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FRASER RIVER EXTENDED STREAMFLOW PREDICTION SYSTEM

Stanley J. Woodcock, Michael Thiemann, and Larry E. Brazil *
Riverside Technology, inc., Fort Collins, Colorado

Esther Vincent and Andy Pineda*
Northern Colorado Water Conservancy District, Berthoud, Colorado

1. INTRODUCTION

The Municipal Subdistrict of the Northern Colorado Water Conservancy District (Subdistrict) operates the Windy Gap Project (Project) that diverts water from the Colorado River to municipal water users on the Northern Front Range of Colorado. The majority of the water diverted by the Windy Gap Project is derived from the Fraser River, which is a tributary of the Colorado River. The Project consists of a diversion dam on the Colorado River, a 549,000 m^3 reservoir, a pumping plant, and a 9.65 kilometer pipeline to Lake Granby. The Windy Gap Project can deliver an average of 59.2 million m^3 of water annually, primarily between April and July. During the spring runoff, water is pumped from Windy Gap Reservoir to Lake Granby, where it is stored for delivery through the Colorado-Big Thompson (C-BT) Project facilities. (***Figure 1***). Streamflow forecasts are critical to optimize the operation of the Project, which is constrained by an energy contract to operate the pumps, as well as by senior water rights both upstream and downstream of the Windy Gap Reservoir that can prevent any diversion at Windy Gap. The RiverTrak® hydrologic modeling application (Riverside Technology, inc.) was therefore implemented to perform extended runoff predictions of the Subdistrict's allocation of the Fraser River water. The RiverTrak® software employs snow and soil moisture accounting models, initialized to current conditions and driven by historic climatologic inputs, to predict plausible streamflow scenarios (traces) for the Fraser river basin. The Subdistrict uses these traces to derive probabilistic predictions that help to manage an optimal pumping schedule.

*Corresponding authors address: Stanley J. Woodcock, Michael Thiemann and Larry E. Brazil, Riverside Technology, inc., 2290 E. Prospect Road, Suite 1, Fort Collins, CO 80525. Esther Vincent and Andy Pineda, Northern Colorado Water Conservancy District, 220 Water Avenue, Berthoud, CO 80513.

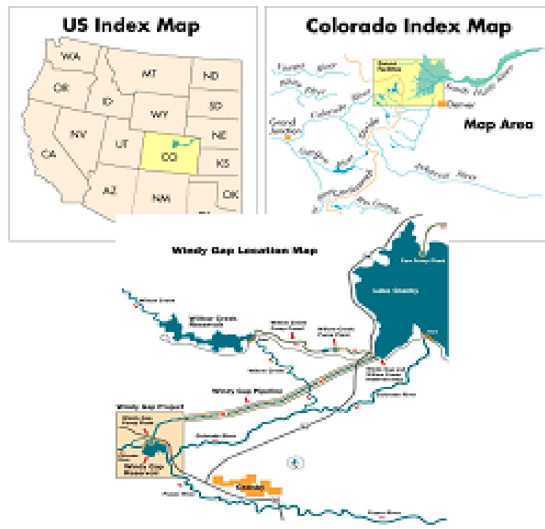

Figure 1. Project Location

2. SYSTEM COMPONENTS

The Subdistrict's streamflow prediction system consists of three components, which are described below.

The first system component is the RiverTrak® Forecaster software, a streamflow forecasting tool that runs in conjunction with an existing data collection system on a personal computer. The RiverTrak® Forecaster software is integrated with a supporting database which manages system configuration data, input, and results. The system simulates the hydrologic response of a watershed as a function of real-time precipitation, temperature, flow, and other data to produce short-term deterministic forecasts. Input data are ingested automatically but also can be entered, viewed, and edited manually. Streamflow forecasts are generated for locations in a watershed called forecast points.

The RiverTrak® Forecaster system uses a variety of independent modeling operations that are configured to generate continuous forecast information. These operations are continuous, physically based, conceptual models that are designed to produce streamflow forecasts for a variety of hydrologic conditions. They are organized in an *operations table*, which defines the modeling sequence from snow accumulation and snow melt to simulated flows at the forecast point. Each component uses parametric data, which were determined through model calibration during the system implementation to ensure that the hydrologic forecasts adequately match actual runoff volumes and timing. The operations include:

- SnowPack (snow model)
- Sacramento Soil Moisture Accounting Model
- UnitHydrograph

Snow modeling in RiverTrak® Forecaster is based on the National Weather Service (NWS) Snow-17 Snow Accumulation and Ablation Model, which uses temperature as an index for snow accumulation and melt. Computed snowmelt is passed to the rainfall-runoff model. During periods when snow pack and snowfall are not a consideration, the snow model passes the precipitation input directly to the rainfall-runoff model without modification. Rainfall-runoff modeling is performed using the NWS Sacramento Soil Moisture Accounting Model, which simulates the continuous movement of water from rain or snowmelt in various soil layers to produce runoff from a basin. A unit hydrograph model time distributes the stream channel inflow estimated by the Sacramento model to a streamflow hydrograph at the forecast point. The operations save model states at each time step so that initial conditions are available for future simulations.

The second system component is the RiverTrak® ESP software which employs historical (instead of real-time) meteorological data, along with the conceptual hydrologic models described above, to produce multiple plausible long-term streamflow predictions. One possible streamflow trace is hereby simulated for each year of historical meteorological data, using current model states supplied by the RiverTrak® Forecaster component as initial hydrologic conditions. These streamflow traces are therefore conditional and reflect the variability of potential future streamflow, based on current hydrological situation in the basin.

The final system component is ESPADP, an analysis package developed by the NWS to provide statistical and graphical analysis of time series data, ESP time series in particular. These data are read in from trace files produced by the RiverTrak® ESP component. ESPADP provides a wide array of analysis capability. Because of the probabilistic nature of ESP output, time series are broken up into sequences of realizations. ESPADP processes each year of simulation as an independent trace. ***Figure 2*** presents the ESPADP analysis window with 24 years of traces originating from a RiverTrak® ESP run. The traces, commonly referred to as a spaghetti plot, represent possible realizations of streamflow for the Fraser River. Data can be aggregated to larger time steps for analysis purposes. For example, hourly data can be processed to daily, weekly, or monthly time steps, some multiple of each, or it can span the entire forecast period. Analysis variables could include minimum values over some interval, maximum values, mean values, instantaneous values, accumulations (total values), the number of days to a maximum value, the number of days to a minimum value, the number of days to some threshold value, or the number of days below or above some threshold value. Simple statistics over the ensemble of traces can be generated in an expected value plot. Minimum, maximum, mean, and standard deviation statistics are shown over the ensemble of years corresponding to each analysis variable over a specific interval. Probability interval plots can be generated to capture some of the risk-based analysis required in probabilistic forecasting. The ensemble of traces over each analysis variable and user-specified interval can be converted into a distribution with exceedance probabilities displayed as a histogram. ***Figure 3*** depicts the chances of exceeding a river level for any given day. From analysis such as this, information about risk of expected water supply at a forecast point can be provided to decision makers. ESPADP also offers a mechanism to manually weight historical years. Using the entire historical period of interest, weights can be defined for each year depending upon an estimate of likelihood of occurrence. These weights are normalized, then incorporated into subsequent analysis of the ensemble of traces. For example, year weighting can help condition the hydrologic forecast to El Niño signatures by excluding or weighting historical years.

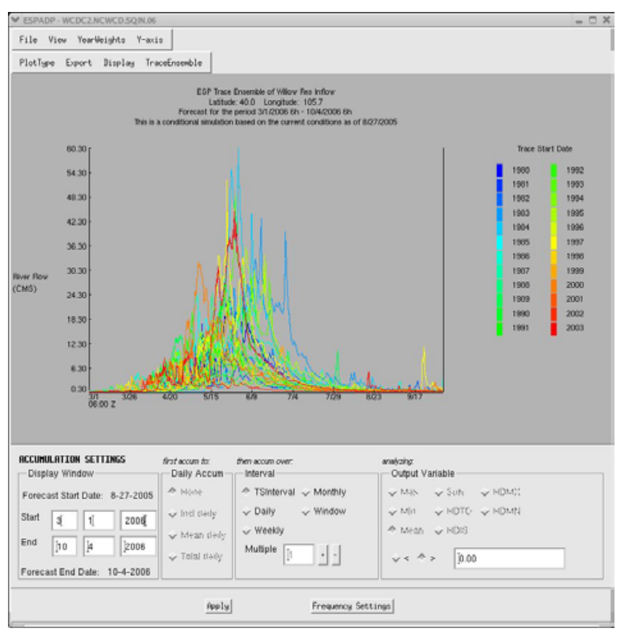

Figure 2. Spaghetti plot in ESPADP analysis window

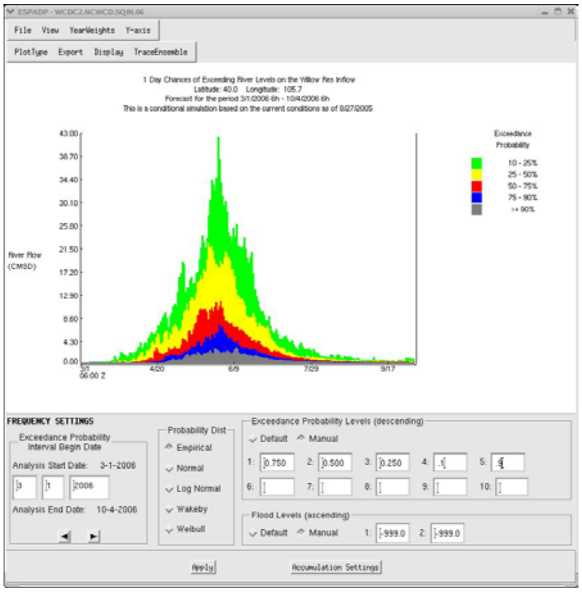

Figure 3. Exceedance probability plot in ESPADP

3. FRASER RIVER IMPLEMENTATION

The Windy Gap Project which pumps water from the Colorado River through a six-mile pipeline into Lake Granby derives most of the water from the Fraser River. Management of the pumping schedule is a complex set of interdependent factors for staff at Northern Colorado Water Conservancy District (NCWCD). These factors include water supply forecasts from the Fraser River, upstream and downstream water rights on the Colorado River and energy contracts to operate the pumps. In January 2005 Riverside Technology, inc. (RTi) installed the RiverTrak® Forecaster/ESP software along with ESPADP at the NCWCD to improve the forecasting capability for the Fraser River Basin. In this implementation, the RiverTrak®/ESPADP system uses real-time precipitation and temperature data gathered from various sources to automatically produce real-time streamflow forecasts. Three forecast points are defined in the Fraser Basin: Moffat Collection System (***Figure 4***) contributing to a diversion via the Moffat Tunnel, Upper Area Basin below the Moffat Collection System contributing to the Fraser River and Lower Area Basin contributing to the Fraser River. The delineation of the Moffat Collection System Basin was fundamental to produce a usable and realistic forecast of the water available for pumping at the Windy Gap diversion. Historically most of the runoff produced above the Moffat Collection System is diverted via Denver Water's senior water rights through the Moffat Tunnel and is not available to the Windy Gap Project. Typically, only water produced by the basin below the Moffat Collection System (Upper Area Basin below Moffat Collection system and Lower Area Basin) is available for pumping at the Windy Gap diversion, although in wetter years some water produced by the upper basin above the Moffat Collection System can be bypassed to the lower part of the basin.

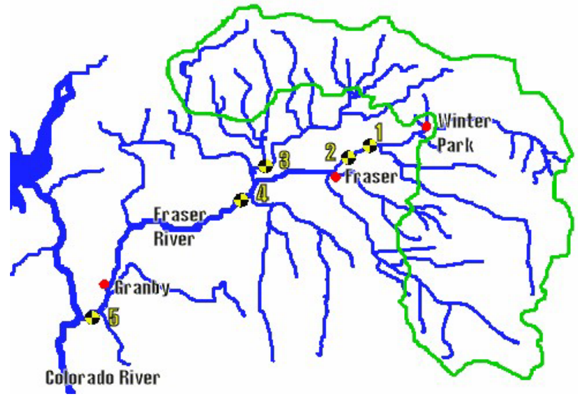

Figure 4. Moffat Collection System

Models employed include the NWS Snow-17 and Sacramento Soil Moisture Accounting models. ***Figure 5*** shows the region and the basins of interest. The simulated basins vary in their snowpack conditions, and in order to reflect these differences and to produce accurate forecasts, the models were area-specifically calibrated using available historic data records. In order to simulate the complex snow conditions in the spring season, the system also supports the updating of computed snow water equivalent in the Snowpack Model to observed conditions.

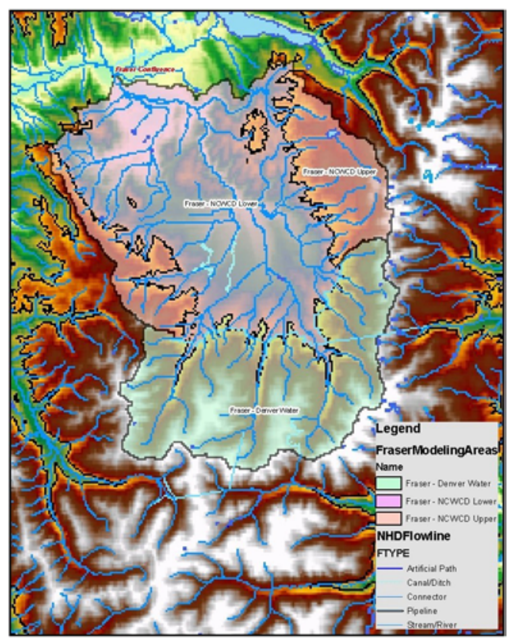

Figure 5. Fraser Modeling Area

4. DECISION MAKING PROCESS

Several factors control the amount of water that can be pumped through the Windy Gap Project. The first one is the amount of water diverted from Denver Water through the Moffat Collection System. The second one is the most senior water right on the Colorado River, which is commonly referred to as the Shoshone call. When the Shoshone call is on, the Windy Gap diversion is called out of priority. Even if water is physically available at the point of diversion, water has to be bypassed to satisfy the call. A third controlling factor is the by-pass flow requirements below the pumping station. Minimum flow requirements downstream of the Windy Gap Reservoir can force the project to bypass water for irrigation water rights. Typically 2.55 m^3/s cfs have to be released to meet irrigation calls downstream but in dryer years the minimum flow requirements can go up to 3.82 m^3/s. The last factor is the constraints imposed by the energy contract between the Municipal Subdistrict and the United States department of Energy Western Area Power Administration's that sets the allocation of federal power to the Subdistrict.

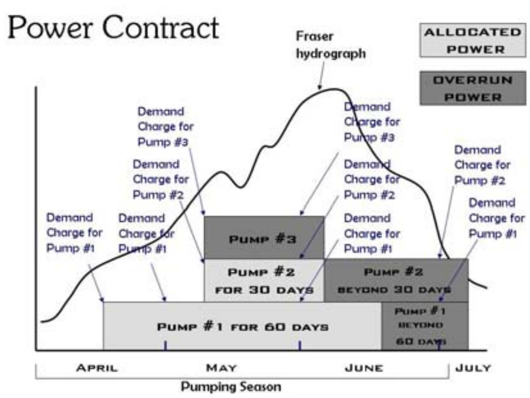

Figure 5. Power Allocation

The Subdistrict can use a certain amount of power, which is designated as the Allotted Power, at a preferred rate. Any use of power beyond what is defined in the Allotted Power is called the Overrun Power. Overrun Power energy has to be purchased at market rates, which are considerably higher than the preferred rate of the Allocated Power. Additionally, a Demand Charge is added to the energy cost every time a pump is turned on or a new month starts (***Figure 6***) The Allotted Power is defined as the energy necessary to operate one pump for 60 continuous days within the Pumping Season (April, May, June) and one more pump during 30 continuous days within the 60-day period.

Traces produced by the RiverTrak®/ESPADP system are used as input in a spreadsheet model developed by Subdistrict staff that models river operation and simulates various Windy Gap Pumping scenarios. The model enables the user to turn each of the four pumps on or off and through a trial and error process maximize the pumping volume and minimize the pumping costs by examining the effects of various pumping start dates on those variables.

The model is operated using various hydrology scenarios corresponding to exceedance probabilities computed by the ESPADP system at the 25th, 50th, 75th, and 90th percentile levels and to various assumptions regarding Moffat Tunnel diversions. Typically, two scenarios are envisioned: 1) all the water produced by the upper basin above the Moffat Collection System is assumed to be diverted, 2) Moffat diversion forecasts produced by Denver Water for various exceedance probability levels are subtracted from the upper basin hydrograph. Then each scenario is ran at the 25th, 50th, 75th, and 90th percentile levels.

Individual years extracted from the Traces can also be used as input into the model to look at similar years hydrology and potential pumping.

5. CONCLUSION

In 2005, the RiverTrak®/ESPADP system was instrumental in the decision making process to determine when to start pumping, when to turn additional pumps on and whether to extend pumping outside of the 60 day pumping season. The model provided real-time data, which was not available in previous years and provided confidence to the decision makers. During the first year of operating the RiverTrak®/ESPADP system, this resulted in the earliest start of pumping and the second to highest volume pumped in the history of the Windy Gap Project (which started operating in 1985). The real-time forecast enabled the Subdistrict to synchronize the operation of the Project with the peak of the hydrograph thereby optimizing the pumping (***Figure 7***).

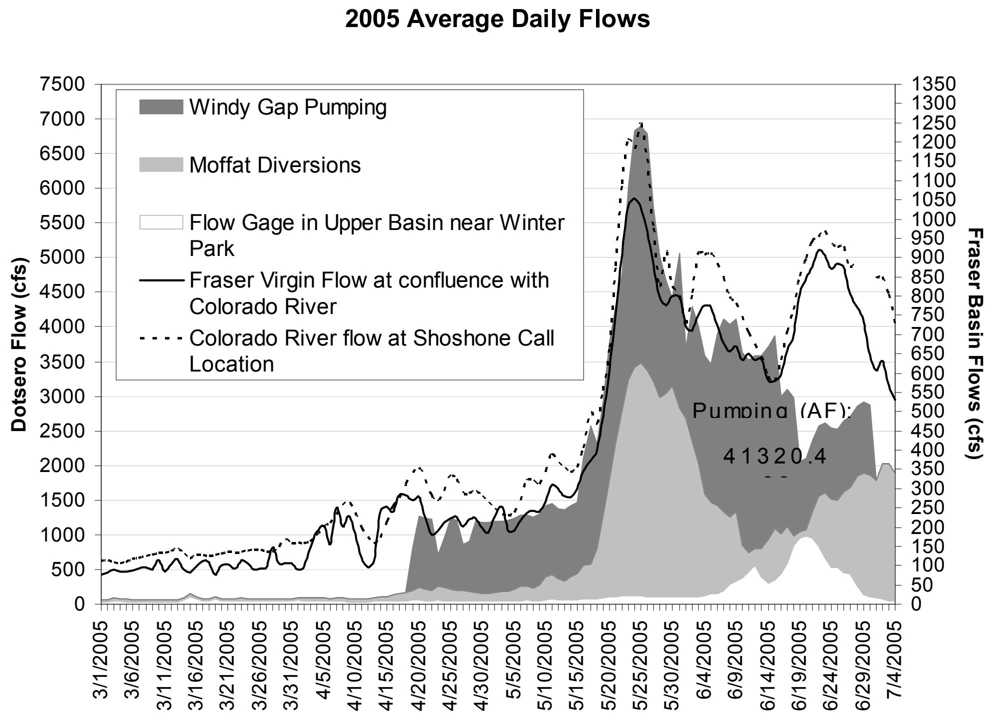

Figure 7. 2005 Average Daily Flows