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INCORPORATING HYDROCLIMATIC VARIABILITY IN RESERVOIR MANAGEMENT AT FOLSOM LAKE, CALIFORNIA

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1. INTRODUCTION

Evaluating and incorporating hydrologic variability is an essential part in the management of water resources. This takes on greater importance as we face uncertain and potentially straining states of climate. Ensemble streamflow prediction methods have provided a means of incorporating historical climatic forcing variability and uncertainty in the modeling and forecasting of inflows to reservoir hydrosystems. The next step of effectively utilizing such forecasts into the operational management of water resource systems is an important issue of research.

The paper presents an integrated forecast-control methodology for reservoir hydrosystems. It is an end-to-end methodology that incorporates information from Global Climate Models (GCMs), reservoir inflow forecast ensembles, and a decision support system for the reservoir operation and management. The reservoir module includes an assessment system that allows for quantification of management benefits under varying operational plans or inflow forecast scenarios. The aim of this research effort has been to assess the utility of climate information in reservoir management.

The integrated methodology is applied to the management of the Folsom Lake reservoir in Northern California. Initial analysis for this reservoir, presented in Carpenter and Georgakakos (2001) and Yao and Georgakakos (2001), indicated significant potential for management benefits with the integrated approach. Their analysis used historical retrospective studies and hypothetical future climate conditions, and compared hydrologic forecasts and management benefits for various forecast scenarios both with and without the use of climate information from a particular GCM. In this paper, their results are extended by introduction of alternative forecast scenarios from a second climate model. For this second climate model, both AMIP-type simulation and forecast data are used. Intercomparison reported in this paper was made using data from the historical period 1964-1993. The results indicate variable gain in management benefits over the operational forecast scenario for the different GCM models.

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2. INTEGRATED METHODOLOGY

The integrated forecast-control methodology was developed as a means of incorporating hydrologic variability in operational reservoir management. It has been used in assessments of the utility of incorporating such variability in reservoir systems management (Georgakakos, et al. 1998a; Georgakakos, et al. 1998b). A schematic of the methodology is presented in Figure 1. The method features explicit accounting and forward propagation of uncertainty at each stage. The main components of the methodology (indicated in Figure 1 by the rectangular boxes) are:

(a) Incorporation of Information from GCMs. Typically, this information is in the form of monthly estimates of atmospheric variables (precipitation, temperature, etc.). The GCM information is on large spatial scales (on the order of several 100,000 km^2) compared to the scale of a watershed (e.g., 1000 km^2). Therefore, bias adjustment and downscaling methodologies are applied to provide suitable input to the hydrologic model components.

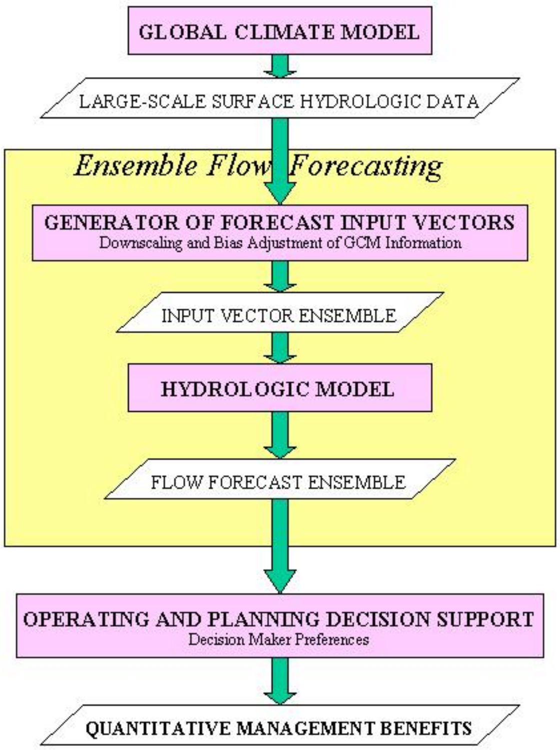

Figure 1. Schematic representation of the integrated forecast-management system. (Adopted from Carpenter and Georgakakos, 2001.)

(b) Generation of Ensemble Forecasts of Inflows. Hydroclimatic variability is included through the generation of ensemble hydrologic model forecasts of reservoir inflows. The hydrologic models are based on operational models and procedures used by the US National Weather Service for the particular application basin. These forecasts account for both hydroclimatic-input and model uncertainty.

(c) Reservoir Operation Simulation, Decision Support and Assessment
The reservoir module takes as input the full inflow forecast uncertainty through the ensemble of inflow forecasts. The reservoir decision component includes models that operate over a range of time scales, from mid- to long-range objectives such as water supply and flood control (daily to monthly), to short-term control of energy production (daily to hourly), to turbine commitment and load dispatching on hourly time steps. Adaptive and dynamic decision methods establish operational trade-offs, that allow the system managers to optimize system performance. The assessment model can then quantify management benefits for given objective criteria and for specified release schedules.

For additional information on the integrated methodology and the ensemble forecasting formulation, the reader is referred to Carpenter and Georgakakos (2001). Yao and Georgakakos (2001) provide details on the reservoir modeling components and specific information on the application of these components to Folsom Lake.

3. FOLSOM LAKE APPLICATION

The Folsom Lake Reservoir is located on the American River in Northern California, approximately 40 km upstream of the city of Sacramento. Three forks of the American River (North, Middle and South Forks) drain approximately 4800 km^2 of mountainous terrain and combine to provide the inflow to Folsom Lake. The reservoir has multiple objectives including hydroelectric power production, flood control, low flow augmentation and water supply. In collaboration with forecast and management agencies, specific objectives and constraints were incorporated into the numerical modeling of the Folsom system.

Hydrologic modeling is based on an adaptation of the NWS operational model. It is applied to the three tributary forks and local reservoir drainage using hydrologic input (rain + snow melt estimates) provided by the California-Nevada River Forecast Center (CNRFC) for the period 1964-1993. This modeling results in ensemble forecasts of total reservoir inflow. The reservoir modeling ingests the inflow forecast ensembles, develops management trade-offs at given reliability level, and, given management decisions regarding operating policy, produces release schedules? The assessment model is then used to assess the management benefits for the specified reservoir operation.

Several forecast scenarios are intercompared. These scenarios included ensemble forecasts made both with and without the use of climate information from different GCM models. The ensemble forecast scenarios are described below:

(a) ESP – a variant of the ensemble streamflow prediction method commonly used by the U.S. National Weather Service (NWS) to produce probabilistic forecasts of flows. The methodology assumes past hydroclimatic forcing is equally likely to occur over the forecast horizon.

(b) CGCM1 – a variation of the ESP method, where historical hydrologic forcing is conditioned on GCM information from the Canadian coupled model CGCM1 from the Canadian Centre for Climate Modeling. Specifically in this application, this conditioning is based on the frequency distribution of the CGCM1 monthly precipitation estimates. There is one realization of the CGCM1 model simulations for the historical period.

(c) ECHAM3 – similar to case (b) above, except that in this case multiple AMIP-type simulations of the Max Planck Institute for Meteorology ECHAM3 model are used to condition the hydrologic forcing. There are 10 members in the ECHAM3-AMIP simulation ensemble.

(d) ECHAM3-FOR – similar to case (c) above, except that in this case the ECHAM3 model forecasts of precipitation are used. These include 3-month forecasts of precipitation for the months of September-October-November (SON), December-January-February (DJF), March-April-May (MAM), and June-July-August (JJA). There are 5 ensemble members for the case of ECHAM3 forecasts, covering the period 1970-1993.

In addition to the above ensemble forecast scenarios, the reservoir management assessment includes two deterministic forecasts:

(e) Operational – based on a simulated operational forecast record. Operational forecast are made based on regression relationships between monthly reservoir inflow volumes and up-to-date observations of snow-pack and meteorological variables within the watershed.

(f) Perfect – based on perfect foresight of future inflows.

For each forecast scenario, a total of 100 ensemble inflow forecasts were generated, including both input forcing and model uncertainties, and were fed to the reservoir management models. The forecasts had daily resolution and a maximum forecast lead-time of 60 days. Forecasts were produced every five days for the historical period 1964-1993.

4. DISCUSSION OF RESULTS

In this section, summary results are presented in terms of hydrologic forecast reliability and reservoir management benefits for the various input forecast scenarios described above.

4.1 Hydrologic Forecast Reliability

As an indicator of forecast performance, ensemble inflow forecast reliability was examined. Along with measures such as overall forecast bias, reliability is important to reservoir management. Forecasts with low reliability can lead to more frequent violations of reservoir level and release constraints. Reliability diagrams are used in this work with a resolution of a decile in frequency. A reliability score, RS, is defined is an overall measure of how well the forecast probabilities correspond to observed frequencies for specific forecast criteria. Better performance is indicated by lower RS values. The forecast resolution was also examined through the sample frequency distribution of forecasts by decile. The RS score used is given by

$$RS = \frac{\sum N_{f_i} (P_{f_i} - F_{o_i})^2}{\sum N_{f_i}}$$

where N_{fi} is the number of forecast values in decile i, P_{fi} and F_{oi} are the forecast and observed frequencies for decile i.

For this analysis, forecast reliabilities for forecast volumes of a given duration being in the upper and lower terciles of their distributions were determined. Volume was chosen as most relevant to reservoir management. Figure 2 presents the reliability scores for inflow volumes in the lower and upper tercile of their distributions for different ensemble forecast scenarios and for accumulation periods of 30- and 60-days. These results consider only those forecasts made during the "wet" season for Folsom Lake, October through April.

For all cases, the reliability score is quite low (< 0.015), indicating reliable forecasts. Comparison of the GCM-conditioned scenarios with the base ESP forecast results can be used to assess whether the use of GCM information in the generation of ensemble inflow forecasts improved the reliability of the hydrologic forecasts. With the exception of forecasts of the 30-day volume in the lower tercile, the use of climate information in generating ensemble forecasts generally yields more reliable results (the CGCM1 conditioned case produces a slightly higher RS value). Additionally, the use of the ECHAM3 model precipitation estimates for conditioning of the hydrologic input forcing produces lower RS values than when the CGCM1 model is used. Furthermore, use of the ECHAM3 model forecasts, ECHAM3-FOR, (as opposed to simulations) shows further improvement in reliability for lower tercile volumes. Generally, improvement in reliability score is more pronounced for low inflow volumes and for longer accumulation periods.

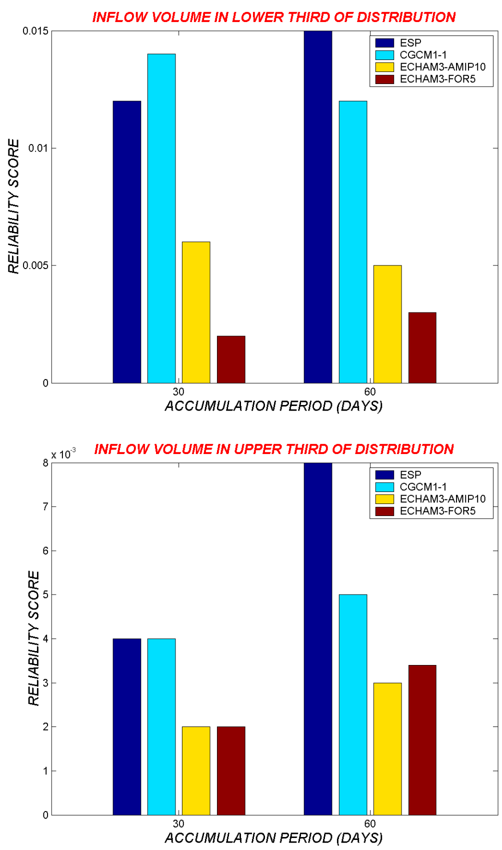

Figure 2. Reliability score RS for system forecasts of 30- and 60-day inflow volumes being in their lower (upper panel) and upper (lower panel) tercile of their distributions.

4.2 Reservoir Management Benefits

The primary objectives of Folsom Reservoir include water supply, flood control and energy production. Through the reservoir decision support and assessment models, benefits for specific objective criteria can be quantified based on reservoir operation decisions. Table 1 presents examples of these benefits for Folsom Lake under different forecast scenarios computed over the historical analysis period (1964-1993). The Table includes total energy production [GWH], spillage in billion cubic feet [bcf] and flood damage [million $] for each case. In addition to the ensemble inflow forecast scenarios, the Table includes the two deterministic runs based on operational forecast procedures and perfect forecasts. The ECHAM3-FOR (ECHAM3 forecast output) is not included in the table due to the different in the historical period covered by this scenario.

In comparison with the operational forecast procedure, a fairly significant reduction in spillage and flood damage, accompanied by an increase in energy production, is observed for the ensemble forecast scenarios – or when hydroclimatic variability is taken into consideration in reservoir management. The use of GCM information in generating ensemble forecasts produces mixed results in terms of the criteria presented when compared to the base ESP method that uses climatology in the forecasts. The CGCM1-conditioning forecasts produced lower values of spillage and flood damage over the historical period compared to the base ESP case, albeit with lower total energy production. The ECHAM3-conditioning scenario produced higher total energy, but also higher total spillage.

5. CONCLUSIONS

The paper presented an integrated forecast-control methodology, used to incorporate hydroclimatic variability in reservoir operation and management. The methodology is exemplified for Folsom Reservoir in California through retrospective analyses over the period 1964-1993. These analyses include forecasts made both with and without the use of climate information from global climate models. The impact of the use of various GCM models is examined (a single

Table 1. Management objectives values

Scenario	*Energy*	*Spillage*	*Flood Damage*
Operational**	620	11.6	842
ESP	635	7.2	220
CGCM1	633	6.1	105
ECHAM	636	8	220
Perfect**	662	4.8	0

*** Operational and Perfect forecasts are deterministic runs.*
** Units: Energy = [GWH];*
Spillage = [bcf];
Flood damage (maximum) = [million $]

realization of the CGCM1 model simulations, a 10-member ensemble of the ECHAM3 model simulations, and a 5-member ensemble of the ECHAM3 model forecasts).

The results show improvement in reservoir inflow forecast reliability when GCM information is used to condition the hydrologic ensemble forecast model input. Use of different GCM models for climatic information shows variance in the ensemble forecast reliability for inflow volumes in the extreme terciles of volume distribution, with use of the ECHAM3 model producing lower reliability scores (thus more reliable forecasts) when compared to results with the CGCM1 model for this reservoir and criteria selected.

The management objectives were quantified for various inflow forecast scenarios and presented in Table 1. Inclusion of hydroclimatic variability through ensemble inflow forecasting indicates significant gains in management objectives over the deterministic operational simulation. Improvement is made in all presented objective criteria for both the base ESP and GCM-conditioned scenarios. The results for the GCM-conditioned scenarios as compared to the ESP climatology run are mixed and depend of the particular objective.

An effort to apply this integrated forecast-management methodology to other large reservoirs in northern California in close collaboration with Federal and State agencies is in the initial stages of development. The goal for this new effort is to study the northern California reservoir system (including Folsom, Shasta, Oroville and Trinity Dams), to assess the utility of climate forecasts for this reservoir system, and to develop a forecast-management computational system that can be used operationally.

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