process the output from the multiple simulations to determine the probability of the lakes filling this water year, the confidence interval associated with target end-of-month lake levels, etc.).

4.2 Tarrant Regional Water District (Fort Worth, Texas) Water Supply Reliability Study

AMEC recently completed an evaluation of water supply reliability for the Tarrant Regional Water District (TRWD). The study used a Monte-Carlo approach to developing reliability statistics. The TRWD planning model was modified to reflect various possible future scenarios including estimated demands through 2060 and possible future infrastructure enhancements. The results of the study are being used to evaluate the timing of additional infrastructure capital expenditures and water rights yield, as well as providing a benchmark for drought response planning.

The Monte Carlo simulation approach involved performing repeated simulations with the RiverWare model (using MRM) while varying a particular variable or variables of interest. In this case, synthetic hydrologic traces were generated for the 1941-2003 simulation period, each of which was based on the historically observed patterns of hydrology. These synthetic traces were then simulated using various system policy and infrastructure configurations and estimated future demands. Statistical analysis of the results (using GPAT) provides estimates of reliability for a variety of “resource indicators” such as delivery shortages, reservoir elevation targets, etc.

The first step in the Monte-Carlo evaluation process was generating the synthetic traces based on the 1941-2003 period. The RiverWare model had already been developed using a set of naturalized inflows for each of the reservoir objects for the time period of January 1941 to December of 2003. We classified each year in this period as wet, average, or dry based on the total annual naturalized inflow into the TRWD system reservoirs, and used random sampling to develop 100 different sets of hydrologic inflows. The inflow values were taken from the set of naturalized inflows, so no new inflow values were created, and the sequence of those inflows (on an annual basis) were varied such that the 1941 – 2003 pattern of wet, dry and average years was maintained. These 100 synthetic traces, each for the period of January 1941 to December 2003, were used to provide the hydrologic variability for each of the cases studied. Evaporation coefficients and demand data for the various water users vary by year according to hydrologic conditions as well. When generating each synthetic trace, we also synchronized these evaporation and demand data to maintain consistency across the data sets. This is not to say that historical demand data were used, but rather that the patterns of historical demand fluctuations remained synchronized with the resampled hydrology (e.g., if August 1940 was particularly dry, the evaporation data and demands for that month were also likely proportionately higher, and that covariance is carried through as part of the resampling).

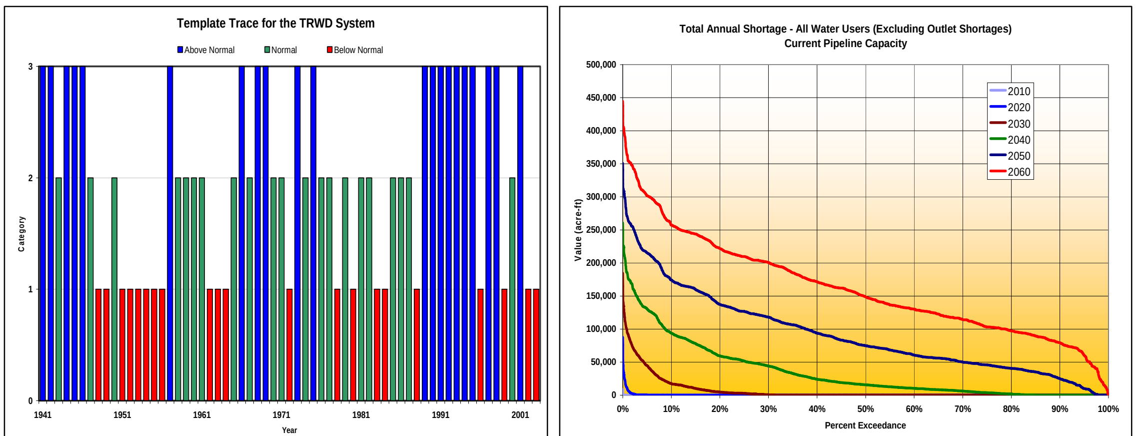

Figure 4. Left: Category (below normal = 1, normal = 2, above normal = 3) of each year in the index inflow time series for the TRWD system. Right: Total Annual Shortage (all water users) – Cumulative Distribution Function

Hydrosphere modified the monthly RiverWare planning model provided by TRWD to run the 100 synthetic traces. RiverWare's Multiple Run Management utility (MRM) was used to enhance the model to simulate 100 concurrent runs, each for the January 1941 to December 2003 time period, each time the model was executed. Input DMIs were created that automatically import one of 100 sets of hydrologic inflows between each of the 100 simulations. The result of an entire model simulation is 100 RiverWare simulations, each with a different set of hydrologic inflows, such that all 100 synthetic traces are used.

5. Summary

A powerful suite of tools for planning of river and reservoir systems with unceratinly consists of a non-parametric method for developing synthetic hydrologies, a method for long-lead forecasting based on climate indicators, a simulation and optimization model to generate many runs with the stochastic traces, and a statistical post-processing tool for analysis of results. These tools are built around RiverWare, a modeling tool developed at the University of Colorado (CU), sponosored by the U.S. Bureau of Reclamation, the Tennessee Valley Authority, and the U.S. Army Corps of Engineers. RiverWare is avilable through the CU Office of Technology Transfer.

These tools can be used for planning projects and operations that maximize the benefits of the objectives and provide risk and reliability-based results for responsible decision-making.

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