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PILOT PROJECT RESULTS FROM A PROBABILITY BASED LONG RANGE WATER MANAGEMENT/SUPPLY FORECAST

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ABSTRACT

A pilot project sponsored by the National Oceanic and Atmospheric Administration/National Weather Service (NOAA/NWS), Riverside Technology, inc. (RTi), Denver Water Department (DW) and Colorado State University (CSU) and carried out with cooperation from the Bureau of Reclamation (BOR) was established to demonstrate the value of long range forecasting for the purpose of improving water management of complex reservoir systems. The project objectives are to define a methodology of incorporating long range probabilistic forecasts into reservoir operations and quantify the benefits of the forecast information. The Denver Water Department has the primary responsibility to provide adequate water to subscribers in the Denver Metropolitan area. In doing so it diverts water from the Colorado River Basin to Eastern Colorado, sells hydroelectric power, while complying with other competing water rights and commitments in the water supply network. The Extended Streamflow Prediction System (ESP) developed by NOAA/NWS was used to supply probabilities of equaling or exceeding weekly, monthly, or seasonal flows. Strategies based upon these probabilities and modeling techniques developed at Colorado State University were applied to the water supply system. Initial results show how a reliable water supply was assured and overall usable water yields from the reservoir system were increased while optimizing benefits from other competing demands, such as, hydropower and recreation.

INTRODUCTION

Proper management of water resources is vital to the Nation's economy, the quality of our environment, and our overall social well-being. Water management decisions that affect water resources systems are a daily routine. In most cases, these water management decisions are based on localized ad-hoc information systems that cause inefficient and wasteful utilization of the Nation's water resources. The science of real-time hydrologic forecasting, and potential computer and telecommunications resources to support the associated data processing, has reached the point that significant advances can now be made in river forecasting to provide improved flood warnings and information for water managers. A NOAA initiative, Water Resources

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Forecasting Services (WARFS) provides improved hydrologic forecast models that produce probabilistic forecasts for water management decisions makers.

In the fall of 1991, a cooperative project was initiated to demonstrate the value of WARFS, integrating new technologies for the purpose of improving water resource forecasting services in the Colorado Basin, and in particular, the Blue and Williams Fork River Basins. It will provide the basis for planning and preparation of a national program.

This approach will be based on a reconstitution of historical events at a site where ESP information is now available. The site consists of three reservoirs on adjacent rivers, Williams Fork, Dillon, and Green Mountain Reservoirs. A period of water years 1986 through 1991 will be used to make an assessment on how operations would occur with and without the ESP forecasts. An analysis will be performed to determine the benefits of having the additional information provided by ESP. The NWS River Forecast System will be used to provide short-, and long-range streamflow and volume predictions and associated probabilities, so that water managers can portray various operational strategies.

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NATIONAL WEATHER SERVICE RIVER FORECAST SYSTEM (NWSRFS)

Advanced observations, enhanced data integration techniques, improved models, and expanded historical and real-time hydrometeorological data bases provide a strong technical base for comprehensive water resource forecast information. The key element of WARFS is NWSRFS. The system consists of many computer models and procedures to simulate important meteorological, hydrologic, and hydraulic processes. The system is made up of three components; the Calibration System (CS), the Operational Forecast System (OFS), and the Extended Streamflow Prediction System (ESP). All these components share the same models and processes.

Calibration System -- The CS performs tasks needed to process historical hydrometeorological data and to estimate model parameters for a specific basin.

Operational Forecast System -- The OFS uses real-time hydrometeorological data in conjunction with short term meteorological forecasts to generate streamflow forecasts for hours or a few days into the future. It maintains an accounting of the current models states. These state values describe the hydrologic condition of the basin, including the snow cover, soil moisture, and channel storage.

Extended Streamflow Prediction System -- ESP enables the hydrologist to make extended probabilistic forecasts of streamflow and other hydrological variables. ESP assumes that historical meteorological data are representative of possible future conditions and uses these as input data to hydrologic models along with the current states obtained from the OFS component. A separate streamflow time series is simulated for each year of historical data using the current conditions as the starting point for each simulation. The streamflow time series can be analyzed for peak flows, minimum flows, flow volumes, etc., for any period in the future. A statistical analysis is performed using the values obtained from each year's simulation to produce a probabilistic forecast for the streamflow variable. This analysis can be repeated for different forecast periods and additional streamflow variables of interest. Short-term quantitative forecasts of precipitation and temperature can be blended with the historical time series to take advantage of any skill in short-term meteorological forecasting. In addition, knowledge of the current climatology can be used to weight the years of simulated streamflow based on the similarity between the climatological conditions of each historical year and the current year.

ESP's flexibility and conceptual basis allows it to have many applications, including water supply forecasts, flood control planning, drought analysis, hydropower planning, and navigation forecasts. The ESP probabilistic forecasts provide uncertainty information needed by water managers for risk-based decisions. As in the project, the streamflow time series generated by ESP can be output as products, so that they can be used in reservoir simulation/optimization models to investigate how operations might be improved.

PROJECT AREA DESCRIPTION

The project is located on the western slopes of the Rocky Mountains in Colorado. It comprises a drainage area of 828-square miles (2145 km^2) including most of the areas encompassing the Blue and Williams Fork Rivers. The basins are divided into a set of collection systems, the Moffat and Roberts Tunnel, Williams Fork, Dillon, and Green Mountain Reservoirs.

The primary function of these systems is to provide a reliable water supply to the east side of the Continental Divide, specifically, the metropolitan area of Denver. A second role is to produce power which is used to offset delivery costs and lost power production due to diverting water outside the basins. A number of critical decisions must be made on a daily basis. The reservoirs are operated in an attempt to meet competing goals, such as water supply, flood control, power production, maintenance of instream inflows for aquatic life, and recreation. Operational decisions must consider water supply demands, water requirements of more senior water users, power interference, and most importantly, providing a reliable water supply.

The Williams Fork 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 Divide to the Fraser River Basin. From the Fraser River, water is conveyed through the Moffat Tunnel to the east side of the Divide. 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. Hydropower is generated at

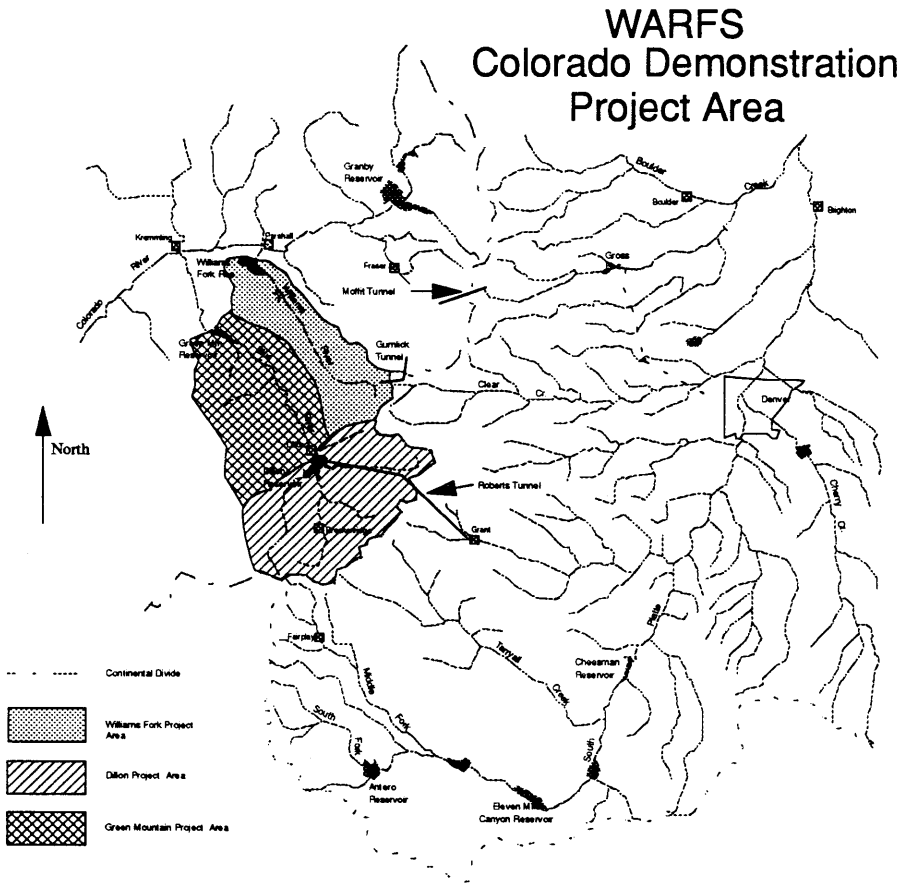

Figure 1. Project Area

Williams Fork Reservoir as replacement power lost by DW operations.

The Roberts Tunnel System consists of the Robert Tunnel and Dillon Reservoir. Dillon Reservoir collects runoff from the Blue River and then conveys the water over the Continental Divide through the Roberts Tunnel. Power is generated at both the Roberts Tunnel and Dillon Reservoir. Green Mountain Reservoir is downstream of Dillon and is used to generate power and provide replacement water for water diverted east through the Big-Thompson Project. Recreation is an important local activity on

Dillon Reservoir, so high water levels are maintained as long as possible during the summer season. A Blue Ribbon trout fishery is located between Dillon and Green Mountain and Dillon Reservoir releases are made to support this fishery.

TECHNICAL APPROACH

Two major steps were required to incorporate ESP forecast information into reservoir operations and then perform an initial estimate of the benefits; (1) the verification of ESP forecast information and (2) the modeling of reservoir operations at the three demonstration area reservoirs.

The purpose of the first effort is to assess the accuracy of the forecasts for the period of record to be used in the modeling tasks. The second effort will consist of the adaptation and implementation of operational models for use at DW.

ESP verification selected a suitable period of historical record for reconstitution of operations. The period selected was based on adequacy of records of operations, data quality, and hydrologic variation. The project period is the 1986 through 1991 water years. ESP verification was 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 consisted primarily of tasks to incorporate ESP forecast information into DW operations in the Blue and Williams Fork River Basins. Green Mountain Reservoir was included because of integral relationships of that operation to the Dillon Reservoir operation. Emphasis was placed on the use of existing models to simulate DW operations. MODSIM was selected as the reservoir simulation model. One criterion for model selection was its suitability for use with ESP inputs. After selection of MODSIM, rules were defined to represent operations of the DW systems. The model was verified and recalibrated using historical releases made during the selected reconstitution period.

Once the model adequately represents DW operations, tasks will be performed to optimize the operational rules using the historical calibration period. Optimization will be made using CSUDP, a generalized dynamic programming code. The optimization procedure will consider operational constraints, such as water supply targets that must always be met and trade-offs of reservoir uses.

Modifications will be made to allow the reservoir model to use ESP forecast information. Runs will be made to simulate operations in the reconstitution period. ESP information will be evaluated along with optimization techniques. Benefits associated with the optimization and the additional ESP information will be computed. Calculation of these benefits will be aided by discussions with DW personnel defining the value of water for various uses such as water supply, hydropower, and recreation.

The results of the benefits analysis will be used to modify the operational reservoir model for use in real-time by DW operations personnel. The project will result in the development of state-of-the-art decision support tools that can be used to improve the management of DW reservoirs. The tools will allow decision makers to assess risk as part of the decision process. Completion of this project is expected at the end of calendar year 1993.

PRELIMINARY RESULTS

In the early stages of this project, ESP information was made available to DW operations personnel for analysis. Their first attempt to utilize the probabilistic information obtained through ESP was applied to a simple spread sheet, allowing the managers to look at different operating scenarios. One scenario looked at a construction project at Williams Fork Reservoir during the spring of 1992. The project involved drawing the reservoir down to allow reconstruction of boat ramps. DW needed to evaluate the risk of not refilling the reservoir prior to the end of spring runoff. The penalties for not filling the reservoir were smaller hydropower revenues and limitations in their operations during releases at the time the "call" on the Colorado River arrives. The streamflow volumes and exceedance probabilities were used to consciously weigh the risks of the proposed project and then make an informed decision

Water managers interested in ESP forecasts usually want to know the accuracy of this information. ESP forecast performance is evaluated on how accurate the probability distribution of the variables represent the true statistical distribution. It is not possible to judge the procedures significance using the forecast value. By monitoring the performance of a model over a number of events, error statistics can be complied to give an understanding of the forecast skill. An ESP Verification System has been developed to help quantify the forecast skill of the particular calibrated ESP model. The system is comprised of two parts: a trace generation component and a trace analysis component. The generation program generates historical traces for one year in length and at weekly or monthly intervals throughout the historical period. These represent an individual forecast. The trace analysis component makes a statistical verification of these sets of historical hydrologic traces. The verification program answers the following considerations: are the probabilistic statements from ESP correct and is there skill in the value of the forecasts. The forecast skill is assessed using the forecasts and looking at the percent reduction of the root mean square error. To verify the exceedance probability values, the forecast was transformed to a standardized deviate and tested for normal distribution with a mean of zero (using t-statistic). Even when the conditional distribution is not normal, the test is valid for large n.

ESP verification results showed significant skill in forecasting seasonal (April-July) snow-melt volumes. The monthly forecast's in root-mean-square errors exhibited the following reductions: December (-11.5%), January (-29.8%), February (-35.5%), March (-33.1%), and April (-36.2%). Verification also indicated the ESP procedure reasonably estimates the conditional probability distribution of the streamflow variable.

MODSIM is a network simulation model developed at Colorado State University. It has been extensively utilized throughout the State of Colorado for many major water projects. The model requires strict bounds on each network link and satisfaction of the mass balance at each node. Unlike most network models, MODSIM uses an optimization technique to find the optimal network solution. The Lagrangian relaxation algorithm calculations uses integer numbers, allowing for high computational speeds and the ability to execute on a desk top computer.

Calibration is a two step process: (1) a hydrologic calibration that verifies the water balance in the system and (2) an administration calibration that verifies release priorities and operating policy assumptions.

MODSIM has demonstrated it can accurately represent complex river and operational priority systems. It is excellent for utilizing the ESP hydrologic forecasts, especially the uncertainty information. The project area river system and operational constraints have been successfully calibrated. Work is continuing on evaluating the significance and benefits of the ESP information.

CONCLUSIONS

An ESP verification system was developed to described the skill (both statistically and quantitatively) and develop confidence among the water management community in the abilities of the NWSRFS technology. The verification results were presented for Dillon. The procedure exhibited significant skill in forecasting the seasonal volume. In the future, the ESP Verification system may be used routinely to estimate the forecast skill after calibration but before it is brought on-line operationally.

Preliminary results show that the information available through ESP 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 maintain any hydrologic models. The NWS will continuously run the models and make the forecast data available for DW analysis.

The project has produced a framework for understanding how probabilistic hydrologic information can be used to improve water management activities. MODSIM was demonstrated as a useful tool to fully integrate management schemes for monitoring water supply reliability and related operational priorities. It provides a useful platform to integrate ESP probabilistic information with the management scenarios required of today's water managers. The final step in this project is to quantify the benefits obtained by incorporating the ESP risk information with network and optimization modelling techniques.

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