Presented at the AWRA 28th Annual Conference and Symposia, November 1-5, 1992, Reno, Nev.

DEVELOPMENT OF A DECISION SUPPORT SYSTEM TO IMPROVE RESERVOIR OPERATIONS WITHIN THE DENVER WATER RESERVOIR SYSTEM

Douglas B. Greer,[1] Mark Waage, P.E.,[2] Donald P. Laurine,[3] and Wentao Liu[4]

ABSTRACT: A cooperative research project is currently underway to demonstrate the use of National Weather Service (NWS) Extended Streamflow Prediction (ESP) forecast information in reservoir management activities. The purpose of the project is to determine how ESP forecast information can be incorporated into reservoir operations and to quantify the benefits obtained by using the information. This paper will present the results of the first phase of the project. The effort will involve verification of ESP forecast information and modeling of operations at two DW reservoirs. Once the model adequately represents DW operations, the operational rules will be optimized using a dynamic programming tool such as CSUDP. Modifications to the model will be made to allow incorporation of ESP forecast information. Operation of the system will be simulated using historical data with and without ESP forecast information, as well as with and without optimization. Benefits associated with the optimization and ESP information will be computed. These results will be used in the design of a real-time decision support system that will be used in the operation of the DW reservoir system.

INTRODUCTION

Riverside Technology, inc. (RTi), the National Weather Service (NWS), and Colorado State University (CSU) are working cooperatively with Denver Water (DW) to improve the operations of DW's water diversion and reservoir system through the incorporation of improved forecast information. DW water managers have the complex and difficult task of best managing the limited supply of water available. This task is further complicated by the complexity of the agreements that control the timing and quantity of how water may be diverted and stored. The water manager's job can be made easier by extended forecast information on possible quantities of water available for use by the system. The purpose of this cooperative project is to determine how forecast information can be incorporated into reservoir

[1]Senior Hydrologist, Riverside Technology, inc., 2821 Remington Street, Fort Collins, CO 80525.
[2]Water Resource Engineer, Denver Water, 1600 W. 12th Avenue, Denver, CO 80524.
[3]WARFS Implementation Leader, Colorado River Forecast Center, National Weather Service, Salt Lake City, UT.
[4]Graduate Research Assistant, Colorado State University, Fort Collins, CO 80523.

operations and also to quantify the benefits of using this information. Extended streamflow forecasts are currently being produced for DW managers through the use of the NWS ESP procedures. The NWS's River Forecast System (NWSRFS) will be discussed further below.

THE NATIONAL WEATHER SERVICE HYDROLOGIC FORECAST SYSTEM

Significant advances have occurred in the last few years in the capabilities of computers and real-time communications. Corresponding gains in the advancement of river forecasting science have also occurred. The combined result of these advances has been improved availability of forecast information for water managers--the goal toward which the NWS has been working cooperatively with state, local, and other federal agencies, as well as private entities (Fread et al. 1991). The result of this work is an initiative through which the NWS will be able to supply better water resource information, thereby enabling water managers to make more informed--and therefore less risky--decisions. This initiative is known as Water Resources Forecasting System (WARFS).

The key component of WARFS is NWSRFS. The system consists of a number of computer models and procedures (Figure 1) that simulate

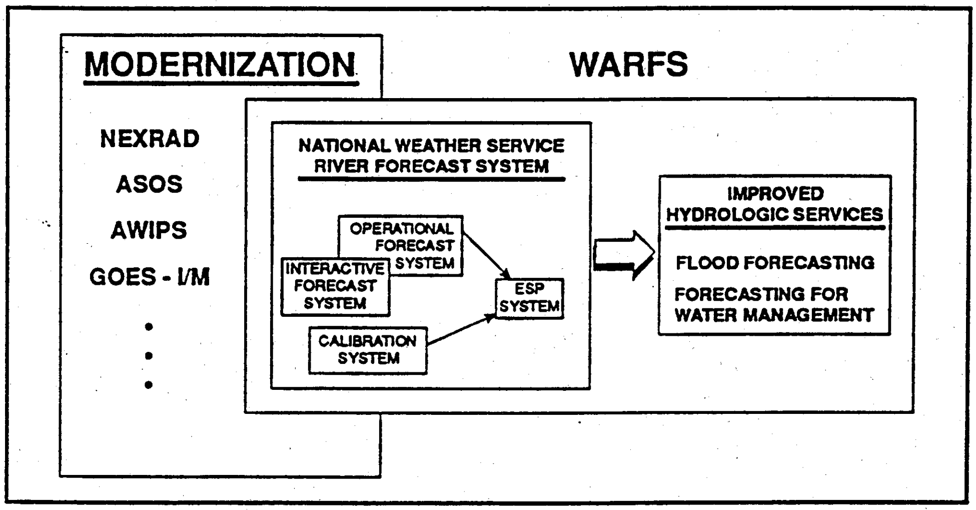

Figure 1. WARFS and the NWS River Forecast System (Fread et al. 1991).

important hydrologic and hydraulic processes, such as soil moisture accounting, channel routing, and reservoir operation. The same models are used in all components of the NWSRFS. The components of NWSRFS are as follows:

- Calibration System (CS). The CS processes historic hydrometeorological data to estimate hydrologic model parameters of a basin for use in the forecast system.

- Operational Forecast System (OFS). The OFS uses real-time data as input to the calibrated models to generate streamflow forecasts for hours or a few days into the future. The system also keeps track of the current model states (state variables) for use in producing ESP forecasts. Note that the OFS is run daily at the NWS River Forecast Centers (RFC). This important activity consumes considerable computer and personnel resources.

- Interactive Forecast System (IFP). The IFP is the real-time version of OFS. This system allows a forecaster to interactively generate forecasts for hours or a few days into the future. IFP uses the same model source code as the OFS and provides the same information as OFS but also allows a forecaster to interactively perform a "what if" analysis more easily.

- Extended Streamflow Prediction System (ESP). The ESP system uses present watershed conditions and the updated values of the state variables produced by OFS, combined with future time series of precipitation, temperature, and evaporation, to produce probability estimates for a number of streamflow variables (Figure 2). The procedure assumes that any of the

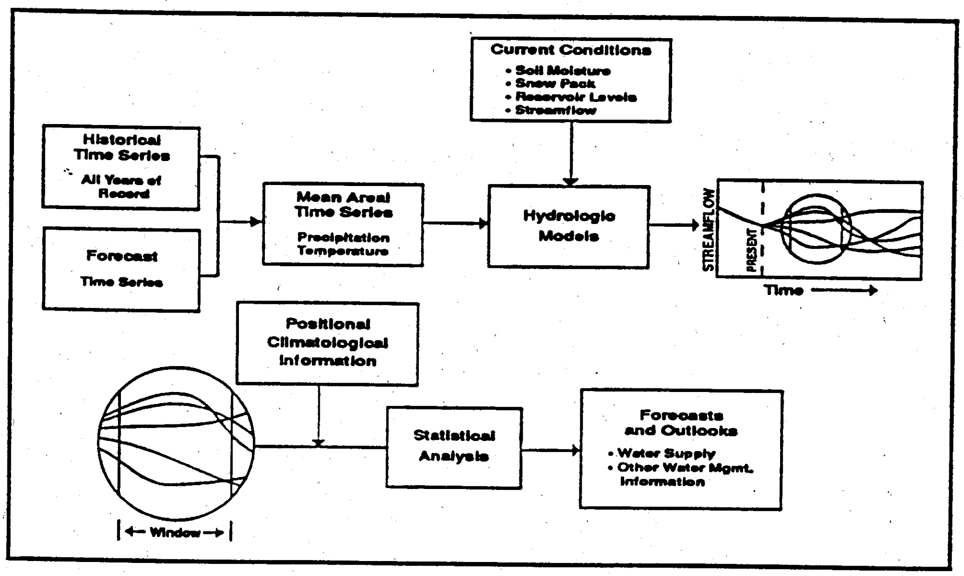

Figure 2. Extended Streamflow Prediction Procedure.

historical time series of precipitation, temperature, evaporation have an equal probability of occurring in the current year. When these time series and the updated values of the state variables are run through the calibrated simulation system, a set of discharge time series is produced. Generally, at least 20 years of historical data is used to ensure accurate probability estimates. Current short-term meteorological forecasts are used to provide a transition into the future. Probability forecasts are then generated by analyzing the series of discharges for a given period of time (forecast window) and for certain streamflow variables (Anderson 1986, Day et al. 1992).

THE DENVER WATER SYSTEM

DW operates three collection systems to supply raw water from the western side of the Continental Divide in Colorado to the metropolitan area of Denver. These collection systems are the Moffat Tunnel, the Roberts Tunnel, and the Williams Fork Systems. Surface runoff is collected from a 622-square-mile area and transmitted through a network of tunnels to the east side of the Continental Divide. From here, the water is conveyed through a series of reservoirs in tributaries of the South Platte River.

The Denver Water system was chosen as a demonstration and implementation candidate to show the benefits of WARFS. The primary goal of the Denver Water system is to supply a reliable source of good quality water to Denver, but there are other goals as well. Excess supply is sold to the surrounding suburbs. Hydropower is generated to offset the cost of the water supply and to pay back power interference caused by DW operations. A number of critical decisions must be made on a daily basis, mainly dealing with the operations of the reservoir system. The reservoirs are operated to attempt to meet competing goals, such as water supply, flood control, power production, maintenance of instream flows for aquatic life, and recreation. Operational decisions must consider water supply demand, water requirements of more senior water users, power interference, and most importantly, providing reliable water supply. The project location is shown in Figure 3.

Denver Water Department Demonstration Project

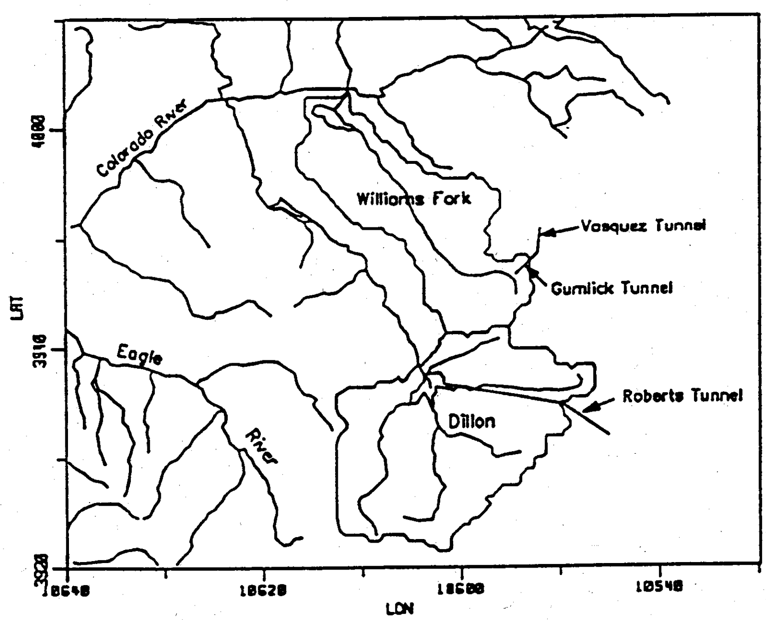

Figure 3. Project Area.

The DW system was studied to determine how useful information could be provided for water managers. Another concern was selecting components of the system that were not too complex for use in the demonstration study, yet included a reservoir. Components of the Williams Fork Collection System and the Roberts Tunnel Collection

System were selected. The Moffat Tunnel Collection system was not selected because this system does not contain any reservoirs.

The Williams Fork Collection System consists of a collection system, the Gumlick Tunnel, and Williams Fork Reservoir. The collection system and Gumlick Tunnel convey water collected in the head waters of the Williams Fork River on the west side of the Continental Divide to the Fraser River Basin. This water is then conveyed by the Moffat Tunnel under the Continental Divide into South Boulder Creek and Gross Reservoir for raw water supply. Williams Fork Reservoir is used to supply replacement water when the "call" comes on the Colorado River and the Gumlick Tunnel is diverting out of priority. Water may also be exchanged from Williams Fork Reservoir for water stored in Dillon Reservoir. Hydropower is generated at Williams Fork Reservoir for replacement of power lost by DW operations.

The Roberts Tunnel Collection System consists of the Roberts Tunnel and Dillon Reservoir. Dillon Reservoir collects runoff from the Blue River and conveys the water under the Continental Divide through the Roberts Tunnel into the North Fork of the South Platte River for raw water supply. Power generated at Dillon Reservoir and at Williams Fork Reservoir is used as replacement power when operations at Dillon Reservoir interfere with power generation at Green Mountain Reservoir, downstream. Also, the largest hydropower plant part of the DW system is found at the east portal of the Roberts Tunnel, so maximizing power revenues are an important objective. Recreation is an important local activity on Dillon Reservoir, so high water levels are maintained as long as possible in the reservoir during the summer recreation season. A Blue Ribbon trout fishery is located downstream of Dillon Reservoir, and DW maintains minimum releases to support this fishery.

DEMONSTRATION PROJECT

The purpose of the project is to determine how ESP forecasts can be incorporated into reservoir operations and to quantify the benefits obtained by using this information. The NWS Colorado Basin River Forecast Center runs ESP on a regular basis for the Williams Fork and Blue River basins. However, the NWS cannot provide all the ESP information required by all users at all locations. The first step in the project was to provide a mechanism to transfer the ESP information from the NWS to DW. This resulted in the development of an interactive ESP analysis tool that would run on a PC. The tool allowed DW to access and analyze the ESP information for use in their operations.

ESP Interactive Analysis Program (IAP)

The system was implemented in two steps to allow DW to analyze and display the ESP information on inflows to Williams Fork Reservoir and Dillon Reservoir. The steps are described below.

Step 1. Software was developed in coordination with the NWS to download ESP trace data to a DW computer via modem. The Colorado RFS runs ESP daily and generates the ESP output traces for one year into the future. The system allows DW personnel to automatically download the data.

Step 2. The second step involved development of a program to allow DW personnel to analyze ESP data and produce a graphical display of the results. DW needs probabilistic forecasts of monthly volume inflows for February through September and probabilistic forecasts of weekly inflow volumes for May through July.

After meetings with DW, it was determined that the necessary decision making information from the program should include tables of numbers and graphical displays and include probabilistic weekly or monthly forecasts of reservoir inflows for the appropriate time windows. The resulting stage-two program is interactive and provides DW personnel with the capability to select from a variety of input options, such as basin of interest, weekly or monthly forecasts, streamflow volume or peak flow forecasts, and forecast window. The output consists of probabilistic reservoir inflows with exceedance probabilities of 0.9, 0.7, 0.5, 0.3, and 0.1. Weekly forecasts can be generated for up to 12 weeks, and monthly forecasts can be obtained for up to one year in the future.

Project Plan

Several tasks must be completed to perform the assessment of the benefits ESP forecast information provides in reservoir operations. The technical approach will consist of two main efforts: (1) verification of ESP forecast information and (2) modeling of reservoir operations at two DW reservoirs. The first effort will entail assessing the accuracy of the forecasts for the period of record to be used in the modeling tasks. The second effort will entail the adaptation and implementation of operational models for use at DW.

The first task in the ESP verification will be selection of a suitable period of historical record for reconstruction of operations. The period will be selected based on adequacy of records of operations data quality, and hydrologic variation. The ESP verification will be performed by generating and statistically analyzing ESP forecast traces for the verification period. The verification information will be used to determine the accuracy of the forecasts and how representative the results of the project will be for other locations.

The modeling effort will consist primarily of tasks to incorporate ESP forecast information into DW operations in the Blue and Williams Fork River basins. The emphasis will be on the use of existing models to simulate DW operations. The first task will be selection of a suitable model for use in the project. The most likely candidates are MODSIM and HEC-5. One criterion for model selection will be its suitability for use with ESP inputs. Once the operational model is selected, rules will be developed for the model based on input from operational personnel at DW. The model will be verified and recalibrated if necessary using the historical releases made during the selected reconstitution period.

Once the model adequately represents DW operations, the operational rules will be optimized using the historical calibration period. Optimization will be made using an existing code such as

CSUDP, a generalized dynamic programming code. The optimization procedure will consider operational constraints, such as the requirement that water supply targets must always be met, and will allow the examination of trade-offs of reservoir uses, such as power, recreation, minimum flows, and minimized spills, while meeting all release and diversion demands.

Modifications will be made to allow the model to use ESP forecast information. Runs will be made to simulate operations in the reconstitution period. The model will be used in four simulations: (1) non-optimized without ESP information, (2) non-optimized with ESP information, (3) optimized without ESP information, and (4) optimized with ESP information. Benefits associated with the optimization and the additional ESP information will be computed. Calculations of these benefits will be aided by discussions with DW personnel to define the value of water for various uses, such as water supply, hydropower, and recreation.

Preliminary Results

One result of the project is that the IAP is being used in the operation of Williams Fork Reservoir and Dillon Reservoir. The program has allowed the DW managers to study different operating scenarios and evaluate the associated risks. One example of use of the program involves a construction project at Williams Fork Reservoir during the spring of 1992. The project involved drawing the reservoir down to a level that would allow reconstruction of boat ramps. DW needed to evaluate the risk of not refilling the reservoir prior to the end of spring runoff if the reservoir were drawn down late in the spring. The penalties for not refilling the reservoir are smaller hydropower revenues and possible undesirable modification of their operations after the call comes on the Colorado River. DW performed an analysis using the IAP. The probabilistic streamflow volumes and exceedance probabilities were used to consciously weigh the risks of the proposed project and then make an informed decision.

A verification system has been developed to assess the forecast skill of the NWS ESP procedure for individual basins. The system is designed to reconstruct ESP forecasts for historical dates and to compare these forecasts with the observed streamflow. The system includes a component to generate ESP historical streamflow traces and another component to analyze the traces. ESP forecasts for historical dates are generated from the traces for particular streamflow variables (e.g., volume and forecast windows), and forecast error statistics are then computed. The system was used to compute verification statistics for the April through July inflow volume forecasts for Dillon Reservoir (Day et al. 1992). The results indicated that there was significant skill in the forecasts and that the skill will probably be increased when the model calibrations are improved.

Most of the data collection has now been completed. MODSIM was selected as the reservoir simulation model to be used on the project. MODSIM has already been used to successfully simulate other parts of the upper Colorado River system and is the most appropriate program to use on this project. A preliminary Williams Fork - Dillon network has been formulated to be used with MODSIM. Simulation of reservoir operations will be conducted using this network, which was developed in consultation with DW personnel.

CONCLUSIONS

The project is still in its early stages; however, preliminary results show that the information available through the ESP IAP can be extremely useful in the decision process by providing DW personnel with timely probabilistic information about future hydrologic events. This information has been used for daily operations, long-term planning, and risk analysis. For the first time, DW personnel have the benefit of using all available ESP information without having to run or maintain any hydrologic models on a routine basis. The NWS will continuously run the models and make the forecast data available for DW analysis.

Much additional work is yet to be done. The project thus far has produced a framework for understanding how probabilistic hydrologic information can be used to improve water management activities. As the project continues, additional water management tools will be produced to enable DW personnel to do a better job in the operation of their reservoir system.

REFERENCES

Anderson, E.A. (1986). "The National Weather Service River Forecast System and its Application to Cold Regions." Hydrologic Research Laboratory, National Weather Service, NOAA, Silver Spring, MD.

Day, G.N., L.E. Brazil, C.S. McCarthy, and D.P. Laurine. (1992). "Verification of National Weather Service Extended Streamflow Prediction Procedure." To be included in AWRA's Symposium Proceedings on Managing Water Resources During Global Change. Reno, NV, November 1-5.

Fread, D.L., G.F. Smith, and G.N. Day. (1991). "The Role of Real-Time Interactive Processing in Support of Water Resources Forecasting in the Modernized Weather Service." Proceedings of the Seventh International Conference on Interactive Information and Processing Systems for Meteorology, Oceanography, and Hydrology. New Orleans, American Meteorological Society, January 13-18.