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GEORGAKAKOS A P CE

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Title: OPTIMAL REGULATION OF THE SAVANNAH RIVER SYSTEM

PROJECT ADMINISTRATION DATA

OCA contact: William F. Brown 894-4820

Sponsor technical contact	Sponsor issuing office
MR. FRANK DE LA SIERRA, EN-B	MS. JUDY HACKNEY/CESAS-CT-P
(912)944-5265	(912)944-5898
US ARMY CORPS OF ENGRS, SAVANNAH DIS	USA ENGR DIST, SAVANNAH CORPS/ENGRS
P.O. BOX 889	P.O. BOX 889
SAVANNAH, GA 31402-0889	SAVANNAH, GA 31402-0889

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INITIATION OF E-20-602. THIS IS A FIXED PRICE CONTRACT.

5R250

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

NOTICE OF PROJECT CLOSEOUT

Closeout Notice Date 08/02/91

Project No. E-20-602 | Center No. R6605-0A0

Project Director GEORGAKAKOS A P | School/Lab CIVIL ENGR

Sponsor ARMY/CORPS OF ENGINEERS

Contract/Grant No. DACW21-88-C-0043 | Contract Entity GTRC

Prime Contract No. ______

Title OPTIMAL REGULATION OF THE SAVANNAH RIVER SYSTEM

Effective Completion Date 901231 (Performance) 901231 (Reports)

Closeout Actions Required:	Y/N	Date Submitted
Final Invoice or Copy of Final Invoice	Y	
Final Report of Inventions and/or Subcontracts	Y	
Government Property Inventory & Related Certificate	N	
Classified Material Certificate	N	
Release and Assignment	Y	
Other ______	N	

Comments ______

Subproject Under Main Project No. ______

Continues Project No. ______

Distribution Required:

Project Director	Y
Administrative Network Representative	Y
GTRI Accounting/Grants and Contracts	Y
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Research Property Managment	Y
Research Security Services	N
Reports Coordinator (OCA)	Y
GTRC	Y
Project File	Y
Other ______	N
______	N

NOTE: Final Patent Questionnaire sent to PDPI.

OPTIMAL REGULATION OF THE SAVANNAH RIVER SYSTEM

Monthly Progress Report (March 1 - April 15, 1989)

The following paragraphs summarize the research activity pursued in relation to the aforementioned research project:

1. Becoming familiar with the Compaq 386/25 microcomputer and support programs. In particular, experience was gained with the operation of the Ryan McFarland FORTRAN compiler and its differences with the main frame FORTRAN programming language. This activity is part of our effort to understand the limitations of this microcomputer with respect to memory storage and computer time requirements. These limitations will affect the software design.

2. Evaluation of the HEC-1 streamflow forecasting model. HEC-1 is a physically-based model and, with proper calibration, it can be as good streamflow predictor as any other similar model. Additional reason to select HEC-1 is that the C.O.E. has already had valuable experience with its use in the Savannah system. A weakness is that it is strictly deterministic and cannot provide estimates of the forecast errors. This last deficiency can be corrected if available rainfall-runoff data are available to reliably estimate the forecast error statistics. This along with its efficient use on the Compaq 386/25 microcomputer are currently investigated.

3. Development of reservoir characteristic curves. A part of the control program is a detail description of the reservoir dynamics and functions. These characteristics are reflected on the curves reflecting (a) the elevation versus storage relationship, (b) the tailwater versus outflow relationship, and (c) the turbine power output versus net head and discharge relationship. These curves were developed for each reservoir and turbine using nonlinear regression analysis and data from the Savannah River reservoir regulation manual. The regression statistics indicate satisfactory correspondence between the actual and the computed values.

E-20-602

OPTIMAL REGULATION OF THE SAVANNAH RIVER SYSTEM

Monthly Progress Report (April 16 - May 31, 1989)

During the above–mentioned period, our research efforts concentrated on the formulation of the control model for the operation of the Savannah river reservoirs. This model will be programmed to find optimal hydropower schedules by invoking several control levels. The control levels distinguish between peak and off–peak generation periods and seek to maximize energy output during the former while meeting other operational objectives as constraints. Each control level is further decomposed into dynamic and static modules. The dynamic module accepts turbine discharge rates form the static module and utilizes probabilistic inflow forecasts with stochastic control techniques to determine optimal energy generation schedules. The static module regulates each turbine to generate power at best efficiency or some prespecified output. This problem breakdown in multiple levels and modules enhances controller flexibility and overall computational efficiency. In the months to follow, this model will be programed on the COMPAQ 386/25 microcomputer system, tested in several case studies, and coupled with the HEC–1 forecasting model. Most of this work is expected to be completed during the upcoming summer months.

E-20-602

OPTIMAL REGULATION OF THE SAVANNAH RIVER SYSTEM

Monthly Progress Report (June 1 - July 31, 1989)

The research work performed from June 1st through July 31st primarily focused on three areas. These areas include the implementation of the HEC-1 forecasting model, the microcomputer implementation of a weekly control model, and the research, acquisition, and implementation of a suitable graphics input-output software.

Using preliminary data from the Savannah River basin, the HEC-1 model was implemented and tested on both a main frame and a microcomputer system. From the programming point of view, HEC-1 can now be coupled with the control models under development. However, communication with the COE Savannah District Office revealed that the existing hydrologic data base is insufficient for proper model calibration. More specifically, HEC-1 calibration requires simultaneous rainfall-runoff measurements at several points in the basin. As of now, however, streamflow gages have not been installed, and runoff observations are not available. According to the information provided by the Savannah District COE Office, such gages are currently under authorization and are expected to be functional early next year. Given the above circumstances, we decided to halt HEC-1 calibration efforts and concentrate on the development of the control models. When it is time to couple control with forecasting, the existing data base will be reevaluated and hopefully used to calibrate HEC-1. If this is not possible, the models will be tested with fictitious data. In that case, model calibration with actual data will have to be performed by the Corps of Engineers at some later date.

E-20-602

OPTIMAL REGULATION OF THE SAVANNAH RIVER SYSTEM

Monthly Progress Report (August 1 - September 13, 1989)

The research work performed from August 1st through September 13th was concerned with the implementation of a suitable user-program interface to facilitate user input and include graphics displays. During this project period, the GSS*GKS graphics kernel software was implemented on the COMPAQ 386/25 personal computer and was coupled with the weekly control model previously developed. This user–program interface system automates and simplifies the program's input–output process and overall usage. It provides a menu–driven programming environment which allows the user to enter various hydrologic and operational data from the screen (using a mouse), see screen displays of the system current or future storage, release, and energy generation sequences, or produce hard–copy graphics of the same plots. Overall, this program–user interface provides a friendly programming environment and facilitates the hands–on–experience user training.

A major function of the Savannah River system is energy generation. This activity is also coordinated by the South Eastern Power Administration (SEPA) in that they determine the minimum energy generation and capacity levels to become available during any given period. Since these quantities affect the operation of the Savannah system, it is important that the fashion in which they are determined is clearly understood and, if necessary, taken into account in the present research project. Thus, a visit to SEPA at Elberton, Georgia, was scheduled and took place on September 5th, 1989. This investigator had the opportunity to familiarize himself with the SEPA goals and their procedures and obtaine various energy generation and power capacity commitments and contracts. This information is presently evaluated and a determination will be made as to whether and how it can be incorporated in the control model under development.

The second research activity centered on the programming and microcomputer implementation of a weekly control model. This model was briefly described in the previous progress report and constitutes a comprehensive representation of system dynamics and objectives. The computer code is written in the 77 FORTRAN programming language and is currently being tested on the COMPAQ 386/25 personal computer. This computer program presently includes simple input-output procedures using and generating ASCII files.

The third part of our research was concerned with a suitable user-program interface to facilitate user input and include graphics displays. Such data as unit shut–down and minimum generation schedules and demand forecasts can be conveniently entered and checked from screen menus, and optimal sequences can be graphically displayed. Our examination of ten software packages indicated that most existing graphics programs are incompatible for our purposes, the main deficiency being that they cannot be called from inside FORTRAN programs. The only software with this capability is the GSS*GKS graphics software which is presently being researched and implemented on the COMPAQ 386/25 personal computer. The GSS*GKS software is, however, a generic set of graphics tools which need to be tediously combined and custom-tailored. This activity will be pursued over the upcoming month of August. Overall, improving the program–user interface will lead to a more effective application and will lessen the possibility of user error.

E-20-602

OPTIMAL REGULATION OF THE SAVANNAH RIVER SYSTEM

Monthly Progress Report (September 14 - November 7, 1989)

The research work performed during this project period aimed in the development of a river routing model which can be integrated with the reservoir control scheme being developed. This scheme is cast in state space–form and is incompatible with the well researched hydraulic routing models. This work demonstrates that a much simpler model, the Muskingum–Cunge, can be put in state–space format and perform quite comparably to the numerical hydraulic models. Additionally, this routing formulation allows the use of available real-time discharge measurements for model and forecast updating. A more detailed description of the new model can be found in the attached paper which is scheduled to appear in the *Journal of Water Resources Research*.

A STATE-SPACE MODEL FOR HYDROLOGIC RIVER ROUTING

Aris P. Georgakakos

School of Civil Engineering, Georgia Institute of Technology,

Atlanta 30332

Konstantine P. Georgakakos

Department of Civil and Environmental Engineering and Iowa Institute of Hydraulic Research, The University of Iowa, Iowa City 52242

Evangelos A. Baltas

School of Civil Engineering, Georgia Institute of Technology,

Atlanta 30332

ABSTRACT

In this paper a state-space formulation of the Muskingum-Cunge routing scheme is proposed. The state-space formulation utilizes real-time discharge measurements, accounts for modeling and observation errors, and allows real-time updating through a Kalman filter estimator. The new model is tested in two different geotechnical conditions to forecast six-hour discharge values in hypothetical channels. For realism, the geomorphologic characteristics of these case studies are determined based on the Regime theory. DWOPER, a field tested numerical dynamic routing model, was used to provide ground truth data for the validation of the proposed model.

1. INTRODUCTION

Efficient flood routing schemes are useful in a variety of engineering applications. Flood warning systems depend on flow predictions from rainfall–runoff and river routing models and, more often than not, are the only defense against life-threatening and costly floods [e.g., Georgakakos and Bras, 1982, Georgakakos, 1987]. Likewise, river routing models are an integral part of operational reservoir management schemes which are concerned with water supply at demand locations in a timely manner. Recent advances in reservoir control [Wasimi and Kitanidis, 1983; Kitanidis and Foufoula–Georgiou, 1987; Georgakakos and Marks, 1987; and Georgakakos, 1989] favor dynamic, state–space, system formulations due to (1) their computational efficiency and (2) their ability to account for natural and model uncertainties. However, the most effective river routing schemes, the "hydraulic" methods [Weinmann and Laurenson, 1979], are not directly compatible and cannot be integrated with these formulations. On the other hand, simpler river routing schemes, collectively known as "hydrologic" routing methods [Fread, 1985], can easily be cast into state–space format and utilized by modern reservoir control techniques. These methods can be kinematic [Mein et al., 1974], ignoring both inertia and gravity terms in the momentum equation, or diffusion type [Cunge, 1969], ignoring only inertia terms. The hydrologic routing methods do not model the exact flow equations and become approximate when inertia effects are important; their performance, however, can be enhanced if flow measurements are taken into account.

The purpose of this study is to design effective flood routing models which can benefit from the existing research experience and can utilize real-time measurement information. The approach taken is to convert a promising hydrologic routing scheme in state-space form, model its inaccuracies through random error terms, and establish an updating scheme based on modern estimation theory results and discharge measurements. The coefficients of this model can readily be determined by channel characteristics, inflow-outflow measurements, or both, while its updating mechanism allows for more accurate flow predictions.

Although many published papers address the real-time flood routing issue using estimation theory methods and regression-type models [e.g., Bolzern, et al., 1980; Maissis, 1977], very few published studies utilize dynamical routing models (with measurable parameters) in state space form and estimation theory methods for real time updating. Notable exceptions are the following three studies: Muzik [1974] converted a simplified kinematic routing model to a state space form for real time overland flow prediction. Moll [1986] used a deterministic flood routing model of the convection-diffusion type to produce preliminary flow forecasts. These forecasts were subsequently improved using a regression-type model with parameters obtained by a Kalman Filter. Lastly, Hoos, et al. [1989] proposed the use of a deterministic flood routing scheme that approximates the convection-diffusion model with constant coefficients, together with a heuristic updating procedure.

The Muskingum-Cunge routing scheme and its representation in state-space form is presented in Section 2. This model is linked with a stochastic filtering scheme and tested in realistic case studies in Sections 3 and 4. Section 5 summarizes the research findings.

2. STATE-SPACE REPRESENTATION OF THE MUSKINGUM-CUNGE ROUTING MODEL

Simplified river routing models have drawn the attention of many researchers over the last 50 years. Included among these models are the Muskingum model [Nash, 1959; Overton, 1966; Cunge, 1967; Koussis, 1978; Ponce and Yevjevich, 1978; Ponce, 1978], kinematic models [Mein et al., 1974, Georgakakos and Bras, 1982], the kinematic wave model [Lighthill and Whitham, 1955], the SSARR model [Rockwood, 1958], and the Muskingum-Cunge model [Cunge, 1969]. Fread (1983) demonstrates that all simplified routing models share a common basis and can be derived from his Unified Coefficient Routing Model. This model has the following form:

$$O(t+\Delta t) = C_1 I(t) + C_2 I(t+\Delta t) + C_3 O(t) + C_4 \tag{1}$$

where $O(t)$ is the outflow value from a channel reach of length Δx at time t, $I(t)$ is the inflow to this reach at time t, Δt is the time step, and C_1, C_2, C_3 are routing coefficients which may be empirically derived or evaluated from the hydraulic characteristics of the channel reach. Coefficient C_4 accounts for the effect of lateral inflows along the routing reach.

Equation (1) may be rewritten in the following form:

$$Q_{i+1}(t+1) = C_1\, Q_i(t) + C_2\, Q_i(t+1) + C_3\, Q_{i+1}(t) + C_4, \tag{2}$$

where Q denotes discharge, subscript i denotes the upstream end of the routing reach, subscript i+1 denotes the downstream end of the routing reach, and time instants t and t+1 are Δt time units apart. The coefficients C_1, C_2, C_3 and C_4 are given by the following expressions:

$$C_0 = 1 + \psi\, \tilde{a} - X \tag{3a}$$

$$C_1 = [(1-\psi)\, \tilde{a} + X]/C_0 \tag{3b}$$

$$C_2 = (\psi \bar{a} - X)/C_0 \tag{3c}$$

$$C_3 = [1 - (1-\psi) \bar{a} - X]/C_0 \tag{3d}$$

$$C_4 = \bar{q} \Delta x \bar{a}/C_0 \tag{3e}$$

$$\bar{a} = c \Delta t/\Delta x \tag{3f}$$

$$\bar{q} = [q_i(t) + q_i(t+1)]/2 \tag{3g}$$

$$0 \le \psi \le 1 , \tag{3h}$$

$$0 \le X \le 1 . \tag{3i}$$

In the above equations, $\bar{q}$ is the lateral inflow or outflow along the reach Δx during the interval Δt, and c is the wave celerity. Fread [1983] demonstrates how each simplified routing model may result from the previous formulation through appropriate definition of the parameters $(\psi, X, \bar{a})$. For instance, the Muskingum-Cunge procedure results when

$$\psi = 1/2, \tag{4a}$$

$$X = (1/2) [1 - q_0/(c \Delta x S_0)], \text{ and} \tag{4b}$$

$$\bar{a} = c \Delta t/\Delta x = \Delta t/K, \tag{4c}$$

where q_0 is the unit-width discharge, K is the travel time through reach Δx, and S_0 is the channel bottom slope. As mentioned by Fread [1983], the above value of ψ and the form of Equation (4b), guarrantee model stability. This is a very desirable model property with implications that will become clear in the case study section.

Fread [1983] suggests the following procedures for the estimation of these paramaters:

The wave celerity c can be computed from

$$c = \beta V = 1.27\ \beta\ S_0^{0.3}\ q_0^{0.4}\ /n^{0.6} \qquad (5a)$$

where

V is the average cross-sectional velocity,

$$\beta = 1.67 - 0.67\ A_0/B_0^2\ (dB_0/dy), \qquad (5b)$$

A_0 is the associated cross-sectional area,

B_0 is the associated channel top width,

(dB_0/dy) is the rate of change of B_0 with depth y, and

n is the Manning coefficient.

Parameter K may be computed from $K = \Delta x/c$ where Δx is the routing reach length and c is the wave celerity. K may also be estimated from measured inflow-outflow hydrographs as the time interval between the inflow and outflow centroids.

The routing interval Δt can be obtained from

$$\Delta t \leq T_r/M\ , \qquad (5c)$$

where T_r is the time of rise of the inflow hydrograph and M is an integer in the range of 6 to 20. Large M values imply rapid and nonuniform inflow variation.

The routing reach length Δx must be restricted to the following range for numerical accuracy reasons:

$$\Delta x \leq 0.5\ [c\Delta t + q_0/(cS_0)]. \qquad (5d)$$

The channel energy slope S_0 may be approximated by the channel bottom slope and estimated as the longitudinal average over the reach Δx. It may also be computed from Manning's equation by

$$S_0 = Q_0^2\ B_0^{4/3}\ n/(2.21\ A_0^{10/3})\ , \qquad (5e)$$

where Q_0 is the uniform initial flow with associated top width B_0 and cross-sectional area A_0.

In natural channels, the estimated hydraulic characteristics that enter or are computed from the Manning's equation represent spatial and temporal averages. For instance, the appropriate depth-discharge relation is given by

$$\bar{Q} = 1.49\, S_0^{1/2}\ \bar{A}^{5/3} / (n\ \bar{B}^{2/3}) , \tag{5f}$$

where the notation $\bar{Y}$ represents the average of the variable Y over the time interval Δt and along the reach Δx. $\bar{A}$ and $\bar{B}$ denote the cross-section area and the top width respectively and are known functions of the average depth $\bar{y}$.

Fread (1983) suggests two routing methods by the model given (see also the earlier work by Price [1978] and Ponce and Yevjevich [1978]). In the linear form of the Unified Coefficient Routing Model, parameters q_0, A_0, B_0 and (dB_0/dy) may be assumed constant; they are usually associated with a reference discharge Q_0 such as the mean of the discharge hydrograph, the peak, or that at the center of mass. Then, coefficients C_1, C_2, C_3, and C_4 are constants for each Δx routing reach and throughout the duration of the routing computations.

In the nonlinear routing form, the coefficients vary with each reach Δx and each time step Δt. The computations start by estimating the discharge $Q_{i+1}(t+1)$ using a linearly extrapolated value:

$$\hat{Q}_{i+1}(t+1) = Q_{i+1}(t) + [Q_{i+1}(t) - Q_{i+1}(t-1)] \tag{6}$$

(where the symbol "^" denotes estimate).

Then, the average discharge $\bar{Q}$ is obtained from

$$\bar{Q} = 0.25\ [Q_i(t) + Q_i(t+1) + \hat{Q}_{i+1}(t) + Q_{i+1}(t+1)], \tag{7}$$

and $\tilde{y}$, $\tilde{A}$, and $\tilde{B}$ are obtained from Equation (5f). Lastly, parameters q_0, c, X, K, C_1, C_2, C_3, and C_4 are specified as described previously, and Equation (2) is invoked to compute $Q_{i+1}(t+1)$. The procedure is then advanced to another routing reach or another time step, whenever the difference $|\hat{Q}_{i+1}(t+1) - Q_{i+1}(t+1)|$ is smaller than a prespecified threshold [Fread, 1983]. If this difference does not fulfil the requirement, then $\hat{Q}_{i+1}(t+1)$ is replaced by $Q_{i+1}(t+1)$, and the procedure is repeated.

Generally, all simplified routing models are limited to applications where backwater effects (due to channel restrictions, tributary inflows, or other conditions) are negligible and wave propagation is in the downstream flow direction only. However, diffusion-type models are better approximations of the exact flow dynamics and are potentially more accurate. The Muskingum-Cunge model was selected here because it is a diffusion-type model [Cunge, 1969].

Consider a river segment which requires N routing reaches. Direct application of the routing Equation (2) to each reach results in the following set of difference equations:

$$Q_1(t+1) = C_{1,1}\, Q_0(t) + C_{1,2}\, Q_0(t+1) + C_{1,3}\, Q_1(t) + C_{1,4} \qquad (8a)$$

$$Q_2(t+1) = C_{2,1}\, Q_1(t) + C_{2,2}\, Q_1(t+1) + C_{2,3}\, Q_2(t) + C_{2,4} \qquad (8b)$$

$$\vdots$$

$$Q_i(t+1) = C_{i,1}\, Q_{i-1}(t) + C_{i,2}\, Q_{i-1}(t+1) + C_{i,3}\, Q_i(t) + C_{i,4} \qquad (8c)$$

$i = 3,4,\ldots,N.$

A state-space formulation requires that quantities at time (t+1) are obtained in terms of their values at time t. The previous equations can be converted into such a recursive scheme if the flow $Q_{i-1}(t+1)$ on the right-hand side of the routing equation for reach i is substituted by its expression from the routing equation for reach i-1. As illustrated in Appendix A, these operations lead to the following vector equation:

$$Q(t+1) = A\, Q(t) + B\, U(t) + C\, q(t), \tag{9}$$

where $Q(t) = [Q_1(t)\ Q_2(t)\ \ldots\ Q_N(t)]^T$ (the superscript T denotes transpose), $U(t) = [Q_0(t)\ Q_0(t+1)]^T$, and $q(t) = [\bar{q}_1(t)\ \bar{q}_2(t)\ \ldots\ \bar{q}_N(t)]$.

Equation (9) constitutes the state equation of the routing model and describes the change in the state of the system, Q(t), responding to the inputs U(t) and q(t). Matrices A, B, and C are related to the routing coefficients as derived in the appendix.

The above system will be assumed observable through measurements of the discharge $Q_N(t)$ at the outlet of the last reach Δx_N. Thus, the associated observation equation can be stated as follows:

$$z(t) = H^T\, Q(t)\ , \tag{10}$$

where $H = [0\ 0\ \ldots\ 1]^T$, and z(t) represents the observation at time t. Equation (10) is the output equation and relates observations to the system's states. Equations (9) and (10) summarize the deterministic state space formulation of the routing model. Matrix A represents the proportion of the current system state Q(t) which contributes to the state change. This state feedback plays a major role in determining the future system behavior. The elements of matrices B and C represent the proportion of each input variable that affects each of the state variables. The outputs z(t) are related to the state through the scaling vector H^T. It is noted that all elements of coefficient matrices can be determined from the hydraulic characteristics of the channels. These coefficients are constants if the linear philosophy of the previous section is adopted; otherwise, they are time-varying.

3. STOCHASTING FILTERING AND PREDICTION

The need to convert a deterministic state-space formulation into a stochastic one arises from the possibility of modeling errors. Errors may stem from inadequate modeling, incorrect estimates of parameters, or uncertainties in observations. Typically, these inaccuracies are accounted for by adding random error terms to the state and observation equations:

$$Q(t+1) = \mathbf{A}\, Q(t) + \mathbf{B}\, U(t) + \mathbf{C}\, q(t) + \mathbf{w}(t) \qquad (11a)$$

$$z(t) = \mathbf{H}^T Q(t) + v(t). \qquad (11b)$$

The terms $\mathbf{w}(t)$ and $v(t)$ represent two uncorrelated, zero-mean, white-noise sequences with covariance parameters $E\{\mathbf{w}(t)\mathbf{w}(t)^T\} = \mathbf{P}_W(t)$ and $E\{v^2(t)\} = R(t)$, respectively. Their covariance functions satisfy

$$E\{\mathbf{w}(t_1)\, \mathbf{w}(t_2)\} = \mathbf{P}_W(t)\, \delta(t_1 - t_2) \qquad (12a)$$

$$E\{v(t_1)\, v(t_2)\} = R(t)\, \delta(t_1 - t_2), \qquad (12b)$$

where $\delta(t)$ is the Kronecker delta and $E\{\cdot\}$ denotes expectation. It is assumed that the initial state $Q(0)$ is statistically known by its mean vector and covariance matrix. $Q(0)$, $\mathbf{w}(t)$ and $v(t)$ are mutually uncorrelated.

The goal of the stochastic model is to combine the system dynamics with the measurement information to optimally estimate the state vector. Two desirable properties of these optimal estimates are to be (1) unbiased and (2) have the smallest error variance among all other unbiased estimators. In the case of linear systems with white Gaussian statistics, such estimates are obtained from the Kalman Filter (Kalman, 1960).

Let $\hat{Q}(t/t)$ and $\Sigma(t/t)$ denote the best estimate and error covariance matrix of the state at time t given observations up to and including time t, and let $\hat{Q}(t+1/t)$ and $\Sigma(t+1/t)$ be the corresponding quantities at time t+1 given the same observation data. (Symbol (t+1/t) means (t+1)/t, not t+(1/t).) The time update portion of the Kalman filter algorithm provides a prediction $\hat{Q}(t+1/t)$ of the state at time t+1 along with the associated error covariance $\Sigma(t+1/t)$. The measurement update corrects the previous estimates based on the measurement $z(t+1)$ at time t+1 to yield the aposteriori estimate $\hat{Q}(t+1/t+1)$ and its error covariance $\Sigma(t+1/t+1)$. For these reasons the following discrete-time Kalman filter equations are also called predictor-corrector equations:

(i) *Prediction:* (effect of system dynamics)

state estimate: $$\hat{Q}(t+1/t) = A\,\hat{Q}(t/t) + B\,\hat{U}(t) + C\,\hat{q}(t) \tag{13a}$$

error covariance: $$\Sigma(t+1/t) = A\,\Sigma(t/t)\,A^T + B\,P_u B^T + C\,P_q C^T + P_w \tag{13b}$$

$t = 0,1,2...$

(ii) *Correction:* (effect of measurement z(t))

state estimate: $$\hat{Q}(t+1/t+1) = \hat{Q}(t+1/t) + K(t+1)\,\nu(t+1) \tag{14a}$$

error covariance: $$\Sigma(t+1/t+1) = [I - K(t+1)\,H^T]\,\Sigma(t+1/t), \tag{14b}$$

$$K(t+1) = \Sigma(t+1/t)\,H\,[H^T\,\Sigma(t+1/t)\,H + R]^{-1}, \tag{14c}$$

$$\nu(t+1) = z(t+1) - H^T\,\hat{Q}(t+1/t)\ , \tag{14d}$$

$t = 0,1,2...$

P_u and P_q are the covariance matrices of the vectors U and q which are assumed to be independent white noise sequences. It is noted that Eq. (13b) yields a suboptimal estimate of the predicted state covariance in that the autocorrelation function of U is not identically equal to zero (see definition following Eq. (A.4)). The vector $K(\cdot)$ is the Kalman gain and $\nu(\cdot)$ the Kalman innovations variable. However, for the system under consideration the measurement update step simplifies as follows:

$$\hat{Q}_i(t+1/t+1) = \hat{Q}_i(t+1/t) + \frac{\Sigma_{iN}(t+1/t)}{\Sigma_{NN}(t+1/t)+R}\,[z(t+1) - \hat{Q}_N(t+1/t)] \tag{15a}$$

$$\Sigma_{ij}(t+1/t+1) = \Sigma_{ij}(t+1/t) - \frac{\Sigma_{iN}(t+1/t)\,\Sigma_{Nj}(t+1/t)}{\Sigma_{NN}(t+1/t) + R} \tag{15b}$$

where $\hat{Q}_i(t/s)$ and $\Sigma_{ij}(t/s)$ represent respectively the i^{th} and the ij^{th} elements of the vector $\hat{Q}(t/s)$ and the matrix $\Sigma(t/s)$.

The performance of a stochastic filtering scheme is enhanced if the system is observable, controllable, or both. Systems which are both controllable and observable have the following two desirable properties: (1) their stochastic filtering design is stable, and (2) their state-space formulation is irreducible (see Kailath, 1980 and Chen, 1970). The first implies that, in the state estimator, the observation errors do not accumulate, while the second guarantees that there does not exist any other state-space model of smaller than N dimension. The controllability and observability study of the present system is taken up in Appendix B. It is there shown that this state-space model has both of these properties and, therefore, it is theoretically expected to display optimal performance.

4. CASE STUDIES

The performance of the state-space routing model previously presented is tested here in a series of case studies with various geomorphologic characteristics. These characteristics include channel slope, cross-sectional shape, roughness, length, and bed and bank material. For consistency and realism, the characteristics of each case study were determined using the regime theory of channel morphology [Blench, 1957; Simons and Albertson, 1960; Henderson, 1966]. In each case, both the linear and the nonlinear state-space routing models were implemented, and the results were compared to those from the Dynamic Wave OPERational (DWOPER) model developed by Fread [1978]. DWOPER has extensively been tested in various river systems and has been shown to have less than a 5% error margin. In this work, DWOPER furnishes the ground truth data.

The regime theory [Henderson, 1966, Section 10.6] is empirical and is based on field studies of man-made channels. Given the nature of the bed and bank material and an estimate of the dominant flow, the regime theory equations describe the geotechnical conditions (cross-sectional characteristics and bottom slope) which are eventually expected to develop in the channel. To bracket the response of most natural channels, two material types are considered: (1) sand bed and banks and (2) a coarse non-cohesive material. The same dominant discharge of 100,000 cfs is assumed for both types. The regime theory characteristics for these two cases are shown on Table 1. It can be seen that sandy channels are associated with very mild slopes (about 0.002%) and wide cross-sections (of 996 feet average width); while the coarse noncohesive channels are expected to form steeper slopes (0.18%) and narrower cross-sections (of 498 feet average width). To investigate the effect of multiple reaches and various channel lengths, three different channel cases are considered for each material type. These channels consist of one, three, and five 100-mile reaches respectively, and their cross-sections are trapezoidal with the Table 1 characteristics. The input hydrographs vary from approximately 25,000 to 100,000 cubic feet per second and are shown on Figure 1. Most computational runs to be presented utilize the 1st input hydrograph (solid line), while the 2nd input hydrograph is used for verification purposes. The input hydrographs are assumed non-random, and lateral inflows are not included in this analysis. A routing interval of 6 hours is used in all cases, and the routing duration is 84 time steps (21 days). For realism, the observed values (DWOPER results) are assumed to have a 5% measurement error. The covariance of the state equation error, $w(t)$, is assumed to be diagonal; namely, $P_w(t) = \sigma^2 I$, where I is the unit matrix and σ is a scalar.

Sandy Channels

Figure 2 shows results from deterministic linear and nonlinear Muskingum-Cunge model runs for the sandy channel cases. The line with the designation "actual" represents the outflow discharge from each channel as predicted by the DWOPER model with the 1st input hydrograph shown on Figure 1 as input; the one designated "observed" is the "actual" distorted by random errors; and the lines labelled "linear" and "nonlinear" portray the 6-hr predicted outflows, using the linear and nonlinear Muskingum-Cunge state space models respectively. These models are implemented as explained in Section 2 based on the flow and channel characteristics in Table 1. In all cases, the predicted outflows are seen to diverge from the actual results, with the disparity becoming more apparent in the longer channels. As a quantitative basis for evaluating these and subsequent results, the following are calculated and reported: (1) model bias, (2) square error, (3) time-to-peak error, and (4) peak discharge error. All four criteria are computed based on the discrepancies between predicted and actual flow sequences and are reported in Table 4 under the "Linear Deterministic" and "Nonlinear Deterministic" designations. The time-to-peak and peak discharge errors are estimated as averages based on the two hydrograph peaks shown in the graphs. The table reports the values of these criteria for each of the three channel cases (one, three, and five reaches). In general, the nonlinear models are better predictors of peak timing than peak discharge. Overall, however, both model types exhibit poor performance, indicating that the Muskingum-Cunge routing procedure becomes inadequate in channels with very mild slopes. This may be a general deficiency of the diffusion routing models which ignore the inertia terms in the flow resistance equation. On very flat channels, the inertia effects may become substantial and invalidate the diffusion approximation. In such situations, using real-time discharge measurements may lead to improved model performance.

Figure 3 shows the model predictions when outflow observations are taken into consideration through the state estimation procedure detailed in Section 3. In these runs, the parameter σ^2 is estimated according to the Maximum Likelihood Parameter Estimation Method (Schweppe [1973], Chapter 14) and is reported in Table 2 along with the optimal value of the likelihood function. Smaller σ^2 values generally indicate better dynamical models. As this error variance gets smaller (relative to the measurement error variance), the state estimation procedure "pays more attention" to the system dynamics than to the value of the measurements. (This effect can mathematically be understood by examining Equation (15a).) Thus, Table 2 indicates that the nonlinear Muskingum-Cunge model is a more accurate routing simulator. Smaller system error variances are also desirable for another reason which will become apparent in the multi-lag forecast comparisons included later in this section. The performance statistics of these runs are reported in Table 4 under the "Linear State Estimation" and "Nonlinear State Estimation" headings. Judging by the square and the peak discharge errors, these results indicate that the models predictive power improved (the peak discharge error is now within 5% of the actual values). However, the discrepancy in the peak timing is either the same as in the deterministic models or became worse. Close examination of the Figure 3 graphs shows that model predictions are very sensitive to current measurements. Thus, if the measurement sequence is not reflective of peak timing, neither are the model predictions.

A necessary step in any model building attempt is model verification by validating the underlying assumptions. If the state-space model has the correct structure and parameters, the innovation sequence $\nu(t)$ should be a white noise process. To test the whiteness properties of the innovation sequence, its autocorrelation function was computed. The top graph of Figure 5 displays this function for the linear model case in the three reach system. The autocorrelations for all other cases exhibit very similar shapes. The two horizontal lines delineate the 95% confidence band. Namely, there is a 5% chance that even though the autocorrelation coefficient is actually zero, the autocorrelation estimate falls outside this range. Thus, the fact that two autocorrelation estimates cross the 95% confidence band is not indicative of an invalid model. However, the fact that the autocorrelation sequence appears to have a nonrandom shape indicates that it may be possible to improve model performance by optimally adjusting additional model parameters.

In view of the diffusion model approximation where the friction slope $S_f = S_0 - \partial y/\partial x - v/g\ \partial v/\partial x - 1/g\ \partial v/\partial t$ (with S_0 being the bottom slope, y the depth, v the velocity, and g the specific gravity) is approximated by only the first two terms, the slope of the Muskingum-Cunge models was selected as an appropriate parameter for estimation. For the linear models, the unknown parameter set also includes the reference discharge. The estimation of these parameters was again performed using the Maximum Likelihood approach. Table 3 includes the optimal parameter estimates for all reach cases and models. The most notable observation is that the Maximum Likelihood slope estimates are approximately 60% higher than the actual channel slopes. The significance of this adjustment can be appreciated by the drastic reduction of the σ^2 estimates which are at least one order of magnitude less than their values in Table 2. The new slope estimates considerably strengthen the models' predictive power. This improvement is evident in the demonstration runs included in Figure 4 and the performance statistics in Table 4 (section entitled "State and Parameter Estimation"). The peak discharge predictions are now within 1% of the actual values, and the times-to-peak are estimated with much better accuracy. Overall, the nonlinear model slightly out performs the linear model, although the latter additionally has the reference discharge calibrated by the data set. The reference discharge estimates suggest that the optimal discharge values are closer to the average input hydrograph discharge (58,000 cfs) than to its peak value (102,000 cfs). Lastly, the innovation sequence whiteness is examined and established by the autocorrelation functions, one typical example of which (linear model three reach channel) is displayed as the second graph in Figure 5.

The previous performance evaluations were carried out using the data set which was also used in the parameter estimation process. Naturally, the question is whether the models will maintain their performance under different data sets. To this end one more simulation experiment was run using the 2nd hydrograph in Figure 1 and the three reach channel system. This hydrograph served as the input to both the DWOPER and the state-space routing models, whose parameters were set equal to the Maximum Likelihood values previously determined (Table 3). This experiment is displayed as the first graph in Figure 6 and demonstrates a rather close agreement of the predicted with the actual values. Peak discharge values were estimated with a 2% accuracy, and the times-to-peak exhibit an error between 6 and 12 hours. The square error is comparable to that of the last experiment, and the innovations autocorrelations sequence (Figure 7) validates the optimality of the estimation process. The important conclusion from these results is that the model slope adjustment is not the result of data fitting; it is a structural modification of the Muskingum-Cunge routing scheme necessary to enhance its performance in channels with flat slopes. Preliminary experimentation with channels of various slopes indicates that this adjustment becomes important in channels with slopes milder than 0.0002 (approximately 1 ft per mile). However, detailed investigations are currently being performed to better substantiate this conclusion.

The last two graphs in Figure 6 demonstrate multi-lag forecasting using the proposed state-space routing models. These models have the same parameter values reported in Table 3 and are run in the three reach system with the second input hydrograph. The forecasts are issued from the 40th 6-hour interval and the lead time is 30 6-hour periods (7.5 days). Namely, the last observation taken is at time 40 and the models are then run "open loop" over 30 time steps. The graphs display the forecast mean and 95% confidence band. The results indicate good agreement between forecasted and actual flows, with the latter always contained within the 95% probability band. This band is wider in the linear model due to the larger error variance. Thus, an added advantage of the nonlinear state-space routing procedure is higher forecast accuracy. Furthermore, both forecast probability bands eventually attain steady states, indicating that both state-space formulations are stable. This is a very desirable property as it warrants that forecast accuracy does not deteriorate as the forecast lead time increases. Hence, both models are capable of long-lead flood forecasting. The three properties of stability, observability, and controllability are general indicators of optimal system model and Kalman Filter performance.

Coarse Noncohesive Channels

The second set of experiments evaluates the model performance in coarse noncohesive channels with steep slopes. Figure 8 compares deterministic model predictions with actual flows in one, three, and five reach channels, respectively. The graphs verify that the Muskingum-Cunge routing procedure performs very well in channels with steep slopes and negligible inertia effects. Table 6 reports the associated performance measures and indicates that the peak discharge error is less than 2% and the time-to-peak predictions are essentially flawless. Some discrepancy still exists with respect to the timing and magnitude of the linear model low flow predictions. Figure 9 presents the results of the stochastic models with parameters calibrated using the Maximum Likelihood estimation approach. The estimated parameters are reported in Table 5 and the performance evaluation measures are included in Table 6. The Maximum Likelihood slope estimates are within 5 to 10% of the actual channel slopes, indicating that slope adjustment is not critical in this case. Comparison of the deterministic and stochastic models based on the Table 6 results suggests that the two model types perform in a comparable fashion. The correlograms for the stochastic model innovation sequences (not shown) verify that residual autocorrelations are statistically negligible.

Thus, it would appear that the value of discharge measurements in steep channels is minimal. However, all previous experiments assume exact knowledge of the channel characteristics, namely, the slope and roughness coefficient. In practice, these parameters are commonly misestimated due to the lack of accurate field data. In light of such imperfect system representations, the proposed stochastic model and parameter estimation procedures are generally useful.

5. CONCLUDING REMARKS

This work investigated the utility of state-space formulations in river routing. Two state-space models were suggested based on the linear and nonlinear forms of the Muskingum-Cunge routing procedure and were coupled with a Kalman filter estimator. The method was tested in channels with very mild and very steep bottom slopes. The results indicate that utilizing flow measurements improves the predictive ability of the Muskingum–Cunge routing scheme, especially in channels with mild slopes. Adjusting the slope of the Muskingum–Cunge model drastically improved model performance and forecasting ability in flat slopes (≤ 0.0002). This adjustment was performed using Maximum Likelihood estimation methods and was found to be independent of the hydrograph shape. However, more research is needed to quantify the nature of this correction by relating it to the actual bottom slope and possibly the downstream channel conditions. In conclusion, the computational experience presented in this work demonstrates that the stochastic Muskingum–Cunge formulation can effectively utilize real–time flow measurements for improved performance in a variety of open channels.

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APPENDIX A

State Space Representation of the Routing Equations

Substituting Equation (8a) into Equation (8b) and rearranging yields

$$Q_2(t+1) = C_{2,3}\, Q_2(t) + (C_{2,1} + C_{2,2}\, C_{1,3})\, Q_1(t) + C_{2,2}\, C_{1,1}\, Q_0(t)$$
$$+ \; C_{2,2}\, C_{1,2}\, Q_0(t+1) + C_{2,2}\, C_{1,4} + C_{2,4} \qquad \text{(A.1)}$$

Similarly, substitution of this equation into the routing expression for the 3rd reach gives the following result:

$$Q_3(t+1) = C_{3,3}\, Q_3(t) + (C_{3,1} + C_{3,2}\, C_{2,3})\, Q_2(t) +$$
$$+ (C_{3,2}\, C_{2,1} + C_{3,2}\, C_{2,2}\, C_{1,3})\, Q_1(t) + C_{3,2}\, C_{2,2}\, C_{1,1}\, Q_0(t)$$
$$+ C_{3,2}\, C_{2,2}\, C_{1,2}\, Q_0(t+1) + C_{3,2}\, C_{2,2}\, C_{1,4} + C_{3,2}\, C_{2,4}$$
$$+ C_{3,4} \qquad \text{(A.2)}$$

In general

$$Q_i(t+1) = C_{i,3}\, Q_i(t) + (C_{i,1} + C_{i,2}\, C_{i-1,3})\, Q_{i-1}(t)$$
$$+ C_{i,2}\, (C_{i-1,1} + C_{i-1,2}\, C_{i-2,3})\, Q_{i-2}(t)$$
$$+ C_{i,2}\, C_{i-1,2}\, (C_{i-2,1} + C_{i-2,2}\, C_{i-3,3})\, Q_{i-3}(t) + \dots$$
$$+ C_{i,2}\, C_{i-1,2} \cdots C_{3,2}\, (C_{2,1} + C_{2,2}\, C_{1,3})\, Q_1(t)$$
$$+ C_{i,2}\, C_{i-1,2} \cdots C_{2,2}\, C_{1,2}\, Q_0(t+1)$$
$$+ C_{i,2}\, C_{i-1,2} \cdots C_{2,2}\, C_{1,1}\, Q_0(t) + C_{i,4} + C_{i,2}\, C_{i-1,4}$$
$$+ C_{i,2}\, C_{i-1,2}\, C_{i-2,4} + \dots + C_{i,2}\, C_{i-1,2} \cdots C_{3,2}\, C_{2,4}$$
$$+ C_{i,2}\, C_{i-1,2} \cdots C_{2,2}\, C_{1,4} \qquad \text{(A.3)}$$

where $i = 3,4,\dots,N$.

Using matrix notation, these equations can be expressed in the following equivalent form:

$$Q(t+1) = A\,Q(t) + B\,U(t) + c \tag{A.4}$$

where $Q(t) = [Q_1(t)\ Q_2(t)\ \ldots\ Q_N(t)]^T$,

$U(t) = [Q_0(t)\ Q_0(t+1)]^T$,

$$\underset{(N\times N)}{A} = \begin{bmatrix} C_{1,3} & 0 & \cdots & 0 \\ C_{2,1} + C_{2,2}\,C_{1,3} & C_{2,3} & \cdots & 0 \\ \vdots & & & \vdots \\ \prod_{i=3}^{N-1} C_{i,2}(C_{2,1} + C_{2,2}\,C_{1,3}) & \cdots & C_{N-1,3} & 0 \\ \prod_{i=2}^{N} C_{i,2}(C_{2,1} + C_{2,2}\,C_{1,3}) & & \cdots & C_{N,3} \end{bmatrix}$$

$$\underset{(N\times 2)}{B} = \begin{bmatrix} C_{1,1} & C_{1,2} \\ C_{2,2}C_{1,1} & C_{2,2}C_{1,2} \\ \vdots & \vdots \\ \prod_{i=2}^{N} C_{i,2}\,C_{1,1} & \prod_{i=2}^{N} C_{i,2}\,C_{1,2} \end{bmatrix}$$

and $$\underset{(N\times 1)}{c} = \begin{bmatrix} C_{1,4} \\ C_{2,4} + C_{2,2}\,C_{1,4} \\ \vdots \\ C_{N,4} + C_{N,2}\,C_{N-1,4} + \ldots + \prod_{i=2}^{N} C_{i,2}\,C_{1,4} \end{bmatrix}$$

Vector c is related to the lateral inflow (or outflow), and, in certain cases, may not be present. However, when this model is used as a part of a rainfall-runoff forecasting scheme, the lateral inflow will also be an input, and Equation (A.4) must be considered as follows:

$$\mathbf{Q}(t+1) = \mathbf{A}\,\mathbf{Q}(t) + \mathbf{B}\,\mathbf{U}(t) + \mathbf{C}\,\mathbf{q}(t)\ , \tag{A.5}$$

where $\mathbf{q}(t) = [\bar{q}_1(t)\ \bar{q}_2(t)\ \ldots\ \bar{q}_N(t)]^T$ and

$$\underset{(N\times N)}{\mathbf{C}} = \begin{bmatrix} d_{1,4} & 0 & \cdots & 0 \\ C_{2,2}\, d_{1,4} & d_{2,4} & \cdots & 0 \\ \vdots & \vdots & & \vdots \\ \prod_{i=2}^{N} C_{i,2}\, d_{1,4} & \prod_{i=3}^{N} C_{i,2}\, d_{2,4} & \cdots & d_{N,4} \end{bmatrix}$$

with $d_{i,4} = \Delta x_i\, \bar{a}_i / C_{i,0}$ (see Equation 3e).

For the segments originating from reservoirs, the input $\mathbf{U}(t)$ will represent reservoir releases, while for those emerging from watersheds, it will represent predicted runoff rates.

APPENDIX B

Observability and Controllability Study

A system is observable if and only if a finite series of observations $\{z(t_0), z(t_1), \ldots, z(t_M)\}$ is enough to uniquely determine the initial value of the state vector at time t_0. Equivalently, the previous system is observable (Kailath, 1980, Chapter 2) if and only if the matrix

$$O = \begin{bmatrix} H^T \\ \hline sI - A \end{bmatrix} \tag{B.1}$$

has rank N for all s. Substituting H^T and A from Section 2 of the paper results in

$$\underset{[(N+1)xN]}{O} = \begin{bmatrix} 0 & 0 & & 1 \\ \hline s - A_{1,1} & 0 & \cdots & 0 \\ - A_{2,1} & s - A_{2,2} & \cdots & 0 \\ \vdots & \vdots & & \vdots \\ - A_{N,1} & - A_{N,2} & \cdots & s - A_{N,N} \end{bmatrix} \tag{B.2}$$

where the elements $A_{i,j}$ represent the corresponding entries of the matrix A defined following Equation (A.5). The critical values of s for which this matrix may not fulfil the observability requirement are the eigenvalues of A. (If s is not an eigenvalue, the determinant det(sI - A) will be nonzero and thereby matrix O will have rank N.) Given the structure of matrix O, the system is observable if we cannot find an (NxN) submatrix with at least one zero column or row for any value of s. The critical values of s are now restricted to $A_{1,1}$ and $A_{N,N}$, but one can easily verify that in either case no (NxN) submatrix with at least one zero row or column can be found. Thus, the system is observable.

A system is controllable if and only if, given any initial state vector $Q_I(t_0)$ and any terminal state vector Q_T, there exists a finite time t_M and an input sequence $\{U(t_0), U(t_1), \ldots, U(t_M)\}$ which "drives" the system from $Q_I(t_0)$ to Q_T. Alternatively, the system is controllable if and only if the matrix $(sI - A \mid B)$ has rank N for all s. (The following proof refers to the system represented by Equation (A.4); however, controllability of the system in Equation (A.5) can also be proved in a similar manner.)

Substituting A and B from Appendix A yields

$$\underset{[Nx(N+2)]}{C =} \left[\begin{array}{cccc|cc} s-A_{1,1} & 0 & \cdots & 0 & C_{1,1} & C_{1,2} \\ -A_{2,1} & s-A_{2,2} & \cdots & 0 & C_{2,2}C_{1,1} & C_{2,2}C_{1,2} \\ \vdots & \vdots & & \vdots & \vdots & \vdots \\ -A_{N-1} & -A_{N,2} & \cdots & S-A_{N,N} & \prod_{i=2}^{N} C_{i,2}C_{1,1} & \prod_{i=2}^{N} C_{i,2}C_{1,2} \end{array}\right] \qquad (B.3)$$

Using arguments similar to those of the observability proof we can easily show that we cannot find an (NxN) submatrix with at least one zero column or row for any value of s. Thus the system is also controllable.

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List of Tables

Table 1: Case Study Channel Characteristics

	Sandy Bed and Banks (1st case)	Coarse Noncohesive Material (2nd case)
Dominant Discharge (cfs)	100,000	100,000
Wetted Perimeter (ft)	1106.80	553.39
Bottom Width (ft)	907.325	452.57
Average Width (ft)	996.117	498.05
Surface Width (ft)	1084.91	543.54
Hydraulic Radius (ft)	32.809	14.51
Water Depth (ft)	32.51	15.49
Cross-section Area (ft^2)	32386.9	7718.01
Velocity (ft/sec)	3.087	12.95
Bottom Slope	0.00002	0.0018
Bank Angle (degrees)	20.11	18.81
Manning n	0.022	0.0288
Unit-width disch. (cfs/ft)	92.1735	183.978
Coefficient β	1.569	1.567
Wave speed c (ft/sec)	4.67	20.156

Table 2: Sandy Channels; Maximum Likelihood Error Variance σ^2 (cfs^2)

Model	One Reach	Three Reaches	Five Reaches
Linear	11,763,715.	6,357,972.	2,719,302.
	(-816.4)	(-806.6)	(-794.2)
Nonlinear	7,724,831.	3,676,790.	1,209,868.
	(-808.5)	(-800.2)	(-787.8)

Table 3: Sandy Channels; Maximum Likelihood Slope, Reference Discharge (cfs), and Error Variance σ^2 (cfs^2)

Case	Slope	Reference Discharge	Variance σ^2	Likelihood Value
		Linear Models		
1 Reach	3.3×10^{-5}	41,247.	473,691.	-781.0
3 Reaches	3.2×10^{-5}	60,849.	1,175,422.	-791.0
5 Reaches	3.1×10^{-5}	57,263.	152,357.	-778.7
		Nonlinear Models		
1 Reach	3.3×10^{-5}	-	1,286,775.	-786.8
3 Reaches	3.2×10^{-5}	-	307,196.	-786.2
5 Reaches	3.1×10^{-5}	-	4.	-773.7

Table 4: Sandy Material: Evaluation of Linear and Nonlinear Models

Model	Bias [cfs]	Square Error [cfs^2 x10^6]	Time-to-Peak Error [hrs]	Peak Disch. Error [cfs,%]	
Linear Deterministic	-66,088.	4,750.	-9	-4,705.	(5.4%)
	-28,574.	3,333.	-24	-6,192.	(8.5%)
	44,473.	1,427.	-27	-3,905.	(6.0%)
Nonlinear Deterministic	-61,514.	2,642.	-6	-6,911.	(7.7%)
	-81,195.	1,664.	-6	-8,892.	(12.9%)
	-66,864.	687.	-6	-5,806.	(8.9%)
Linear State Estimation	-45,172.	1,002.	+3	-4,781.	(5.3%)
	-42,626.	730.	+24	-3,055.	(4.2%)
	+15,434.	912.	+9	-763.	(1.0%)
Nonlinear State Estimation	-51,098.	787.	+3	-5,145.	(5.7%)
	-45,977.	498.	+18	-3,006.	(4.1%)
	-19,747.	890.	+21	-1,356.	(1.8%)
Linear State & Prmtr. Est.	-11,441.	92.	+3	457.	(0.5%)
	9,464.	171.	+3	804.	(1.1%)
	34,882.	151.	+12	755.	(1.3%)
Nonlinear State & Prmtr. Est.	-22,219.	228.	0	-1,200.	(1.3%)
	-8,018.	70.	+3	-496.	(0.6%)
	-13,099.	76.	+12	-113.	(0.1%)

Table 5: Coarse Noncohesive Channels; Maximum Likelihood Slope, Reference Discharge (cfs), and Error Variance σ^2 (cfs^2)

Case	Slope	Reference Discharge	Variance σ^2	Likelihood Value
		Linear Models		
1 Reach	1.9×10^{-3}	60,681.	1,465,717.	-777.0
3 Reaches	1.8×10^{-3}	61,770.	2,004,593.	-795.1
5 Reaches	1.8×10^{-3}	63,000.	1,704,025.	-803.7
		Nonlinear Models		
1 Reach	1.9×10^{-3}	-	430,465.	-772.4
3 Reaches	1.8×10^{-3}	-	329,180.	-779.1
5 Reaches	1.8×10^{-3}	-	691,267.	-787.7

Table 6: Cohesive Material: Evaluation of Linear and Nonlinear Models

Model	Bias [cfs]	Square Error [cfs^2 x10^6]	Time-to-Peak Error [hrs]	Peak Disch. Error [cfs,%]
Linear Deterministic	-18,028.	178.	0	446. (0.5%)
	-35,511.	1,320.	0	1,132. (1.2%)
	-31,343.	3,020.	+3	1,870. (1.9%)
Nonlinear Deterministic	134.	8.	0	472. (0.5%)
	-17,402.	72.	0	1,131. (1.2%)
	-37,682.	205.	+3	1,779. (1.8%)
Linear State Estimation	-10,464.	64.	0	775. (0.8%)
	-13,976.	379.	+3	1,225. (1.3%)
	-9,131.	801.	+6	3,579. (3.6%)
Nonlinear State Estimation	-167.	8.	0	471. (0.5%)
	-16,028.	69.	0	1,122. (1.2%)
	-28,324.	165.	+3	1,854. (1.9%)

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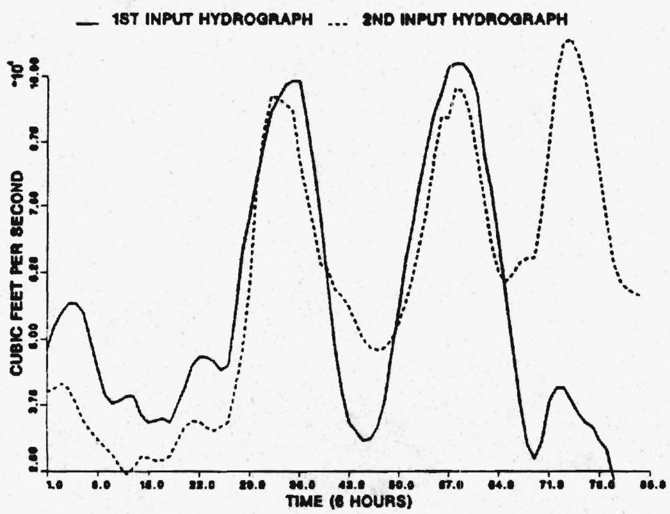

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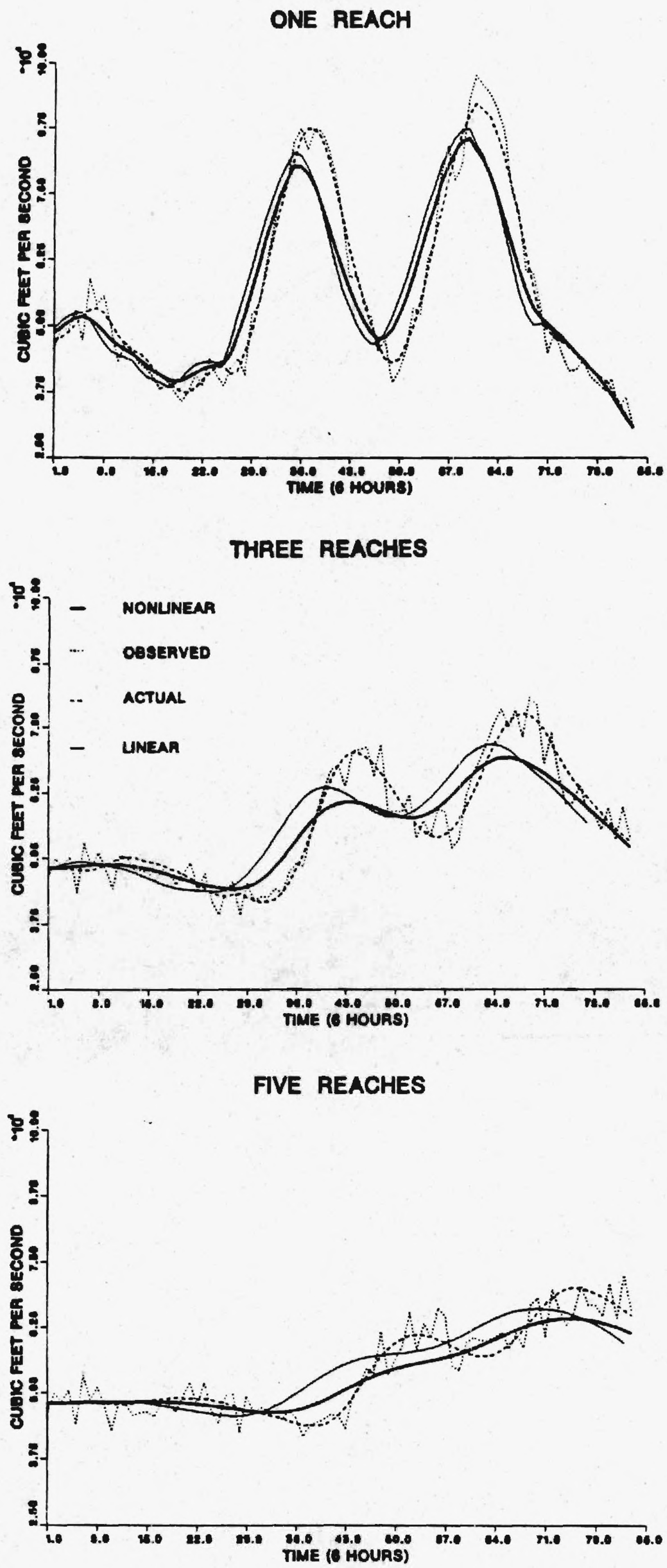

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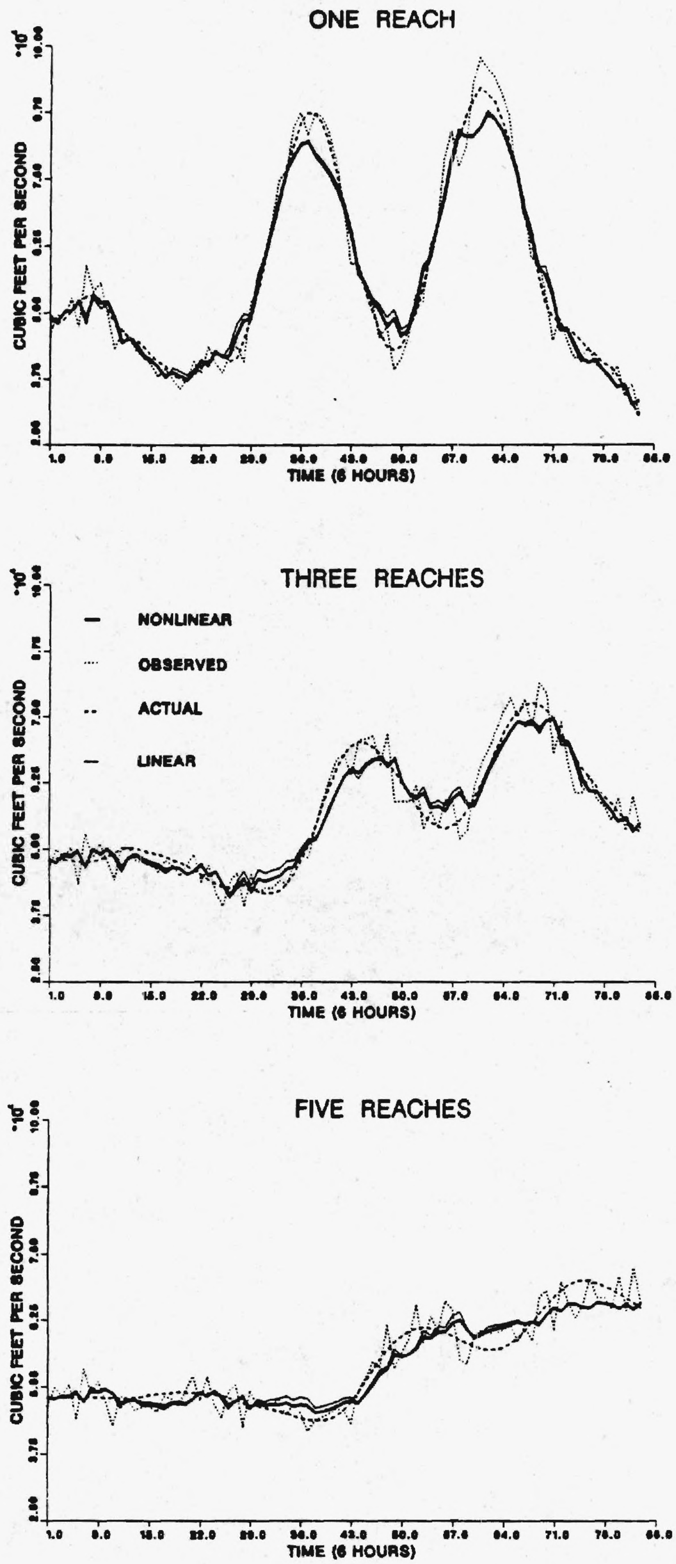

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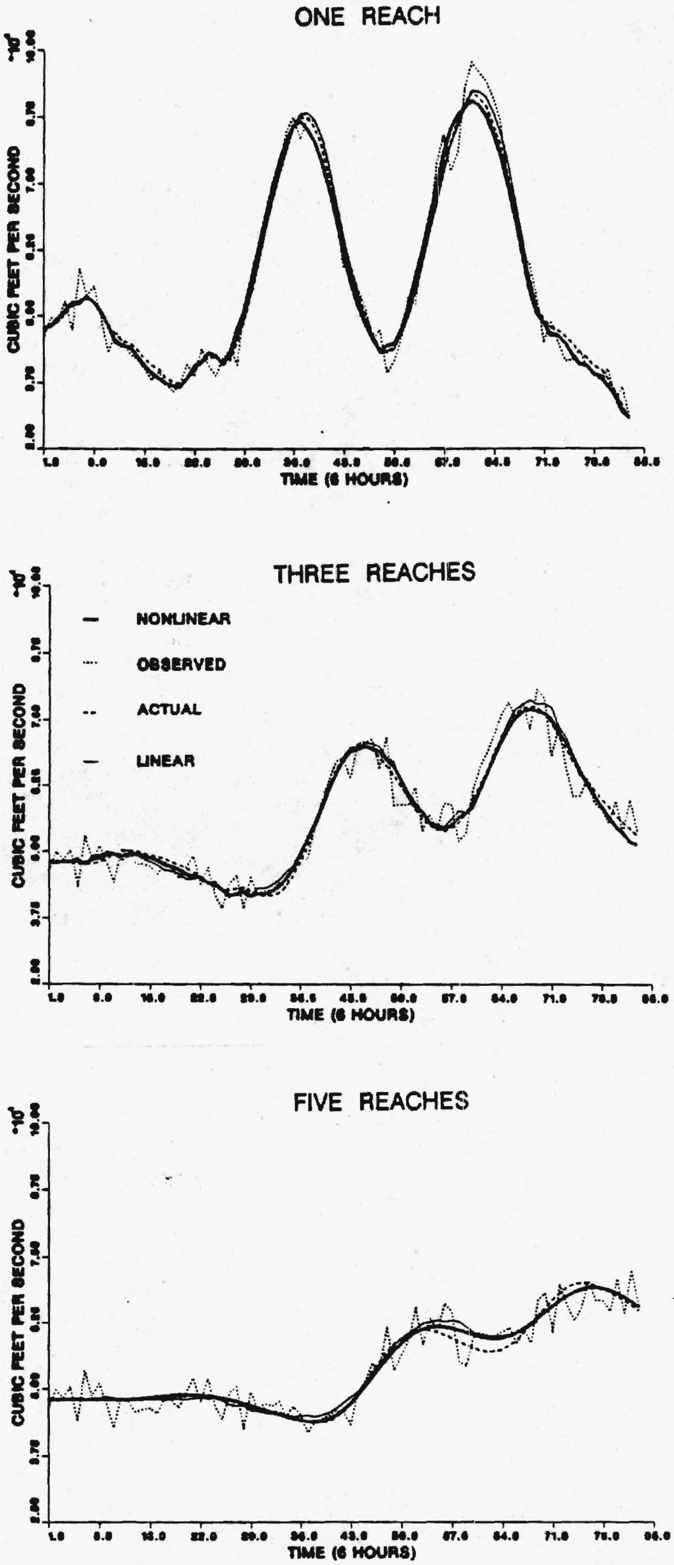

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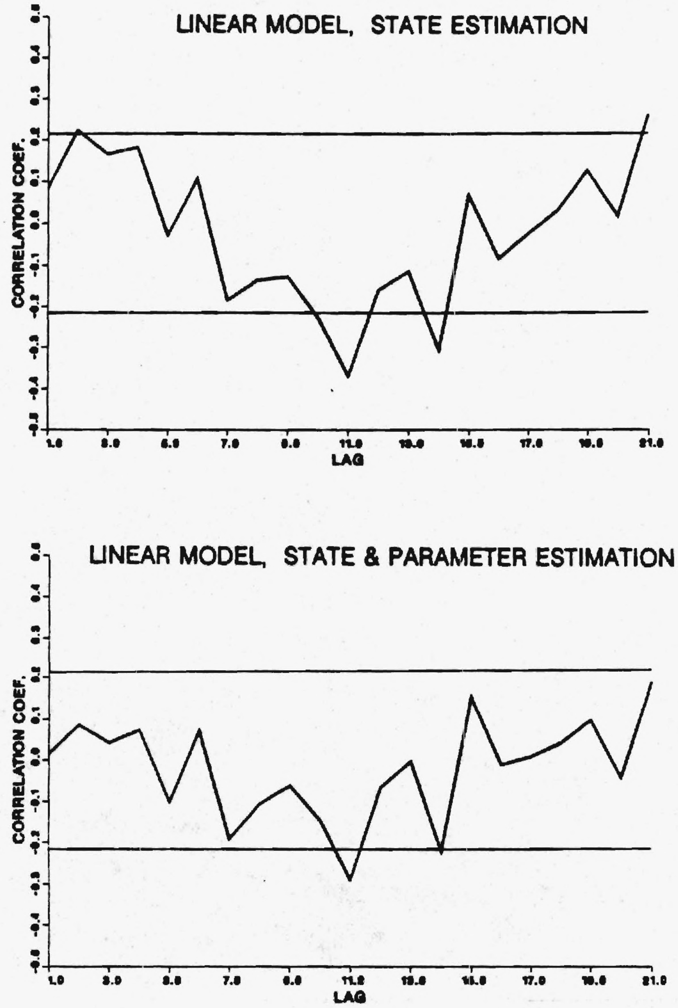

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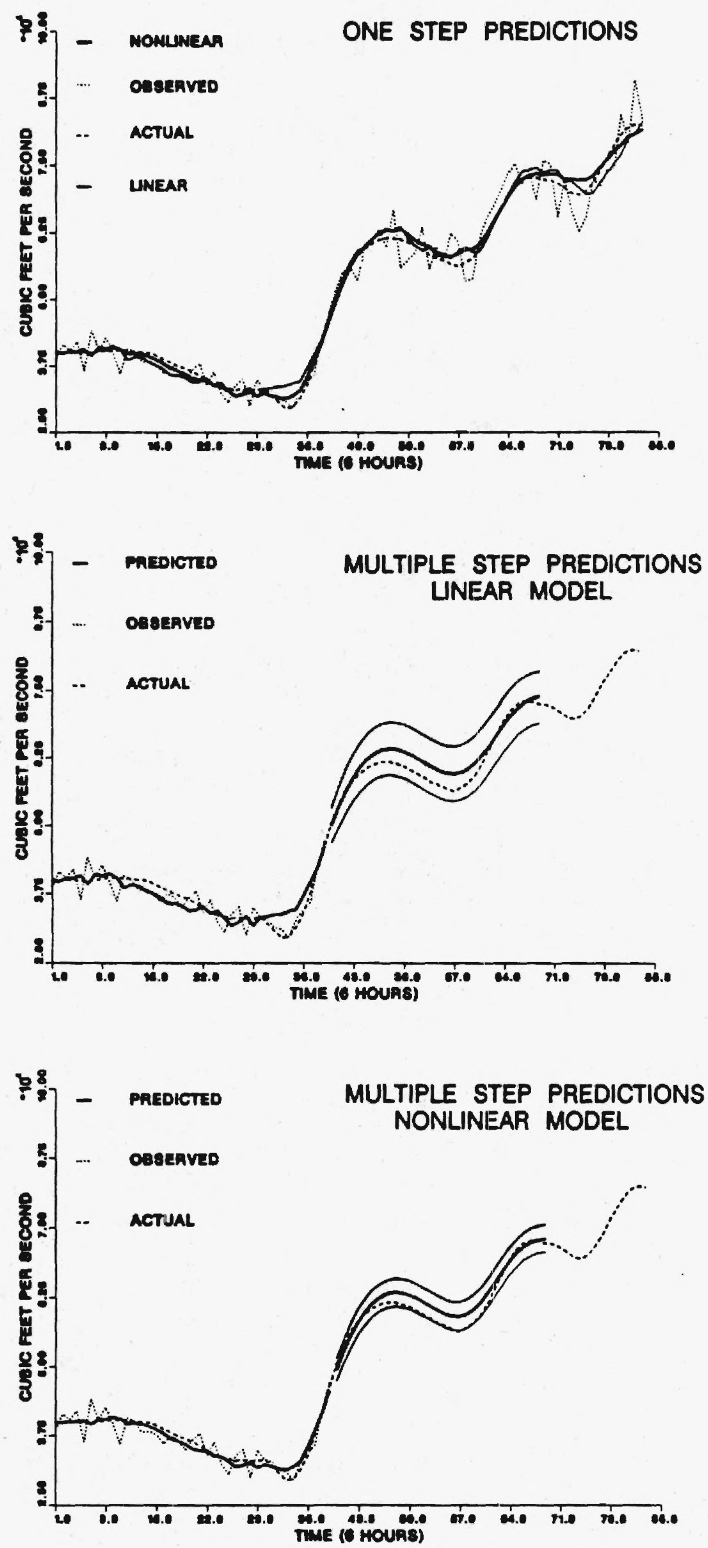

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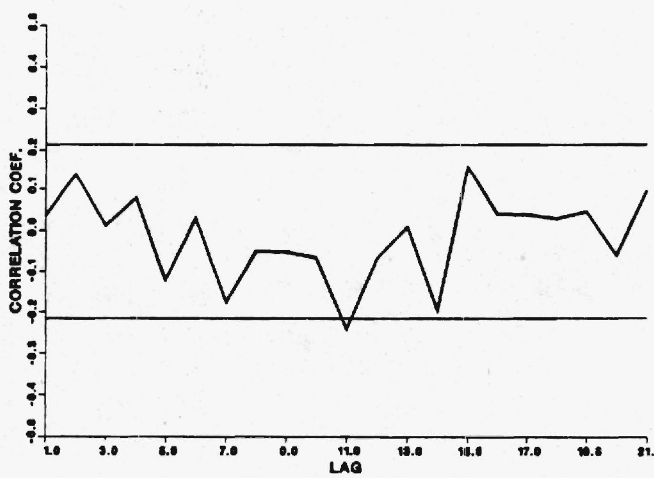

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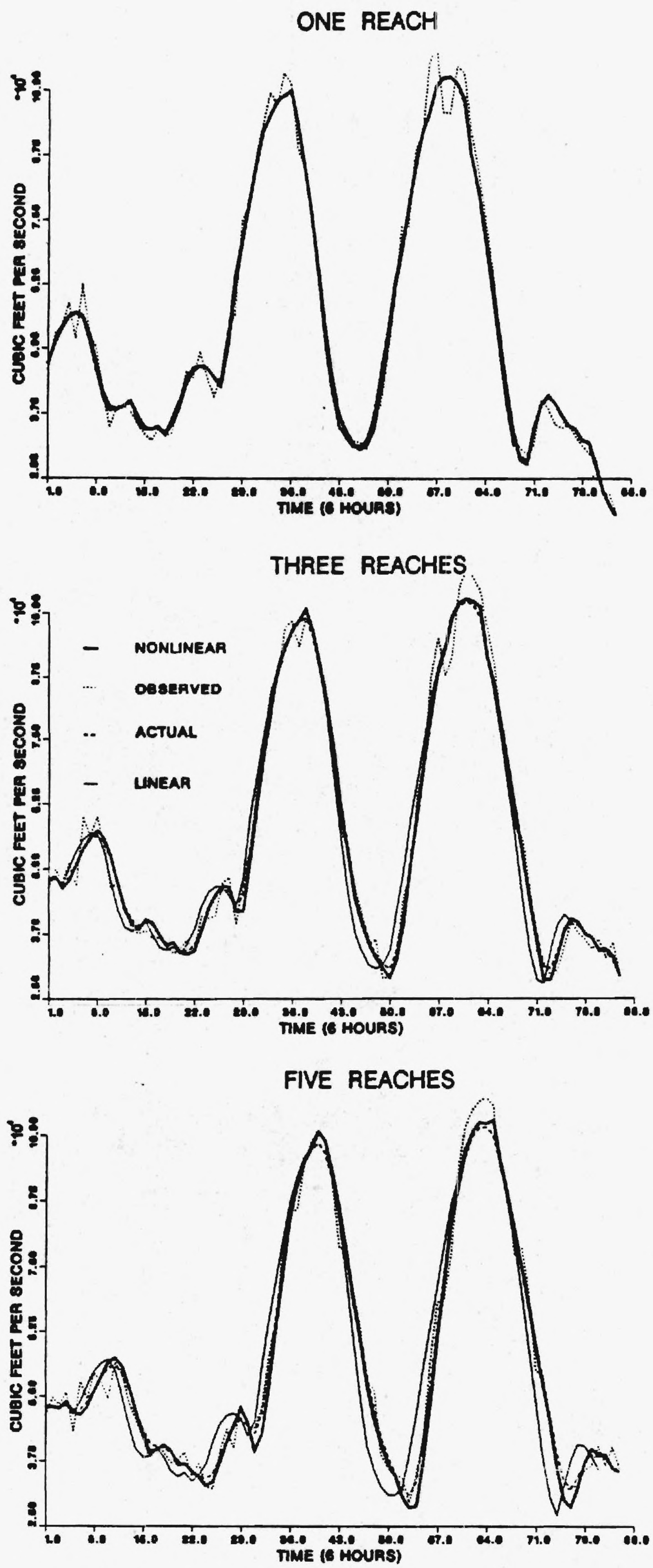
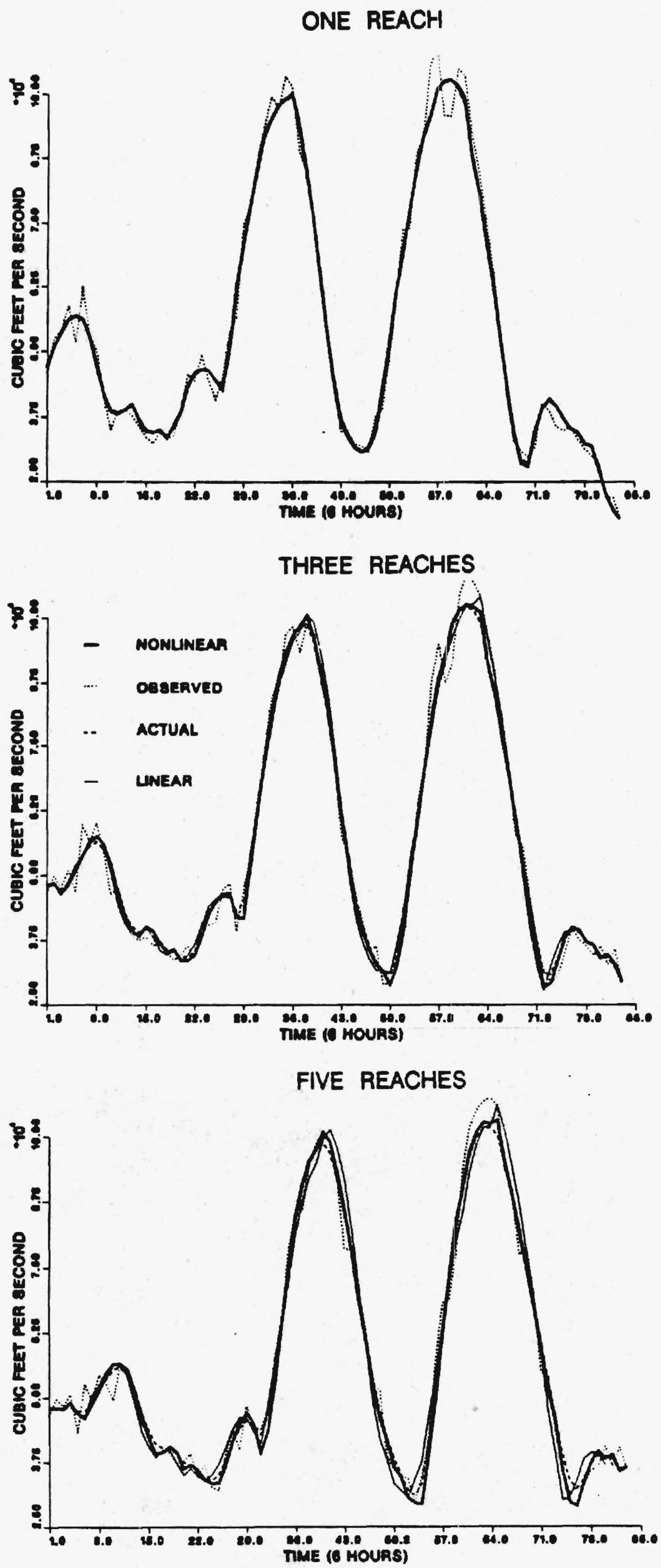


Figure 8: Coarse Noncohesive Channels; Deterministic Models



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OPTIMAL REGULATION OF THE SAVANNAH RIVER SYSTEM

Progress Reports (May 1, 1990 - November 30, 1990)

The research activities during this project period included (**a**) visits to Hartwell, Russell and Thurmond Reservoirs and extensive discussions with and data collection from the system operators, (**b**) discussions with SEPA as to their role in the operation of the Savannah reservoirs, (**c**) meetings and discussions with Georgia Power personnel to clarify their role in the operation of the Savannah reservoirs, (**d**) Corps personnel from the Savannah and SAD offices, and (**e**) refinement of the control model based on the feedback received. We feel that the above meetings and discussions, though time consuming, enhanced our understanding of the current management practices and will result in a practically more useful model. A more detailed discussion of our research follows:

MANAGEMENT PRACTICES

The real-time operation of the Savannah Reservoir System requires the close collaboration of several agencies. The operational schedules are first tentatively decided on a weekly basis by the U.S. Army Corps of Engineers District in Savannah. These schedules include hydropower energy and capacity declarations, water releases, and end-of-the-week predicted storages for each system reservoir. The schedules are announced on Wednesday and apply for the week beginning Saturday. In these determinations, the Districts take into consideration current storage levels and turbine availability, and plan on energy generation and capacity amounts based on previous operational experience and the specific water release requirements authorized for each reservoir. The decision process is assisted by simple water balance computations incorporating the energy generation characteristics of each hydroelectric facility. The above reservoir release and energy generation schedules are then provided to the Corps' South Atlantic Division (SAD) office.

The role of SAD is to insure that the energy and capacity declarations satisfy the contracts of the Southeastern Power Administration (SEPA) with various electric cooperatives and municipalities. If the declarations fall short of these commitments, SAD negotiates with the Savannah and Mobile Districts in an effort to revise their schedules within the other water release constraints. In these revisions, SAD considers the seasonal as well as the over-year storage and energy generation potential of each project. Namely, during above-normal flows, energy is principally drawn from the smaller reservoirs in the Apalachicola and Alabama-Coosa basins which have limited over-year storage capability. During dry years, the large Savannah River projects pick up most of the power demand.

SEPA markets the energy and power capacity available by the Corps projects to electric cooperatives and municipalities (consumers). Such contracts are usually established with the consumers for a period of ten years. SEPA also has contracts with power companies (e.g., Georgia, Alabama, and Duke Power) which own the transmission lines and "wheel" energy to consumers. In practice, the consumers buy energy and capacity from the power companies and receive credit for the amounts produced by the Corps projects. The contracts stipulate that federal energy and capacity be used to cover the peak power demand period. The consumers would prefer to maximize SEPA's contractual commitments due to the relatively low rates of the federal energy. However, if SEPA contracts exceed the amounts actually produced by the Corps projects, SEPA is obligated to buy the contractual deficit from the open energy markets at 3 to 5 times higher rates. This cost is eventually transferred to the consumers in the form of rate increases. If, on the other hand, SEPA under-estimates federal energy production, excess energy may reach the consumers at higher cost. Thus from the standpoint of SEPA and its customers, the contracted and actually available energy and power amounts must be in close agreement.

SEPA determines the energy contracts based on system simulations with historical inflow sequences (1925 through present). The power capacity availability is based on simulations with the drought of 1981 (3rd worst drought on record as of 1985) and is taken as the minimum power capacity of each reservoir during this period. As mentioned, the weekly energy and power amounts thus contracted remain in effect for the next ten years. However, SEPA energy and capacity rates to the consumers may change every five years or less to recover the cost of energy purchases.

The power companies complete the decision making process by scheduling the energy generation and capacity availability at each system reservoir in accordance with the contractual commitments. In effect, the power companies are authorized to take the energy and capacity amounts stipulated in the SEPA contracts to meet the power demand of their customers. However, the SEPA consumers receive credit for the contracted energy and capacity amounts which must be applied to the hours of peak power demand. (From the power companies standpoint, a unit of energy or capacity sold by SEPA is a unit taken from their own sales, and, therefore, it is to their benefit to discourage high SEPA contractual commitments.) The power companies determine their rates by an economic model that takes into account outages and operational costs and performs dispatching of all power plants in their system. The power companies schedule the contracted energy generation and capacity availability on an hourly basis so as to minimize their operational costs. The hourly schedules are simply the weekly amounts divided by five and applied over the peak generation period of each day. (Weekends are not peak power demand periods.) These schedules are communicated to the operators of the Corps projects every Friday.

ELQG CONTROL SOFTWARE

This section describes the control software that is presently being implemented for the Savannah River system sponsored by the Savannah Corps District.

The software is based on the ELQG control method [*Georgakakos, 1984, Georgakakos and Marks, 1987, and Georgakakos 1989a, 1990*] and is organized as follows: The model includes three control levels N, F, and D (Figure 1) to guide the system during normal, flood, or drought periods respectively. The search for the optimal release and energy generation sequences starts at control level N. This level seeks to optimize the releases over the established horizon such that (a) the minimum release requirements are met, (b) energy generation and available power capacity levels are in accordance with contractual commitments, (c) the likelihoods of spillage or storage depletion are insignificant over the control horizon, and (d) the available turbines "run" at best efficiency or at specified overload levels depending on the power capacity commitments. Reservoir storage constraints are stated in a probabilistic format based on user-defined constraint violation tolerance levels. For example, the constraint relating to storage depletion requires that the probability that the reservoir storage falls below the conservation storage zone be less than or equal to a user-defined risk level (e.g., 2.5%).

ELQG determines the optimal sequences using the two-module optimization scheme shown on Figure 2. Module I in this scheme is concerned with the optimization of the release sequences over time. Module II specifies the each turbine's power load based on its characteristics and the forebay and tailwater reservoir elevations. (Although it is desirable that turbines "run" at best efficiency to maximize energy output for a given release volume, power commitments may require that turbines are overloaded by 20 to 25% above

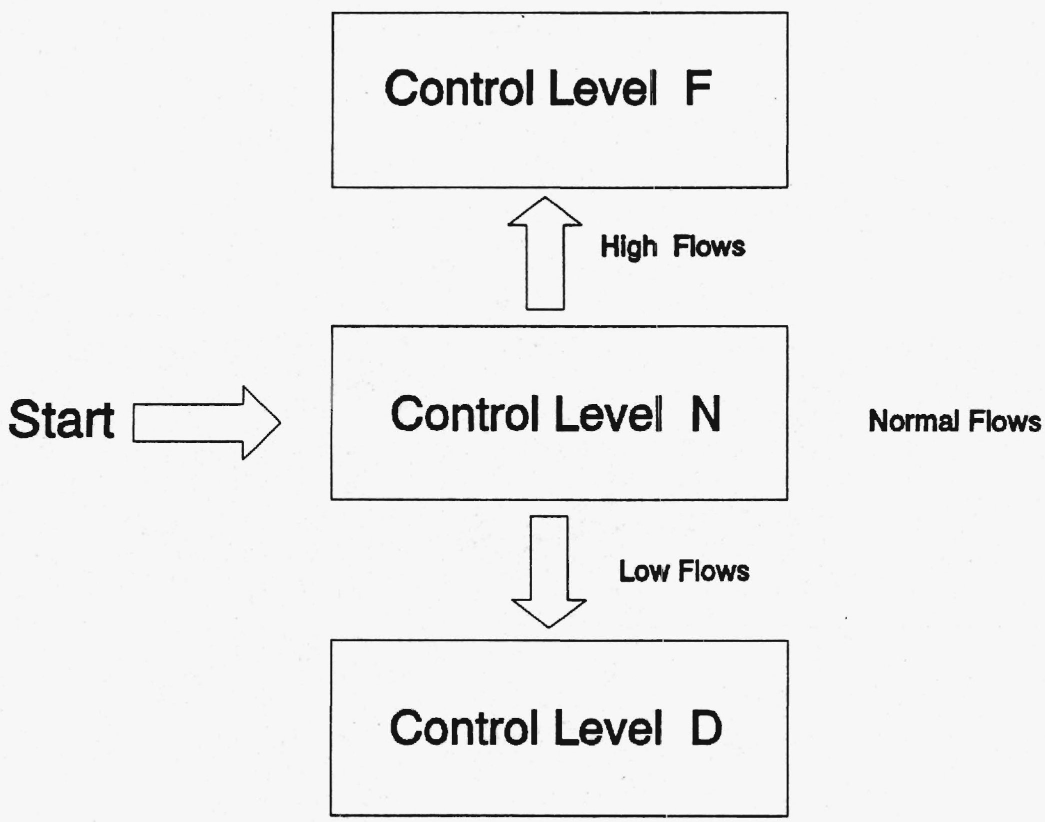

Figure 2: A Two-Module Optimization Process

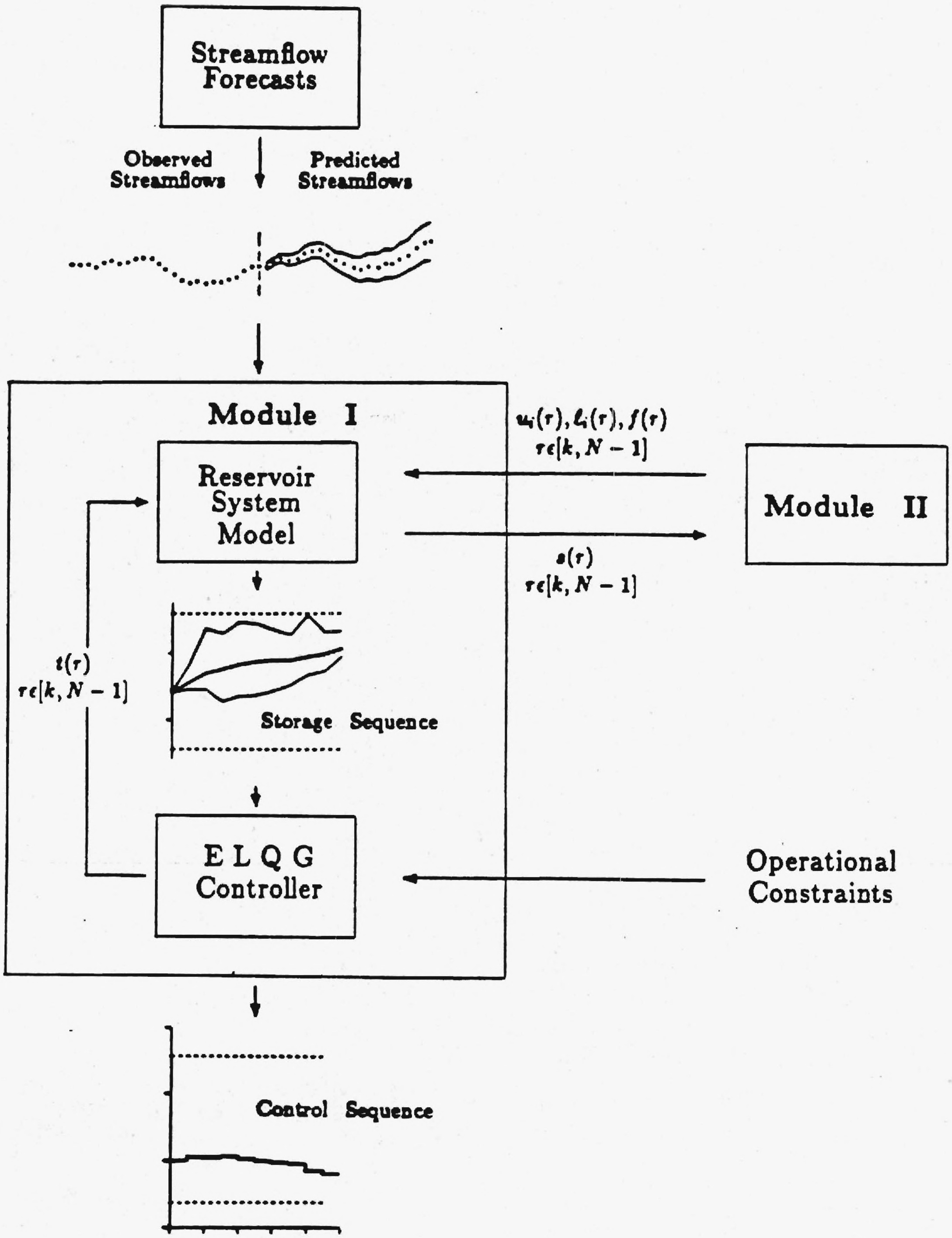

Figure 2: A Two-Module Optimization Process

their nominal capacity rating.) The above scheme can utilize inflow forecasts from any available forecasting model. The forecasts are used together with a given release sequence to generate the probability density of the reservoir storage at each week of the control horizon. The goal of the control algorithm is to find that release sequence which gives rise to the most desirable probabilistic storage sequence. As discussed by *Georgakakos, 1989b*, the better the forecasting model, the less reluctant the controller is to let the reservoir approach the constraint levels.

If this optimization process identifies a release sequence that does not violate any of the afore-mentioned constraints, then ELQG terminates. This week's optimal release and energy generation schedules are recommended for implementation, and the process is re-initiated at the beginning of the next week. If, however, the optimization process is unable to determine a feasible release sequence preventing violation of the upper or lower probabilistic storage bounds over the foreseeable future, then ELQG respectively activates its F (flood) or D (drought) control level.

The purpose of the F Control Level is to (a) prevent excessive releases, and (b) generate as much energy as possible. Since the objective now is to release as much water as possible through the system turbines, this level "runs" the turbines at maximum energy output.

The purpose of the Control Level D is to minimize the impacts of low flows during the anticipated drought period. Drought period operations are initiated if at any time of the control horizon the storage probability densities violate a user-defined lower storage threshold (e.g., the bottom of the conservation pool) with significant probability (e.g., more than 2.5%). In a situation like this, it may be more beneficial to start conserving water in advance, with moderate release deficits, than to implement severe rationing at some later time. During the drought operational mode, the energy generation proceeds at best turbine efficiency to maximize energy output. One must realize that even if the storage probability density violates the drought threshold, deficits will not necessarily take place. Even if one continues to release the normal amounts, it is only *possible* that deficits will eventually become mandatory. Thus, it is up to the management authority to determine the risk level which they feel is tolerable. This is one example of the various operational trade-offs that the management authority has to resolve in real time. As discussed next, ELQG is programmed to generate such trade-offs and solicit the involvement of the system operators.

A key feature of the ELQG control scheme is its ability to meet reliability constraints. The tolerance level for each constraint and time period is specified by the user and can be varied to explore the Pareto Optimal Surface among the system objectives. (In an application with the Savannah three-reservoir system, *Georgakakos, 1989a*, demonstrated that the ELQG user-specified tolerance levels are actually realized in practice, a feature which is presently unique among reservoir control methods.) The previous ELQG multilevel control structure is also convenient to segregate the trade-offs pertinent to each operational mode.

During normal operations, one may consider increasing the firm or the total energy generation, especially during periods of above average inflows, at the expense of having a lower end storage. ELQG quantifies this trade-off in real time by incrementing the firm or total energy target, performing the optimizations, and recording the end-of-the-year storage levels. If desired, this investigation may also be conducted for a multi-year period. The trade-off is expressed in terms of the mean firm or total energy output versus the mean terminal storage, or in terms of any percentile from the associated probability distributions. The program then prompts the user for his most preferable operational choice and proceeds to identify the associated release and energy generation schedules to realize this selection. Rather than specifying the weekly energy targets, a separate option allows the user to input predicted energy prices, and it determines the energy generation sequence that maximizes the associated economic gains of their customers as a function of the end reservoir storage. (As previously mentioned, every killowatt hour (KWH) purchased by the Corps Projects is a KWH of lost sales to the power companies.) By varying the end storage, the program also generates the associated trade-off. These features are especially convenient if the Corps wishes to investigate various energy generation scenarios from each system reservoir or clusters of reservoirs.

During floods, a trade-off exists between energy generation and the downstream release level. Namely, energy generation may be increased if the releases are allowed to exceed the flood control thresholds. One must weigh the value of the additional energy generation (or the savings from the equivalent thermal energy) versus the risk of flood damages.

During droughts the issue is to determine the time distribution of low flows which minimize the downstream drought impacts. The implied trade-off involves deferring rationing versus the risk of a major shortage.

In view of the changing operational conditions, the ability to generate operational trade-offs is pivotal in the real-time management of any multipurpose reservoir system.

This ELQG implementation is developed on microcomputers. More specifically, the program "runs" on 286, 386, or 486 machines under the DOS operating system. The program is presently integrated with extensive graphics routines based on the GSS*GKS graphics software. This software will be able to generate, at "run time", screen and hard copy plots of the reservoir storage, release, and energy generation probabilistic sequences as well as of the afore-mentioned operational trade-offs. The program will be driven by menus to facilitate the input process and provide the user with intuitive understanding of the computations in progress. The control software without the graphics interface but with extensive output files will also "run" on main frames or workstations. The user may then utilize the output files in connection with any graphics software at his disposal to generate plots.

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OPTIMAL REGULATION OF THE SAVANNAH RIVER SYSTEM

ARIS P. GEORGAKAKOS

Associate Professor

May 1991

School of Civil Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332

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Aris P. Georgakakos

Associate Professor

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School of Civil Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332

DISCLAIMER

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1. INTRODUCTION

Reservoir operation certainly provides ample opportunity to use computer-aided management tools. Except for simple systems, namely, small, single objective reservoirs, where optimal decisions are obvious, the decision making process must take into account a plethora of complicating factors. Uncertain inflows, reservoir and river dynamics, hydroelectric plant characteristics, flood and drought concerns, water supply, energy generation commitments and economics, water quality standards, recreational activities, local and regional water use conflicts and legislation, and public opinion are but a few of the parameters influencing reservoir management decisions. Computer-aided management tools including data management and interactive graphics systems and computer models are being extensively used by reservoir management authorities to process and store information. However, their usage in real-time decision making has been limited.

Reservoir management computer models are usually classified as simulation or optimization models. Among the two, simulation models are more popular among practitioners but require multiple runs and thorough understanding of system operation to be of any practical value. Optimization models are more effective in identifying potential operational policies, yet their usage in real time reservoir operation is a very rare occurrence. The primary underlying factors are that (a) until recently, optimization models could not handle the complexities of large multipurpose reservoir systems; (b) model developers are often unaware of how such decisions are taken in practice and fail to integrate their research products within the existing organizational structures; and (c) practicing engineers are not traditionally trained on advanced optimization methods and feel uncomfortable using them.

However, recent reservoir control research advances combined with fascinating developments in the computer industry provide new opportunities for model use in real time reservoir management. Modern reservoir control methods can now handle dimensionally large systems with both multiple objectives and operational constraints. And, of equal importance, control models can now be implemented on readily accessible microcomputers which encourages potential widespread use and numerous practical applications. Combined with interactive input-output graphics interfaces, management models can be designed to maximize user involvement and provide intuitive understanding of the computations in progress.

This report describes a state-of-the-art reservoir control model developed for the management of the Savannah River System. The model is designed to assist the decision making authorities evaluate the impacts of various operational alternatives and select the one which represents the best compromise among system outputs. The model can be used at various levels of the decision making process including the Savannah U.S. Army Corps of Engineers District, the South Atlantic Corps Division, and the Southeastern Power Administration.

The report includes five sections and three appendices. Section 2 describes the

Savannah Reservoir System and discusses the current management practices. Section 3 details the features of the control model, and Section 4 presents typical case studies. Section 5 identifies areas of improvement and concludes the report. The appendices include the reservoir characteristic curves and a step-by-step description of the optimization algorithms. A user's manual is provided as a separate document.

2. THE SAVANNAH RIVER SYSTEM

2.1 System Description

The Savannah River (Figure 1) originates in the Blue Ridge mountains of Southwest North Carolina and flows along the Georgia/South Carolina border before reaching the Atlantic Ocean at Savannah, Georgia. This river plays an important economic role for the surrounding counties of the Georgia/South Carolina area. The river drains a total of 10,579 square miles, 179 of which are in North Carolina, 4,530 are in South Carolina, and 5,870 are in Georgia. The river is primarily controlled by the Hartwell, Richard B. Russell, and Thurmond Reservoirs which are owned and operated by the U.S. Army Corps of Engineers, Savannah District.

Some characteristics of these projects are summarized in Table 1. (This information was compiled from the Savannah River Basin Reservoir Regulation Manual [1974].) Together with Lake Lanier, Hartwell and Thurmond are the largest reservoirs in the south east with usable storages approaching or exceeding 1.5 million acre-feet. The crucial role of these three projects during the recent droughts cannot be over-emphasized. If these projects did not exist, the recent droughts would have devastated the local economy .

Table 1: Reservoir Characteristics

	Hartwell	Russell	Thurmond
Year Completed	1961	1986	1954
Drainage Area, square miles	2,088	2,837	6,144
Conservation Pool, acre-feet (Elevation Range, feet)	1,415,500 (625-660)	126,864 (470-475)	1,045,000 (312-330)
Flood Control Pool, acre-feet (Elevation Range, feet)	293,100 (660-665)	139,922 (475-480)	390,000 (330-335)
Power Capacity, MW (Number of Turbines)	344 (5)	300 (4)	282 (9)

The operational objectives include flood control, navigation, water supply, recreation, pollution abatement, fish and wild life management, and power generation. The construction of the dams virtually eliminated severe flooding which prior to 1954 had disastrous consequences including the loss of life. With regard to navigation, a minimum Thurmond outflow of 5,800 cfs had initially been authorized to provide the necessary river depth from Augusta to Savannah for commercial shipping. Since 1979, however, commercial shipping has been abandoned, and the river now accommodates only recreational boating. Water supply withdrawals are estimated to be one billion gallons per day serving both domestic and industrial users. A minimum release of 3,600 cfs is required to facilitate the

Figure 1: The Savannah River System

withdrawals at the water supply intakes downstream of Thurmond. Lake recreation has become an official project purpose attracting over 20 million visitors annually and generating significant revenues. Pollution abatement and fish and wild life management require a 4,500 cfs minimum release from Thurmond. Lastly, the Savannah River hydroelectric facilities produce almost half of the Southeastern Power Administration (SEPA) commitments to various industries and municipalities. The SEPA system includes eight additional hydropower plants on the Apalachicola-Chattahoochee-Flint and Alabama-Coosa river basins.

2.2 Management Practices

The real-time operation of the Savannah Reservoir System requires the close collaboration of several agencies. The operational schedules are first tentatively decided on a weekly basis by the U.S. Army Corps of Engineers District in Savannah. These schedules include hydropower energy and capacity declarations, water releases, and end-of-the-week predicted storages for each system reservoir. The schedules are announced on Wednesday and apply for the week beginning Saturday. In these determinations, the Districts take into consideration current storage levels and turbine availability, and plan on energy generation and capacity amounts based on previous operational experience and the specific water release requirements authorized for each reservoir. The decision process is assisted by simple water balance computations incorporating the energy generation characteristics of each hydroelectric facility. The above reservoir release and energy generation schedules are then provided to the Corps' South Atlantic Division (SAD) office.

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SEPA markets the energy and power capacity available by the Corps projects to electric cooperatives and municipalities (consumers). Such contracts are usually established with the consumers for a period of ten years. SEPA also has contracts with power companies (e.g., Georgia, Alabama, and Duke Power) which own the transmission lines and "wheel" energy to consumers. In practice, the consumers buy energy and capacity from the power companies and receive credit for the amounts produced by the Corps projects. The contracts stipulate that federal energy and capacity be used to cover the peak power demand period. The consumers would prefer to maximize SEPA's contractual commitments due to the relatively low rates of the federal energy. However, if SEPA contracts exceed the amounts actually produced by the Corps projects, SEPA is obligated to buy the contractual deficit from the open energy markets at 3 to 5 times higher rates. This cost is eventually transferred to the consumers in the form of rate increases. If, on the other hand, SEPA under-estimates federal energy production, excess energy may reach the consumers at higher cost. Thus from the standpoint of SEPA and its customers, the contracted and actually available energy and power amounts must be in close agreement.

SEPA determines the energy contracts based on system simulations with historical inflow sequences (1925 through present). The power capacity availability is based on simulations with the drought of 1981 (3rd worst drought on record as of 1985) and is taken as the minimum power capacity of each reservoir during this period. As mentioned, the weekly energy and power amounts thus contracted remain in effect for the next ten years. However, SEPA energy and capacity rates to the consumers may change every five years or less to recover the cost of energy purchases.

The power companies complete the decision making process by scheduling the energy generation and capacity availability at each system reservoir in accordance with the contractual commitments. In effect, the power companies are authorized to take the energy and capacity amounts stipulated in the SEPA contracts to meet the power demand of their customers. However, the SEPA consumers receive credit for the contracted energy and capacity amounts which must be applied to the hours of peak power demand. (From the power companies standpoint, a unit of energy or capacity sold by SEPA is a unit taken from their own sales, and, therefore, it is to their benefit to discourage high SEPA contractual commitments.) The power companies determine their rates by an economic model that takes into account outages and operational costs and performs dispatching of all power plants in their system. The power companies schedule the contracted energy generation and capacity availability on an hourly basis so as to minimize their operational costs. The hourly schedules are simply the weekly amounts divided by five and applied over the peak generation period of each day. (Weekends are not peak power demand periods.) These schedules are communicated to the operators of the Corps projects every Friday.

3. Control Model

Control methods are mathematical procedures for the systematic screening of potential solutions to an optimization problem. In systems with multiple objectives, the existence of one solution superior with respect to all objectives is very unlikely. This is especially true in reservoirs where conflicts almost always exist between hydropower and flood control, water supply and recreation, and hydropower and water conservation. In such situations, the notion of one optimal solution is meaningless unless specific priorities are established on the value of each objective. This approach has traditionally been adopted in the reservoir control literature and is one important reason why the majority of the control models remained unutilized in practice. Real time reservoir control is a process where decisions must routinely balance objectives amongst themselves and over time. What is more, the dynamic nature of water resources issues necessitates constant reevaluation of operational priorities and goals. What is presently most desirable may become less satisfying in the future due to changes in demographics, regional economy, public awareness and pressure, and other reasons far too intangible to quantify or firmly prioritize. It is the role of the responsible operating authority to constantly weigh these and other factors and implement operational policies in the best interest of the system users.

To this end, the role of a real time control model emerges as follows: First, the effects of various operational scenarios can be explored and presented to the decision making authority for review. This information can take the form of tradeoffs depicting how various sets of priorities affect each system output. A tradeoff curve is the result of several optimization runs, each one of which operates under a different set of objective priorities. After reviewing this information, the management authority can decide what constitutes a desirable compromise among the system uses and select the most satisfying tradeoff point. The model can subsequently be invoked to produce the control sequence (generation time and turbine power level schedules) which realizes the selection made. In this setting, the control model (or its developer) does not infringe on the responsibility of the management authority; rather, it provides the necessary information to evaluate the impacts of the various operational options. The operational policy is set by the management authority based on this and other considerations.

This interactive approach combines the benefits of advanced control methods with the experience of the system managers and constitutes the basis for the design of the control model for the Savannah River system. The model includes three control levels (see Figure 1) corresponding to normal, drought, and flood conditions. Each level addresses the specific concerns and tradeoffs pertaining to each operational condition but is invoked at the user's discretion, regardless of the current inflow and reservoir level situation.

During normal operation, the system is expected to meet the energy and power contracts established by the SouthEastern Power Administration (SEPA). At the same time, the lakes should remain near the target levels specified by the rule curves. The target levels vary seasonally and have been determined to provide a certain degree of flood protection,

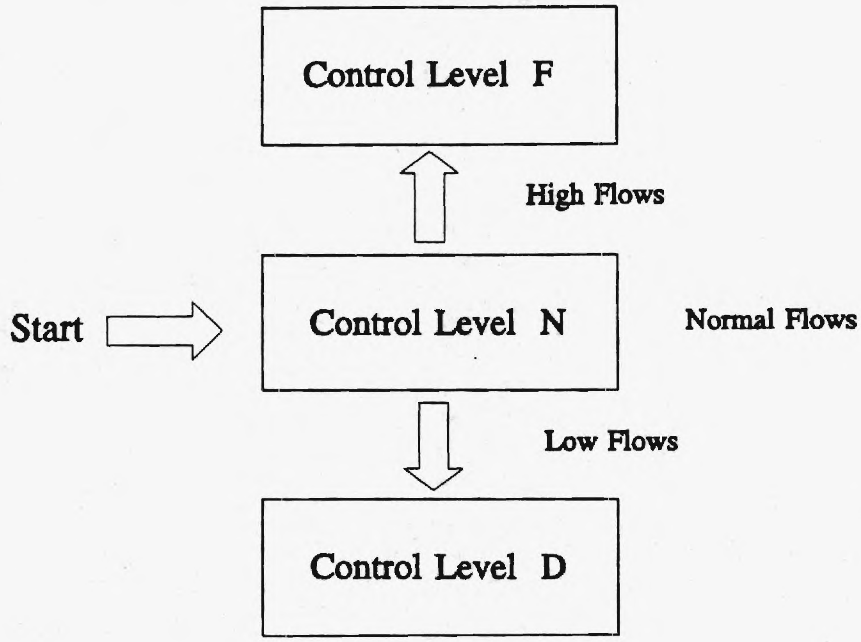


Figure 2: A Multilevel Control Model

allow for water conservation, and permit recreation activities such as swimming, fishing, and boating. The tradeoff determined in this level is between energy generation on one hand and flood control, storage conservation, and recreation on the other. The second set of objectives is reflected on the deviations of the storage from the target sequences prescribed by the rule curve.

At the onset or during droughts, the management authority is faced with the dilemma to (**a**) continue normal operations and risk early reservoir depletion and major water shortages versus (**b**) to start curtailing system outflow and energy generation to sustain reduced water supplies longer. To aid in resolving this dilemma, the model generates tradeoffs between system outflow, energy generation, and reservoir levels.

During floods, the objective is to avoid damage-causing outflows while containing reservoir levels within the flood control pool. However, this may not always be possible and the system operator should carefully weigh the merit of maintaining current discharge levels versus the risk of having to release excessively later. Excessive releases are likely when reservoir levels exceed the top of the flood control pool as the spillway gates can only partially control outflow. Furthermore, the policy of avoiding spillage by initiating moderate releases early also favors energy generation. This tradeoff is resolved in the flood control level.

In generating the various tradeoffs, the control model must also satisfy several operational requirements such as (**a**) meeting the established power contracts, (**b**) guaranteeing a two hour minimum generation daily commitment during weekdays, (**c**) meeting a weekly average outflow constraint, (**d**) observing a maximum outflow rate bound, (**e**) balancing reservoir drawdowns to provide equal recreation opportunities at the three lakes, and (**f**) observing a certain order during the refiling process after droughts or during the emptying process after floods.

The control model (Figure 2) includes three basic components: a forecasting model and two optimization modules. Module I determines the optimal energy generation schedules such that energy generation and reservoir levels conform to a certain set of priorities and weekly outflows are within allowable limits. Module II specifies turbine power loads based on turbine characteristics, net hydraulic head, outflow constraints, and power commitments. The control process starts with the generation of inflow forecasts from an appropriate forecasting model. The forecasts can be either deterministic or stochastic. Deterministic inflow forecasts consist of a certain inflow sequence. Stochastic inflow forecasts consist of the mean, variance, and skewness inflow sequences. The forecasts are used together with a nominal generation time sequence to develop deterministic or probabilistic forecasts for each reservoir storage over the control horizon. The goal of the control algorithm is to find the generation time schedules giving rise to the most desirable deterministic or probabilistic storage sequences. The optimization procedure is iterative between Modules I and II and over time. This procedure is based on the Extended Linear Quadratic Gaussian (ELQG) control method [*Georgakakos and Marks, 1987, and Georgakakos, 1989*] but includes several new modifications and improvements. The three control model components are discussed in the following sections.

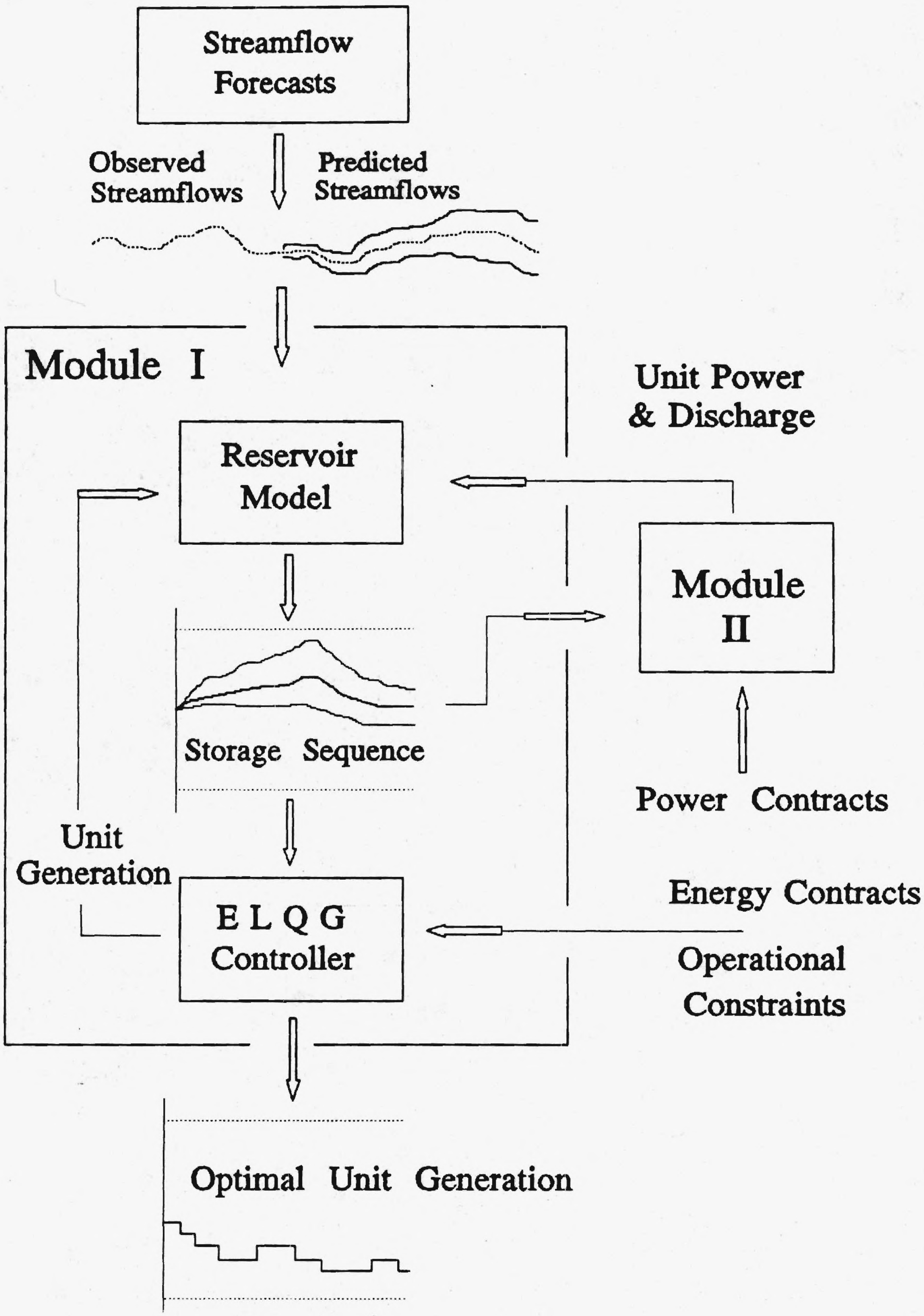


Figure 3: A Two-Module Optimization Scheme

3.1 Streamflow Model

The streamflow model includes three inflow forecasting possibilities. The first utilizes the historical weekly inflow mean, variance, and skewness, derived based on 63 years of reservoir inflow data (from 1925 through 1987). The second offers the option of using historical sequences of a given rank. For example, if the control horizon is 10 weeks and the user wishes to use the 3rd worst drought inflow sequences of the record, this option searches through the historical records at the time of the current date and identifies the 10-week inflow sequence which ranks 3rd lowest in total inflow volume to each lake. As an example, the following three figures depict the driest, average, and wettest years of record for each reservoir.

The third inflow forecasting possibility is based on subjective inflow information provided by the user. Under this procedure, the user must provide three inflow parameters for each period (week or day) of the control horizon. These parameters are (1) an inflow level which is always expected to be exceeded, (2) an inflow level expected to exceed the actual inflow with a likelihood of 50%, and (3) an inflow level expected to exceed the actual inflow with a likelihood of 95%. Using this information, appropriate three-parameter log-normal probability functions are determined and eventually translated into a similar description of the reservoir storage and elevation sequences.

The previous forecasting procedures are adequate during normal conditions or droughts. Operations during floods, however, would greatly benefit by the use of rainfall-streamflow predictors. Such models could utilize telemetried information from remote and on-site sensors and issue reliable hourly streamflow forecasts. Although the development of such models may require an upfront expense in improving basin instrumentation, it may be well worth the cost.

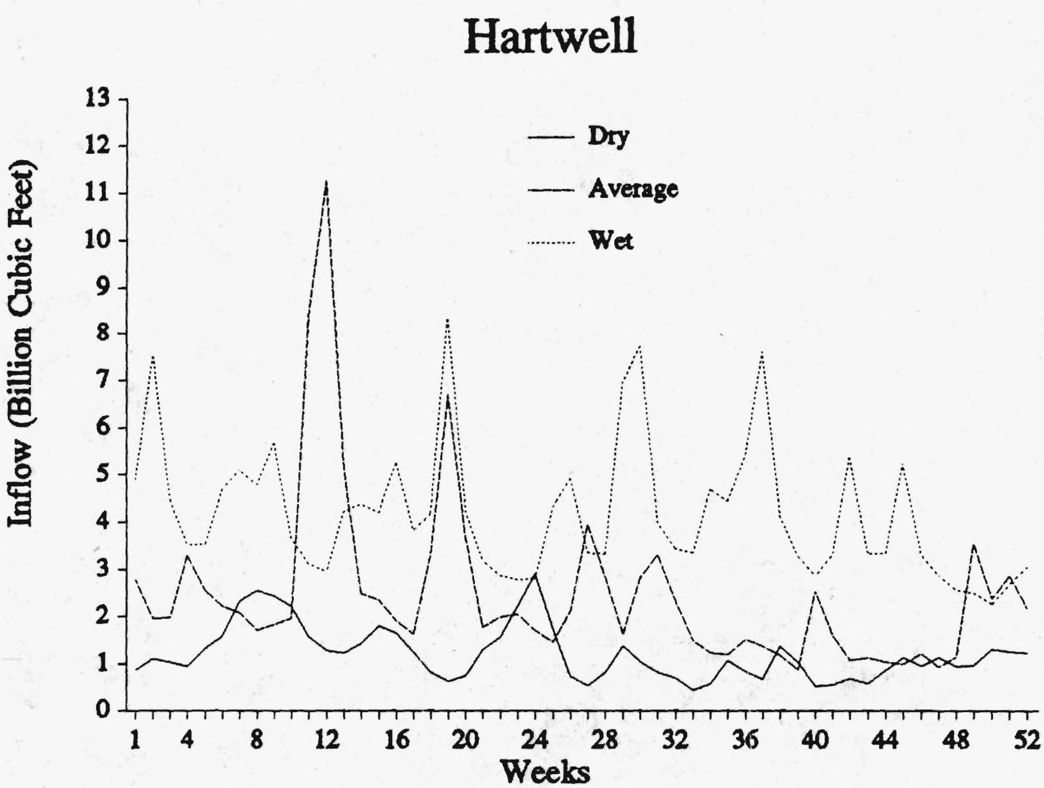


Figure 4: Hartwell Inflow Range

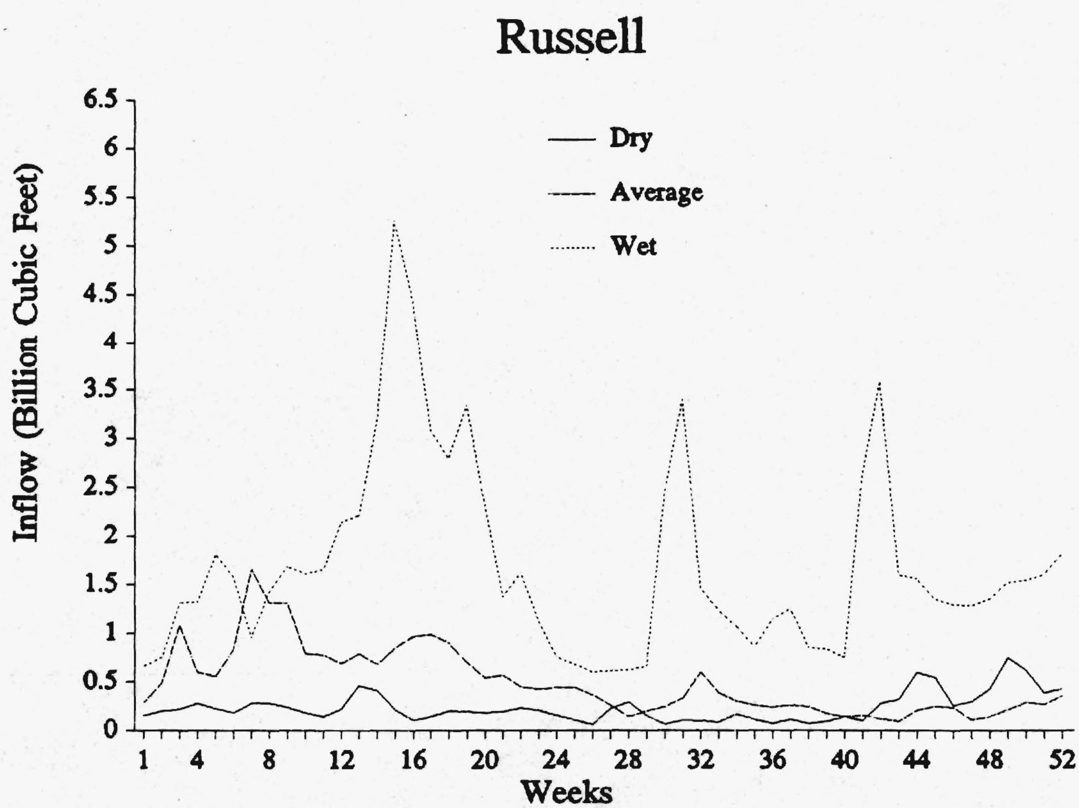


Figure 5: Russell Inflow Range

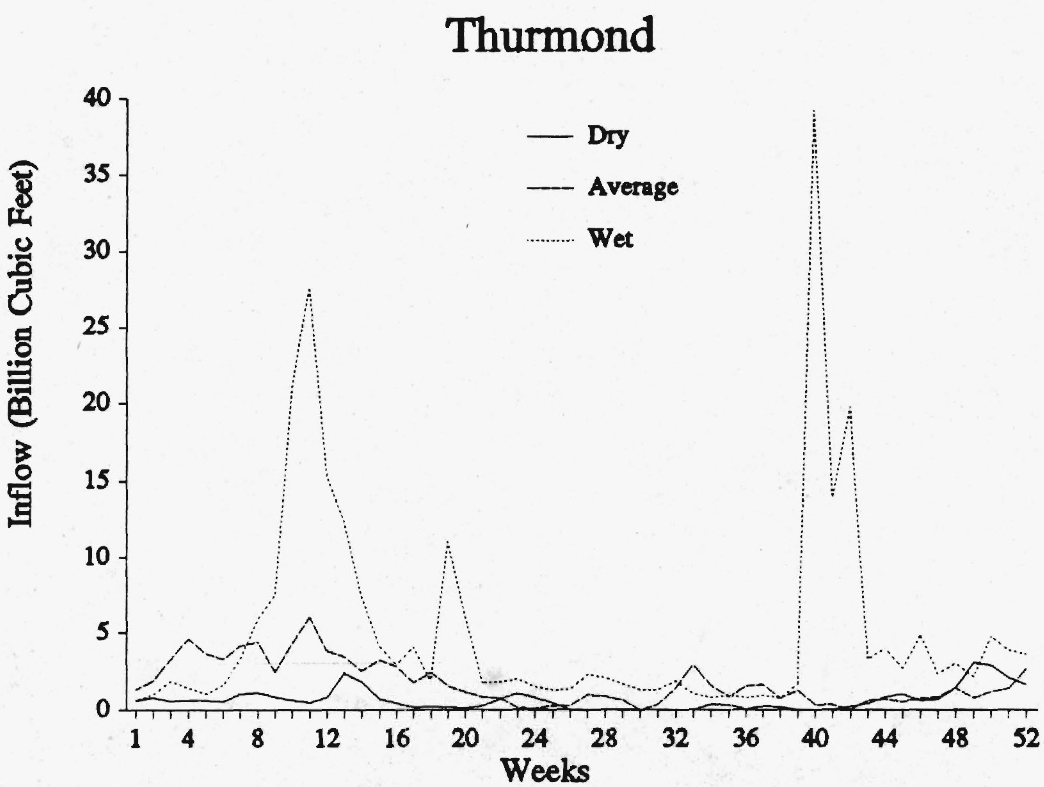


Figure 6: Thurmond Inflow Range

3.2 Control Module I

The optimization scheme includes two control modules designed to efficiently handle all system operational objectives and constraints. The control tasks are divided as follows: Module I optimizes system performance over time and handles energy generation targets, minimum generation requirements, storage balancing directives, and total outflow constraints. Module II handles constraints and targets of instantaneous quantities such as power generation (MW) and release (cfs). The two modules periodically exchange information to ensure long and short term operational consistency. This new control design has been motivated by the idiosyncracies of the Savannah reservoir system but it can be adapted for other systems as well. The following sections describe the elements of the control problem and outline an optimization algorithm for its solution.

3.2.1 System Dynamics

The dynamics of the Savannah reservoir system can be described by water balance relationships. The significance of the symbols used is explained below:

$$
\begin{aligned}
S_H(k+1) &= S_H(k) - B_H(k)\, t_H(k) + w_H(k) \\
B_H(k) &= \pi_1 \sum_{i=1}^{n_H} \xi_H(i,k)\, u_H(i,k) \\[1em]
S_R(k+1) &= S_R(k) + B_H(k)\, t_H(k) - B_R(k)\, t_R(k) + w_R(k) \\
B_R(k) &= \pi_1 \sum_{i=1}^{n_R} \xi_R(i,k)\, u_R(i,k) \\[1em]
S_T(k+1) &= S_T(k) + B_R(k)\, t_R(k) - B_T(k)\, t_T(k) + w_T(k) - C_T(k) \\
B_T(k) &= \pi_1 \sum_{i=1}^{n_T} \xi_T(i,k)\, u_T(i,k) \\
C_T(k) &= \pi_2 \sum_{i=8}^{9} \xi_T(i,k)\, u_T(i,k)
\end{aligned}
\qquad (1)
$$

$S_J(k)$: storage volume [billion cubic feet--bcf] of reservoir J at the beginning of time period k; J may be H, R, or T, representing Hartwell, Russell, or Thurmond respectively;

$t_J(k)$: generation times [hours] for the hydroelectric plant at reservoir J during time period k;

$w_J(k)$: local inflow volume [bcf] in reservoir J during time period k, known by its statistical moments (mean, variance, and perhaps skewness);

$u_J(i,k)$: discharge [cfs] through turbine $i = 1,2,...,n_J$, during time period k; n_J denotes the number of turbines in reservoir J ($n_H = 5$, $n_R = 4$, and $n_T = 9$);

$\xi_J(i,k)$: turbine status index signifying outage ($\xi = 0$) or fully operational condition ($\xi = 1$);

π_1, π_2: unit conversion factors.

Turbines 8 and 9 of Thurmond are small service units and are used to supply electricity to the power plant. They are operated independently of the main turbines. Coefficient π_1 converts units of discharge [cfs] to units of storage [bcf] per hour; namely, $\pi_1 = 60x60/10^9$. Coefficient π_2 converts units of discharge [cfs] to units of storage [bcf] per time period k; namely, if k represents a week and the service station units "run" continuously, $\pi_2 = 7x24x60x60/10^9$. Large flood events may necessitate the operation of the reservoir spillways. In such situations, the previous equations are modified to include spillway outflow.

Although the above equations appear linear, they are complicated by the dependence of turbine discharge on power levels and the net hydraulic head. The latter is the difference between forebay and tailwater elevations and is a nonlinear function of reservoir storage and outflow. These relationships were determined through regression analysis on existing data and are included along with their validity ranges and measures of accuracy in Appendix A. In the two-module control context, the turbine discharges are provided by Module II and the previous equations become linear. In matrix form, the system equations can be stated as follows (bold-face type denotes vector or matrix quantities:

$$\begin{bmatrix} S_H(k+1) \\ S_R(k+1) \\ S_T(k+1) \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} S_H(k) \\ S_R(k) \\ S_T(k) \end{bmatrix} + \begin{bmatrix} -B_H(k) & 0 & 0 \\ B_H(k) & -B_R(k) & 0 \\ 0 & B_R(k) & -B_T(k) \end{bmatrix} \begin{bmatrix} t_H(k) \\ t_R(k) \\ t_T(k) \end{bmatrix} + \begin{bmatrix} w_H(k) \\ w_R(k) \\ w_T(k) - C_T(k) \end{bmatrix} \quad (2)$$

$$= \boldsymbol{A}\,\boldsymbol{S}(k) + \boldsymbol{B}(k)\,\boldsymbol{t}(k) + \boldsymbol{w}(k),$$

$$k = 0,1,\ldots,N-1.$$

System model (1) is a central component of the control scheme. It describes the changes in the variables to be controlled (storages) in response to the controllable and uncontrollable inputs (generation times, turbine discharges, and inflows). The purpose of the control modules I and II is to seek out the most desirable operational scenarios.

3.2.2 Performance Index and Constraints

The performance index quantifies the system response to various operational policies. It is usually a function of actual system outputs such as energy generation and reservoir levels. The performance index chosen for the control problem in module I is as follows:

$$J = E\{\sum_{k=0}^{N-1} \alpha(k)[E^*(k) - t_H(k)\,P_H(k) - t_R(k)\,P_R(k) - t_T(k)\,P_T(k)]^2$$

$$+ \beta_H(k)[H_H(S_H(k)) - H_H^*(k)]^2 + \beta_R(k)[H_R(S_R(k)) - H_R^*(k)]^2 + \beta_T(k)[H_T(S_T(k)) - H_T^*(k)]^2$$

$$+ \beta_H(N)[H_H(S_H(N)) - H_H^*(N)]^2 + \beta_R(N)[H_R(S_R(N)) - H_R^*(N)]^2 + \beta_T(N)[H_T(S_T(N)) - H_T^*(N)]^2\},$$

(3)

where

E{ }:	represents expectation of the random quantities in the braces;
$E^*(k)$:	is an energy target to be met by all reservoirs collectively, [MWH];
$P_J(k)$:	is the power generation at reservoir J, J=H,R,T, [MW];
$t_J(k)$:	is the generation time at reservoir J, [HRS];
$H_J(S_J(k))$:	is the elevation versus storage relationship of reservoir J (Appendix A), [FT];
$H_J^*(k)$:	is a target elevation for reservoir J, [FT];
$\alpha(k)$:	is a weight used to place preferences between energy generation and other objectives;
$\beta_J(k)$:	are weights used to equalize or differentiate reservoir drawdowns;
k:	denotes time period, [Week], [Day], or [4-HRS]; and
N:	is the control horizon.

The optimization problem consists of finding the generation time sequences $\{t_H(k), t_R(k), t_T(k),\ k=0,1,\ldots,N-1\}$ which minimize J subject to the system equations of the previous section and the following constraints:

$$
\begin{aligned}
& t_J^{\min}(k) \le t_J(k) \le t_J^{\max}(k), \\
& J = H,R,T, \qquad\qquad (4) \\
& k = 0,1,\dots,N-1.
\end{aligned}
$$

In this module, the power generation levels $P_J(k)$ are provided by Module II and are considered fixed quantities. During the Module I solution process, Module II is invoked periodically and updates these values.

The performance index includes two different types of terms. The first encourages meeting the energy targets $E^*(k)$ (depicted on Figure 3), while the second drives reservoir levels in the proximity of the target levels $H_J^*(k)$. The target levels are indicators of normal, drought, or flood conditions and correspond to the lines shown on Figure 4. The last line in each reservoir represents the bottom of the conservation pool while the first represents the top of the flood control pool. The second line in each graph represents reservoir levels recommended by the rule curve. The lines divide reservoir storage in four regions denoted I, II, III, and IV. During normal conditions, reservoir levels are in regions II and III; during droughts, reservoir levels fall in regions III and IV; while during floods reservoir levels rise into regions II or I. The control problem formulated in this section includes several parameters which can be tuned to the specific operational requirements of each region. This and other issues are explained in the following subsections. Indepedently of the specific parameter values, the control problem is solved using the optimization algorithm detailed in Appendix B.

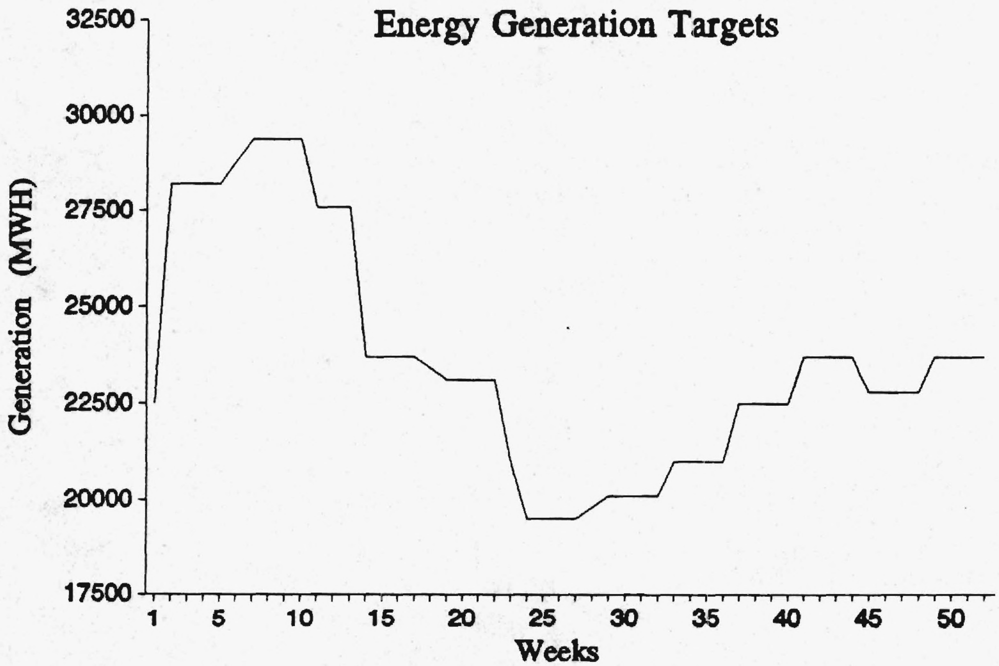


Figure 7: Energy Generation Targets

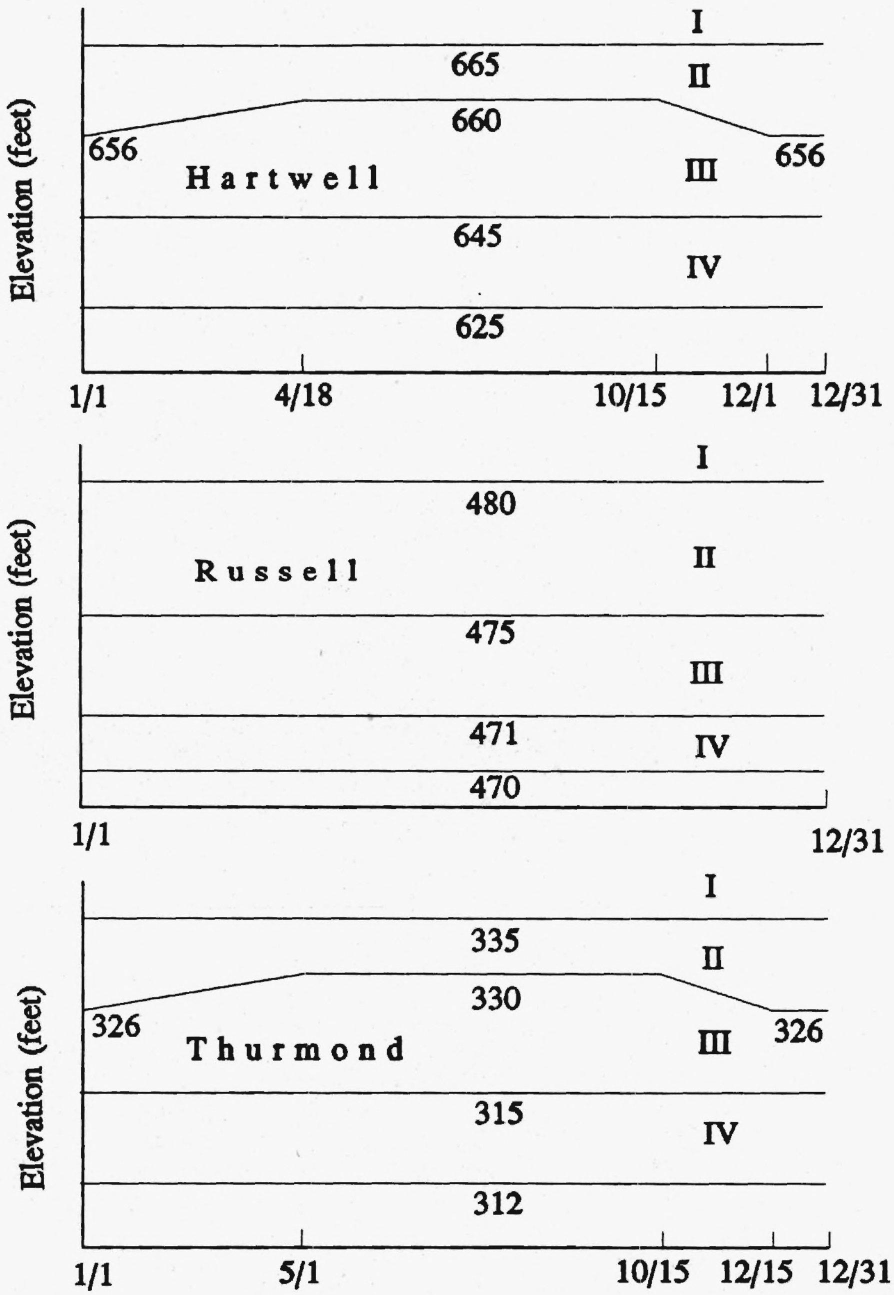


Figure 8: Target Reservoir Levels (Not to Scale)

3.2.3 Normal Operation

The normal mode of operation is associated with regions II and III and proceeds in weekly time intervals. During normal conditions, the decision is whether to prioritize energy generation over flood control, storage conservation, and recreation requirements. The second set of objectives can be reflected by the deviations of the reservoir levels from the target sequences prescribed by the rule curve. This tradeoff can be quantified by varying coefficient α relative to coefficients β (in the Performance Index) and performing a series of optimization runs to identify the generation time sequences associated with each priority level. Both sets of coefficients are assumed time invariant ($\alpha(k)=\alpha$, $\beta_J(k)=\beta_J$, for all k and J). If {E(k) and $H_J(k)$, J=H,R,T, k=0,...,N} denote the resulting optimal energy and reservoir elevation sequences for a particular set of priorities, the tradeoff can be presented in terms of the following quantities:

$$E^{norm}(\alpha,\beta) = \frac{\sqrt{\sum_{k=0}^{N-1}[E^*(k)-E(k)]^2}}{N-1}$$

$$H^{norm}(\alpha,\beta) = \frac{\sqrt{\sum_{J=H,R,T}\sum_{k=0}^{N-1}[H_J^*(k)-H_J(k)]^2}}{N}, \tag{5}$$

where E^{norm} and H^{norm} quantify the deviations of the mean energy generation and reservoir elevations from their respective targets. One may also generate more detailed tradeoff statistics such as the maximum positive deviation over the control horizon, the average positive deviation over the control horizon, the maximum negative deviation over the control horizon, and the average negative deviation over the control horizon.

Each tradeoff point (optimization run) is subject to operational constraints. These constraints and their modeling within the framework presented is discussed next.

1. A minimum energy generation requirement of two hours daily, except weekends, for each reservoir is mandated in the energy contracts. This requirement corresponds to 10 hours per week and is modelled as the lower bound $t_J^{min}(k)$ in Equation (4).

2. A minimum weekly outflow rate of 5800 cfs from Thurmond must also be enforced for such downstream uses as water supply, water quality, and fish and wild life preservation. For the benefit of hydropower, this outflow volume is released during the peak generation hours which include the period between 7:00 to 22:00 hours, Monday through Friday. (Weekends are off-peak generation periods.) Outflow is then re-regulated at the storage impoundments below Thurmond to a temporally more uniform pattern. This requirement can also be expressed through the lower bound $t_T^{min}(k)$ in Equation (4):
where ξ and u represent turbine availability and discharge (as in Equation (1)), the number

3.2.4 Drought Operation

Drought operation is associated with regions III and IV and is also scheduled in weekly time intervals. Droughts are stressfull periods for reservoir systems. The critical issue is how to stage outflow reductions, if any, without undully taxing downstream users (water supply and wild life and fish preservation) or upstream interests (energy generation and recreation). This tradeoff can be generated by varying the minimum weekly outflow rate and recording the changes in energy generation and lowest pool levels. To account for future uncertainty, outflow reductions can be staged from a maximum to a minimum level (e.g., 5800 to 3600 cfs) using the following or a similar expression:

$$Q_T^{min}(k) = (F^{max} - F^{min})\theta^k + F^{min}, \quad k = 0,1,...,N-1, \tag{7}$$

where Q_T^{min} is the weekly average release from Thurmond, F^{max} and F^{min} are the outflow rate bounds, and θ is a parameter which can be varied from one to zero causing the average (over the control horizon) outflow rate to change from F^{max} to F^{min}. For each value of Q_T^{min}, the minimum generation hours necessary to realize this outflow rate can be determined as in the previous section (Equation (6)).

The general features of the drought model component are similar to those for normal operation of the previous section. Namely, there exists a two-hour minimum generation requirement daily, and reservoir drawdowns should comply with the storage balancing constraint. This mode is additionally designed to handle situations where the reservoirs are drawn into region IV (below the balancing storage ranges of 660-645, 475-471, and 330-315 feet). On such occasions, Hartwell has still another 20 feet of conservation storage remaining and provides most of the water supply, while Russell and Thurmond are drawn down to 470 and 312 feet respectively. During refiling, the process is reversed. Hartwell fills up faster than the other two projects until all three reach the levels of 645, 471, and 315. Thereafter they adhere to the balancing constraint and refill proportionally. The model accomplishes this operation through adjustment of the target values $H_J^*(k)$ in the performance index and appropriate calibration of the coefficients β_J, J=H,R,T. More specifically, in region IV, $H_J^*(k)$ are set equal to 645, 471 and 315 respectively for J=H,R,T, and the magnitude of the coefficient β_J is highest for J=R and lowest for J=H. If the reservoirs rise back into region III, these parameters are changed to the values for normal operation.

3.2.5 Flood Operation

The flood operation mode should be activated when the reservoirs rise into regions II or I. Region II is similar to regions III and IV except that reservoir levels exhibit rapid variations due to higher inflow and release rates. Rapid variations may invalidate a weekly model, and, therefore, the control time scale in this operational mode and region is one day. Region I is quite different from any other region due to uncontrolled spillway outflows when reservoir levels exceed 665 feet (Hartwell), 480 feet (Russell), and 335 feet (Thurmond). Such releases are unavoidable due to the spillway design prohibiting outflow over the gate top. As reservoir levels rise above the previous thresholds and spillway gates are necessarily raised, water begins to flow through the opening created between the gate bottom and the spillway sill. Spillway outflow can be much higher than turbine releases and necessitates an even finer time scale. Thus, when reservoirs rise into region I, the model operates in 4-hour time intervals. Spillway outflow can be related to reservoir level as reported in Appendix A.

During flood events, the objective is to avoid damage-causing outflows while containing reservoir storage within the flood control pool (region II). However, this may not always be possible and the system operator should carefully weigh the benefit of maintaining current discharge levels versus the risk of being forced to release excessively later (region I). This tradeoff can be explored by examining the potential effects of various maximum release bounds. Flood control operations in region II are modelled as before by Equations (1) (system dynamics), (3) (performance index), and (4) (constraints). The requirement of storage balancing is desirable during the filling process and is also enforced via appropriate calibration of the performance index parameters. The evacuation of the flood waters is effected for the downstream reservoir first. The maximum release bound being varied refers to instantaneous discharge and mainly affects module II. Module II computes the turbine generation and discharge necessary to accomplish a specific release bound and returns these characteristics to module I. Spillway operation is not invoked even if power capacity cannot realize the specified discharge level. On such occasions, the facility operates at full power.

In region I, reservoir dynamics must include spillway outflow. One may proceed by explicitly including the associated terms in the system equations (1) and accordingly modify the optimization routines (for nonlinear effects). An alternate route would be to model spillway outflow through adjustment of the generation bounds, $t_T^{min}(k)$ and $t_T^{max}(k)$. This is the approach adopted herein because is simpler and can be implemented within the previous model framework with minimal additional programming and run-time memory requirements. Let

$$Q_J(k) = \sum_{i=1}^{n_J} u_J(i,k) \tag{8}$$

be the total turbine discharge at reservoir J and $R_J^{min}(k)$ and $R_J^{max}(k)$ be the minimum and maximum spillway outflow rates. These rates are determined based on the mean reservoir storage and the relationships provided in Appendix A. Consider the following adjustment of the generation bounds:

$$
\begin{aligned}
t_J^{\min}(k) &= \frac{\Delta t\left(Q_J(k) + R_J^{\min}(k)\right)}{Q_J(k)} \\
t_J^{\max}(k) &= \frac{\Delta t\left(Q_J(k) + R_J^{\max}(k)\right)}{Q_J(k)},
\end{aligned}
\tag{9}
$$

where Δt is the time discretization interval (4 hours). The above expressions establish a control variable range such that the model formulated earlier (outflow through turbines only) can also account for spillway flow. It is noted that in this case, the generation time bounds exceed the physical Δt duration. In the interest of energy generation, when the reservoirs are in region I, the turbines run at full power.

3.3 Control Module II

The purpose of the second optimization module is to determine the turbine power and discharge levels that meet established power contracts and various outflow constraints for each period of the control horizon. For the solution of this problem, Module II is provided with the mean storage sequences computed by Module I. The problem formulation and solution method is presented using the following notation:

u_{ij}: discharge [cfs] of turbine j, $j=1,\ldots, n_i$, at reservoir i, i=H,R,T (Hartwell, Russell, and Thurmond);

P_{ij}: power [MW] of turbine j at reservoir i;

P_i^*: power target [MW] for reservoir i; and

U_i^*: maximum outflow rate [cfs] for reservoir i.

With these definitions, the objective is to find $\{P_{ij}$ and u_{ij}, $i=H,R,T$, $j=1,\ldots, n_i\}$ such that

$$\begin{aligned} &\sum_{j=1}^{n_i} P_{ij} = P_i^* , \\ &\sum_{j=1}^{n_i} u_{ij} \leq U_i^* , \\ &\sum_{j=1}^{n_i} u_{ij} \quad minimum . \end{aligned} \tag{10}$$

It is noted that the previous statements imply maximization of hydroelectric plant efficiency by generating a desired power target with the least outflow. An equivalent objective would be to attain the power target observing the outflow constraint and maximizing plant efficiency, η, defined as

$$\eta = \frac{\sum_{j=1}^{n_i} P_{ij}}{c\, H_n \sum_{j=1}^{n_i} u_{ij}} \tag{11}$$

where H_{in} is the net hydraulic head and c is a numerical constant. If the outflow constraint is binding and prevents the generation of the power target, plant efficiency can be maximized by maximizing power production.

It is noted that the problems for the individual reservoirs are not coupled. Thus, to facilitate the notation, subscript i will hereafter be omitted. As indicated in Appendix A, turbine discharge is related to power through

$$u_j = a_j\left(\frac{P_j}{H_n}\right)^2 + b_j\left(\frac{P_j}{H_n}\right) + c_j, \tag{12}$$

where u is in cfs, P in MW, H_n feet, and {a,b,c} are coefficients specific to each turbine.

The previous discussion summarizes the objectives of Module II. To achieve these objectives, Module II formulates and solves the following optimal control problem for each hydroelectric plant:

$$\begin{aligned}
&J = \alpha(X_{n_i+1} - P^*)^2 + \beta(Y_{n_i+1} - U^*)^2 \\
&\textit{subject to } X_{j+1} = X_j + P_j,\ \ j = 1,\dots,n_i,\ \ X_1 = 0, \\
&\qquad Y_{j+1} = Y_j + \frac{a_j}{H_n^2}P_j^2 + \frac{b_j}{H_n}P_j + c_j,\ \ j = 1,\dots,n_i,\ \ Y_1 = 0, \\
&\qquad P_j^{\min} \le P_j \le P_j^{\max},\ \ j = 1,\dots,n_i,
\end{aligned} \tag{13}$$

where α and β are coefficients weighing the two performance index terms. In the above formulation, the individual turbine power levels constitute the control variables and the cumulative turbine discharges and power levels constitute the state variables. The performance index minimizes the square deviations of the total plant outflow and power generation from the respective targets. Adjusting the values of α, β, P^*, and U^*, one can use Problem 5 to accomplish various power generation objectives including those stated earlier.

1. When $\alpha >> \beta$ and U^* is set equal to a small value, the solution to Problem 5 yields P_js that accomplish the overall power target P^* while minimizing outflow.

2. When $\alpha << \beta$ and P^* is set equal to a large value, the solution maximizes power generation while assuring that outflow equals U^*.

In this work, Module II is programmed to first solve Case 1. If the resulting total outflow (Y_{n_i+1}) exceeds the maximum allowable rate, then Case 2 is solved and yields the optimal power and discharge levels. The solution algorithm is based on the Projected Newton Method and is fully detailed in Appendix C.

4. CASE STUDIES

This section describes four case studies pertaining to normal, drought, moderate flood, and large flood operation conditions. The purpose is to provide additional insight in the control scheme by presenting and interpreting results from typical operational scenarios. The reader is also referred to the User's Manual for a detailed description of the associated computer software [*Georgakakos, 1991*].

4.1 Normal Operation

The input parameters for the first case study are reported below:

Table 2: Normal Operation Case Study: Input Parameters

Parameter	Entry
Starting Date:	03 11 1991 Monday
Initial Lake Elev. (Feet):	658.58 (H), 475.00 (R), 328.30 (T)
Operational Mode:	Normal
Control Horizon (Weeks):	20
Turbine Outages:	Russell, Unit 2, 06/01/91 through 06/30/91
Turbine Overload (%):	15 (Hartwell), 15 (Russell), 15 (Thurmond)
Energy Targets:	Figure 7, Section 3.2.2
Reservoir Level Targets:	Figure 8, Section 3.2.2
Inflow Forecasting:	Historical Inflow Statistics
Reliability Level (%):	95
Min. Weekly Outflow (cfs):	5,800
Maximum Discharge (cfs):	30,000
Number of Tradeoff Points:	8

The turbine overload is determined with respect to the nominal unit capacity and represents the maximum allowable power level. Inflow forecasting is based on the historical inflow means, variances, and skewnesses for each calendar week of the control horizon. The minimum allowable weekly outflow from Thurmond is an operational constraint discussed in Section 3.2.3. The maximum allowable discharge represents the upper bound of the instantaneous outflow rates.

Figure 9 depicts the normal operation tradeoff. The tradeoff is illustrated in terms of the deviations from the mean energy generation and reservoir elevation targets (Section 3.2.3). The tradeoff curve essentially summarizes the effects of potential operational policies. Each point is optimal in the sense that there does not exist any control policy able to reduce either deviation without increasing the other. Equivalently, there cannot be any points inside the triangular shape defined by the curve and the horizontal and vertical axis. The tradeoff indicates that there exist operational policies able to track the reservoir elevation targets (point of intersection with the horizontal axis), or track the energy targets (point of intersection with the vertical axis), or attain some compromise between these two

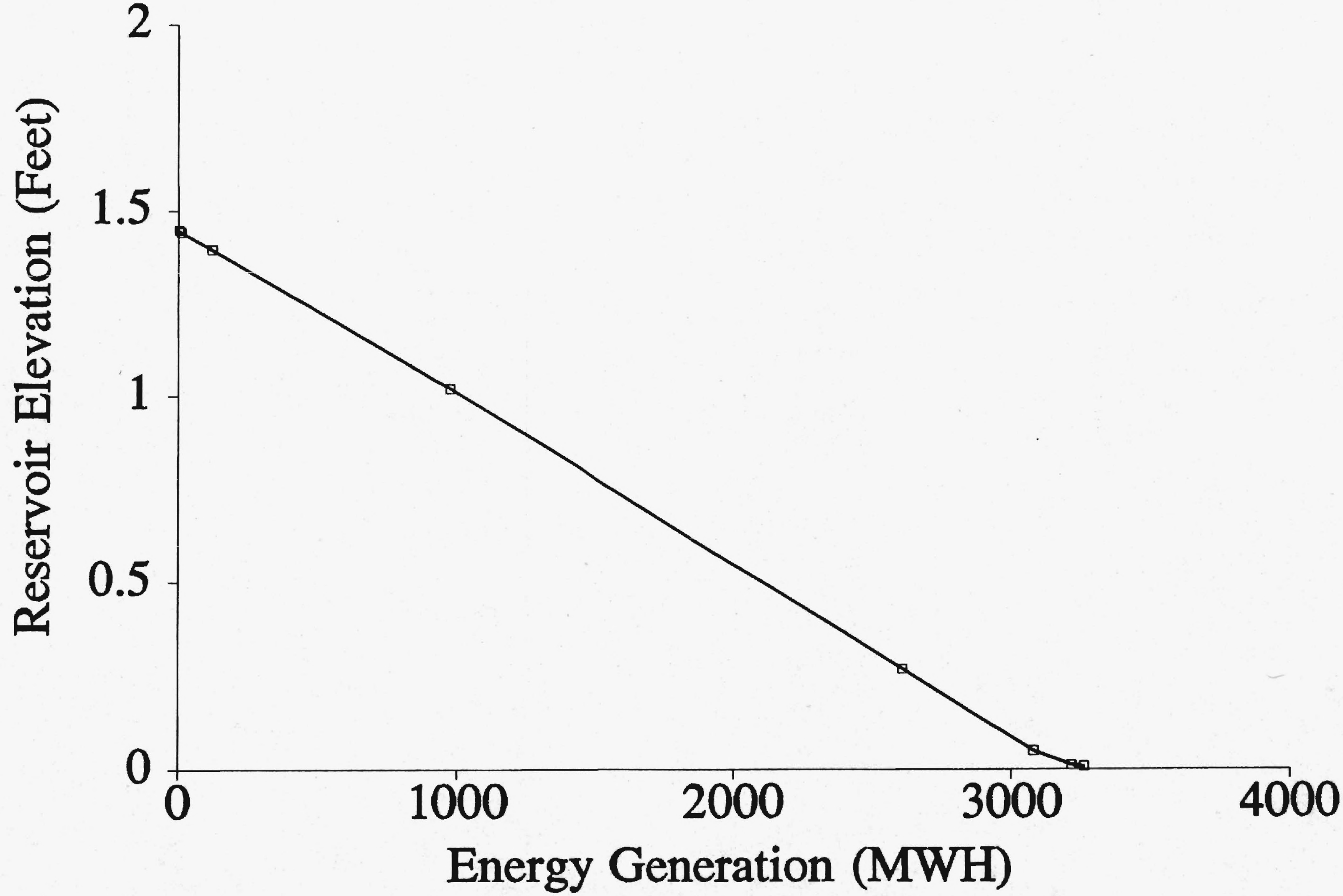


Figure 9: Normal Operation Tradeoff

extremes. Since all tradeoff points are optimal depending on the relative priorities among the system objectives, the curve is not suggestive of any particular point. It is the function of the operating authority to review this information and decide which is the most desirable operational point.

To this end, it may be helpful to examine the reservoir generation and elevation sequences associated with various tradeoff points. Figure 10 depicts these sequences for the case where full priority is placed on minimizing deviations from the elevation targets. The reservoir elevation graphs include the four characteristic levels discussed in Section 3.2.2 (Figure 8), mean elevation sequence (thicker line), and the associated 95% probability bands. In this case where the priority is to attain the elevation targets, the mean elevation sequences exactly coincide with their respective targets. The widths of the elevation probability bands change depending on the inflow statistics and the objective priorities. The probability bands indicate the elevation ranges where the system reservoirs are expected to be contained at 95% reliability if they are operated according to the recommendations made by the method. The Figure also shows the optimal generation sequences (thicker line) along with their upper and lower bounds. As explained in Section 3.2.3, the lower generation bounds reflect a two-hour daily generation requirement (except weekends) and a minimum weekly outflow rate of 5,800 cfs from Thurmond. Other sequences may also be examined to gain insight on the impacts of different operational priorities associated with other tradeoff points.

Detailed information on turbine characteristics is also available for each week of the control horizon. A sample for the 12th week is included as Table 3. The table reports the beginning-of-the-week storage (bcf) and elevation (ft) along with their associated probability bands. The mean inflow in (cfs) is also recorded followed by several turbine data: Peak turbine power (MW) and outflow (cfs), peak and off-peak generation times (hrs), total peak and off-peak energy generation (MWH), total power output (MW), actual turbine outflow (cfs), and spillway outflow (cfs). The distinction of "peak" and "off-peak" power made herein is based on a 15 hour peak power demand period (7:00 to 22:00 hours), Monday through Friday. Weekends are off-peak periods. Turbine power and discharge levels are determined by the optimization procedures of Module II (Section 3.3). The minimum and maximum release requirements are always met. For instance, Thurmond does not meet its power target of 322 MW (=40 x 7 x 1.15) because the total outflow discharge would have exceeded 30,000 cfs. Instead, discharge is constrained at 30,000 cfs, and turbine power levels are found such that overall plant power production is maximized. If, due to outage schedules, some of the turbines are inoperative (as in the case of Russell), the other turbines must pick up as much of the power deficit as possible and are likely to use up all of their capacity and operate longer. This output file also includes the characteristics of the two small service station units at Thurmond. It is assumed that one of these units will at any time be operative at the 1 MW power level. The minimum weekly outflow requirement of 5800 cfs from Thurmond is satisfied as the following computation indicates: (29998.64 x 40.52 + 104.39 x 168) / 168 ≈ 7,340 cfs. After the most desirable operational point has been decided, this information can be used to schedule the turbine power generation and discharge rates for the first week of the control horizon. At the beginning of the next week, the procedure should be repeated with updated information on project inflows, water levels, and energy demands.

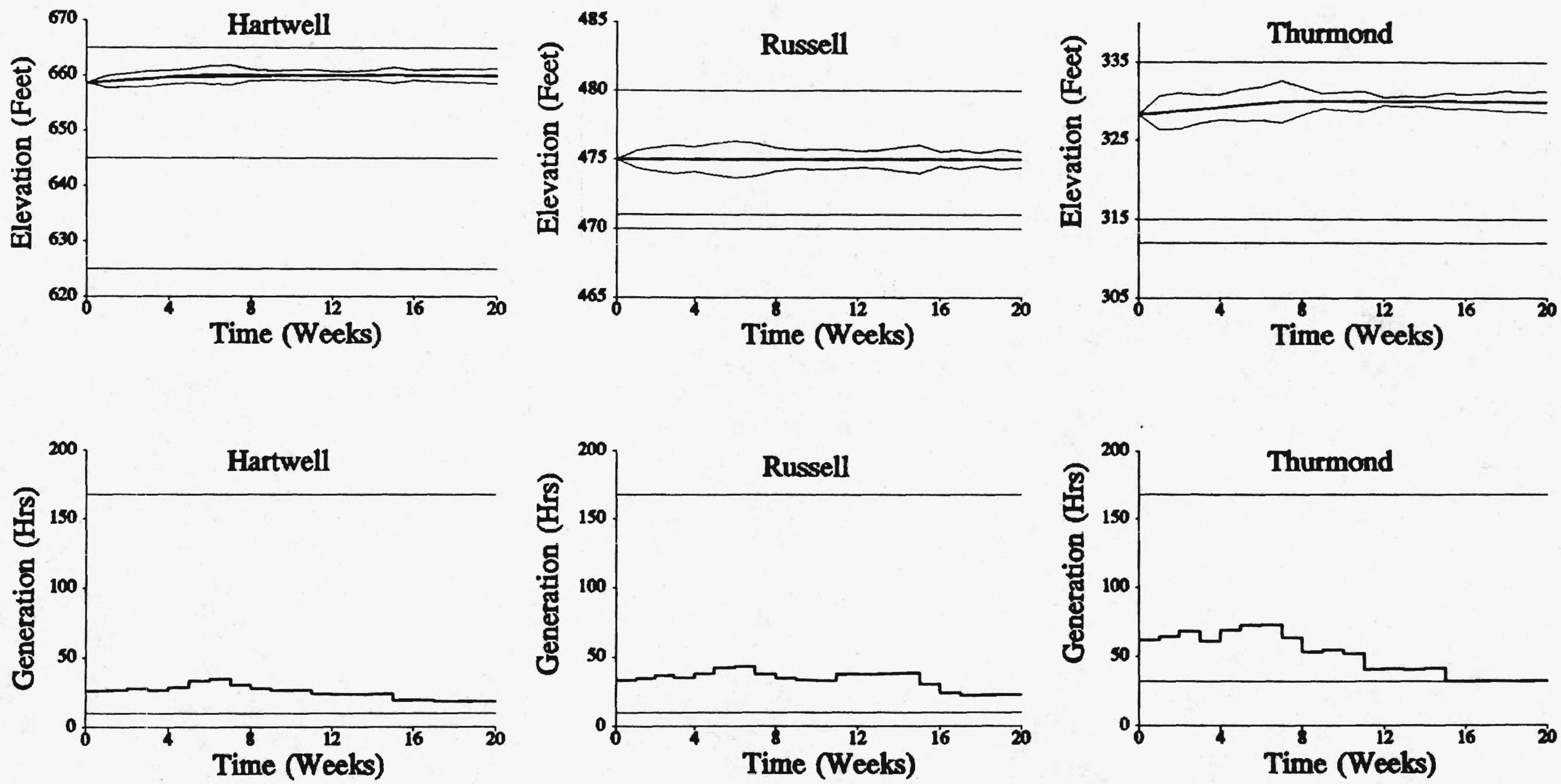


Figure 10: Reservoir Sequences for Normal Operation

Table 3: Normal Operation Case Study: Detailed Schedule Sample

WEEK 12
3/11/1991

HARTWELL

PERCENTILES:	5.00%	MEAN	95.00%
BEGINNING STORAGE (BCF):	108.61	111.06	113.54
ENDING STORAGE (BCF):	109.21	111.04	112.89
BEGINNING ELEVATION (FT):	658.99	660.01	661.01
ENDING ELEVATION (FT):	659.24	660.00	660.75

MEAN INFLOW (CFS): 4198.97

TURBINE NO.:	1	2	3	4	5
PEAK POWER (MW):	75.90	75.90	75.90	75.90	92.00
OUTFLOW (CFS):	5718.34	5718.34	5718.34	5718.34	6970.24

PEAK GENERATION (HRS):	23.79	OFF-PEAK GEN. (HRS):	0.00
PEAK ENERGY (MWH):	9411.32	OFF-PEAK ENERGY (MWH):	0.00
TOTAL POWER OUTPUT (MW):	395.60		
TURBINE OUTFLOW (CFS):	29843.58		
SPILLWAY OUTFLOW (CFS):	0.00		

RUSSELL

PERCENTILES:	5.00%	MEAN	95.00%
BEGINNING STORAGE (BCF):	43.89	44.70	45.53
ENDING STORAGE (BCF):	44.03	44.70	45.38
BEGINNING ELEVATION (FT):	474.29	475.00	475.71
ENDING ELEVATION (FT):	474.42	475.00	475.58

MEAN INFLOW (CFS): 992.49

TURBINE NO.:	1	2	3	4
TURBINE POWER (MW):	86.25	0.00	86.25	86.25
OUTFLOW (CFS):	7765.81	0.00	7765.81	7765.81

PEAK GENERATION (HRS):	37.64	OFF-PEAK GEN. (HRS):	0.00
PEAK ENERGY (MWH):	9740.34	OFF-PEAK ENERGY (MWH):	0.00
TOTAL POWER OUTPUT (MW):	258.75		
TURBINE OUTFLOW (CFS):	23297.44		
SPILLWAY OUTFLOW (CFS):	0.00		

THURMOND

PERCENTILES:	5.00%	MEAN	95.00%
BEGINNING STORAGE (BCF):	105.40	109.46	113.62
ENDING STORAGE (BCF):	107.86	109.46	111.07
BEGINNING ELEVATION (FT):	328.70	330.00	331.31
ENDING ELEVATION (FT):	329.49	330.00	330.51

MEAN INFLOW (CFS): 2108.43

TURBINE NO.:	1	2	3	4	5	6	7
TURBINE POWER (MW):	44.55	44.54	44.52	44.51	44.48	44.45	37.10
OUTFLOW (CFS):	4400.73	4399.45	4397.87	4395.83	4393.12	4389.28	3622.35
SERVICE UNITS (MW):	1.00	0.00					
OUTFLOW (CFS):	104.39	0.00					

PEAK GENERATION (HRS):	40.52	OFF-PEAK GEN. (HRS):	0.00
PEAK ENERGY (MWH):	12323.06	OFF-PEAK ENERGY (MWH):	0.00
TOTAL POWER OUTPUT (MW):	304.14		
TURBINE OUTFLOW (CFS):	29998.64		
SPILLWAY OUTFLOW (CFS):	0.00		

4.2 Drought Operation

The following parameters were used in the drought case study:

Table 4: Drought Operation Case Study: Input Parameters

Parameter	Entry
Starting Date:	08 19 1991 Monday
Initial Lake Elev. (Feet):	655.00 (H), 473.50 (R), 325.00 (T)
Operational Mode:	Drought
Control Horizon (Weeks):	20
Turbine Outages:	None
Turbine Overload (%):	25 (Hartwell), 25 (Russell), 25 (Thurmond)
Energy Targets:	Figure 7, Section 3.2.2
Reservoir Level Targets:	Figure 8, Section 3.2.2
Inflow Forecasting:	50% of worst drought sequence on record
Reliability Level (%):	Deterministic Analysis
Min. Outflow Range (cfs/wk):	3,600 to 5,800
Maximum Discharge (cfs):	30,000
Number of Tradeoff Points:	8

The minimum outflow range refers to minimum weekly outflow volumes released from Thurmond and specifies the range over which the tradeoff will be developed (Section 3.2.4).

Figure 11 depicts the drought operation tradeoffs. The figure includes four graphs quantifying the effects of Thurmond weekly outflow on average system energy generation and minimum reservoir levels over the 20-week control horizon. As seen by these graphs, the operating authority is faced with the tradeoff of early reservoir depletion versus a reduction of system outflow and energy generation. More specifically under the assumed hydrologic conditions, a Thurmond outflow reduction from 5,800 to 3,600 cfs is expected to cause a weekly average energy generation reduction from 22,642 to 13,620 MWH and a corresponding rise in minimum reservoir levels from 638.87 to 647.94 for Hartwell, 470.79 to 472.13 for Russell, and 314.30 to 318.07 for Thurmond. The decision of which is the best operating point depends on the value of maintaining higher reservoir levels in view of the necessary energy generation and system outflow reductions.

The reservoir sequences associated with the 5,800 cfs minimum weekly outflow are shown on Figure 12. The graphs demonstrate that reservoir storages adhere to the balancing constraint according to which reservoir drawdowns are equalized in Region III. Reservoir levels are expected to enter Region IV at the beginning of the 15th week. From that time onward, Hartwell, with still another 20 feet of conservation storage remaining, provides most of the water supply, while Russell and Thurmond are slowly drawn toward the bottom of their conservation storage (470 and 312 feet respectively). This operational change in Region IV shows up as a break in the tradeoff graphs. Although not demonstrated in this case study, Hartwell refills faster than the other two reservoirs until all three enter back into Region III. Thereafter, they adhere to the balancing constraint and refill proportionally.

A sample of more detailed turbine characteristics for the 17th week of the control horizon is shown in Table 5. At that time, the reservoirs are already in Region IV and Hartwell provides most of the required water (as can be seen by comparing the weekly drawdowns). The turbines do not operate at the specified 25% overload, because the 30,000 cfs maximum discharge constraint is more binding. Thus, turbine power levels are determined such that plant efficiency is maximized (as explained in Section 3.3). At Thurmond, this necessitates that two turbines be inoperative. The 5,800 cfs weekly average outflow from Thurmond is met as the following computation indicates: $(30{,}003.54 \times 31.83 + 115.45 \times 168) / 168 \approx 5{,}800$. All power is produced during the peak generation period.

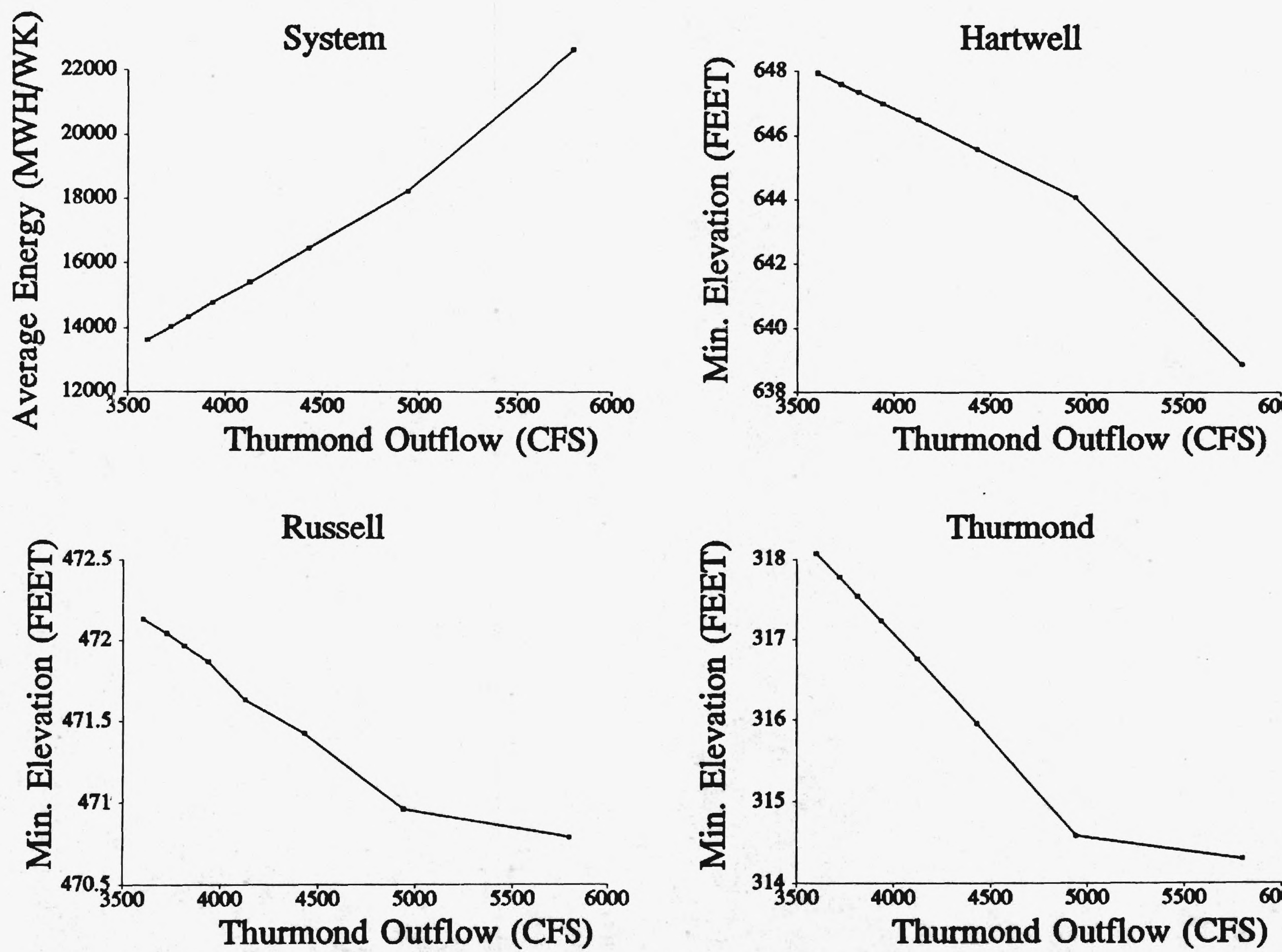
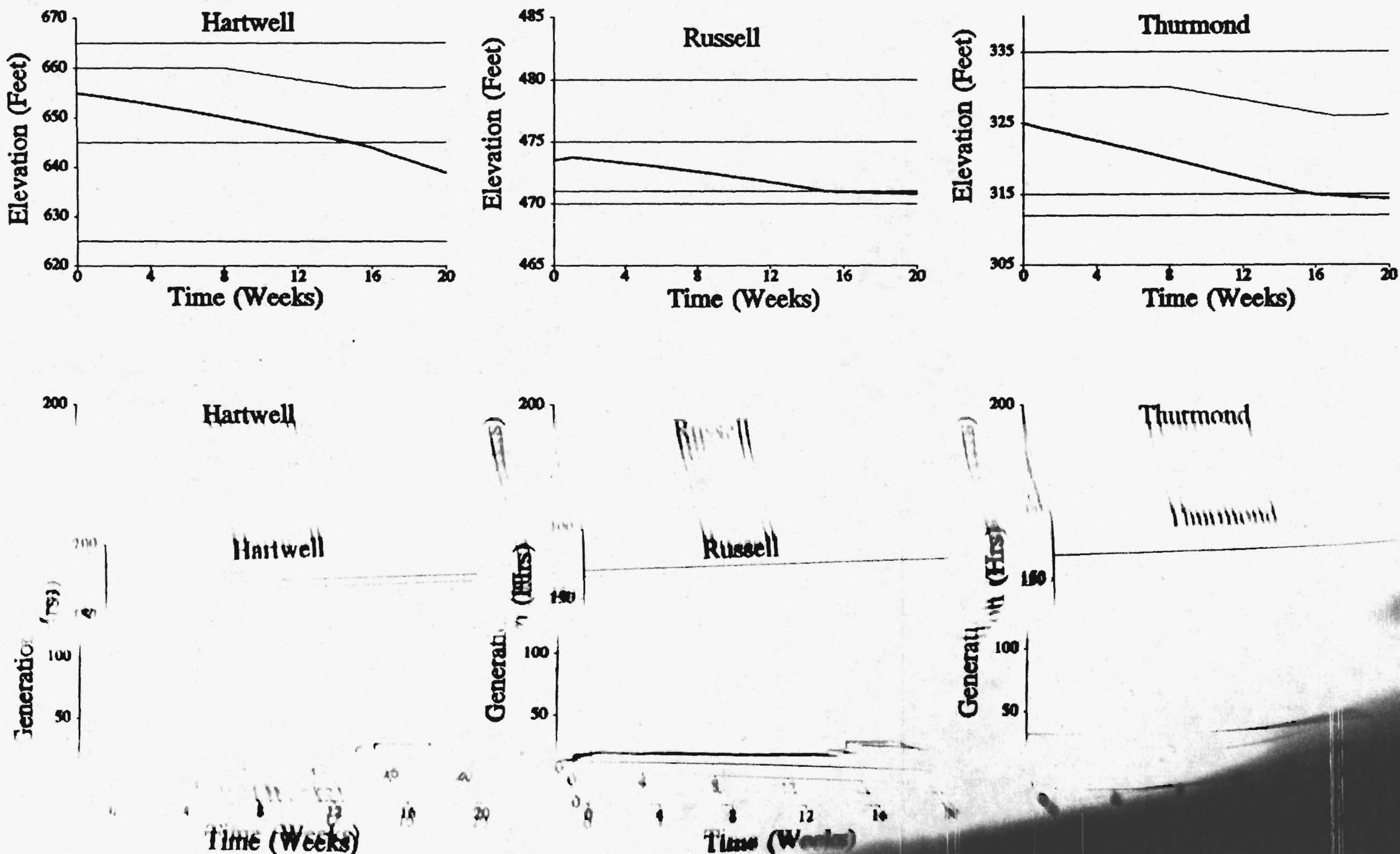


Figure 11: Drought Operation Tradeoffs



Hartwell
Russell
Thurmond
Elevation (Feet)
Time (Weeks)
Hartwell
Thurmond
Hartwell
Russell
Time (Weeks)

Table 5: Drought Operation Case Study: Detailed Schedule Sample

```
---------------------------  W E E K  17  --------------------------------
                              8/19/1991

  H A R T W E L L
  PERCENTILES:                  50.00%     MEAN      50.00%
  BEGINNING STORAGE (BCF):      77.33      77.33     77.33
  ENDING STORAGE (BCF):         75.02      75.02     75.02
  BEGINNING ELEVATION (FT):    643.93     643.93    643.93
  ENDING ELEVATION (FT):       642.62     642.62    642.62
  MEAN INFLOW (CFS):    1010.00
  TURBINE NO.:               1       2       3       4       5
  PEAK POWER (MW):       74.71   74.59   74.41   74.15   62.59
  OUTFLOW (CFS):       6236.37 6224.92 6208.81 6184.07 5145.04
  PEAK GENERATION (HRS):       27.00  OFF-PEAK GEN. (HRS):        0.00
  PEAK ENERGY (MWH):         9733.72  OFF-PEAK ENERGY (MWH):      0.00
  TOTAL POWER OUTPUT (MW):   360.46
  TURBINE OUTFLOW (CFS):   29999.20
  SPILLWAY OUTFLOW (CFS):      0.00

  R U S S E L L
  PERCENTILES:                  50.00%     MEAN      50.00%
  BEGINNING STORAGE (BCF):      40.20      40.20     40.20
  ENDING STORAGE (BCF):         40.16      40.16     40.16
  BEGINNING ELEVATION (FT):    470.97     470.97    470.97
  ENDING ELEVATION (FT):       470.92     470.92    470.92
  MEAN INFLOW (CFS):      54.00
  TURBINE NO.:               1       2       3       4
  TURBINE POWER (MW):    93.75   93.75   93.75   74.20
  OUTFLOW (CFS):       7845.43 7845.43 7845.43 6463.74
  PEAK GENERATION (HRS):       27.73  OFF-PEAK GEN. (HRS):        0.00
  PEAK ENERGY (MWH):         9856.69  OFF-PEAK ENERGY (MWH):      0.00
  TOTAL POWER OUTPUT (MW):   355.44
  TURBINE OUTFLOW (CFS):   30000.02
  SPILLWAY OUTFLOW (CFS):      0.00

  T H U R M O N D
  PERCENTILES:                  50.00%     MEAN      50.00%
  BEGINNING STORAGE (BCF):      69.47      69.47     69.47
  ENDING STORAGE (BCF):         69.16      69.16     69.16
  BEGINNING ELEVATION (FT):    314.89     314.89    314.89
  ENDING ELEVATION (FT):       314.74     314.74    314.74
  MEAN INFLOW (CFS):     331.00
  TURBINE NO.:               1       2       3       4       5        6        7
  TURBINE POWER (MW):    48.20   48.16   48.09   47.95   45.43     0.00     0.00
  OUTFLOW (CFS):       6170.72 6157.76 6137.24 6097.85 5439.97     0.00     0.00
  SERVICE UNITS (MW):     1.00    0.00
  OUTFLOW (CFS):        115.45    0.00
  PEAK GENERATION (HRS):       31.83  OFF-PEAK GEN. (HRS):        0.00
  PEAK ENERGY (MWH):         7569.86  OFF-PEAK ENERGY (MWH):      0.00
  TOTAL POWER OUTPUT (MW):   237.82
  TURBINE OUTFLOW (CFS):   30003.54
  SPILLWAY OUTFLOW (CFS):      0.00

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4.3 Moderate Flood Operation

This case study is representative of moderate floods where reservoir elevations do not exceed the top of the flood control pools (665, 480, and 335 feet respectively for Hartwell, Russell, and Thurmond). A case of large floods where reservoir elevations rise above the flood control pools and spillways become operative is described in the next section. This case study was performed with the following inputs:

Table 6: Moderate Flood Case Study: Input Parameters

Parameter	Entry
Starting Date:	03 25 1991 Monday
Initial Lake Elev. (Feet):	660.00 (H), 475.00 (R), 330.00 (T)
Operational Mode:	Flood
Control Horizon (Days):	20
Turbine Outages:	None
Turbine Overload (%):	25 (Hartwell), 25 (Russell), 25 (Thurmond)
Energy Targets:	Figure 7, Section 3.2.2
Reservoir Level Targets:	Figure 8, Section 3.2.2
Inflow Forecasting:	70% of hypothetical forecasts shown below
Reliability Level (%):	95
Min. Weekly Outflow (cfs):	5,800
Max. Discharge Range (cfs):	20,000 to 40,000
Number of Tradeoff Points:	8

hypothetical inflow forecasts used in this case study are shown in Figure 13. The ...sts are described by (1) the inflow level 100% likely to be exceeded, (2) the inflow ...50% likely to be exceeded, and (3) the inflow level 5% likely to be exceeded. The ...um discharge range specifies the tradeoff computation range.

Figure 14 depicts the resulting tradeoffs. The figure includes four graphs ...trating the effects of maximum discharge on average system energy generation ... per Day) and maximum reservoir levels over the 20-Day control horizon. As ..., energy generation increases with the discharge bound (a total increase of 8,207 ...er Day) but tapers off at 35,000 to 40,000 cfs where turbines reach their power ...n limit. Maximum reservoir elevation and maximum discharge are inversely ... A maximum discharge increase from 20,000 to 40,000 cfs causes a maximum ...elevation decrease from 664.43 to 661.51 feet at Hartwell, 479.41 to 476.09 feet at ...d 334.45 to 331.03 feet at Thurmond. Thus approximately, a 6,100 cfs discharge ...uses one foot elevation fall and a 2,500 MWH per Day reduction in energy ... The operating authority is again faced with the responsibility to evaluate the ...d intangible impacts of these tradeoffs and determine the most satisfying point ...

...reservoir ...quences associated with the 20,000 cfs maximum discharge are shown

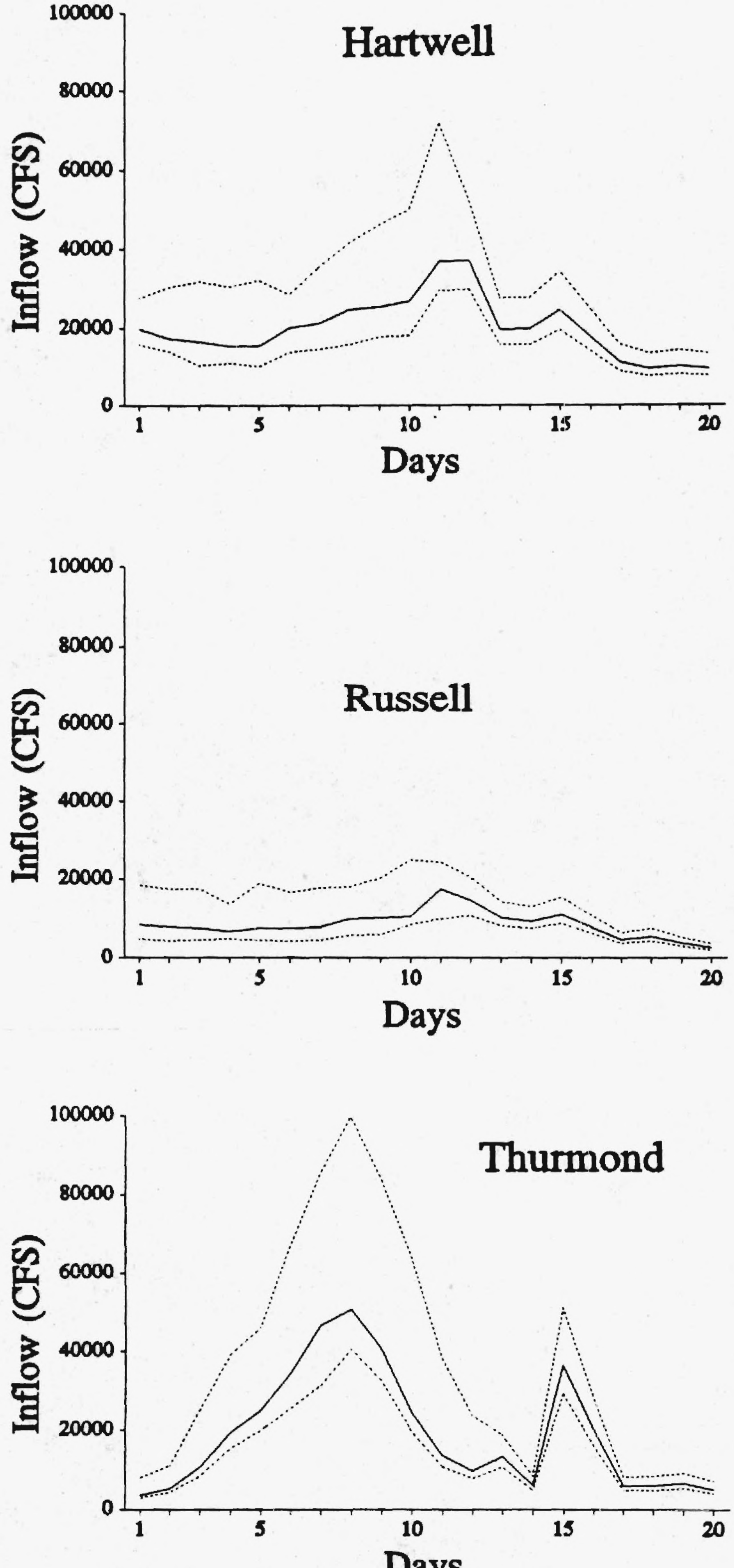

Figure 13: Inflow Forecasts for the Flood Operation Case Studies

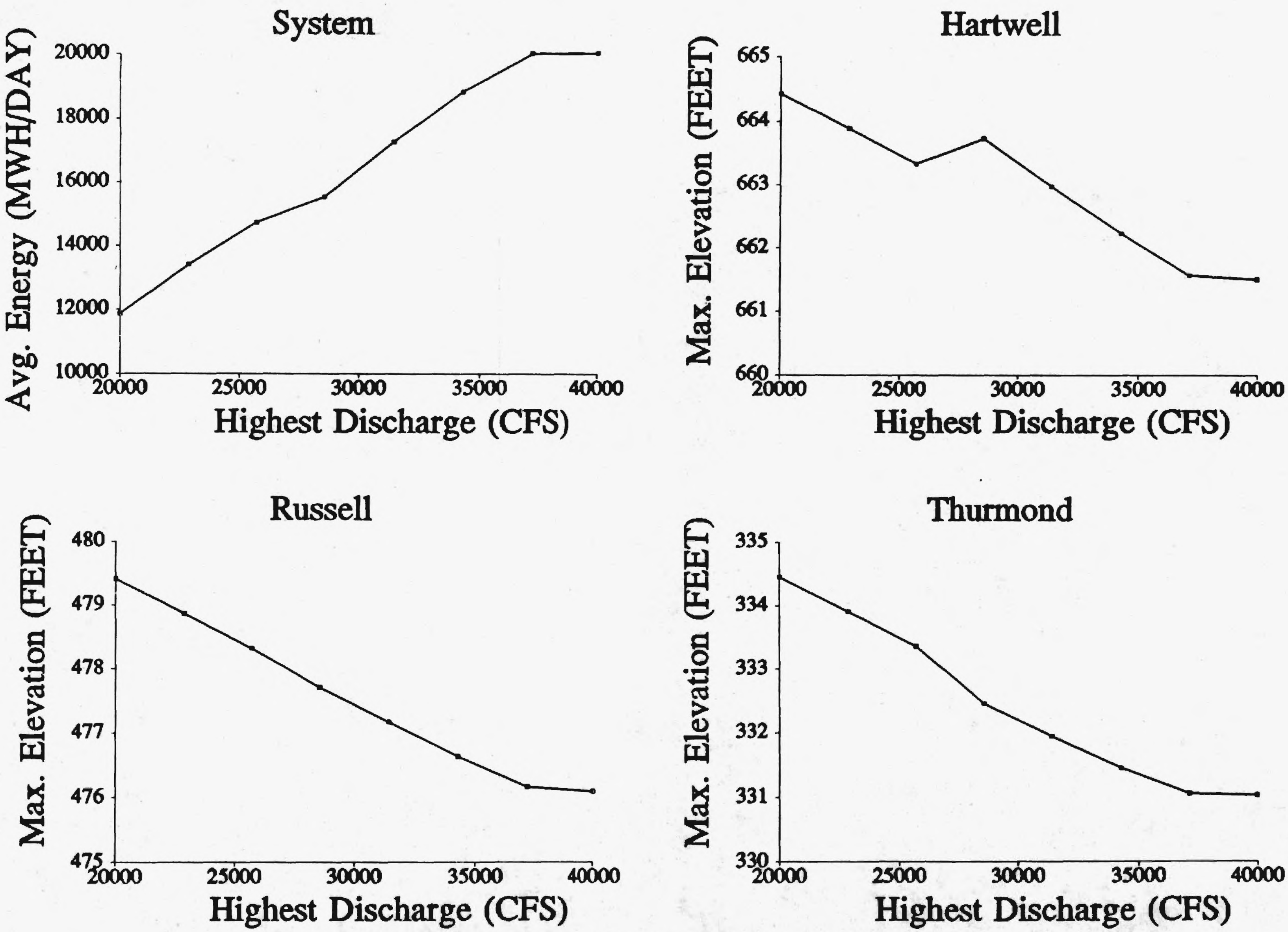

Figure 14: Moderate Flood Operation Tradeoffs

on Figure 15. The form of the graphs is similar to those for normal and drought operation except that the control variables are expressed in average daily outflow rates rather than in generation hours. (This change is primarily necessary for the large flood case where total outflow includes turbine and spillway flow.) The control scheme is able to contain reservoir levels within Region II. In this region, the control scheme is designed to accomplish the following operational objectives: (1) When reservoir levels rise, they rise equally above 660 (Hartwell), 475 (Russell), and 330 (Thurmond) feet. (2) As long as reservoir elevations are within the flood control pools (660-665, 475-480, and 330-335), the maximum downstream discharge is limited by either the discharge corresponding to the power capacity or the currently active maximum discharge constraint, whichever is less. Namely, within the flood control pools, spillways are not activated. (3) During falling reservoir levels, Thurmond is emptied faster than Russell, and Russell is emptied faster than Hartwell. As seen by these graphs, these objectives are accomplished by regulating the Hartwell and Russell outflow rates. Thurmond outflow is as high as possible.

A sample of more detailed turbine characteristics for the 12th day of the control horizon is shown in Table 7. All hydroelectric facilities operate for more than 15 hours and, therefore, also generate during the off-peak period. Due to the 20,000 cfs highest discharge limitation, some turbines are inoperative. The others are scheduled to generate power at maximum plant efficiency. The spillways are still not functional.

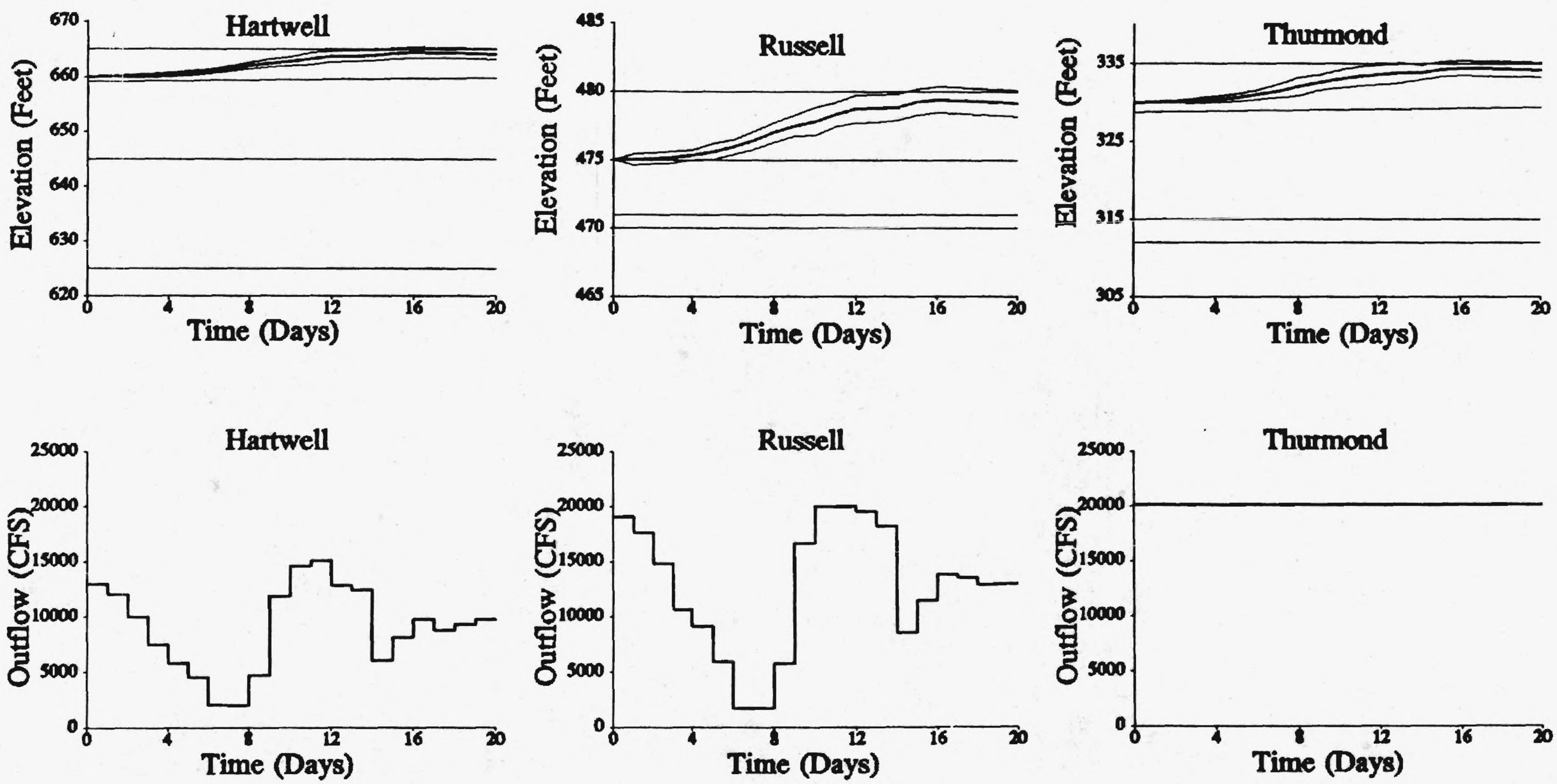

Figure 15: Reservoir Sequences for Moderate Flood Operation

Table 7: Moderate Flood Operation Case Study: Detailed Schedule Sample

```
---------------------------  D A Y   12  --------------------------------
                           4/ 5/1991 FRIDAY

 H A R T W E L L
 PERCENTILES:                      5.00%     MEAN      95.00%
 BEGINNING STORAGE (BCF):       116.67    119.48     122.33
 ENDING STORAGE (BCF):          117.96    120.53     123.13
 BEGINNING ELEVATION (FT):      662.26    663.35     664.45
 ENDING ELEVATION (FT):         662.76    663.76     664.75
 MEAN INFLOW (CFS):  27198.52
 TURBINE NO.:                 1         2         3         4         5
 PEAK POWER (MW):         67.15     67.19     67.26     75.98      0.00
 OUTFLOW (CFS):         5522.36   5510.89   5493.47   3473.29      0.00
 PEAK GENERATION (HRS):        15.00  OFF-PEAK GEN. (HRS):           3.09
 PEAK ENERGY (MWH):          4163.74  OFF-PEAK ENERGY (MWH):      857.86
 TOTAL POWER OUTPUT (MW):     277.58
 TURBINE OUTFLOW (CFS):     20000.02
 SPILLWAY OUTFLOW (CFS):        0.00

 R U S S E L L
 PERCENTILES:                      5.00%     MEAN      95.00%
 BEGINNING STORAGE (BCF):        47.64     48.71      49.80
 ENDING STORAGE (BCF):           48.00     49.21      50.44
 BEGINNING ELEVATION (FT):      477.47    478.34     479.21
 ENDING ELEVATION (FT):         477.76    478.74     479.72
 MEAN INFLOW (CFS):  10713.59
 TURBINE NO.:                 1         2         3         4
 TURBINE POWER (MW):      93.71     93.71     27.85      0.00
 OUTFLOW (CFS):         8333.34   8333.34   3333.33      0.00
 PEAK GENERATION (HRS):        15.00  OFF-PEAK GEN. (HRS):           9.00
 PEAK ENERGY (MWH):          3229.01  OFF-PEAK ENERGY (MWH):     1937.41
 TOTAL POWER OUTPUT (MW):     215.27
 TURBINE OUTFLOW (CFS):     20000.02
 SPILLWAY OUTFLOW (CFS):        0.00

 T H U R M O N D
 PERCENTILES:                      5.00%     MEAN      95.00%
 BEGINNING STORAGE (BCF):       116.41    120.45     124.58
 ENDING STORAGE (BCF):          117.05    121.18     125.41
 BEGINNING ELEVATION (FT):      332.16    333.38     334.60
 ENDING ELEVATION (FT):         332.36    333.60     334.84
 MEAN INFLOW (CFS):   8531.49
 TURBINE NO.:                 1         2         3         4         5         6         7
 TURBINE POWER (MW):      44.72     44.61     44.45     44.18     33.96      0.00      0.00
 OUTFLOW (CFS):         4225.87   4215.07   4198.94   4171.27   3188.37      0.00      0.00
 SERVICE UNITS (MW):       1.00      0.00
 OUTFLOW (CFS):          100.86      0.00
 PEAK GENERATION (HRS):        15.00  OFF-PEAK GEN. (HRS):           9.00
 PEAK ENERGY (MWH):          3178.82  OFF-PEAK ENERGY (MWH):     1907.29
 TOTAL POWER OUTPUT (MW):     211.92
 TURBINE OUTFLOW (CFS):     19999.51
 SPILLWAY OUTFLOW (CFS):        0.00

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4.4 Large Flood Operation

Large floods are those that force reservoir levels above the top of the flood control pools (Region I). In such situations, spillway gates clear the crest and water begins to flow through the opening. Thus, during large floods spillway flow cannot be avoided. The operator can still regulate spillway outflow by further raising the gates. The maximum outflow takes place when the passage is completely unblocked. When spillways operate, reservoir levels change faster, and the daily time scale becomes inadequate. Hence, when reservoir levels enter Region I, the control procedure is designed to switch into four-hour time intervals. The input parameters for this case study are reported in the following table. The main differences with the inputs of the previous section are that the forecasted inflows are 175% of the hypothetical inflows depicted in Figure 13 and that the allowable discharge range is from 30,000 to 70,000 cfs.

Table 8: Large Flood Case Study: Input Parameters

Parameter	Entry
Starting Date:	02 11 1991 Monday
Initial Lake Elev. (Feet):	660.00 (H), 475.00 (R), 330.00 (T)
Operational Mode:	Flood
Control Horizon (Days):	20
Turbine Outages:	None
Turbine Overload (%):	25 (Hartwell), 25 (Russell), 25 (Thurmond)
Energy Targets:	Figure 7, Section 3.2.2
Reservoir Level Targets:	Figure 8, Section 3.2.2
Inflow Forecasting:	175% of hypothetical inflow forecasts
Reliability Level (%):	95
Min. Weekly Outflow (cfs):	5,800
Max. Discharge Range (cfs):	30,000 to 70,000
Number of Tradeoff Points:	8

Figure 16 depicts the resulting tradeoffs. As before, the graphs present the effects of the specified maximum discharge range on energy generation (MWH per Day) and the maximum reservoir levels over the control horizon. It is noted, however, that the discharge range shown on the horizontal axis is a desirable user-specified range and may not represent actual discharges. In Region I, actual discharges depend upon reservoir levels and may be outside the specified range. Energy generation increases with the discharge bound until turbines reach their power generation limit. The form of this tradeoff segment is primarily influenced by Region II. Subsequently, the tradeoff line tapers off as the discharge bound becomes inconsequential. Specifically, in Region I turbines run at full power to minimize energy losses due to spillway outflow. Maximum reservoir elevations are predicted to exceed the top of the flood control pools by one or two feet, indicating that operational controls are limited in this region. Lower reservoir levels could result only if the user-specified discharge bound was increased substantially.

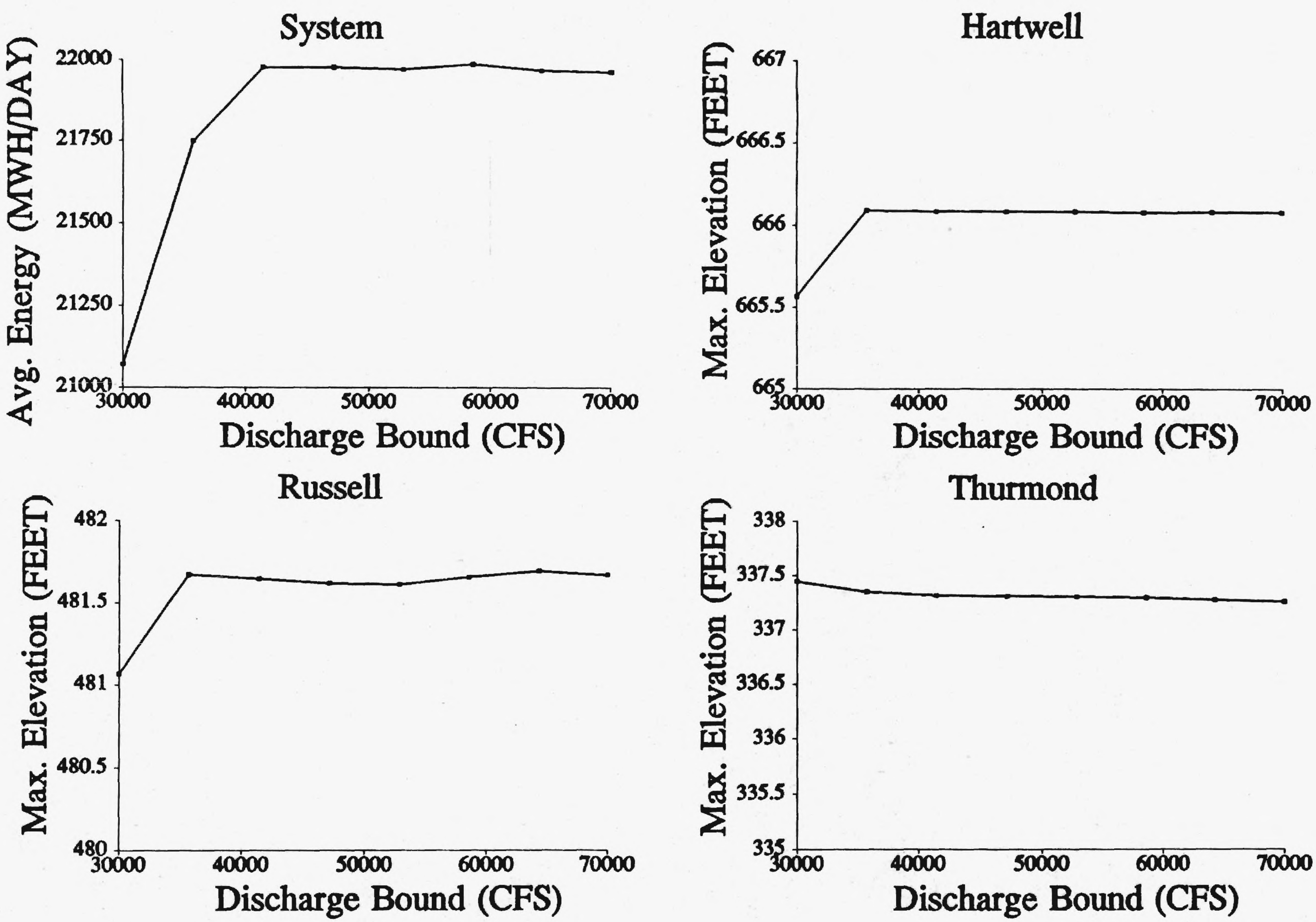

Figure 16: Large Flood Operation Tradeoffs

The reservoir sequences associated with a maximum discharge of 70,000 cfs are shown on Figure 17. As seen by these sequences, at the end of the 8th day, reservoir levels enter Region I, and operation reverts into four-hour time steps. Thurmond discharge is briefly maintained below 70,000 cfs, but it quickly rises to 122,000 cfs. The highest discharges for the other two projects are 51,000 cfs for Hartwell and 73,000 cfs for Russell. The four-hour system operation is simulated for 20 time steps.

Detailed schedules are either in daily or in four-hourly time steps. A sample of a four-hour schedule is included in Table 8. All hydroelectric facilities operate at full power. Spillway discharge is determined by the induced surcharge curves included in Appendix A.

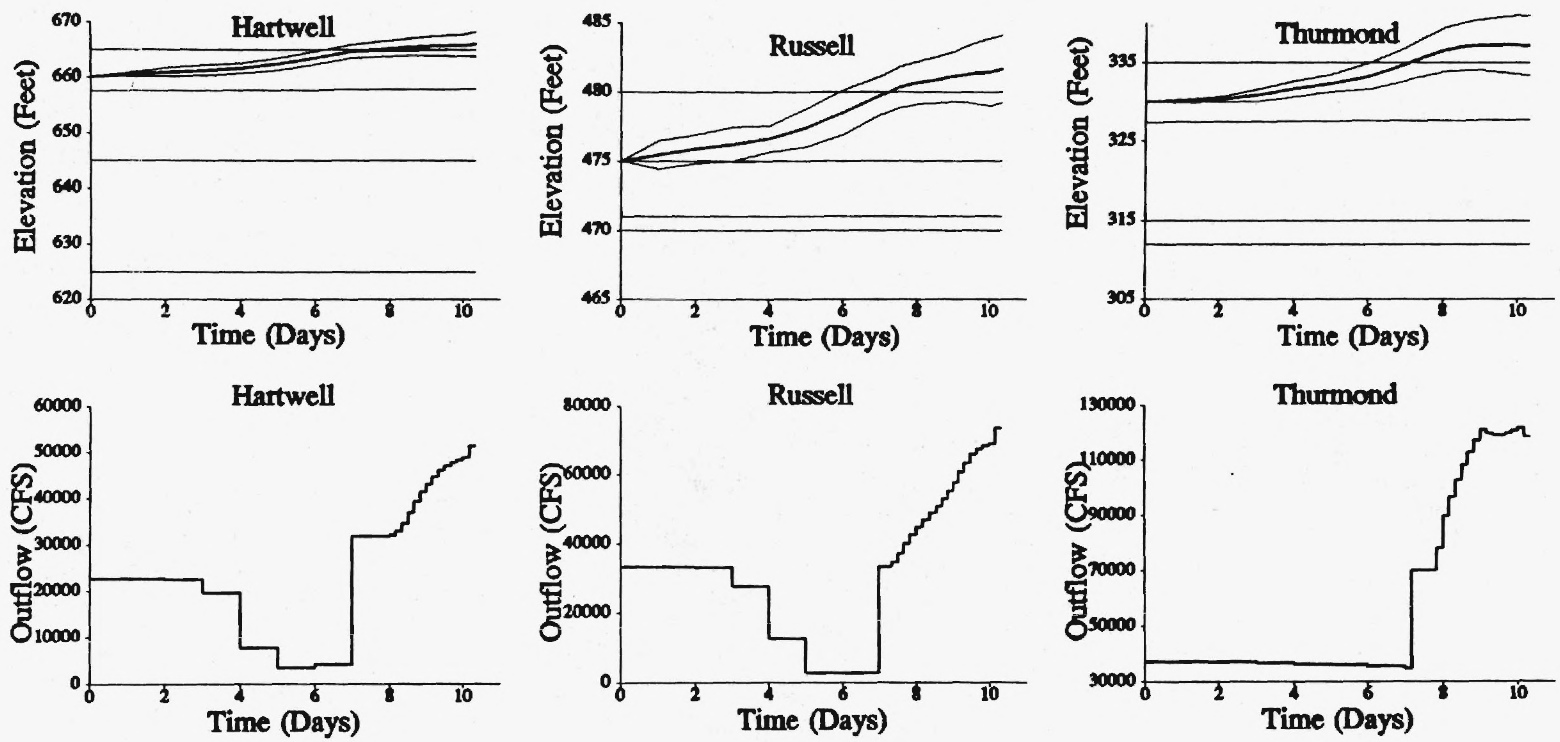

Figure 17: Reservoir Sequences for Large Flood Operation

Table 8: Large Flood Operation Case Study: Detailed Schedule Sample

```
---------------------------- 2/21/1991 THURSDAY ----------------------------
                              HOURS  0 -  4

 H A R T W E L L
 PERCENTILES:                     5.00%     MEAN      95.00%
 BEGINNING STORAGE (BCF):       120.82    126.03    131.39
 ENDING STORAGE (BCF):          120.86    126.40    132.09
 BEGINNING ELEVATION (FT):      663.87    665.83    667.77
 ENDING ELEVATION (FT):         663.89    665.96    668.02
 MEAN INFLOW (CFS):  74140.98
 TURBINE NO.:                 1        2        3        4        5
 PEAK POWER (MW):         82.50    82.50    82.50    82.50   100.00
 OUTFLOW (CFS):         6140.89  6140.89  6140.89  6140.89  7496.35
 PEAK GENERATION (HRS):           0.00  OFF-PEAK GEN. (HRS):          4.00
 PEAK ENERGY (MWH):               0.00  OFF-PEAK ENERGY (MWH):     1719.99
 TOTAL POWER OUTPUT (MW):   430.00
 TURBINE OUTFLOW (CFS):   32059.89
 SPILLWAY OUTFLOW (CFS):  16792.76

 R U S S E L L
 PERCENTILES:                     5.00%     MEAN      95.00%
 BEGINNING STORAGE (BCF):        49.53     52.67     55.93
 ENDING STORAGE (BCF):           49.68     52.83     56.11
 BEGINNING ELEVATION (FT):      479.00    481.44    483.87
 ENDING ELEVATION (FT):         479.12    481.57    484.00
 MEAN INFLOW (CFS):  31544.85
 TURBINE NO.:                 1        2        3        4
 TURBINE POWER (MW):      93.75    93.75    93.75    93.75
 OUTFLOW (CFS):         8365.98  8365.98  8365.98  8365.78
 PEAK GENERATION (HRS):           0.00  OFF-PEAK GEN. (HRS):          4.00
 PEAK ENERGY (MWH):               0.00  OFF-PEAK ENERGY (MWH):     1499.99
 TOTAL POWER OUTPUT (MW):   375.00
 TURBINE OUTFLOW (CFS):   33463.71
 SPILLWAY OUTFLOW (CFS):  35488.99

 T H U R M O N D
 PERCENTILES:                     5.00%     MEAN      95.00%
 BEGINNING STORAGE (BCF):       120.97    133.83    147.51
 ENDING STORAGE (BCF):          120.56    133.53    147.34
 BEGINNING ELEVATION (FT):      333.54    337.26    341.01
 ENDING ELEVATION (FT):         333.41    337.17    340.97
 MEAN INFLOW (CFS):  31693.59
 TURBINE NO.:                 1        2        3        4        5        6        7
 TURBINE POWER (MW):      50.00    50.00    50.00    50.00    50.00    50.00    49.99
 OUTFLOW (CFS):         5640.98  5640.98  5640.98  5640.98  5640.98  5640.98  5638.79
 SERVICE UNITS (MW):       1.00     0.00
 OUTFLOW (CFS):          108.00     0.00
 PEAK GENERATION (HRS):           0.00  OFF-PEAK GEN. (HRS):          4.00
 PEAK ENERGY (MWH):               0.00  OFF-PEAK ENERGY (MWH):     1399.96
 TOTAL POWER OUTPUT (MW):   349.99
 TURBINE OUTFLOW (CFS):   39484.65
 SPILLWAY OUTFLOW (CFS):  82337.52

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```

5. Summary and Research Recommendations

The control method described herein is designed to assist the operational management of the Savannah River system. The essence of the method is to quantify the operational tradeoffs of interest and present the responsible authority with the information necessary to make sound decisions. Except for the Savannah U.S. Army Corps of Engineers District, the model can benefit the decision process at the Corps' South Atlantic Division and the Southeastern Power Administration.

The control method and the system operation can be enhanced by the development of a rainfall-runoff model for short-term streamflow forecasting. Such model would utilize real-time measurements from on-site or remote sensors and would reliably simulate the characteristics of the rainfall-runoff process. The main impacts of a more accurate streamflow model would be to (1) conserve water and (2) reduce the allocated flood control storage. The minimum release from Thurmond is established to maintain the same flow rate at Augusta. Depending on rainfall, however, local drainage downstream of Thurmond may significantly supplement the flow and, if timely anticipated, lower the necessary release from Thurmond. This would minimize unnecessary releases (especially during droughts) and increase water conservation. More accurate reservoir inflow forecasts would result in more effective management during floods and would allow for higher reservoir levels without compromising flood protection. In turn, higher reservoir levels would enhance energy generation at the same release levels. Thus, although the development of more elaborate streamflow models would require an upfront expense in improving basin instrumentation, it might well be worth the cost.

As mentioned, the Savannah River System is a part of a larger reservoir system whose energy generation is marketed by the Southeastern Power Administration. This system includes eight additional reservoirs in the Apalachicola-Chattahoochee-Flint and Alabama-Coosa basins (Buford, West Point, George, Woodruff, Carters, Allatoona, Jones Bluff, and Millers Ferry). Although these eleven reservoirs are situated in geographically separate drainage basins, their operation should be coordinated. The energy and power capacity produced by this system is marketed to a number of electric cooperatives and municipalities through contracts with several power companies (Georgia Power, Alabama Power, Duke Power and others). The energy flow among the power companies integrates all projects into one system and creates the need for coordination. The control methodology developed for the Savannah River can also be extended to include the entire system. A model with the ability to quantify the impacts of various operational policies systemwide would provide a standard basis for agency communication and would expedite and enhance the decision making process.

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APPENDIX A

Reservoir Characteristic Curves

A.1 Power Curves

The following power curves were developed by the U.S. Army Corps of Engineers and provide the relationship between turbine dishcarge, net hydraulic head, and power.

$$u = a\left(\frac{P}{H_n}\right)^2 + b\left(\frac{P}{H_n}\right) + c,$$

where u represents turbine discharge [cfs], P is turbine power [MW], H_n is the net hydraulic head [feet], and {a,b,c} are coefficients specific to each turbine. The values of the coefficients are given below:

A.1.1 Hartwell:

Units 1 through 4: (Nominal Power Capacity 66 MW)

If $P/H_n \geq 0.114706$,
$a = 6.574949267 \times 10^3$
$b = 8.684960867 \times 10^3$
$c = 0.782939157 \times 10^3$

Otherwise, $u = 0.$ and $P = 0.$

Unit 5: (Nominal Power Capacity 80 MW)

If $P/H_n \geq 0.130207$,
$a = 5.792000000 \times 10^3$
$b = 8.684960867 \times 10^3$
$c = 0.888741800 \times 10^3$

Otherwise, $u = 0.$ and $P = 0.$

A.1.2 Russell:

Units 1 through 4: (Nominal Power Capacity 75 MW)

If $P/H_n \geq 0.$
$a = 0.749000000 \times 10^1$
$b = 0.110000000 \times 10^5$
$c = 0.122000000 \times 10^4$

Otherwise, $u = 0.$ and $P = 0.$

A.1.3 Thurmond:

Units 1 through 7: (Nominal Power Capacity 40 MW)

If $P/H_n > 0.3452806$, $a = 0.129395100 \times 10^6$
$b = -0.684310400 \times 10^5$
$c = 0.128589900 \times 10^5$

If $0.09219858 \leq P/H_n \leq 0.3452806$, $a = 0.1163776 \times 10^5$
$b = 0.7155400 \times 10^4$
$c = 0.7993339 \times 10^3$

If $P/H_n \leq 0.09219858$, $u = 0.$
$P = 0.$

Service Station Units 1 and 2: (Nominal Power Capacity 1 MW)

$$If\ P > 0,\ u = \frac{P}{H_n}\left(12 + \frac{1000 - P}{700}\right) + 16$$
$$If\ P = 0,\ u = 0$$

where u is obtained in cfs when P is expressed in KW and H_n in feet.

It is noted that the net hydraulic head H_n in the above equations represents the difference between the forebay and tailwater elevations. These levels can be obtained as a function of reservoir storage or total outflow and are given below.

A.2 Elevation (H) versus Storage (S) Curves

The following curves were developed via regression analysis on actual elevation-storage data provided by the Savannah District of the U.S. Army Corps of Engineers.

Hartwell	
Curve	$H = \exp\{a + bS + c\,ln(S) + d[ln(S)]^2\}$
Units	H: Feet S: Acre-Feet
Coefficient Values	a = 0.54990041 x 10^{1} b = 0.25170283 x 10^{-8} c = 0.71184497 x 10^{-1} d = -0.29063993 x 10^{-3}
Validity Range	H: 620 - 675 Feet S: 1,002,300 - 3,512,500 Acre-Feet
Residual† Error St. Dev.	0.018 Feet

Russell	
Curve	$H = \exp\{a + bS + c\,ln(S) + d[ln(S)]^2\}$
Units	H: Feet S: Acre-Feet
Coefficient Values	a = 0.58877892 x 10^{1} b = 0.49993385 x 10^{-8} c = -0.36854802 x 10^{-1} d = 0.40740122 x 10^{-2}
Validity Range	H: 460 - 503 Feet S: 681,784 - 1,998,533 Acre-Feet
Residual Error St. Dev.	0.0017 Feet

†The residual error is the difference of the predicted from the actual data value.

Thurmond	
Curve	$H = \exp\{a + bS + c\,ln(S) + d\,[ln(S)]^2 + e\,[ln(S)]^3\}$
Units	H: Feet S: 10^3 Acre-Feet
Coefficient Values	a = -0.10043373×10^2 b = $-0.62156863 \times 10^{-4}$ c = 0.63159531×10^1 d = -0.86380405 e = $0.40628874 \times 10^{-1}$
Validity Range	H: 310 - 348 Feet S: 1,375 - 4,025 10^3 Acre-Feet
Residual Error St. Dev.	0.0975 Feet

A.3 <u>Tailwater Elevation (t) versus Outflow (Q) Curves</u>

The following curves were developed using regression analysis on actual outflow tailwater elevation data provided by the Savannah District of the U.S. Army Corps of Engineers.

Hartwell	
Curve	$$t = \exp\{a + bQ + cQ^2 + d\ln(Q) + \frac{e}{Q}\}$$
Units	t: Feet Q: 10^3 cfs
Coefficient Values	a = 0.61520043 x 10^1 b = 0.11935499 x 10^{-3} c = -0.37161098 x 10^{-7} d = 0.70877097 x 10^{-2} e = 0.16925465 x 10^{-1}
Validity Range	t: 475 - 518 Feet Q: [1 - 535] x 10^3 cfs
Residual Error St. Dev.	0.174 Feet

Russell's tailwater is affected by the water elevation in Thurmond (H).

Russell		
Curve $If\ H \le 31.5\ \&\ Q \le 0.25\ ,$ $t = Q + 30.25$ $If\ H \le 31.5\ \&\ Q > 0.25\ ,$ $t = \exp\{ a_1 + b_1 Q + c_1 ln(Q) + d_1 ln(H) \}$ $If\ H > 31.5\ \&\ (Q \le Q_0\ ,\ Q_0 = \max\{0.25\ ,\ 3H - 94.5\})\ ,$ $t = H$ $If\ H > 31.5\ \&\ Q_0 \le Q \le 18\ ,$ $t = \exp\{ a_2 + b_2 Q + c_2 Q^2 + d_2 ln(Q) + e_2 [ln(Q)]^2 + f_2 H + g_2 ln(H) \}$ $If\ H > 31.5\ \&\ Q > 18\ ,$ $t = \exp\{ a_3 + b_3 Q + c_3 Q^2 + d_3 ln(Q) + e_3 [ln(Q)]^2 + f_3 H + g_3 ln(H) \}\}$		
Units	t: 10^{-1} Feet Q: 10^4 cfs H: 10^{-1} Feet	
Coefficient Values $a_1 = 0.28776055 \times 10^1$ $b_1 = 0.11934631 \times 10^{-2}$ $c_1 = 0.69158239 \times 10^{-2}$ $d_1 = 0.16292329$	$a_2 = 0.10679235 \times 10^2$ $b_2 = 0.55312604 \times 10^{-4}$ $c_2 = 0.27745164 \times 10^{-4}$ $d_2 = -0.27362004 \times 10^{-3}$ $e_2 = 0.36705793 \times 10^{-3}$ $f_2 = 0.12457930$ $g_2 = -0.32305717 \times 10^1$	$a_3 = 0.19178625 \times 10^2$ $b_3 = 0.31409075 \times 10^{-2}$ $c_3 = -0.11946631 \times 10^{-4}$ $d_3 = 0.22368452 \times 10^{-1}$ $e_3 = -0.98748458 \times 10^{-2}$ $f_3 = 0.21231130$ $g_3 = -0.64962863 \times 10^1$
Validity Range	t: (30.25 - 51.8) 10^{-1} Feet Q: (0 - 60) 10^{-4} cfs H: (30.0 - 34.5) 10^{-1} Feet	
Residual Error St. Dev.	Maximum St. Dev. 1.3 Feet Error-free for most of the applicable range.	

Thurmond	
Curve	*If* $Q \leq 0.25$, $t = 18.7 + 0.4\,Q$ *If* $Q > 0.25$, $t = \exp\{\,a + b\,Q + c\,Q^2 + d\,ln(Q) + e\,[ln(Q)]^2\,\}$
Units	t: 10^{-1} Feet Q: 10^4 cfs
Coefficient Values	a = 0.61520043×10^1 b = $0.11935499 \times 10^{-3}$ c = $-0.37161098 \times 10^{-7}$ d = $0.70877097 \times 10^{-2}$ e = $0.16925465 \times 10^{-1}$
Validity Range	t: $[18.7 - 25.5] \times 10^{-1}$ Feet Q: $[0 - 100] \times 10^4$ cfs
Residual Error St. Dev.	0.196 Feet

Validity Range	Q: [6- 810] x 10^3 cfs H: [438 - 490] Feet
Residual Error St. Dev.	2.3 x 10^3 cfs

Thurmond	
Curve	$If\ H \leq 300,$ $Q = 0,$ $If\ H > 300$ $Q = a + b\,H + c\,ln(H) + d\,[ln(H)]^2$
Units	Q: 10^3 cfs H: Feet
Coefficient Values	a = 0.45998528 x 10^7 b =-0.88736259 x 10^3 c =-0.17875183 x 10^7 d = 0.18018425 x 10^6
Validity Range	Q: [5 - 1,095] x 10^3 cfs H: [302.25 - 347] Feet
Residual Error St. Dev.	2.8 x 10^3 cfs

A.5 <u>Spillway Outflow (Q) versus Reservoir Elevation (H) Induced Surcharge Curves</u>

The following curves estimate spillway outflow when reservoir elevations exceed the top of the flood control pool and water escapes under the gates.

Hartwell	
Curve $If\ H \le 665,$ $Q = 0,$ $If\ 665 < H \le 666.4,$ $Q = \exp\{a + b(H-665) + c(H-665)^2 + d(H-665)^3\}$ $If\ 666.4 < H \le 669.12,$ $Q = 100.296 + 133.715(H-666.4)$ $If\ H > 669.12,$ $Q =$ *spillway outflow with gates fully open*	
Units	Q: 10^3 cfs H: Feet
Coefficient Values	a $= -0.48334328 \times 10^1$ b $= 0.23076364 \times 10^2$ c $= -0.23736696 \times 10^2$ d $= 0.84923487 \times 10^1$
Validity Range	Q: $[0 - 562.5] \times 10^3$ cfs H: [665 - 674] Feet
Residual Error St. Dev.	0.197 10^3 cfs

Russell

Curve

$$
\begin{aligned}
&\text{If } H \le 480\,, \\
&\quad Q = 0\,, \\
&\text{If } 480 < H \le 484.67\,, \\
&\quad Q = \exp\{\, a + b\,(H-480) + c\,(H-480)^2 + d\,(H-480)^3 + e\,(H-480)^4 \} - 40 \\
&\text{If } 484.67 < H \le 485\,, \\
&\quad Q = 260 + 1181.818\,(H-484.67) \\
&\text{If } H > 485\,, \\
&\quad Q = \textit{spillway outflow with gates fully open}
\end{aligned}
$$

Units	Q: 10^3 cfs H: Feet
Coefficient Values	a = 0.36854816×10^{1} b = 0.24374046 c = 0.25053242 d = $-0.86775716 \times 10^{-1}$ e = $0.89587572 \times 10^{-2}$
Validity Range	Q: [0 - 810] x 10^3 cfs H: [480 - 490] Feet
Residual Error St. Dev.	3.184 10^3 cfs

Thurmond

Curve

$$
\begin{aligned}
&\text{If } H \le 335\,, \\
&\quad Q = 0\,, \\
&\text{If } 335 < H \le 340.1\,, \\
&\quad Q = \exp\{\, a_1 + b_1\,(H-335) + c_1\,(H-335)^2 + d_1\,(H-335)^3 + e_1\,(H-335)^4 \} - 30 \\
&\text{If } 340.1 < H \le 342.925\,, \\
&\quad Q = \exp\{\, a_2 + b_2\,(H-335) + c_2\,(H-335)^2 + d_2\,(H-335)^3 + e_2\,(H-335)^4 \} - 30 \\
&\text{If } H > 342.925\,, \\
&\quad Q = \textit{spillway outflow with gates fully open}
\end{aligned}
$$

Units	Q: 10^3 cfs H: Feet
Coefficient Values $a_1 = 0.33768539 \times 10^1$ $b_1 = 0.82666590$ $c_1 = -0.10428377$ $d_1 = -0.39464559 \times 10^{-2}$ $e_1 = 0.17256951 \times 10^{-2}$	 $a_2 = -0.76751935 \times 10^1$ $b_2 = 0.77483690 \times 10^1$ $c_2 = -0.17453463 \times 10^1$ $d_2 = 0.17591423$ $e_2 = -0.62933894 \times 10^{-2}$
Validity Range	Q: [0 - 1,095] x 10^3 cfs H: [335 - 347] Feet
Residual Error St. Dev.	4.267 10^3 cfs

APPENDIX B

Optimization Algorithm for Module I

This appendix outlines the optimization algorithm for Module I. The control problem is as follows:

Find the generation time sequences $\{t_H(k), t_R(k), t_T(k),\ k=0,1,\ldots,N-1\}$ which minimize the following performance index J,

$$
\begin{aligned}
J &= E\{ \sum_{k=0}^{N-1} g(S(k),t(k),k) + g(S(N),N) \} \\
&= E\{ \sum_{k=0}^{N-1} \alpha(k)\,[E^*(k) - t_H(k)\,P_H(k) - t_R(k)\,P_R(k) - t_T(k)\,P_T(k)]^2 \\
&\quad + \beta_H(k)\,[H_H(S_H(k)) - H_H^*(k)]^2 + \beta_R(k)\,[H_R(S_R(k)) - H_R^*(k)]^2 + \beta_T(k)\,[H_T(S_T(k)) - H_T^*(k)]^2 \\
&\quad + \beta_H(N)\,[H_H(S_H(N)) - H_H^*(N)]^2 + \beta_R(N)\,[H_R(S_R(N)) - H_R^*(N)]^2 + \beta_T(N)\,[H_T(S_T(N)) - H_T^*(N)]^2 \},
\end{aligned}
\tag{1}
$$

subject to the system equations,

$$
\begin{aligned}
\begin{bmatrix} S_H(k+1) \\ S_R(k+1) \\ S_T(k+1) \end{bmatrix}
&= \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}
\begin{bmatrix} S_H(k) \\ S_R(k) \\ S_T(k) \end{bmatrix}
+ \begin{bmatrix} -B_H(k) & 0 & 0 \\ B_H(k) & -B_R(k) & 0 \\ 0 & B_R(k) & -B_T(k) \end{bmatrix}
\begin{bmatrix} t_H(k) \\ t_R(k) \\ t_T(k) \end{bmatrix}
+ \begin{bmatrix} w_H(k) \\ w_R(k) \\ w_T(k) - C_T(k) \end{bmatrix} \\
&= A\,S(k) + B(k)\,t(k) + w(k), \\
k &= 0,1,\ldots,N-1, \\
S(0)&\ known,
\end{aligned}
\tag{2}
$$

and the following constraints:

$$
\begin{aligned}
t_I^{\min}(k) \le t_I(k) \le t_I^{\max}(k)&, \\
I = H,R,T&, \\
k = 0,1,\ldots,N-1&.
\end{aligned}
\tag{3}
$$

The algorithm presented next is an outgrowth of the Extended Linear Quadratic Gaussian (ELQG) control method [*Georgakakos and Marks, 1987, and Georgakakos, 1989*], adapted to this problem. (In what follows, bold-face type denotes matrix or vector quantities.)

1. Set the generation time sequences $\{t(k), k=0,...,N-1\}$ equal to some initial feasible values (nominal sequence) such as the midpoint of the permissible range (B.3).

2. Determine the mean state sequence $\{\bar{S}(k), k=0,...,N\}$ corresponding to the nominal control sequence:

2.1 Set $k=0$ and $\bar{S}(0)=S(0)$, and invoke module II to obtain the turbine power levels $\{P_I(i,0), I=H,R,T, i=1,...,n_I\}$, and discharges $\{u_I(i,0), I=H,R,T, i=1,...,n_J\}$.

2.2 Evaluate the elements of matrix **B**(0) and the scalar $C_T(0)$:

$$\begin{aligned} B_H(0) &= \pi_1 \sum_{i=1}^{n_H} \xi_H(i,0)\, u_H(i,0), \\ B_R(0) &= \pi_1 \sum_{i=1}^{n_R} \xi_R(i,0)\, u_R(i,0), \\ B_T(0) &= \pi_1 \sum_{i=1}^{n_T} \xi_T(i,0)\, u_T(i,0), \\ C_T(0) &= \pi_2 \sum_{i=8}^{9} \xi_T(i,0)\, u_T(i,0), \end{aligned} \tag{4}$$

where $\xi_I(i,0)$ are the turbine outage indicators and π_1 and π_2 are constants (see discussion following equation (1) in the section entitled "System Dynamics.")

2.3 Determine the mean state vector at time 1, $\bar{S}(1)$:

$$\bar{S}(1) = A\,\bar{S}(0) + B(0)\,t(0) + \bar{w}(0), \tag{5}$$

where $\bar{w}(0)$ is the mean value of vector **w**(0). ($\bar{w}_3(0)=\bar{w}_T(0)-C_T(0)$.)

2.4 Set $k=1,...,N-1$, and repeat steps 2.1 through 2.3.

3. Determine the perturbation coefficients:

$$q(N) = \nabla_{\bar{S}(N)}\big(g(\bar{S}(N),N\big) = \begin{bmatrix} q_H(N) \\ q_R(N) \\ q_T(N) \end{bmatrix}, \text{ where}$$

$$q_I(N) = 2\,\beta_I(N)\,[H_I(\bar{S}_I(N)) - H_I^*(N)]\,\frac{\partial H_I(\bar{S}_I(N))}{\partial \bar{S}_I(N)},\ I = H,R,T;$$

$$q(k) = \nabla_{\bar{S}(k)}\big(g(\bar{S}(k),t(k),k)\big) = \begin{bmatrix} q_H(k) \\ q_R(k) \\ q_T(k) \end{bmatrix},\ k=0,\ldots,N-1, \quad \text{where}$$

$$q_I(k) = 2\,\beta_I(k)\,[H_I(\bar{S}_I(k)) - H_I^*(k)]\,\frac{\partial H_I(\bar{S}_I(k))}{\partial \bar{S}_I(k)},\ I = H,R,T;$$

$$r(k) = \nabla_{t(k)}\big(g(\bar{S}(k),t(k),k)\big) = \begin{bmatrix} r_H(k) \\ r_R(k) \\ r_T(k) \end{bmatrix},\ k=0,\ldots,N-1, \quad \text{where}$$

$$r_I(k) = 2\,\alpha(k)\,[E^*(k) - t_H(k)\,P_H(k) - t_R(k)\,P_R(k) - t_T(k)\,P_T(k)]\,P_I(k),\ I = H,R,T;$$

$$Q(N) = \nabla^2_{S(N)S(N)}\big(g(\bar{S}(N),N)\big) = \begin{bmatrix} Q_H(N) & 0 & 0 \\ 0 & Q_R(N) & 0 \\ 0 & 0 & Q_T(N) \end{bmatrix}, \text{ where}$$

$$Q_I(N) = 2\,\beta_I(N)\left(\frac{\partial[H_I(S_I(N))]}{\partial S_I(N)}\right)^2 - 2\,\beta_I(N)\,[H_I(S_I(N)) - H_I^*(N)]\,\frac{\partial^2[H_I(S_I(N))]}{\partial^2 S_I(N)},\ I=H,R,T;$$

$$Q(k) = \nabla^2_{S(k)S(k)}\big(g(\bar{S}(k),t(k),k)\big) = \begin{bmatrix} Q_H(k) & 0 & 0 \\ 0 & Q_R(k) & 0 \\ 0 & 0 & Q_T(k) \end{bmatrix},\ k=0,\ldots,N-1, \quad \text{where}$$

$$Q_I(k) = 2\,\beta_I(k)\left(\frac{\partial[H_I(S_I(k))]}{\partial S_I(k)}\right)^2 - 2\,\beta_I(k)\,[H_I(S_I(k)) - H_I^*(k)]\,\frac{\partial^2[H_I(S_I(k))]}{\partial^2 S_I(k)},\ I=H,R,T.$$

(6a)

$$R(k) = \nabla^2_{s(k)s(k)}(g(S(k),s(k),k)) = \begin{bmatrix} R_{HH}(k) & R_{HR}(k) & R_{HT}(k) \\ R_{RH}(k) & R_{RR}(k) & R_{RT}(k) \\ R_{TH}(k) & R_{TR}(k) & R_{TT}(k) \end{bmatrix}, \; k=0,\dots,N-1, \quad \text{where} \tag{6b}$$

$$R_{IJ}(k) = 2\,\alpha(k)\,P_I(k)\,P_J(k)\,, \; I=H,R,T, \; J=H,R,T.$$

4. Determine the gradient and hessian sequences:

4.1 Gradient:

$$\begin{aligned} e(N) &= q(N)\,, \\ e(k) &= A'\,e(k+1) + q(k)\,, \\ \nabla_{s(k)} J &= r(k) + B'(k)\,e(k+1)\,, \\ k &= N, N-1, \dots, 0\,, \end{aligned} \tag{7}$$

4.2 Hessian:

$$\begin{aligned} f(N) &= Q(N)\,, \\ f(k) &= A'\,f(k+1)\,A + Q(k)\,, \\ \nabla^2_{s(k),s(k)} J &= R(k) + B'(k)\,f(k+1)\,B(k)\,, \\ k &= N, N-1, \dots, 0\,. \end{aligned} \tag{8}$$

5. Test algorithm convergence:

5.1 Determine:

$$t_I^{+}(k) = \left\{ \begin{array}{c} t_I^{\max}(k) \quad if \quad t_I(k) - \dfrac{\nabla_{t_I(k)} J}{\nabla^2_{t_I(k),t_I(k)} J} \geq t_I^{\max}(k) \\ t_I(k) - \dfrac{\nabla_{t_I(k)} J}{\nabla^2_{t_I(k),t_I(k)} J} \quad if \quad t_I^{\min}(k) \leq t_I(k) - \dfrac{\nabla_{t_I(k)} J}{\nabla^2_{t_I(k),t_I(k)} J} \leq t_I^{\max}(k) \\ t_I^{\min}(k) \quad if \quad t_I(k) - \dfrac{\nabla_{t_I(k)} J}{\nabla^2_{t_I(k),t_I(k)} J} \leq t_I^{\min}(k) \end{array} \right\} \tag{9}$$

$I = H,R,T, \quad k = 0,\ldots,N-1;$

5.2 Evaluate:

$$W = \sqrt{\sum_{k=0}^{N-1} \sum_{I=H,R,T} [t_I(k) - t_I^{+}(k)]^2} \tag{10}$$

If W is less than a certain threshold, say 0.5, terminate; otherwise continue the iterations.

6. Specify the binding constraint set Π^{+}:

$$\begin{aligned} \Pi^{+} = \{ (I,k)\colon & \left(t_I(k) \geq t_I(k)^{\max} - \epsilon \quad and \quad t_I(k) - \frac{\nabla_{t_I(k)} J}{\nabla^2_{t_I(k),t_I(k)} J} \geq t_I^{\max}(k) - \epsilon \right) \quad or \\ & \left(t_I(k) \leq t_I^{\min}(k) + \epsilon \quad and \quad t_I(k) - \frac{\nabla_{t_I(k)} J}{\nabla^2_{t_I(k),t_I(k)} J} \leq t_I^{\min}(k) + \epsilon \right) \}, \end{aligned} \tag{11}$$

where $\quad I = H,R,T, \quad k = 0,\ldots,N-1, \quad$ and $\quad \epsilon = \min\{0.001, W\}$.

7. Compute the matrix sequence {K(k), k=1,...,N} and the vector sequence {λ(k), k=1,...,N}:

$$K(N) = Q(N),$$
$$K(k) = A'\,K(k+1)\,A + Q(k) \tag{12}$$
$$\qquad - \left([B'(k)\,K(k+1)\,A]^{rc}\right)' \left([R(k) + B'(k)\,K(k+1)\,B(k)]^{rc}\right)^{-1} [B'(k)\,K(k+1)\,A]^{rc}$$
$$k = N-1, N-2, \ldots, 1, 0;$$

$$\lambda(N) = q(N),$$
$$\lambda(k) = q(k) + A'\,\lambda(k+1) \tag{13}$$
$$\qquad - \left([B'(k)\,K(k+1)\,A]^{rc}\right)' \left([R(k) + B'(k)\,K(k+1)\,B(k)]^{rc}\right)^{-1} [r(k) + B'(k)\,\lambda(k+1)]^{r}$$
$$k = N-1, N-2, \ldots, 1, 0.$$

<u>Note:</u> In the above equations, notation $[M]^{rc}$ implies that if (I,k) ϵ Π^+, the Ith row and column of matrix M is deleted and the matrix dimension is reduced accordingly.

8. Determine the Newton Direction for the nonbinding control elements:

$$\delta t(k) = -D(k)\,[\,L(k)\ \delta S(k) + \Lambda(k)\,],$$
$$D(k) = \left([\,R(k) + B'(k)\,K(k+1)\,B(k)\,]^{rc}\right)^{-1},$$
$$L(k) = [\,B'(k)\,K(k+1)\,A\,]^{rc},$$
$$\Lambda(k) = [\,r(k) + B'(k)\,\lambda(k+1)\,]^{r}, \tag{14}$$
$$k = 0, \ldots, N-1,$$

where $\delta S(k)$ is obtained from

$$\delta S(k+1) = A\,S(k) + B(k)\,\delta t(k), \quad k = 0, \ldots, N-1, \quad \delta S(0) = \mathbf{0}.$$

In the previous equation (propagation of state perturbations), if (I,k) ϵ Π^+, $\delta t_I(k) = 0$.

9. Determine the Newton direction for the binding control elements:

$$\delta t(k) = -\frac{\nabla_{t(k)} J}{\nabla^2_{t(k),t(k)} J} \,. \tag{15}$$

10. Determine the stepsize, s, according to the Armijo rule:

$s = \theta^m$, where $\theta \in (0,1)$ and m is the first non-negative integer for which

$$\begin{aligned} &J(\{t(k),\ k=0,\ldots,N-1\}) - J(\{t(k) + \theta^m\,\delta t(k),\ k=0,\ldots,N-1\}) \geq \\ &\qquad -\sigma\left[\sum_{k=0}^{N-1} (\nabla_{t(k)} J)\,[\theta^m\,\delta t(k)]^+\right], \end{aligned} \tag{16}$$

where $[\theta^m\ \delta t(k)]^+$ is given by

$$[\theta^m\,\delta t(k)]_i^+ = \left\{\begin{array}{ll} t_i(k)^{\max} - t_i(k)\ , & if\ \ t_i(k) + \theta^m\,\delta t_i(k) > t_i(k)^{\max} \\ t_i(k) + \theta^m\,\delta t_i(k)\ , & if\ \ t_i(k)^{\min} \leq t_i(k) + \theta^m\,\delta t_i(k) \leq t_i(k)^{\max} \\ t_i(k)^{\min} - t_i(k)\ , & if\ \ t_i(k) + \theta^m\,\delta t_i(k) < t_i(k)^{\min} \end{array}\right\}. \tag{17}$$

Note: Typical values for θ and σ are 0.5 and 0.0001 respectively.

11. Perform the Projected Newton iteration:

$$t^{new}(k) = t(k) + [s\,\delta t(k)]^+\ ,\ k = 0,\ldots,N-1\,. \tag{18}$$

12. Repeat Steps (2) through (11) until convergence.

13. Determine the storage covariance and skewness sequences:

13.1 Covariance:

$$\begin{aligned} &P_s(k+1) = [A - B(k)\,D(k)\,L(k)]\,P_s(k)\,[A - B(k)\,D(k)\,L(k)]' + P_w(k)\,, \\ &\qquad k = 0,\ldots,N-1,\ \ P_s(0) = \mathbf{0}\,, \end{aligned} \tag{19}$$

where $P_s(k)$ is the storage covariance matrix, $P_w(k)$ is the inflow covariance matrix, and D(k) and L(k) are first determined as in Step 8 and then expanded to their original dimensions by including the deleted rows and columns with zero entries.

13.2 Skewness:
The skewness can be computed based on the procedure suggested in *Georgakakos, 1989.* A simpler but less accurate procedure is as follows:

$$
\begin{aligned}
\Gamma_H(k+1) &= c_{11}^3\,\Gamma_H(k) + c_{12}^3\,\Gamma_R(k) + c_{13}^3\,\Gamma_T(k) + \gamma_H(k) \\
\Gamma_R(k+1) &= c_{21}^3\,\Gamma_H(k) + c_{22}^3\,\Gamma_R(k) + c_{23}^3\,\Gamma_T(k) + \gamma_R(k) \\
\Gamma_T(k+1) &= c_{31}^3\,\Gamma_H(k) + c_{32}^3\,\Gamma_R(k) + c_{33}^3\,\Gamma_T(k) + \gamma_T(k) \\
k &= 0,\ldots,N-1\,,
\end{aligned}
\tag{20}
$$

where $\Gamma_I(k)$ represents the skewness for reservoir storage I, $\gamma_I(k)$ is the skewness of the inflow in reservoir I, and c_{ij} is the (i,j) entry of matrix [A-B(k)D(k)L(k)] used in the covariance dynamics. After a few initial time steps, the skewnness is expected to vanish given the additive form of the system dynamics (Eq. B.2) and the Central Limit Theorem.

14. Using the mean, variance, and skewness statistics, define an appropriate probability distribution for each reservoir storage and determine confidence intervals. Typical probability distributions are the two- and three-parameter lognormal distribution (if skewness is significant) and the normal distribution (if skewness is insignificant).

APPENDIX C

Optimization Algorithm for Module II

This appendix details the optimization algorithm for the solution of the Module II control problem. The problem statement is as follows:

Find P_j, $j=1,\ldots, n_i$, to minimize

$$
\begin{aligned}
&J = \alpha(X_{n_i+1} - P^*)^2 + \beta(Y_{n_i+1} - U^*)^2 \\
&\textit{subject to } X_{j+1} = X_j + P_j, \;\; j = 1,\ldots,n_i, \;\; X_1 = 0, \\
&\qquad Y_{j+1} = Y_j + \frac{a_j}{H_n^2}P_j^2 + \frac{b_j}{H_n}P_j + c_j, \;\; j = 1,\ldots,n_i, \;\; Y_1 = 0, \\
&\qquad P_j^{\min} \le P_j \le P_j^{\max}, \;\; j = 1,\ldots,n_i ,
\end{aligned} \tag{1}
$$

where $\{X_j, Y_j, j=1,\ldots,n_i+1\}$ represent the state variables; $\{P_j, j=1,\ldots, n_i\}$ represent the control variables; and α, β, P^*, U^*, and $\{a_j, b_j, c_j, j=1,\ldots,n_i\}$ are constant coefficients. Parameter n_i is the number of currently operational turbines.

The optimization algorithm presented next is based on the Projected Newton Method but includes several original extensions.

1. Set the power levels $\{P_j, j=1,\ldots,n_i\}$ equal to some initial feasible values such as $\max\{P^*/n_i, P_j^{\max}\}$.

2. Find the turbine discharges $\{u_j, j=1,\ldots,n_i\}$ that correspond to the power levels by iterating as follows:

    2.1 Set $u_j=0$, $j=1,\ldots, n_i$;

    2.2 Estimate the net hydraulic head, H_n:

    H_n = Forebay elevation - Tailwater elevation,

    where forebay elevation depends on the mean storage and tailwater elevation depends on the total reservoir outflow as described in Appendix A;

    2.3 Update the turbine discharge estimates:

$$
u_j^{new} = \frac{a_j}{H_n^2}P_j^2 + \frac{b_j}{H_n}P_j + c_j, \;\; j=1,\ldots,n_i; \tag{2}
$$

2.4 Terminate if the following criterion is met; otherwise, return to Step 2.2 and continue the iterations:

$$\left[\sum_{j=1}^{n_i}\left(u_j^{new}-u_j\right)^2\right]^{\frac{1}{2}} \leq 0.01\sum_{j=1}^{n_i} u_j \,. \tag{3}$$

3. Determine the state variable sequences, $\{X_j, Y_j,\ j=1,...,n_i\}$:

$$\begin{aligned} X_{j+1} &= X_j + P_j \\ Y_{j+1} &= Y_j + \frac{a_j}{H_n^2}P_j^2 + \frac{b_j}{H_n}P_j + c_j \\ j &= 1,...,n_i; \end{aligned} \tag{4}$$

4. Determine the co-state variable sequences, $\{\Phi_j, \Psi_j,\ j=1,...,n_i+1\}$:

4.1 Define the Hamiltonian Functional (the symbol " $'$ " denotes transpose):

$$H_j(X_j,Y_j,P_j,\Phi_{j+1},\Psi_{j+1}) = \begin{bmatrix}\Phi_{j+1}\\ \Psi_{j+1}\end{bmatrix}' \begin{bmatrix} X_j + P_j \\ Y_j + \frac{a_j}{H_n^2}P_j^2 + \frac{b_j}{H_n}P_j + c_j\end{bmatrix},\ j=1,...,n_i; \tag{5}$$

4.2 Determine the co-states:

$$\begin{aligned} \begin{bmatrix}\Phi_{n_i+1}\\ \Psi_{n_i+1}\end{bmatrix} &= \nabla_{X_{n_i+1},Y_{n_i+1}}\left(\alpha\,(X_{n_i+1}-P^*)^2+\beta\,(Y_{n_i+1}-U^*)^2\right) = \begin{bmatrix}2\,\alpha\,(X_{n_i+1}-P^*)\\ 2\,\beta\,(Y_{n_i+1}-U^*)\end{bmatrix} \\ \begin{bmatrix}\Phi_j\\ \Psi_j\end{bmatrix} &= \nabla_{X_j,Y_j}(H_j) = \begin{bmatrix}\Phi_{j+1}\\ \Psi_{j+1}\end{bmatrix},\ j=n_i,n_i-1,...,1\,; \end{aligned} \tag{6}$$

Note: In the general case where the performance index is defined as

$$J = \sum_{j=1}^{n_i} g_j(X_j,Y_j,P_j) + g_{n_i+1}(X_{n_i+1},Y_{n_i+1}), \tag{7}$$

the Hamiltonian also includes the "running" cost term $g_j(X_j,Y_j,P_j)$.

5. Determine the perturbation coefficients (bold-face symbols denote vectors or matrices):

$$
\begin{aligned}
\mathbf{A}_j &= \nabla_{X_j,Y_j}\left(\begin{bmatrix} X_j + P_j \\ Y_j + \dfrac{a_j}{H_n^2}P_j^2 + \dfrac{b_j}{H_n}P_j + c_j \end{bmatrix}\right) = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \; j = 1,\ldots,n_i ; \\
\mathbf{B}_j &= \nabla_{P_j}\left(\begin{bmatrix} X_j + P_j \\ Y_j + \dfrac{a_j}{H_n^2}P_j^2 + \dfrac{b_j}{H_n}P_j + c_j \end{bmatrix}\right) = \begin{bmatrix} 1 \\ 2\dfrac{a_j}{H_n^2}P_j + \dfrac{b_j}{H_n} \end{bmatrix}, \; j = 1,\ldots,n_i ; \\
\mathbf{q}_{n_i+1} &= \nabla_{X_{n_i+1},Y_{n_i+1}}\left(\alpha\,(X_{n_i+1} - P^*)^2 + \beta\,(Y_{n_i+1} - U^*)^2\right) = \begin{bmatrix} 2\alpha\,(X_{n_i+1} - P^*) \\ 2\beta\,(Y_{n_i+1} - U^*) \end{bmatrix}; \\
\mathbf{q}_j &= \nabla_{X_j,Y_j}\left(g_j(X_j,Y_j,P_j)\right) = \mathbf{0}, \; j = 1,\ldots,n_i ; \\
r_j &= \nabla_{P_j}\left(g_j(X_j,Y_j,P_j)\right) = 0, \; j = 1,\ldots,n_i ; \\
\mathbf{Q}_{n_i+1} &= \nabla^2_{X_{n_i+1},Y_{n_i+1}}\left(\alpha\,(X_{n_i+1} - P^*)^2 + \beta\,(Y_{n_i+1} - U^*)^2\right) = \begin{bmatrix} 2\alpha & 0 \\ 0 & 2\beta \end{bmatrix}; \\
\mathbf{Q}_j &= \nabla^2_{X_j,Y_j}\left(H_j\right) = \mathbf{0}, \; j = 1,\ldots,n_i ; \\
R_j &= \nabla^2_{P_j,P_j}\left(H_j\right) = 2\,\Psi_{j+1}\frac{a_j}{H_n^2}, \; j = 1,\ldots,n_i ; \\
\mathbf{M}_j &= \nabla^2_{P_j,(X_j,Y_j)}\left(H_j\right) = \mathbf{0}, \; j = 1,\ldots,n_i .
\end{aligned}
\tag{8}
$$

6. Determine the gradient and hessian sequences:

6.1 Gradient:

$$
\begin{aligned}
e_{n_i+1} &= q_{n_i+1}\,,\\
e_j &= A_j' e_{j+1} + q_j = e_{j+1}\,,\\
\nabla_{P_j} J &= r_j + B_j' e_{j+1} = B_j' e_{j+1}\,,\\
j &= n_i, n_i-1, \ldots, 1\,,
\end{aligned}
\tag{9}
$$

6.2 Hessian:

$$
\begin{aligned}
f_{n_i+1} &= Q_{n_i+1}\,,\\
f_j &= A_j' f_{j+1} A_j + Q_j = f_{j+1}\,,\\
\nabla^2_{P_j,P_j} J &= R_j + B_j' f_{j+1} B_j\,,\\
j &= n_i, n_i-1, \ldots, 1\,.
\end{aligned}
\tag{10}
$$

7. Test algorithm convergence:

7.1 Determine:

$$
P_j^{+} = \left\{
\begin{array}{lll}
P_j^{\max} & if & P_j - \dfrac{\nabla_{P_j} J}{\nabla^2_{P_j,P_j}} \geq P_j^{\max} \\[2ex]
P_j - \dfrac{\nabla_{P_j} J}{\nabla^2_{P_j,P_j}} & if & P_j^{\min} \leq P_j - \dfrac{\nabla_{P_j} J}{\nabla^2_{P_j,P_j}} \leq P_j^{\max} \\[2ex]
P_j^{\min} & if & P_j - \dfrac{\nabla_{P_j} J}{\nabla^2_{P_j,P_j}} \leq P_j^{\min}
\end{array}
\right\}, \; j = 1, \ldots, n_i\,;
\tag{11}
$$

7.2 Evaluate:

$$W = \sqrt{\sum_{j=1}^{n_i} (P_j - P_j^+)^2} \tag{12}$$

If W is less than a certain threshold, say 0.01, terminate; otherwise continue the iterations.

Note: The values of P_j^{min}, $j=1,...,n_i$, are obtained in terms of the hydraulic head from the conditions reported in Section A.1 of Appendix A.

8. Specify the binding constraint set Π^+:

$$\Pi^+ = \{ j: (P_j \geq P_j^{max} - \epsilon \ \ and \ \ P_j - \frac{\nabla_{P_j} J}{\nabla^2_{P_j,P_j} J} \geq P_j^{max} - \epsilon) \ \ or$$

$$(P_j \leq P_j^{min} + \epsilon \ \ and \ \ P_j - \frac{\nabla_{P_j} J}{\nabla^2_{P_j,P_j} J} \leq P_j^{min} + \epsilon) \}, \tag{13}$$

where $\quad \epsilon = \min\{ 0.001, W \}$.

9. Compute the matrix sequence $\{K_j,\ j=1,\dots,\ n_i+1\}$ and the vector sequence $\{\lambda_j,\ j=1,\dots,n_i+1\}$:

$$K_{n_i+1} = Q_{n_i+1},$$

$$K_j = A_j' K_{j+1} A_j + Q_j - (B_j' K_{j+1} A_j + M_j)' (R_j + B_j' K_{j+1} B_j)^{-1} (B_j' K_{j+1} A_j + M_j)$$

$$= \begin{bmatrix} K_{j+1}^{(1,1)} - \dfrac{(K_{j+1}^{(1,1)} + K_{j+1}^{(1,2)} B_j^{(2)})^2}{\omega_j} & K_{j+1}^{(1,2)} - \dfrac{(K_{j+1}^{(1,1)} + K_{j+1}^{(1,2)} B_j^{(2)})(K_{j+1}^{(1,2)} + K_{j+1}^{(2,2)} B_j^{(2)})}{\omega_j} \\ K_{j+1}^{(2,1)} - \dfrac{(K_{j+1}^{(1,1)} + K_{j+1}^{(1,2)} B_j^{(2)})(K_{j+1}^{(1,2)} + K_{j+1}^{(2,2)} B_j^{(2)})}{\omega_j} & K_{j+1}^{(2,2)} - \dfrac{(K_{j+1}^{(2,1)} + K_{j+1}^{(2,2)} B_j^{(2)})^2}{\omega_j} \end{bmatrix},$$

$$\omega_j = R_j + K_{j+1}^{(1,1)} + 2\,K_{j+1}^{(1,2)} B_j^{(2)} + (B_j^{(2)})^2 K_{j+1}^{(2,2)},$$

$$j = n_i, n_i-1, \dots, 1; \tag{14}$$

$$\lambda_{n_i+1} = q_{n_i+1},$$

$$\lambda_j = q_j + A_j' \lambda_{j+1} - (B_j' K_{j+1} A_j + M_j)' (R_j + B_j' K_{j+1} B_j)^{-1} (r_j + B_j' \lambda_{j+1})$$

$$= \begin{bmatrix} \lambda_{j+1}^{(1)} - \dfrac{\lambda_{j+1}^{(1)}}{\omega_j} (K_{j+1}^{(1,1)} + K_{j+1}^{(1,2)} B_j^{(2)}) - \dfrac{\lambda_{j+1}^{(2)}}{\omega_j} (K_{j+1}^{(1,1)} B_j^{(2)} + K_{j+1}^{(1,2)} (B_j^{(2)})^2) \\ \lambda_{j+1}^{(2)} - \dfrac{\lambda_{j+1}^{(1)}}{\omega_j} (K_{j+1}^{(2,1)} + K_{j+1}^{(2,2)} B_j^{(2)}) - \dfrac{\lambda_{j+1}^{(2)}}{\omega_j} (K_{j+1}^{(2,1)} B_j^{(2)} + K_{j+1}^{(2,2)} (B_j^{(2)})^2) \end{bmatrix}, \tag{15}$$

$$\omega_j = R_j + K_{j+1}^{(1,1)} + 2\,Kj{+}1^{(1,2)} B_j^{(2)} + (B_j^{(2)})^2 K_{j+1}^{(2,2)},$$

$$j = n_i, n_i-1, \dots, 1.$$

In the computation of K and λ, if $j \in \Pi^+$, evaluate K_j and λ_j from $K_j=K_{j+1}$ and $\lambda_j=\lambda_{j+1}$.

Notes: (i) In the above equations, $V_j^{(n,m)}$ denotes the (n,m) element of matrix (or vector) V_j.
(ii) The value of ω_j should be positive in convex minimization problems. However, if it happens that the search enters concave regions, ω_j will become negative and the algorithm will fail. The following provision is used to overcome this limitation:

$$If \quad \omega_j < \rho\left(\nabla_{P_j}J\right)^2, \quad \omega_j = \nabla^2_{P_j,P_j}J, \tag{16}$$

where ρ is a constant (e.g., $\rho = 0.001$).

10. Determine the Newton Direction for the nonbinding control elements:

$$\begin{aligned}
\delta P_j &= -\frac{1}{\omega_j}\left(L_j\begin{bmatrix}\delta X_j\\ \delta Y_j\end{bmatrix} + \Lambda_j\right),\\
\omega_j &= R_j + K^{(1,1)}_{j+1} + 2\,K^{(1,2)}_{j+1}\,B^{(2)}_j + K^{(2,2)}_{j+1}\,(B^{(2)}_j)^2,\\
L_j &= B'_j\,K_{j+1}\,A_j = B'_j\,K_{j+1},\\
\Lambda_j &= B'_j\,\lambda_{j+1},\\
j &= 1,\dots,n_i,
\end{aligned} \tag{17}$$

where $\begin{bmatrix}\delta X_j\\ \delta Y_j\end{bmatrix}$ is obtained from

$$\begin{bmatrix}\delta X_{j+1}\\ \delta Y_{j+1}\end{bmatrix} = A_j\begin{bmatrix}\delta X_j\\ \delta Y_j\end{bmatrix} + B_j\,\delta P_j, \quad j = 1,\dots,n_i, \quad \begin{bmatrix}\delta X_1\\ \delta Y_1\end{bmatrix} = 0.$$

In the previous equation (propagation of state perturbations), if $j \in \Pi^+$, $\delta P_j = 0$.

11. Determine the Newton direction for the binding control elements:

$$\delta P_j = -\frac{\nabla_{P_j}J}{\nabla^2_{P_j,P_j}J} \tag{18}$$

12. Determine the stepsize, s, according to the Armijo rule:

$s = \theta^m$, where $\theta \in (0,1)$ and m is the first non-negative integer for which

$$J(\{P_j, j=1,\ldots,n_i\}) - J(\{P_j + \theta^m \delta P_j, j=1,\ldots,n_i\}) \geq - \sigma \left[\sum_{j=1}^{n_i} (\nabla_{P_j} J) [\theta^m \delta P_j]^+ \right], \tag{19}$$

where $[\theta^m \ \delta P_j]^+$ is given by

$$[\theta^m \delta P_j]^+ = \begin{Bmatrix} P_j^{\max} - P_j\,, & if \ P_j + \theta^m \delta P_j > P_j^{\max} \\ P_j + \theta^m \delta P_j\,, & if \ P_j^{\min} \leq P_j + \theta^m \delta P_j \leq P_j^{\max} \\ P_j^{\min} - P_j\,, & if \ P_j + \theta^m \delta P_j < P_j^{\min} \end{Bmatrix}. \tag{20}$$

Note: Typical values for θ and σ are 0.5 and 0.0001 respectively.

13. Perform the Projected Newton iteration:

$$P_j^{new} = P_j + [s\, \delta P_j]^+ \,, \ j = 1, \ldots, n_i \,. \tag{21}$$

14. Repeat Steps (2) through (13) until convergence.

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The SAVRES Control Program

Version 1.0

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ARIS P. GEORGAKAKOS

Associate Professor

March 1991

School of Civil Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332

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ARIS P. GEORGAKAKOS

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School of Civil Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332

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CONTENTS

1. INTRODUCTION

The purpose of this manual is to familiarize U.S. Army Corps of Engineers personnel with the usage of the SAVRES program for the operational management of Hartwell, Russell, and Thurmond, the major storage and hydroelectric projects in the Savannah River basin. The manual primarily emphasizes the user–program interface and only briefly describes the program structure. More information on the encoded methodologies can be found in the associated project technical report.

The manual includes five sections and seven appendices. Section 2 describes the SAVRES input files in detail. Sample input files are provided in Appendices A, B, C, and D. Section 3 includes a step–by–step description of three SAVRES runs, respectively pertaining to average, drought, and flood operation conditions. This section explains the additional information interactively requested by SAVRES at run time and illustrates the format of the generated output. Sample output files are included in Appendices E, F, and G. Section 4 itemizes the computer programs and files provided with this manual and gives directions for microcomputer or main frame program implementations. Section 5 outlines possible program extensions and enhancements and concludes the manual.

The best way to become familiar with SAVRES is to experiment with the case studies described herein. The sample input files provided can serve as a starting point for this experimentation. More specifically, the user must first thoroughly cover Section 2. Then, one should install the programs on a computer system and perform the test runs illustrated in Section 3. Further experimentation with new input files and realistic operational conditions will increase one's familiarity and confidence with the SAVRES logic.

SAVRES uses a state–of–the–art methodology for reservoir system management. However, particular attention has been placed in the design of a friendly and intuitive user–program interface. As mentioned in Section 5, this interface can be enhanced further; however, the best enhancements are those that will effectively serve user needs. To this end, the input from the program users will be useful and is especially welcome.

2. THE INPUT FILES

The SAVRES program utilizes information from both input files as well as interactively. The purpose of accepting input from various sources is to make the input process efficient and user friendly, especially under various hydrologic and operational conditions.

The first input file contains system and control parameters essential to all program runs. Other input files may be requested depending on the inflow forecasting procedures selected. The interactive information is supplied by the user at run time and includes data which are likely to differ from day to day. The following two subsections describe the input files. The interactive input process is illustrated in Section 3.

2.1 The First Input File

A sample of the first input file appears in Appendix A and is also included in the program diskette as file INPUT1. In addition to the data records (lines), this file also contains the name of each data variable in SAVRES. These explanatory records are skipped over when the file is actually read. To ease the development of the input files, all read statements utilize free formats. This implies that the data can simply be separated by blank spaces or commas. The first input file contains the following data.

Data Record 1: NHLV(1,1), (HLV(1,1,I), I-1,NHLV(1,1))

NHLV(1,1): Number of data values of array HLV(1,1,I).

HLV(1,1,I): Hartwell elevations (feet) indicating the top of the flood control pool at different dates within the year.

Data Record 2: (IMHLV(1,1,I), IDHLV(1,1,I), I-1,NHLV(1,1))

IMHLV(1,1,I): Month corresponding to the Ith HLV array value specified above.

IDHLV(1,1,I): Day of the month corresponding to the Ith HLV array value specified above.

Data Record 3: NHLV(1,2), (HLV(1,2,I), I-1,NHLV(1,2))

NHLV(1,2): Number of data values of array HLV(1,2,I).

HLV(1,2,I): Hartwell elevations (feet) indicating the top of the conservation pool at different dates within the year. This is also the target elevation sequence prescribed by the rule curve.

Data Record 4: (IMHLV(1,2,I), IDHLV(1,2,I), I=1,NHLV(1,2))

IMHLV(1,2,I): Month corresponding to the Ith HLV array value specified above.

IDHLV(1,2,I): Day of the month corresponding to the Ith HLV array value specified above.

Note on Records 1 through 4: As an example, Records 3 and 4 in the sample input file specify the following rule curve sequence: From January 1st through the 18th of April, Hartwell elevation increase linearly from 656 feet to 660 feet. The latter constitutes the desirable reservoir elevation through the 15th day of September when it starts declining linearly back down to 656 feet on December 1st. From then until the end of the year, the target reservoir elevation is maintained at 656 feet. These records may have as many elements as necessary to characterize the target elevation sequence, but the beginning and end points must correspond to January 1st and December 31st.

Data Records 5, 6, 7, & 8: These records are structured exactly as the previous two record pairs and encode two other critical reservoir level sequences. The first (Records 5 and 6) delineates the levels up to which the drawdown in Hatrwell should be balanced with the drawdown at the other two projects. The second (Records 7 and 8) defines the bottom of the conservation pool.

Data Record 9: TMX(1,1), TMN(1,1), TMX(1,2), TMN(1,2)

TMX(1,1): Maximum generation hours on a weekly basis for the hydroelectric facility at Hartwell.

TMN(1,1): Minimum generation hours on a weekly basis at Hartwell.

TMX(1,2): Maximum daily generation hours at Hartwell.

TMN(1,2): Minimum daily generation hours at Hartwell.

Note on Record 9: The weekly and daily intervals are pertinent to the different operational modes of SAVRES. Operations and decisions during normal or drought conditions are conducted on a weekly time scale. Flood events are handled on a daily or a four hour basis. The minimum generation times specified by TMN currently reflect a two hour minimum generation daily commitment. This commitment does not apply to weekends. By adjusting the values of the TMN array, one could examine the effects of other minimum generation scenarios.

Data Record 10: NT(1)

NT(1): Number of hydropower turbines at Hartwell.

Data Record 11: (PMAX(1,I), I=1,NT(1))

PMAX(1,I): Maximum power load for each turbine at Hartwell. The loads indicated in file INPUT1 represent a 25% overload compared to the nominal turbine capacity. This percentage, however, could be changed to a more appropriate level at run-time.

Data Record 12: (PMIN(1,I), I=1,NT(1))

PMIN(1,I): Minimum power load for each turbine at Hartwell.

Data Records 13 through 24: These records encode the characteristics of the Russell storage and hydropower project and are structured identically to the previous 12 records. The information is stored in the same arrays but in the second dimension. For example, (PMAX(2,I), I=1,NT(2)) includes the maximum power loads for each turbine at Russell and (HLV(2,2,I), I=1,NHLV(2,2)) includes the sequence of the conservation pool top (475 feet). Other levels of significance include the bottom of the conservation pool (470 feet), the top of the flood control pool (480 feet), and the level of 471 feet up to which Russell drawdown should be balanced with the drawdowns at Hartwell and Thurmond to provide equal recreation opportunities at the three lakes.

Data Records 25 through 36: These records encode the characteristics of the Thurmond storage and hydropower project and are structured identically to the records pertaining to Hartwell and Russell. The information is stored in the same arrays but in the third dimension. For example, (PMAX(3,I), I=1,NT(3)) includes the maximum power loads for each Thurmond turbine and (HLV(3,2,I), I=1,NHLV(3,2)) includes the sequence of the rule curve target levels. This sequence calls for a linearly increasing reservoir level from 326 to 330 feet over the period from January 1st through May 1st, a constant 330 feet reservoir level from May 1st through September 15, a linearly decreasing segment from 330 to 326 from September 15 through December 12, and a constant 326 feet level for the remainder of the year. Other levels of interest include the bottom of the conservation pool (312 feet), the top of the flood control pool (335 feet), and the level of 315 feet up to which Thurmond drawdown should be balanced with the drawdowns at Hartwell and Russell. This level balancing requirement prescribes that Hartwell and Thurmond experience the same drawdown from their respective rule curve sequences over the first 15 feet of their conservation pool. At the same period, Russell should fall from the top of its conservation pool (475 feet) to the level of 471 feet.

Data Record 37: CFSMIN, CFSMAX

CFSMIN: Minimum discharge from Thurmond (cfs). This value represents an average weekly or a daily commitment.

CFSMAX: Maximum discharge from Thurmond (cfs). The values for CFSMIN and CFSMAX have been set to 5800 and 30000 cfs respectively. However, the user can alter these values at run time.

Data Record 38: NSTEPS

NSTEPS: Number of data values for arrays ENTRG, WMN, WVR, and WSKW to be read next. These arrays include 52 values pertaining to each week of the year.

Data Records 39 through 42: (ENTRG(I), I=1,NSTEPS)

ENTRG(I): Weekly energy generation target (MWH/week) levels to be met collectively by the three projects.

Data Records 43 through 55: (WMN(1,I), I=1,NSTEPS)

WMN(1,I): Average weekly inflow at Hartwell (billion cubic feet per week - bcf/wk).

Data Records 56 through 68: (WMN(2,I), I=1,NSTEPS)

WMN(2,I): Average weekly inflow at Russell (bcf/wk).

Data Records 69 through 81: (WMN(3,I), I=1,NSTEPS)

WMN(3,I): Average weekly inflow at Thurmond (bcf/wk).

Data Records 82 through 120: These records are structured identically to the previous three record sets and supply values to arrays (WVR(1,I), WVR(2,I), and WVR(3,I), I=1,NSTEPS). These arrays include the standard deviation of the weekly inflows (bcf/wk) at Hartwell, Russell, and Thurmond respectively.

Data Records 121 through 159: These records define arrays (WSKW(1,I), WSKW(2,I), and WSKW(3,I), I=1,NSTEPS) which contain the skewness (third statistical moment) of the weekly inflows (bcf/wk) at Hartwell, Russell, and Thurmond respectively.

Note on Records 43 through 159: The statistical parameters provided in these records have been estimated from 63 years of historical weekly inflows to each project (1925 - 1987). These statistics are used by SAVRES to develop reliability bands around each reservoir's storage and elevation sequences.

2.2 Other Input Files

Version 1.0 of SAVRES includes three inflow forecasting possibilities. The first utilizes the above-mentioned historical statistics and does not require more information. The second offers the option of using historical sequences of a given rank. For example, if the user wishes to run SAVRES with a control horizon of 10 weeks and use the 3rd worst drought sequences of the record, the program searches through the historical records at the time of the current date and identifies the 10-week inflow sequence which ranks 3rd lowest in total inflow volume to each lake. The file with the historical inflow data is called "HISWKLY" and has been included with the program diskette. HISWKLY contains the weekly inflow volumes from 1925 through 1987 (63 years). A short excerpt from the top of this file appears in Appendix B. This file includes a total of 1237 records. The inflow volumes are read in free integer format and are expressed in cfs. Namely, weekly inflow volume can be obtained by multiplying the recorded cfs value times (60x60x24x7). The inflow values are preceded by the starting and ending date (month,day,year) and a project heading. The program requires equal number of inflow for each project.

The third inflow forecasting possibility is based on subjective inflow information provided by the user. Under this procedure, the user must prepare an input file which contains three inflow parameters for each period (week or day) of the control horizon. These parameters are (1) an inflow level which is always expected to be exceeded (F00), (2) an inflow level expected to exceed the actual inflow with a likelihood of 50% (F50), and (3) an inflow level expected to exceed the actual inflow with a likelihood of 95% (F95). Using this information, SAVRES determines appropriate three-parameter log-normal probability functions and eventually translates them into a similar description of the reservoir storage and elevation sequences. The program diskette includes three files with subjective inflow forecasts, named "SUBINF1", "SUBINF2", and "SUBINF3". These files appear in Appendix C and indicate the format required by SAVRES. The files must be organized in three similar blocks pertaining to Hartwell, Russell, and Thurmond. The first line in each block is a header and indicates the number N of data records following. The second line defines the data records in each column in terms of the three forecast parameters (F00, F50, and F95). The remaining N records include the parameter values for N periods of the control horizon. If the control horizon specified by the user exceeds N, the former is truncated accordingly. The inflow forecast files in Appendix C correspond to drought (SUBINF1), average (SUBINF2), and flood (SUBINF3) flow conditions.

Lastly, an input file named "APG3" may be used to enter the turbine outage schedules. An example of such a file appears in Appendix D and includes records read according to the following format: (A1,1X,I1,1X,I6,1X,I6). For example, the entry "H,3,032591,042091" communicates to SAVRES that Hartwell's 3rd turbine will be inoperative from 03/25/91/ through 04/20/91. As explained in the next section, the same information can be provided by the user at run time. In that case, the entries made interactively are recorded in "APG3" and may be used in subsequent SAVRES runs.

Except for input file information, SAVRES requires additional data provided by the user at run time. This interactive input process is illustrated and reviewed in the next section.

3. RUNNING SAVRES

Prior to running SAVRES, the user must include the pertinent input files (see previous section) in the directory of the SAVRES executable code (SAVRES.EXE). This section demonstrates several SAVRES runs using the input files discussed earlier. The objective is twofold: (1) To familiarize the user with the interactive input/output program features, and (2) to highlight the program's capabilities. The example runs are designed to illustrate SAVRES' normal, drought, and flood condition operational modes. In what follows, the user responses are italicized, while the program responses appear in regular type. Several comments are interjected to clarify the meaning of various input parameters and program outputs.

3.1 A Normal Operation Run

Program execution begins by typing SAVRES or the name of the file containing the executable code. First, the program announces itself and then prompts the user for a number of input parameters qualifying precisely the type of run desired.

```
                    Program Prompts                User Responses

+-------------+
+ S A V R E S +-------------+
+-------------+ C O N T R O L +-------------+
              +-------------+ P R O G R A M +
                            +---------------+

ENTER THE NAME OF THE FIRST INPUT FILE         -> INPUT1

ENTER THE NAME OF THE OUTPUT FILE              -> OUTPUT1
```

Comment: The output file contains detailed results generated by SAVRES.

```
ENTER STARTING DATE (E.G., 03,25,1991,MONDAY) -> 05,06,1991,MONDAY
```

Comment: The read format for the date is (I2,1X,I2,1X,I4,1X,A9). Generally except for entries that involve character variables, SAVRES reads user responses in a free format. This implies that the entries may be separated by a comma or a space.

```
ENTER THE INITIAL LAKE ELEVATIONS (FT)         -> 660 475 330

FOR NORMAL  OPERATION ANALYSIS, ENTER  1
FOR DROUGHT OPERATION ANALYSIS, ENTER  2
FOR FLOOD   OPERATION ANALYSIS, ENTER  3       -> 1
```

```
ENTER THE CONTROL HORIZON
WEEKS FOR NORMAL OR DROUGHT CONDITIONS;
DAYS FOR FLOOD CONDITIONS                         -> 10

DO YOU WISH TO ENTER TURBINE OUTAGES? (Y/N)       -> Y

ARE OUTAGE SCHEDULES ALREADY IN FILE? (Y/N)       -> N
```

Comment: The file referred to here is "APG3". If it exists, it can be utilized by SAVRES at this point. If the user's response is "*N*", the program will create or modify APG3 to record the following entries. If APG3 already contains turbine outage schedules, they will be deleted.

```
ENTER TURBINE SHUT-DOWN SCHEDULES ONE AT A TIME
E.G., H,3,032591,042091 INDICATES THAT THE 3RD
TURBINE OF HARTWELL WILL BE DOWN FROM 03/25/91
THROUGH 04/20/91                                  -> R,2,060191,063091
```

Comment: The outage schedules do not have to be entered in any particular order with respect to the reservoirs or the turbines. However, the read format is (A1,1X,I1,1X,I6,1X,I6).

```
WILL THERE BE ANY MORE OUTAGES?            (Y/N) -> N

MAX. TURBINE POWER IS SET AT 25% OVERLOAD
DO YOU WISH TO CHANGE THIS PERCENTAGE? (Y/N)      -> Y

ENTER OVERLOAD PERCENTAGES FOR H, R, & T
E.G., 25,15,10                                    -> 15 15 15
```

Comment: The overload percentages reflect the standing contracts of power capacity sold by the SouthEastern Power Administration (SEPA).

```
FOR HISTORICAL  INFLOW FORECASTS, ENTER 1
FOR STATISTICAL INFLOW FORECASTS, ENTER 2
FOR SUBJECTIVE  INFLOW FORECASTS, ENTER 3         -> 2

50 < ENTER THE RELIABILITY LEVEL (%) < 99.9       -> 95
```

Comment: SAVRES performs both deterministic and stochastic analysis at the user's request. For deterministic analysis, the reliability level should be set to 50%. A reliability level r greater than 50% will invoke stochastic considerations.

```
ENTER INFLOW AND ENERGY MULTIPLIERS               -> 1 1
```

Comment: These multipliers can be used to investigate various hydrologic scenarios and energy generation targets. A multiplier of 1 preserves the forecasted inflow sequences and the energy generation targets included in File INPUT1. A multiplier of 1.3 would introduce a proportional 30% inflow or energy target increase throughout the control horizon.

```
MIN. AND MAX. FLOW RATES FROM THURMOND ARE
 5800 AND  30000 CFS
DO YOU WISH TO CHANGE THEM (Y/N)?                 => N
```

Comment: The above minimum flow rate represents a weekly-averaged quantity. Namely, the total outflow volume devided by (60x60x24x7) should be higher than 5800 cfs. More specifically, turbines run at actual flowrates determined by the power capacity targets or the above-specified upper outflow bound (30000 cfs), whichever is less. However, generation hours are such that total outflow volume does not violate the minimum outflow rate specified here.

```
FOR TRADEOFFS,  ENTER 1
FOR A TEST RUN, ENTER 0                           => 1
```

Comment: The Savannah river system has multiple conflicting objectives. In systems such as these, the optimal decision depends on how much the operator is willing to sacrifice from one system objective in order to gain from another. During normal operation conditions, SAVRES quantifies this conflicting relationship (tradeoff) between energy generation on one hand and flood control, storage conservation, and recreation on the other. The second set of objectives is reflected on the deviations of the storage from the target sequences prescribed by the rule curve. After the tradeoff is quantified, SAVRES expects the user to decide on the most desirable operational policy. After the decision is made, the program generates the optimal power levels and generation time sequences which realize this selection. The option of a test run bypasses the generation of tradeoffs and goes directly into the generation of sequences with given (user-defined) objective priorities. This program option was primarily utilized during the program development phase.

```
ENTER NUMBER OF TRADEOFF CURVE POINTS             => 4
```

NORMAL OPERATION TRADEOFF (FILE OUTPUT1)

(ENERGY-TARGET) STATS. MWH PER WEEK			(ELEVATION-TARGET) STATISTICS - FEET					
			HARTWELL		RUSSELL		THURMOND	
NO.	MAX.	AVG.	MAX.	AVG.	MAX.	AVG.	MAX.	AVG.
1	14814.3	9680.0	0.03	0.01	0.01	0.00	0.02	0.01
	0.0	0.0	-0.01	-0.01	0.00	0.00	0.00	0.00
2	12428.5	7895.2	0.74	0.32	0.07	0.04	0.30	0.11
	0.0	0.0	0.00	0.00	0.00	0.00	0.00	0.00
3	296.6	197.0	3.79	2.03	0.37	0.25	0.99	0.68
	0.0	0.0	0.00	0.00	0.00	0.00	0.00	0.00
4	36.4	4.5	3.87	2.08	0.37	0.26	0.98	0.69
	0.0	0.0	0.00	0.00	0.00	0.00	0.00	0.00

Comment: After the user enters the number of tradeoff curve points, SAVRES performs a series of optimization runs and displays the above table which quantifies the normal operation tradeoff. This table includes two sets of statistics. Energy-related statistics appear on the left and elevation sequence statistics appear on the right. The energy generation statistics pertain to weekly energy from all three projects and its deviations from the target generation sequence. The elevation statistics refer to each individual project. Both sets of statistics are computed as follows: SAVRES begins by setting up as many objective priority combinations as the number of tradeoff points desired. These combinations range from placing full priority to energy generation to placing full priority to reservoir elevation. The resolution between these two extremes depends on the number of tradeoff points selected. The program then runs and identifies the power turbine and generation time sequences that optimize each particular objective priority configuration while meeting all constraints previously established. The energy and reservoir elevation sequences resulting from each optimization run are analyzed on a weekly basis and their deviations from the target sequences give rise to the statistics reported on the tradeoff table. If the analysis is stochastic, the deviations are computed based on the mean energy generation or reservoir elevation sequences. For each quantity and tradeoff point, the table reports four values: (1) The maximum positive deviation over the control horizon, (2) the average positive deviation over the control horizon, (3) the maximum negative deviation over the control horizon, and (4) the average negative deviation over the control horizon. Statistics 3 and 4 are in the second row of each tradeoff point. As seen on the above table, the first tradeoff point places priority on reservoir elevations and attempts to minimize their deviations from the rule curve sequences. The energy deviation is secondary. On the other hand, Tradeoff Point 4 has the reverse priorities. The system now generates the energy contracts and is not concerned with the reservoir storage sequences. As a result, the reservoir elevation sequences deviate from the rule curve values by as much as 3.87 feet for Hartwell, 0.37 feet for Russell, and 0.98 for Thurmond. Intermediate tradeoff points exhibit intermediate deviations. Next, the program offers the option to refine the quantified tradeoff by focusing on a particular tradeoff region or to examine the sequences behind the tradeoff points on display.

```
TO REFINE THIS TRADEOFF,          ENTER 1
TO EXAMINE SPECIFIC SEQUENCES, ENTER 2          -> 1

ENTER TRADEOFF POINT NO. RANGE  (E.G., 2 4)     -> 1 2

ENTER NUMBER OF NEW TRADEOFF CURVE POINTS       -> 4
```

NORMAL OPERATION TRADEOFF (FILE OUTPUT1)

(ENERGY-TARGET) STATS.			(ELEVATION-TARGET) STATISTICS - FEET					
	MWH PER WEEK		HARTWELL		RUSSELL		THURMOND	
NO.	MAX.	AVG.	MAX.	AVG.	MAX.	AVG.	MAX.	AVG.
1	14811.1	9688.6	0.02	0.00	0.00	0.00	0.02	0.00
	0.0	0.0	-0.01	-0.01	0.00	0.00	-0.02	0.00
2	14810.0	9612.3	0.04	0.02	0.01	0.00	0.02	0.01
	0.0	0.0	-0.03	-0.01	0.00	0.00	-0.01	0.00
3	14447.4	9283.3	0.17	0.07	0.02	0.01	0.07	0.03
	0.0	0.0	-0.04	-0.04	0.00	0.00	-0.01	-0.01
4	12428.1	7895.0	0.74	0.32	0.07	0.04	0.30	0.11
	0.0	0.0	0.00	0.00	0.00	0.00	0.00	0.00

Comment: If the selection is to focus on a certain tradeoff region as above, then the original tradeoff is deleted and cannot be retrieved again within the current normal operations program segment. However, one could reenter the normal operations program segment at a later time and recompute the tradeoffs of interest. Alternatively, one could avoid the need for tradeoff refinement by specifying more tradeoff points initially and obtaining better tradeoff curve resolution. However, higher resolution also implies higher computational load and longer waiting times.

```
TO REFINE THIS TRADEOFF,         ENTER 1
TO EXAMINE SPECIFIC SEQUENCES,   ENTER 2        -> 2

ENTER SPECIFIC TRADEOFF POINT NO. (E.G., 2)     -> 1
```

S U M M A R Y   S E Q U E N C E S
NORMAL OPERATION CONDITIONS

HARTWELL			RUSSELL			THURMOND		
ELEV-FT	GEN-HRS	MWH	ELEV-FT	GEN-HRS	MWH	ELEV-FT	GEN-HRS	MWH
660.00	27.84	11014.06	475.00	34.38	11378.75	330.00	52.97	16278.67
660.00	26.72	10571.07	475.00	33.06	10937.75	330.00	54.50	16742.35
660.00	26.56	10507.62	475.00	32.65	10806.48	330.00	52.11	16016.80
660.01	23.79	9411.48	475.00	37.64	9740.36	330.00	40.49	12482.24
660.00	23.37	9245.80	475.00	37.42	9681.28	330.00	41.22	12705.31
660.00	23.53	9309.97	475.00	37.86	9795.71	330.00	40.41	12458.12
659.99	24.39	9647.64	475.00	39.02	10095.96	330.00	42.99	13243.42
660.02	19.38	7664.91	475.00	30.14	7799.16	330.02	31.90	9870.24
660.01	19.50	7714.08	475.00	24.07	7966.41	330.01	31.90	9869.42
659.99	18.36	7264.87	475.00	22.33	7388.74	329.99	31.90	9868.02
660.00			475.00			330.00		

Comment: The summary sequences being displayed correspond to the mean reservoir elevation, the generation time, and the energy generation sequences for each project. In this particular case, the priority is to stay near the rule curve elevation targets. For the period of this run (10 weeks starting 05/06/1991), the targets are 660 for Hartwell, 475 for Russell, and 330 for Thurmond. The table indicates that SAVRES manages to maintain reservoir elevations in the vicinity of the targets throughout the control horizon. The total release from Thurmond is greater or equal to the average weekly outflow requirement of 5800 cfs. If the minimum generation (at least 2 hours during the 5 week days) or outflow requirements made it impossible to maintain target levels, the reservoirs would begin to experience drawdowns. SAVRES ensures that the drawdowns meet the storage balancing requirement. This requirement amounts to equalizing the drawdowns at Hartwell and Thurmond for the first 15 feet of their conservation storage, while Russell is proportionally depleted from 475 to 471 feet. SAVRES is designed to fully comply with this requirement (to the extent feasible). Experimentation with other (drier) inflow scenarios shows that SAVRES accomplishes this balancing requirement within a half of a foot. Severe drawdowns can be avoided if the minimum weekly average flow requirement is reduced.

```
TO REMAIN IN NORMAL OPERATION MODE, ENTER 1
TO EXIT,                            ENTER 0   -> 0
```

Comment: If the user response is to remain in the normal operation mode, the program re-displays the active tradeoff curve and offers the user the opportunity to refine it or examine other sequences. If the user chooses to exit, he may either terminate this SAVRES session by also selecting exit on the following choice menu or continue the analysis. The second choice allows one to reenter the normal operation mode or opt for either of the other two modes (pertaining to drought or flood events).

```
EXITING NORMAL OPERATIONS

TO CONTINUE THE ANALYSIS, ENTER 1
TO EXIT,                  ENTER 0           -> 0

THE RESULTS FOR THIS SESSION ARE IN FILE OUTPUT1
```

Comment: Except for the summary results provided on the screen, SAVRES generates a lot more data regarding the operation of the system. These additional data together with all results displayed on the screen are recorded on the output file the name of which was specified by the user at the beginning of the SAVRES session. The entire output file (OUTPUT1) generated by this case study is included in Appendix E. To facilitate the discussion, an excerpt from this file pertaining to the 8th week of the control horizon is reproduced below.

WEEK 8

5/ 6/1991

H A R T W E L L

PERCENTILES:	5.00%	MEAN	95.00%		
BEGINNING STORAGE (BCF):	107.62	111.09	114.64		
ENDING STORAGE (BCF):	108.76	111.06	113.39		
BEGINNING ELEVATION (FT):	658.58	660.02	661.45		
ENDING ELEVATION (FT):	659.05	660.01	660.95		
MEAN INFLOW (CFS):	3378.58				
TURBINE NO.:	1	2	3	4	5
PEAK POWER (MW):	75.90	75.90	75.90	75.90	92.00
OUTFLOW (CFS):	5717.83	5717.83	5717.83	5717.83	6969.60
PEAK GENERATION (HRS):	19.38	OFF-PEAK GEN. (HRS):	0.00		
PEAK ENERGY (MWH):	7664.91	OFF-PEAK ENERGY (MWH):	0.00		
TOTAL POWER OUTPUT (MW):	395.60				
TURBINE OUTFLOW (CFS):	29840.90				
SPILLWAY OUTFLOW (CFS):	0.00				

R U S S E L L

PERCENTILES:	5.00%	MEAN	95.00%	
BEGINNING STORAGE (BCF):	43.53	44.71	45.91	
ENDING STORAGE (BCF):	44.09	44.70	45.33	
BEGINNING ELEVATION (FT):	473.98	475.00	476.03	
ENDING ELEVATION (FT):	474.47	475.00	475.53	
MEAN INFLOW (CFS):	733.54			
TURBINE NO.:	1	2	3	4
TURBINE POWER (MW):	86.25	0.00	86.25	86.25
OUTFLOW (CFS):	7766.32	0.00	7766.32	7766.32
PEAK GENERATION (HRS):	30.14	OFF-PEAK GEN. (HRS):	0.00	
PEAK ENERGY (MWH):	7799.16	OFF-PEAK ENERGY (MWH):	0.00	
TOTAL POWER OUTPUT (MW):	258.75			
TURBINE OUTFLOW (CFS):	23298.95			
SPILLWAY OUTFLOW (CFS):	0.00			

T H U R M O N D

PERCENTILES:	5.00%	MEAN	95.00%				
BEGINNING STORAGE (BCF):	106.31	109.51	112.77				
ENDING STORAGE (BCF):	106.55	109.48	112.46				
BEGINNING ELEVATION (FT):	328.99	330.02	331.04				
ENDING ELEVATION (FT):	329.07	330.01	330.94				
MEAN INFLOW (CFS):	1568.59						
TURBINE NO.:	1	2	3	4	5	6	7
TURBINE POWER (MW):	44.55	44.54	44.53	44.51	44.48	44.45	37.11
OUTFLOW (CFS):	4400.61	4399.34	4397.76	4395.73	4393.03	4389.21	3622.94
SERVICE UNITS (MW):	1.00	0.00					
OUTFLOW (CFS):	104.38	0.00					
PEAK GENERATION (HRS):	31.90	OFF-PEAK GEN. (HRS):	0.00				
PEAK ENERGY (MWH):	9702.24	OFF-PEAK ENERGY (MWH):	0.00				
TOTAL POWER OUTPUT (MW):	304.17						
TURBINE OUTFLOW (CFS):	29998.62						
SPILLWAY OUTFLOW (CFS):	0.00						

Comment: The additional information contained in this file is as follows: SAVRES generates for each week of the control horizon the beginning-of-the-week storage (bcf) and elevation (ft) along with their associated probability bands. The probability bands indicate the storage and elevation ranges where the system reservoirs are expected to be contained at the specified reliability if they are operated according to the recommendations made by SAVRES. For this week, the band width is about two feet for Hartwell, one foot for Russell, and two feet for Thurmond. The mean inflow in (cfs) is also recorded and is followed by several turbine data. Among these data are peak turbine power (MW) and outflow (cfs), peak and off-peak generation times (hrs), total peak and off-peak energy generation (MWH), total power output (MW), actual turbine outflow (cfs), and spillway outflow (cfs). The distinction of "peak" and "off-peak" power made herein is based on a 15 hour peak power demand period (7:00 to 22:00 hours), Monday through Friday. Weekends are off-peak periods. To determine the turbine power levels, SAVRES optimizes each plant individually and attempts to maximize the energy generation efficiency. Namely, the power levels identified maximize power production for a given total project outflow. The program also ensures that the minimum and maximum release requirement are always met. For instance in the above case study, Thurmond does not meet its power target of 322 MW (=40x7x1.15) because the total outflow would have exceeded 30,000 cfs. Instead, the release is constrained at 30,000 cfs and then the turbine power levels are found such that overall plant power production is maximized. If, due to outage schedules, some of the turbines are inoperative (as in the case of Russell), the other turbines must pick up as much of the power deficit as possible and are likely to use up all of their capacity and operate longer. This output file also includes the characteristics of the two small service station units at Thurmond. It is assumed that one of these units will at any time be operative at the 1 MW power level. The minimum weekly outflow requirement of 5800 cfs from Thurmond is a binding constraint in Week 8 as the following computation indicates: (29998.62 x 31.90 x 60 x 60 + 104.38 x 168 x 60 x 60) /(168 x 60 x 60) ≈ 5800.

In a real–time operation, after the best operational policy has been decided, the information provided in this file should be used to schedule the turbine power generation for the first week of the control horizon. At the beginning of the next week, SAVRES should be run again with updated information on project inflows, water levels and energy demands.

3.2 A Drought Operation Run

The format of the drought mode of SAVRES is very similar to the one described earlier. The comments are primarily intended to provide greater insight of the program functions specific to drought management.

```
                      Program Prompts                 User Responses

+---------------+
+ S A V R E S   +--------------+
+---------------+ C O N T R O L +---------------+
              +----------------+  P R O G R A M +
                               +----------------+

ENTER THE NAME OF THE FIRST INPUT FILE          => INPUT1

ENTER THE NAME OF THE OUTPUT FILE               => OUTPUT2

ENTER STARTING DATE (E.G., 03,25,1991,MONDAY)  => 08,19,1991,MONDAY

ENTER THE INITIAL LAKE ELEVATIONS (FT)          => 655,473.5,325

FOR NORMAL  OPERATION ANALYSIS, ENTER  1
FOR DROUGHT OPERATION ANALYSIS, ENTER  2
FOR FLOOD   OPERATION ANALYSIS, ENTER  3        => 2

ENTER THE CONTROL HORIZON
WEEKS FOR NORMAL OR DROUGHT CONDITIONS;
DAYS FOR FLOOD CONDITIONS                       => 10

DO YOU WISH TO ENTER TURBINE OUTAGES? (Y/N)     => N

MAX. TURBINE POWER IS SET AT 25% OVERLOAD
DO YOU WISH TO CHANGE THIS PERCENTAGE? (Y/N)    => N

FOR HISTORICAL  INFLOW FORECASTS, ENTER 1
FOR STATISTICAL INFLOW FORECASTS, ENTER 2
FOR SUBJECTIVE  INFLOW FORECASTS, ENTER 3       => 1

THE HISTORICAL SEQUENCES ARE RANKED FROM
1 (WORST DROUGHT)  TO  63 (WORST FLOOD)
ENTER DESIRED INFLOW SEQUENCE RANK              => 1

ENTER INFLOW AND ENERGY MULTIPLIERS             => 0.5    1

ENTER A DISCHARGE RANGE (CFS) FOR THURMOND      => 3600. 5800.
```

Comment: This entry is critical in the tradeoff analysis to follow. SAVRES uses this range to examine what would happen to the system if the weekly minimum release from Thurmond varied from 5800 cfs to 3600 cfs. Based on the results one can evaluate the benefits of early rationing versus the risks associated with overdrawn reservoir storages.

```
FOR TRADEOFFS,  ENTER 1
FOR A TEST RUN, ENTER 0                          -> 1

ENTER NUMBER OF TRADEOFF CURVE POINTS            -> 4
```

DROUGHT OPERATION TRADEOFFS (FILE OUTPUT2)

NO.	THURMOND AVG. DISCH. CFS	SYSTEM ENERGY MWH/WK.	RESERVOIR ELEVATION STATISTICS - FEET HARTWELL MIN.	WEEK	RUSSELL MIN.	WEEK	THURMOND MIN.	WEEK
1	5799.95	23869.	650.95	11	473.08	10	320.99	11
2	4727.21	19882.	652.25	11	473.35	9	322.29	11
3	4085.00	17505.	653.02	11	473.49	9	323.05	11
4	3599.76	15716.	653.59	11	473.50	1	323.63	11

Comment: The left side of the drought tradeoff table includes statistics of the outflow from Thurmond and system energy generation. More specifically, the table includes the average Thurmond outflow rates (cfs) over the control horizon. The first and last points correspond to the extremes of the range specified earlier. The intermediate points are characterized by a diminishing outflow pattern from a high to a low value within the specified range. The system energy display the reductions in energy generation, expected as a result of the lower system outflow. The right hand side of the table indicates the minimum elevation of each reservoir and the associated time period. As seen by the above results, one is faced with the tradeoff of early reservoir depletion versus a reduction of the system outflow and energy generation.

```
TO REFINE THIS TRADEOFF,          ENTER 1
TO EXAMINE SPECIFIC SEQUENCES, ENTER 2      -> 2

ENTER SPECIFIC TRADEOFF POINT NO. (E.G., 2)   -> 1
```

S U M M A R Y   S E Q U E N C E S
DROUGHT OPERATION CONDITIONS

HARTWELL			RUSSELL			THURMOND		
ELEV-FT	GEN-HRS	MWH	ELEV-FT	GEN-HRS	MWH	ELEV-FT	GEN-HRS	MWH
655.00	15.28	5894.42	473.50	14.21	4818.44	325.00	31.88	9171.40
654.68	16.42	6324.11	473.79	19.53	6640.76	324.43	31.87	9129.79
654.39	16.34	6282.63	473.71	19.29	6564.54	324.14	31.87	9110.91
654.05	16.08	6180.22	473.63	19.02	6481.35	323.79	31.87	9085.86
653.64	15.92	6097.60	473.53	18.77	6406.39	323.38	31.87	9056.41
653.23	16.35	6246.37	473.42	19.26	6583.11	322.96	31.87	9027.16
652.80	16.05	6117.75	473.31	19.05	6521.89	322.54	31.87	8997.24
652.34	15.04	5718.40	473.19	17.98	6163.62	322.09	31.87	8965.01
651.94	17.94	6804.49	473.09	20.04	6880.97	321.71	31.87	8937.74
651.43	17.74	6707.60	473.07	19.41	6677.58	321.33	31.86	8911.32
650.95			473.08			320.99		

Comment: The sequences associated with the 1st tradeoff point demonstrate SAVRES' ability to meet the balancing storage constraint. The drawdowns experienced by Hartwell and Thurmond below the levels of 660 and 330 do not differ by more than 0.25 of a foot. The table also provides the weekly energy generation schedule. As mentioned, generation of less than 75 hours per week represents peak energy. This information is also useful to the Southeastern Power Administration (SEPA) which markets the energy and the capacity generated by these projects. SAVRES is designed to also handle situations where the reservoirs are drawn below the balancing storage ranges of 660-645, 475-471, and 330-315 feet. On such occasions, Hartwell, with still another 20 feet of conservation storage remaining, provides most of the water supply, while Russell and Thurmond are drawn down to 470 and 312 feet respectively. During refiling, the process is reversed. Hartwell fills up faster than the other two projects until all three reach the levels of 645, 471, and 315. Thereafter they adhere to the balancing constraint and refill proportionally.

```
TO REMAIN IN DROUGHT OPERATION MODE, ENTER 1
TO EXIT,                             ENTER 0  -> 1
```

DROUGHT OPERATION TRADEOFFS (FILE OUTPUT2)

NO.	THURMOND AVG. DISCH. CFS	SYSTEM ENERGY MWH/WK.	RESERVOIR ELEVATION STATISTICS - FEET HARTWELL MIN.	WEEK	RUSSELL MIN.	WEEK	THURMOND MIN.	WEEK
1	5799.95	23869.	650.95	11	473.08	10	320.99	11
2	4727.21	19882.	652.25	11	473.35	9	322.29	11
3	4085.00	17505.	653.02	11	473.49	9	323.05	11
4	3599.76	15716.	653.59	11	473.50	1	323.63	11

Comment: This is the same tradeoff table derived earlier and is redisplayed for the user to examine additional tradeoff point sequences.

```
TO REFINE THIS TRADEOFF,         ENTER 1
TO EXAMINE SPECIFIC SEQUENCES, ENTER 2        -> 2

ENTER SPECIFIC TRADEOFF POINT NO. (E.G., 2)   -> 4
```

S U M M A R Y   S E Q U E N C E S
DROUGHT OPERATION CONDITIONS

HARTWELL			RUSSELL			THURMOND		
ELEV-FT	GEN-HRS	MWH	ELEV-FT	GEN-HRS	MWH	ELEV-FT	GEN-HRS	MWH
655.00	11.53	4446.89	473.50	10.00	3389.85	325.00	19.56	5691.67
654.86	10.02	3863.73	473.83	12.31	4177.58	324.75	19.55	5680.09
654.89	11.14	4294.76	473.84	13.42	4558.86	324.65	19.55	5675.49
654.81	10.90	4199.86	473.82	13.15	4469.78	324.56	19.55	5671.42
654.66	10.75	4140.16	473.78	12.90	4386.51	324.40	19.55	5665.99
654.50	11.07	4257.51	473.74	13.24	4504.69	324.25	19.55	5659.09
654.35	10.70	4115.30	473.70	12.96	4410.09	324.09	19.55	5651.96
654.16	10.00	3842.00	473.65	12.16	4143.91	323.90	19.55	5643.60
654.04	14.06	5395.83	473.62	15.31	5218.28	323.79	19.55	5638.44
653.74	10.07	3858.64	473.69	11.05	3767.94	323.73	19.55	5636.41
653.66			473.76			323.57		

Comment: In comparison to the previous sequence, the generation hours at Thurmond have seriously been reduced due to reduction of the minimum weekly release from Thurmond from 5800 to 3600 cfs. The other projects adjust their schedules accordingly to accomplish reservoir balancing. The overall effect is higher reservoir elevations and less energy production.

```
TO REMAIN IN DROUGHT OPERATION MODE, ENTER 1
TO EXIT,                             ENTER 0  -> 0

EXITING DROUGHT OPERATIONS

TO CONTINUE THE ANALYSIS, ENTER 1
TO EXIT,                  ENTER 0           -> 0

THE RESULTS FOR THIS SESSION ARE IN FILE OUTPUT2
```

Comment: It is again noted that if the user wishes to continue the analysis he may do so without terminating the current SAVRES session. A response of "1" at the last prompt will permit continuation in the same or a different operation mode. File OUTPUT2 is included in Appendix F. An excerpt from this file pertaining to Week 8 is reproduced below:

WEEK 8

8/19/1991

HARTWELL

PERCENTILES:	50.00%	MEAN	50.00%
BEGINNING STORAGE (BCF):	97.57	97.57	97.57
ENDING STORAGE (BCF):	97.29	97.29	97.29
BEGINNING ELEVATION (FT):	654.16	654.16	654.16
ENDING ELEVATION (FT):	654.04	654.04	654.04

MEAN INFLOW (CFS): 1325.97

TURBINE NO.:	1	2	3	4	5
PEAK POWER (MW):	77.49	77.45	77.40	77.33	74.38
OUTFLOW (CFS):	6066.25	6062.86	6058.42	6052.28	5762.01

PEAK GENERATION (HRS):	10.00	OFF-PEAK GEN. (HRS):	0.00
PEAK ENERGY (MWH):	3842.00	OFF-PEAK ENERGY (MWH):	0.00

TOTAL POWER OUTPUT (MW): 384.04

TURBINE OUTFLOW (CFS): 30001.83

SPILLWAY OUTFLOW (CFS): 0.00

RUSSELL

PERCENTILES:	50.00%	MEAN	50.00%
BEGINNING STORAGE (BCF):	43.16	43.16	43.16
ENDING STORAGE (BCF):	43.13	43.13	43.13
BEGINNING ELEVATION (FT):	473.65	473.65	473.65
ENDING ELEVATION (FT):	473.62	473.62	473.62

MEAN INFLOW (CFS): 331.68

TURBINE NO.:	1	2	3	4
TURBINE POWER (MW):	93.74	93.74	93.74	59.43
OUTFLOW (CFS):	8132.64	8132.64	8132.64	5602.10

PEAK GENERATION (HRS):	12.16	OFF-PEAK GEN. (HRS):	0.00
PEAK ENERGY (MWH):	4143.91	OFF-PEAK ENERGY (MWH):	0.00

TOTAL POWER OUTPUT (MW): 340.65

TURBINE OUTFLOW (CFS): 30000.00

SPILLWAY OUTFLOW (CFS): 0.00

THURMOND

PERCENTILES:	50.00%	MEAN	50.00%
BEGINNING STORAGE (BCF):	91.38	91.38	91.38
ENDING STORAGE (BCF):	91.08	91.08	91.08
BEGINNING ELEVATION (FT):	323.90	323.90	323.90
ENDING ELEVATION (FT):	323.79	323.79	323.79

MEAN INFLOW (CFS): 929.55

TURBINE NO.:	1	2	3	4	5	6	7
TURBINE POWER (MW):	47.28	47.23	47.15	47.04	46.80	44.54	0.00
OUTFLOW (CFS):	5109.54	5099.30	5084.55	5061.05	5015.69	4628.99	0.00
SERVICE UNITS (MW):	1.00	0.00					
OUTFLOW (CFS):	108.53	0.00					

PEAK GENERATION (HRS):	19.55	OFF-PEAK GEN. (HRS):	0.00
PEAK ENERGY (MWH):	5475.60	OFF-PEAK ENERGY (MWH):	0.00

TOTAL POWER OUTPUT (MW): 280.04

TURBINE OUTFLOW (CFS): 29999.13

SPILLWAY OUTFLOW (CFS): 0.00

Comment: Notice that Thurmond generates at less than the target power of 350 MW due to the more stringent requirement of maintaining outflow below 30000 cfs. The weekly average release is $(29999.13 \times 19.55 + 108.53 \times 168)/168 \approx 3600$ cfs, as applicable to this tradeoff point.

3.3 Flood Operation Runs

During flood events, the attention is shifted to the high end of the discharge spectrum. The objective is to avoid damage-causing outflows while containing reservoir storage within the flood control pool. However, this may not always be possible and the system operator should carefully weigh the benefit of maintaining current discharge levels versus the risk of being forced to release excessively later. This is the tradeoff that SAVRES helps to resolve in the flood control mode. This section includes two runs. The first is representative of moderate floods where reservoir elevations do not exceed the top of the flood control pools (665, 480, and 335 feet respectively for Hartwell, Russell, and Thurmond). The second run is representative of large floods where reservoir elevations rise above the flood control pools and spillways become operative.

3.3.1 A Moderate Flood Run

```
                   Program Prompts                User Responses

+----------------+
+ S A V R E S   +----------------+
+-------------+  C O N T R O L  +----------------+
              +----------------+  P R O G R A M +
                               +-----------------+

ENTER THE NAME OF THE FIRST INPUT FILE          -> INPUT1

ENTER THE NAME OF THE OUTPUT FILE               -> OUTPUT3

ENTER STARTING DATE (E.G., 03,25,1991,MONDAY)  -> 02,11,1991,MONDAY

ENTER THE INITIAL LAKE ELEVATIONS (FT)          -> 660,475,330

FOR NORMAL  OPERATION ANALYSIS, ENTER  1
FOR DROUGHT OPERATION ANALYSIS, ENTER  2
FOR FLOOD   OPERATION ANALYSIS, ENTER  3        -> 3

ENTER THE CONTROL HORIZON
WEEKS FOR NORMAL OR DROUGHT CONDITIONS;
DAYS FOR FLOOD CONDITIONS                       -> 10

DO YOU WISH TO ENTER TURBINE OUTAGES? (Y/N)     -> N

MAX. TURBINE POWER IS SET AT 25% OVERLOAD
DO YOU WISH TO CHANGE THIS PERCENTAGE? (Y/N)    -> N

ENTER THE NAME OF THE INFLOW FORECAST FILE      -> SUBINF3

50 < ENTER THE RELIABILITY LEVEL (%) < 99.9     -> 95
```

ENTER INFLOW AND ENERGY MULTIPLIERS -> *1 1*

FOR TRADEOFFS, ENTER 1
FOR A TEST RUN, ENTER 0 -> *1*

ENTER A DISCHARGE RANGE (CFS) FOR THURMOND -> *20000. 40000.*

Comment: SAVRES discretizes this range into as many levels as tradeoff points and analyzes each scenario separately.

ENTER NUMBER OF TRADEOFF CURVE POINTS -> *5*

FLOOD OPERATION TRADEOFFS (FILE OUTPUT3)

NO.	THURMOND DISCH. CFS	SYSTEM ENERGY MWH/DAY	RESERVOIR STATISTICS (MAXIMUM VALUES) HARTWELL FEET	HARTWELL CFS	RUSSELL FEET	RUSSELL CFS	THURMOND FEET	THURMOND CFS
1	20000.	10800.	665.17	20000.	480.16	20000.	335.18	20103.
2	25000.	13565.	664.59	25000.	479.53	25000.	334.60	25104.
3	30000.	16103.	663.98	30000.	478.99	30000.	334.00	30106.
4	35000.	18789.	663.39	32793.	478.37	33348.	333.41	35106.
5	40000.	19529.	663.18	32896.	478.13	33354.	333.20	37538.

Comment: The left side of the tradeoff table reports the maximum allowable Thurmond outflow rate applicable to this run and the resulted average weekly energy generation. The right side gives the maximum reservoir elevations reached and the highest actual outflow rates. (The maximum outflow constraint applies to turbine discharges excluding the service units.) As expected, higher outflow rates generate more energy and maintain lower reservoir elevations.

TO REFINE THIS TRADEOFF, ENTER 1
TO EXAMINE SPECIFIC SEQUENCES, ENTER 2 -> *2*

ENTER SPECIFIC TRADEOFF POINT NO. (E.G., 2) -> *4*

SUMMARY SEQUENCES
FLOOD OPERATION CONDITIONS - DAILY

HARTWELL			RUSSELL			THURMOND		
ELEV-FT	CFS	MWH	ELEV-FT	CFS	MWH	ELEV-FT	CFS	MWH
660.00	20830.	6555.57	475.00	30675.	8280.43	330.00	35102.	8179.58
660.00	19455.	6122.75	475.00	28615.	7724.41	330.00	35102.	8179.36
659.99	16583.	5218.79	474.99	24509.	6615.89	329.99	35102.	8179.12
660.06	13038.	4104.96	475.06	18518.	4998.69	330.07	35102.	8183.52
660.23	10651.	3357.15	475.23	16426.	4434.05	330.23	35103.	8193.59
660.48	8808.	2780.77	475.48	11784.	3180.80	330.49	35103.	8209.16
660.91	5511.	1744.72	475.90	6236.	1683.36	330.92	35106.	8232.69
661.52	4773.	1517.06	476.51	5248.	1416.54	331.53	35102.	8271.08
662.27	9232.	2948.10	477.26	11810.	3187.49	332.29	35105.	8319.36
662.91	15694.	5032.07	477.90	21913.	5914.04	332.93	35106.	8358.56
663.39			478.37			333.41		

Comment: In determining the optimal reservoir sequences corresponding to each maximum outflow rate, SAVRES is designed to accomplish the following objectives: (1) When reservoir levels rise, they rise equally above 660 (Hartwell), 475 (Russell), and 330 (Thurmond) feet. (2) As long as reservoir elevations are within the flood control pools (660-665, 475-480, and 330-335), the maximum downstream discharge is either the outflow corresponding to power capacity or the currently active maximum outflow level, whichever is *less*. Namely, within the flood control pools, spillways are not activated. (3) During falling reservoir levels, Thurmond is emptied faster than Russell, and Russell is emptied faster than Hartwell. The first two of the above features are illustrated by the above case study. The user may wish to run additional case studies to gain experience with the fourth as well.

```
TO REMAIN IN FLOOD OPERATION MODE, ENTER 1
TO EXIT,                           ENTER 0  -> 0

EXITING FLOOD OPERATIONS

TO CONTINUE THE ANALYSIS, ENTER 1
TO EXIT,                  ENTER 0        -> 0

THE RESULTS FOR THIS SESSION ARE IN FILE OUTPUT3
```

Comment: File OUTPUT3 is included in Appendix G and provides more complete information on the operation of each system turbine. Of particular interest to the user should also be the storage probability bands for each reservoir. Towards the end of the 10-day period, these bands indicate that the 95% confidence intervals have expanded to about 3 feet. The interpretation of the storage probability bands is that if the system is operated according to the suggestions made by SAVRES, our best ten day forecast is that the reservoir storages will be somewhere within the estimated probability bands with 95% confidence.

The likelihood that the storages will be in the vicinity of the mean values is, of course, higher. Clearly, the forecast for a shorter time span is more accurate as is indicated by the narrower probability bands estimated for the other days of the control horizon.

3.3.2 A Large Flood Run

```
                    Program Prompts                User Responses

+--------------+
+ S A V R E S  +------------+
+--------------+ C O N T R O L +-------------+
                +------------+ P R O G R A M +
                             +---------------+

ENTER THE NAME OF THE FIRST INPUT FILE         => INPUT1

ENTER THE NAME OF THE OUTPUT FILE              => OUTPUT4

ENTER STARTING DATE (E.G., 03,25,1991,MONDAY)  => 02,11,1991,MONDAY

ENTER THE INITIAL LAKE ELEVATIONS (FT)         => 663,478,333

FOR NORMAL  OPERATION ANALYSIS, ENTER  1
FOR DROUGHT OPERATION ANALYSIS, ENTER  2
FOR FLOOD   OPERATION ANALYSIS, ENTER  3       => 3

ENTER THE CONTROL HORIZON
WEEKS FOR NORMAL OR DROUGHT CONDITIONS;
DAYS FOR FLOOD CONDITIONS                      => 10

DO YOU WISH TO ENTER TURBINE OUTAGES? (Y/N)    => N

MAX. TURBINE POWER IS SET AT 25% OVERLOAD
DO YOU WISH TO CHANGE THIS PERCENTAGE? (Y/N)   => N

ENTER THE NAME OF THE INFLOW FORECAST FILE     => SUBINF3

50 < ENTER THE RELIABILITY LEVEL (%) < 99.9    => 95

ENTER INFLOW AND ENERGY MULTIPLIERS            => 2  1

FOR TRADEOFFS,  ENTER 1
FOR A TEST RUN, ENTER 0                        => 1

ENTER A DISCHARGE RANGE (CFS) FOR THURMOND     => 40000. 70000.
```

Comment: SAVRES discretizes this range into as many levels as tradeoff points and analyzes each scenario separately.

ENTER NUMBER OF TRADEOFF CURVE POINTS -> *6*

FLOOD OPERATION TRADEOFFS (FILE OUTPUT4)

	THURMOND	SYSTEM	RESERVOIR STATISTICS (MAXIMUM VALUES)					
	DISCH.	ENERGY	HARTWELL		RUSSELL		THURMOND	
NO.	CFS	MWH/DAY	FEET	CFS	FEET	CFS	FEET	CFS
1	40000.	26738.	664.84	32166.	480.77	44636.	336.00	60802.
2	46000.	26740.	664.84	32166.	480.77	44715.	335.96	59214.
3	52000.	26740.	664.84	32166.	480.78	52000.	335.89	57311.
4	58000.	26740.	664.84	32166.	480.73	58000.	335.81	58000.
5	64000.	26740.	664.84	32166.	480.64	64000.	335.72	64000.
6	70000.	26740.	664.84	32166.	480.61	66883.	335.61	70000.

Comment: As before, the left side of the tradeoff table contains the maximum allowable Thurmond outflow and the average weekly energy generation. The right side gives the maximum reservoir elevations reached and the highest actual outflow rates. Notice that some of the actual outflows exceed the specified bound. This happens because at reservoir elevations above the top of the flood control pool the spillway gates must be raised to avoid overtopping. As the gates are raised, spillway flow develops out of the opening between the crest and the gate bottom. The flow rate depends on the reservoir level and cannot be controlled. The above table shows that if Thurmond outflow is initially restricted, reservoir elevation will eventually rise and actuall outflow will exceed the specified limit. If, on the other hand, higher outflow rates are permitted, reservoir elevations are kept lower. In this mode of operation (large flood), power generation proceeds at the specified target level.

TO REFINE THIS TRADEOFF, ENTER 1
TO EXAMINE SPECIFIC SEQUENCES, ENTER 2 -> *2*

ENTER SPECIFIC TRADEOFF POINT NO. (E.G., 2) -> *1*

S U M M A R Y S E Q U E N C E S
FLOOD OPERATION CONDITIONS - DAILY

HARTWELL			RUSSELL			THURMOND		
ELEV-FT	CFS	MWH	ELEV-FT	CFS	MWH	ELEV-FT	CFS	MWH
663.00	22581.	7244.71	478.00	33341.	8999.94	333.00	35606.	8423.84
663.63	22685.	7307.16	478.62	33253.	8999.94	333.17	35520.	8423.84
664.16	22484.	7266.46	479.14	33202.	8999.94	333.43	35384.	8423.85
664.64	19638.	6366.05	479.63	28613.	7749.63	334.06	35072.	8423.85

S U M M A R Y   S E Q U E N C E S
FLOOD OPERATION CONDITIONS - 4 HRS

HARTWELL			RUSSELL			THURMOND		
ELEV-FT	CFS	MWH	ELEV-FT	CFS	MWH	ELEV-FT	CFS	MWH
664.64	31836.	1719.99	479.63	33229.	1499.99	334.06	35072.	1403.98
664.66	31832.	1719.99	479.78	33234.	1499.99	334.24	34982.	1403.98
664.68	31828.	1719.99	479.94	33240.	1499.99	334.43	34892.	1403.98
664.70	31824.	1719.99	480.10	40000.	1499.99	334.61	34803.	1403.98
664.72	31821.	1719.99	480.18	40000.	1499.99	334.82	34702.	1403.98
664.74	31817.	1719.99	480.26	36511.	1499.99	335.03	40000.	1403.98
664.75	31813.	1719.99	480.38	38153.	1499.99	335.21	40000.	1403.98
664.78	31809.	1719.99	480.51	40565.	1499.99	335.44	46823.	1403.97
664.80	31804.	1719.99	480.62	42774.	1499.99	335.64	53924.	1403.97
664.82	31800.	1719.99	480.70	44619.	1499.99	335.83	60850.	1403.97
664.84			480.77			336.00		

Comment: The above sequences demonstrate how SAVRES operates during large flood events. SAVRES starts the analysis on daily time steps as in the moderate flood case. If, however, reservoir elevations exceed the top of the flood control pools, the control computations switch into four-hour intervals. The finer time resolution is necessary due to the faster reservoir dynamics when spillways are active. In this mode, turbines run at full power and the balancing of reservoir storages is enforced to the extent possible.

```
TO REMAIN IN FLOOD OPERATION MODE, ENTER 1
TO EXIT,                           ENTER 0  -> 0

EXITING FLOOD OPERATIONS

TO CONTINUE THE ANALYSIS, ENTER 1
TO EXIT,                  ENTER 0          -> 0

THE RESULTS FOR THIS SESSION ARE IN FILE OUTPUT4
```

Comment: File OUTPUT4 is included in Appendix H. An excerpt from this file appears below:

2/14/1991 THURSDAY
HOURS 20 - 24

HARTWELL

PERCENTILES:	5.00%	MEAN	95.00%				
BEGINNING STORAGE (BCF):	119.74	123.10	126.53				
ENDING STORAGE (BCF):	119.68	123.15	126.69				
BEGINNING ELEVATION (FT):	663.45	664.74	666.01				
ENDING ELEVATION (FT):	663.43	664.75	666.07				
MEAN INFLOW (CFS): 35366.73							
TURBINE NO.:	1	2	3	4	5		
PEAK POWER (MW):	82.50	82.50	82.50	82.50	100.00		
OUTFLOW (CFS):	6094.52	6094.52	6094.52	6094.52	7438.60		
PEAK GENERATION (HRS):	2.00	OFF-PEAK GEN. (HRS):	2.00				
PEAK ENERGY (MWH):	859.99	OFF-PEAK ENERGY (MWH):	859.99				
TOTAL POWER OUTPUT (MW):	430.00						
TURBINE OUTFLOW (CFS):	31816.68						
SPILLWAY OUTFLOW (CFS):	0.00						

RUSSELL

PERCENTILES:	5.00%	MEAN	95.00%				
BEGINNING STORAGE (BCF):	49.24	51.13	53.07				
ENDING STORAGE (BCF):	49.35	51.29	53.27				
BEGINNING ELEVATION (FT):	478.77	480.26	481.75				
ENDING ELEVATION (FT):	478.85	480.38	481.90				
MEAN INFLOW (CFS): 15356.48							
TURBINE NO.:	1	2	3	4			
TURBINE POWER (MW):	93.75	93.75	93.75	93.75			
OUTFLOW (CFS):	8323.73	8323.73	8323.73	8323.54			
PEAK GENERATION (HRS):	2.00	OFF-PEAK GEN. (HRS):	2.00				
PEAK ENERGY (MWH):	749.99	OFF-PEAK ENERGY (MWH):	749.99				
TOTAL POWER OUTPUT (MW):	375.00						
TURBINE OUTFLOW (CFS):	33294.72						
SPILLWAY OUTFLOW (CFS):	3216.46						

THURMOND

PERCENTILES:	5.00%	MEAN	95.00%				
BEGINNING STORAGE (BCF):	122.15	126.06	130.05				
ENDING STORAGE (BCF):	122.56	126.66	130.85				
BEGINNING ELEVATION (FT):	333.89	335.03	336.19				
ENDING ELEVATION (FT):	334.01	335.21	336.41				
MEAN INFLOW (CFS): 45259.04							
TURBINE NO.:	1	2	3	4	5	6	7
TURBINE POWER (MW):	50.00	50.00	50.00	50.00	50.00	50.00	49.99
OUTFLOW (CFS):	4992.75	4992.75	4992.75	4992.75	4992.75	4992.75	4991.65
SERVICE UNITS (MW):	1.00	0.00					
OUTFLOW (CFS):	102.39	0.00					
PEAK GENERATION (HRS):	2.00	OFF-PEAK GEN. (HRS):	2.00				
PEAK ENERGY (MWH):	699.99	OFF-PEAK ENERGY (MWH):	699.99				
TOTAL POWER OUTPUT (MW):	349.99						
TURBINE OUTFLOW (CFS):	34948.12						
SPILLWAY OUTFLOW (CFS):	4949.48						

4. PROGRAM IMPLEMENTATION

The diskette provided with this manual contains fortran and executable codes and a number of input files. The files with the suffix FOR contain fortran codes while SAVRES.EXE contains the executable code. As discussed in Section 2, Files INPUT1, HISWKLY, SUBINF1, SUBINF2, SUBINF3, and APG3 are SAVRES input files. The fortran codes are written in FORTRAN 77 Standard Programming Language and, after proper compilation, should run on most computer systems. The executable code was generated using the Ryan–McFarland FORTRAN compiler, Version 2.43, with the option for large adjustable arrays. This code will run on IBM–AT 286 and compatible personal computers as well as on 386 and 486 machines. However, the code requires the existence of 80287 or 80387 math co-processors. In the absence of math co-processors, the program must be re-compiled.

On personal computers, the programs can run from either a hard or a floppy disk. To run the programs from a hard disk, establish a new directory named SAVRES, for instance, and make a copy of all files provided. Then, go to that directory and simply type SAVRES to start program execution. The output files are also created at the same directory. For a floppy disk implementation, insert the program diskette in the floppy disk drive, change the DOS prompt to that drive, and type SAVRES to start program execution. The output files are also created on the floppy diskette, and, for this reason, the program diskette provided is not write-protected. To avoid accidental file overwriting, one should run the programs from copies of the original diskette.

To facilitate repetitive SAVRES sessions with minor interactive input differences, one could take advantage of the input/output redirection DOS feature. A batch file must first be created at the directory of SAVRES containing the following command: "SAVRES < FILE1 ", where FILE1 is a file containing all the entries that the user would have made interactively, one after the other. If the batch file is called SAV.BAT, typing SAV at the DOS prompt will initiate SAVRES execution with input taken from file FILE1.

As compiled, SAVRES can accept a control horizon of up to 30 time periods (weeks, days, or 4-hour intervals) depending on the operational mode). This should be sufficient in most cases of interest. However, longer control horizons could be employed by changing the dimensions in MAIN.FOR from 0:30 to 0:N, where N is the new control horizon.

Except for the output file named by the user, SAVRES also creates additional files during execution. These files are temporarily used to store and retrieve certain control model characteristics and are much smaller than the main output file. However, one must ensure that there is enough room on disk for the program to create and use them.

With regard to run time requirements, the demonstration runs in Section 3 take 45 to 50 CPU seconds on a COMPAQ–386 25 Mhz PC. (This time is longer when historical inflow forecasts (HISWKLY) are invoked or when large flood events are analyzed.)

5. FURTHER ENHANCEMENTS AND CONCLUSION

SAVRES was designed to assist the operational management of the Savannah River system. The program includes features that reflect the current operational practices but also utilizes advanced optimization techniques to identify optimal operational policies during normal flow conditions as well as during droughts or floods. SAVRES is organized in a modular form conducive to further enhancements or modifications. To this end some possible useful suggestions follow:

The inflow forecasting procedure currently available with SAVRES is based on historical weekly data or subjective operator forecasts. Such forecasting procedures are adequate during normal conditions or droughts. Operations during floods, however, would greatly benefit by the use of rainfall-streamflow predictors. Although the development of such models may require an upfront expense in improving basin instrumentation, it may be well worth the cost.

The SAVRES input–output procedures can be improved with the use of graphics and menu screens. Such data as tradeoff curves, probabilistic reservoir elevation sequences, unit shut–down and minimum generation schedules and inflow forecasts can be conveniently reviewed and selected from screen menus. A SAVRES version with such features is presently being prepared. Overall, improving the program–user interface usually leads to a more effective application and lessens the possibility of user error.

The control methodology programmed in SAVRES can efficiently handle large reservoir systems. The operation of Hartwell, Russell, and Thurmond is coordinated with other major southeastern reservoirs located in the Appalachicola and Alabama-Coosa basins. The methodology encoded in SAVRES can be used to quantify the impacts of various operational policies systemwide and assist the overall decision making process.

In conclusion, SAVRES was developed as a decision making aid for the operational management of the Savannah River system. Although it has the potential to become fully automated, this program version was designed to extensively interact with the user. As user experience and confidence with the program logic grows, more automated versions can evolve and used operationally.

APPENDIX A

The First Input File (INPUT1)

```
HARTWELL (ELEVATION-FEET):         NHLV(1,1), (HLV(1,1,I),I=1,NHLV(1,1))
                                   2      665. 665.
                                   (IMHLV(1,1,I),IDHLV(1,1,I),I=1,NHLV(1,1))
                                   1 1    12 31
                                   NHLV(1,2), (HLV(1,2,I),I=1,NHLV(1,2))
                                   5      656. 660. 660. 656. 656.
                                   (IMHLV(1,2,I),IDHLV(1,2,I),I=1,NHLV(1,2))
                                   1 1    4 18    10 15    12 1    12 31
                                   NHLV(1,3), (HLV(1,3,I),I=1,NHLV(1,3))
                                   2      645.     645.
                                   (IMHLV(1,3,I),IDHLV(1,3,I),I=1,NHLV(1,3))
                                   1 1    12 31
                                   NHLV(1,4), (HLV(1,4,I),I=1,NHLV(1,4))
                                   2      625.     625.
                                   (IMHLV(1,4,I),IDHLV(1,4,I),I=1,NHLV(1,4))
                                   1 1    12 31
HARTWELL (GENERATION-HRS):         TMX(1,1),TMN(1,1),TMX(1,2),TMN(1,2)
                                   168.     10.        24.       2.
HARTWELL (# OF TURBINES):          NT(1)
                                   5
HARTWELL (TURBINE MAX LOAD-MW):    (PMAX(1,J),J=1,NT(1))
                                   82.5  82.5  82.5  82.5   100
HARTWELL (TURBINE MIN LOAD-MW):    (PMIN(1,J),J=1,NT(1))
                                   15.    15.    15.    15.    17.
RUSSELL (ELEVATION-FEET):          NHLV(2,1), (HLV(2,1,I),I=1,NHLV(2,1))
                                   2      480. 480.
                                   (IMHLV(2,1,I),IDHLV(2,1,I),I=1,NHLV(2,1))
                                   1 1    12 31
                                   NHLV(2,2), (HLV(2,2,I),I=1,NHLV(2,2))
                                   2      475. 475.
                                   (IMHLV(2,2,I),IDHLV(2,2,I),I=1,NHLV(2,2))
                                   1 1    12 31
                                   NHLV(2,3), (HLV(2,3,I),I=1,NHLV(2,3))
                                   2      471.     471.
                                   (IMHLV(2,3,I),IDHLV(2,3,I),I=1,NHLV(2,3))
                                   1 1    12 31
                                   NHLV(2,4), (HLV(2,4,I),I=1,NHLV(2,4))
                                   2      470.     470.
                                   (IMHLV(2,4,I),IDHLV(2,4,I),I=1,NHLV(2,4))
                                   1 1    12 31
RUSSELL (GENERATION-HRS):          TMX(2,1),TMN(2,1),TMX(2,2),TMN(2,2)
                                   168.     10.        24.       2.
RUSSELL (# OF TURBINES) :          NT(2)
                                   4
RUSSELL (TURBINE MAX LOAD-MW):     (PMAX(2,J),J=1,NT(2))
                                   93.75  93.75  93.75  93.75
RUSSELL  (TURBINE MIN LOAD-MW):    (PMIN(2,J),J=1,NT(2))
                                   20.    20.    20.    20.
THURMOND (ELEVATION-FEET):         NHLV(3,1), (HLV(3,1,I),I=1,NHLV(3,1))
                                   2      335. 335.
                                   (IMHLV(3,1,I),IDHLV(3,1,I),I=1,NHLV(3,1))
                                   1 1    12 31
                                   NHLV(3,2), (HLV(3,2,I),I=1,NHLV(3,2))
                                   5      326. 330. 330. 326. 326.
                                   (IMHLV(3,2,I),IDHLV(3,2,I),I=1,NHLV(3,2))
                                   1 1    5 1     10 15    12 15    12 31
                                   NHLV(3,3), (HLV(3,3,I),I=1,NHLV(3,3))
                                   2      315.      315.
                                   (IMHLV(3,3,I),IDHLV(3,3,I),I=1,NHLV(3,3))
                                   1 1    12 31
                                   NHLV(3,4), (HLV(3,4,I),I=1,NHLV(3,4))
```

```
                              2       312.      312.
                              (IMHLV(3,4,I),IDHLV(3,4,I),I=1,NHLV(3,4))
                              1 1    12 31
THURMOND (GENERATION-HRS):    TMX(3,1),TMN(3,1),TMX(3,2),TMN(3,2)
                              168.       10.        24.        2.
THURMOND (# OF TURBINES) :    NT(3)
                              7
THURMOND (TURBINE MAX LOAD-MW): (PMAX(3,J),J=1,NT(3)), PMAX(3,8),PMAX(3,9)
                              50.  50.  50.  50.  50.  50.  50.  1.25  1.25
THURMOND (TURBINE MIN LOAD-MW): (PMIN(3,J),J=1,NT(3)), PMIN(3,8),PMIN(3,9)
                              10.  10.  10.  10.  10.  10.  10.  0.6   0.6
THURMOND OUTFLOW (CFS) RANGE:   CFSMIN,CFSMAX
                              5800.  30000.
ALL PROJECTS (# OF WEEKS):    NSTEPS
                              52
SYSTEM TARGET ENERGY GENERATION (MWH/WEEK): (ENTRG(L),L=1,NSTEPS)
22500 28200 28200 28200 28200 28800 29400 29400 29400 29400 27600 27600 27600
23700 23700 23700 23700 23400 23100 23100 23100 23100 21000 19500 19500 19500
19500 19800 20100 20100 20100 20100 21000 21000 21000 21000 22500 22500 22500
27600 23700 23700 23700 23700 22800 22800 22800 22800 23700 23700 23700 23700
HARTWELL INFLOW MEAN (BILLION CUBIC FEET / WEEK):  (WMN(1,L),L=1,NSTEPS)
     3.096798      3.443577      3.066472      3.239606
     3.101942      3.169633      3.180627      3.546946
     3.435211      3.505944      3.645198      3.502971
     3.706942      3.889548      3.760320      3.260487
     2.990484      2.872388      2.869553      2.539534
     2.511393      2.510909      2.689159      2.043365
     2.055119      2.002986      1.824666      1.884544
     1.967446      1.922088      1.857025      1.889937
     2.286333      2.038248      1.689354      1.646208
     1.694885      1.517741      1.603893      1.752550
     1.845202      1.915312      1.861035      1.902936
     1.876039      1.899202      1.956522      2.076899
     2.364464      2.673395      2.665167      2.647812
RUSSELL INFLOW MEAN (BILLION CUBIC FEET / WEEK):  (WMN(2,L),L=1,NSTEPS)
      .721956       .811073       .742207       .827599
      .756727       .873993       .774635       .877589
      .788325       .840805       .968650       .898954
      .984276       .977639       .912783       .804436
      .721326       .699131       .673203       .600257
      .626946       .645545       .657645       .443648
      .500138       .440537       .465497       .451461
      .472135       .435005       .392275       .415438
      .508988       .444685       .401886       .376856
      .380936       .378032       .401195       .417512
      .380521       .373123       .364618       .376649
      .377202       .445723       .485895       .502143
      .555521       .602331       .576610       .662071
THURMOND INFLOW MEAN (BILLION CUBIC FEET / WEEK):  (WMN(3,L),L=1,NSTEPS)
     2.737536      3.300096      3.750700      3.521837
     2.884547      3.035210      3.448546      4.172955
     3.828278      4.013028      4.180423      3.591395
     4.161892      4.045525      4.039786      3.073238
     2.072603      2.375725      2.169887      1.275178
     1.375090      1.243442      1.497403       .948686
      .845870      1.122718       .863709       .918194
     1.066920      1.048735      1.076876       .756814
     1.133504       .947718       .655382       .695208
      .606498       .500916      1.124378       .764558
     1.065330       .677507       .679236       .687395
      .696867       .869863      1.080679      1.248904
     1.504940      1.659889      1.796170      2.015352
HARTWELL INFLOW ST. DEVIATION (BCF / WEEK):  (WVR(1,L),L=1,NSTEPS)
      1.897287      2.317964      1.672344      1.881870
      1.483464      1.507901      1.402010      2.232458
      1.557323      1.783250      2.033391      1.811612
      1.870337      2.447016      2.574945      1.503065
      1.212038      1.359179      1.496362      1.118728
      1.070970      1.380751      2.131704      0.724414
```

0.997758	1.024063	0.835740	0.947722
1.112393	1.140908	1.001120	1.028775
3.249662	1.660840	1.055914	1.222351
1.132969	0.766412	1.091544	1.512611
1.588381	1.334389	1.402308	1.040189
1.053509	0.991301	0.945901	1.103672
1.429433	2.102467	1.836470	1.598430

RUSSELL INFLOW ST. DEVIATION (BCF / WEEK): (WVR(2,L),L=1,NSTEPS)

0.524687	0.611052	0.518529	0.695862
0.487232	0.958093	0.472122	0.610379
0.452354	0.602696	0.736440	0.623463
0.807175	0.920030	0.839026	0.594895
0.490120	0.523006	0.498163	0.410486
0.445095	0.598981	0.724465	0.356465
0.458273	0.295783	0.488589	0.364468
0.416756	0.463858	0.316113	0.323444
0.634104	0.445909	0.390633	0.358710
0.317835	0.388792	0.426587	0.522662
0.513738	0.353244	0.344133	0.350813
0.317440	0.423691	0.534210	0.508924
0.429435	0.573798	0.484312	0.703211

THURMOND INFLOW ST. DEVIATION (BCF / WEEK): (WVR(3,L),L=1,NSTEPS)

3.273741	3.081089	4.104341	3.529706
2.270294	2.495540	2.665786	3.570264
4.032501	4.285000	3.395756	3.054536
3.790210	4.037682	5.079161	3.401655
1.884182	2.310824	2.500735	0.977469
1.319471	1.106398	1.962197	0.683349
0.936843	1.587901	0.809037	1.001887
1.119384	1.082304	1.728102	0.740626
3.105851	1.776055	0.792746	0.994014
0.867126	0.673433	4.906214	1.841192
2.771608	0.989263	1.078572	0.977037
0.970943	1.693712	1.433277	1.737993
2.888899	2.212393	1.812362	1.919510

HARTWELL INFLOW SKEWNESS (BCF**3 / WEEK): (WSKEW(3,L),L=1,NSTEPS)

12.386803	23.271991	6.376307	10.416223
3.170710	2.825673	2.109942	32.875618
3.803181	8.821585	15.386647	11.373426
9.210579	27.830674	49.107224	3.826798
1.302286	3.168579	4.479932	1.511149
1.559656	7.645225	32.868799	.254259
1.903447	1.839989	.580006	.964107
2.755907	3.682724	2.007745	1.683409
199.572554	12.866690	2.029612	5.061589
4.315976	.819064	3.632230	9.920536
10.958156	3.668630	9.223145	1.719794
2.259799	1.506639	1.754546	2.962646
10.342457	29.753003	12.638905	11.342991

RUSSELL INFLOW SKEWNESS (BCF**3 / WEEK): (WSKEW(3,L),L=1,NSTEPS)

.221226	.293057	.185250	.618753
.110774	4.716060	.107410	.356674
.081845	.402062	.683123	.392736
1.061807	1.979446	1.331604	.390517
.211831	.408136	.208277	.127077
.141837	.683315	1.183773	.130762
.330167	.043084	.438699	.069372
.177743	.456720	.064306	.046795
.942333	.260514	.166398	.105272
.045547	.149705	.159339	.354786
.571449	.077562	.071960	.105800
.052994	.172499	.521042	.391111
.107871	.399976	.195369	1.062046

THURMOND INFLOW SKEWNESS (BCF**3 / WEEK): (WSKEW(3,L),L=1,NSTEPS)

155.714376	48.309682	183.217467	102.960520
20.827638	31.884593	31.426446	77.116308
187.156525	290.846304	54.351730	58.631416
149.736462	204.473080	624.633952	110.301343
20.139230	29.086812	39.106050	1.032501

4.686151	2.463737	21.852658	.681008
2.232622	14.162558	1.112597	2.368865
3.096286	3.018616	26.718318	.903970
186.104804	21.969471	.842013	2.752112
1.475580	.725521	916.420558	38.331228
115.893671	2.053767	4.022748	2.133541
2.899305	22.253927	9.598304	21.648255
160.621905	36.806096	10.173340	14.979361

APPENDIX B

An Excerpt from File HISWKLY

```
01,03,1925   12,26,1987
HISTORICAL INFLOWS FOR HARTWELL (CFS)
16613   8085  12248  11981   6364   5759   5557   5305
 4448   3807   4469   5550   4693   3706   4289   4210
 3555   2986   2424   2957   3274   2388   1999   1876
 1848   1581   2093   2366   1235    904    782   1142
 1379    846    796    803    796    796    890    854
  573    717   1574   3130   2755   2892   3655   1235
 1214   2150   3634   3050   1963   2964   4318   7638
 5420   5384   1812   4030   8323   6198   6702   4606
 3202   5125   6349   6889   2827   2309   2301   2150
 1927   1761   1711   1668   1840   2114   1689   1307
 1524   1632   4779   5816   1524   2165   2625   2503
 2431   1840   1826   1797   1495   1581   2020   1725
 1091   2215   4462   3439   1063   1948   3619   3439
 8279   3799   2431   2309   2388   2388   2633   5081
 6832   4340   6925   4412   2676   2698   2878   3202
 2676   2625   1415   1343   1783   3216   1379   1451
 3735   4188   2143   3000   3583   4952   3346   2366
 2049   1768   1322   1430   2597   1322   1005    976
 1423   1581   1466   1560   1718   1833   2006   2049
 3180   7804   5737   3857   2532   4124   3353   2352
 2755   3339   2525   2834   5074   5175   4368   4476
 4052   2885   1538   1848   7127   9151   4383   7458
 2813   5535   5182   4707   5118   4743   5298   4390
 6666   4714   5449   8135   8445  40755  14445   6097
12471   7631   7213   6428   5485   3792   8330   6896
 7393   5939   3266   1920   2345   2676   2849   2892
 2971   2906   3972   4160   4469   3980   5924   5074
 6011  13307  16418  15222  12349   8315   6140   5686
 5679   7509   8351   9540   7365   6299   6529   5442
 4448   4304   6443   5233   4167   4354   3634   3619
 3360   3072   2489   2028   2265   2834   5319  11801
15071   7336   3727   5571   6018   5492   8589   6810
 7480   6760   4966   5017   5175   5175   4707   5312
 5449   5413   6450   5730   4455   3943   6335   6299
 4786   4332   4534   4282   3915   3590   3295   3871
 4620   4159   3209   3360   3281   2856   2467   1984
 2056   2496   2287   2128   1934   1559   1495   1459
 1495   1876   2100   1992   1790   1840   1956   1941
 2028   1999   4073   4397   2870   4340   4390   3137
 3706   4275   4253   3828   3050   2510   2222   2294
 2705   3626   4080   3029   2676   3497   5161   5413
 3771   4440   4728   4520   4700   2993   2712   2344
 2100   2114   1977   2064   2388   2604   2525   2208
 2352   2892   2589   1977   1653   1797   1768   1768
 1783   1408   1466   1343   1466   1588   1437   1696
 1790   5333  10735  10281   7069   6363  11333  10058
 5117   5024   7156   4908   5240   5470   4008   4347
 3915   7141   6255   5333   4231   3295   4059   5189
 3641   3605   3749   3122   3353   8222   5838   2813
 2697   2323   2064   2741   7256   4383   3036   2697
 2244   2921   2035   2100   2661   3029   4916  15683
 4793   9878   3756   3475   5521   5434   5254  13494
10663  18168   9597   7537   5427   6176   5024   9381
 6709   7292   5377   5319   4865   5470   4541   4376
 4376   6904   4563   3979   5542   4087   4174   3821
 2460   2452   2028   4527   2308   2762   3684   2373
 2849   2741   2719   2841   4210   4332   2741   2308
 2337   2251   2035   3158   2056   2172   2705   2244
```

APPENDIX C

File SUBINF1

```
20 SUBJECTIVE INFLOW FORECASTS (CFS) FOR HARTWELL (320)
       F00       F50       F95
     1907.     2384.     4099.
     1187.     1484.     2929.
      916.     1145.     3489.
      812.     1016.     3320.
      444.      555.     1721.
      334.      418.     1543.
      254.      317.     1412.
      962.     1203.     3564.
     1193.     1491.     3938.
      928.     1160.     3507.
     1982.     2478.     4221.
     1556.     1945.     4528.
      375.      468.     1609.
      570.      713.     1927.
     1809.     2262.     4940.
     1763.     2204.     4865.
     1360.     1700.     4210.
     1809.     2262.     4940.
      933.     1167.     3517.
     1417.     1772.     4303.
20 SUBJECTIVE INFLOW FORECASTS (CFS) FOR RUSSELL (315)
       F00       F50       F95
      525.      656.     1853.
      467.      584.     1759.
      352.      440.     1572.
      335.      419.     1544.
      329.      411.     1535.
      202.      253.      729.
      202.      253.      729.
      139.      174.      626.
      173.      217.      682.
      220.      274.      857.
      116.      145.      588.
      110.      138.      579.
       76.       94.      323.
       93.      116.      351.
       99.      123.      460.
       35.       44.      157.
       29.       37.      148.
       18.       42.      129.
       18.       42.      129.
       47.       58.      176.
20 SUBJECTIVE INFLOW FORECASTS (CFS) FOR THURMOND (310)
       F00       F50       F95
     1452.     1815.     4359.
     1095.     1368.     4779.
      588.      735.     2955.
       29.      136.      847.
       17.      122.      828.
       35.      143.      856.
       17.      122.      828.
       35.      143.      856.
       23.      129.      837.
       29.      136.      847.
       29.      136.      847.
      478.      598.     1777.
      415.      519.     1674.
      109.      137.     1178.
      305.      382.     1496.
      225.      281.     1365.
       40.      150.      966.
```

35.	143.	956.
26.	117.	809.
282.	353.	1459.

File SUBINF2

20 SUBJECTIVE INFLOW FORECASTS (CFS) FOR HARTWELL (320)

F00	F50	F95
3023.	4030.	12045.
2958.	3944.	12916.
3244.	4326.	13488.
3044.	4059.	13089.
2531.	3375.	10062.
2337.	3116.	10673.
2769.	3692.	11538.
2191.	2921.	9382.
1613.	2150.	9226.
1440.	1920.	9880.
1629.	2172.	9258.
1759.	2345.	9517.
2661.	3548.	11322.
3946.	5262.	15893.
2358.	3144.	10717.
1824.	2431.	9647.
2148.	2864.	9295.
4465.	5953.	15930.
3514.	4686.	15029.
2439.	3252.	10879.

20 SUBJECTIVE INFLOW FORECASTS (CFS) FOR RUSSELL (315)

F00	F50	F95
519.	692.	2038.
573.	764.	2146.
627.	836.	2454.
638.	851.	2476.
595.	793.	2490.
913.	1218.	4027.
1043.	1391.	4886.
616.	822.	2533.
643.	858.	2687.
611.	815.	2322.
562.	750.	2225.
433.	577.	1665.
271.	361.	1241.
357.	476.	1514.
395.	527.	1490.
254.	339.	1309.
233.	310.	966.
157.	210.	714.
71.	94.	342.
584.	779.	2468.

20 SUBJECTIVE INFLOW FORECASTS (CFS) FOR THURMOND (310)

F00	F50	F95
2199.	2931.	9397.
1923.	2564.	9846.
1664.	2218.	9327.
2760.	3680.	11521.
1329.	1772.	6658.
1248.	1664.	6496.
4224.	5632.	16448.
3246.	4329.	15493.
1232.	1642.	5463.
616.	821.	2532.
1178.	1570.	5355.
2631.	3508.	11261.
1734.	2312.	8468.
529.	706.	2159.

535.	713.	2270.
529.	706.	2259.
73.	105.	318.
203.	258.	886.
85.	127.	411.
190.	250.	896.

File SUBINF3

20 SUBJECTIVE INFLOW FORECASTS (CFS) FOR HARTWELL (320)

F00	F50	F95
15799.	19749.	27648.
13898.	17372.	30321.
10458.	16573.	31802.
10991.	15489.	30484.
10184.	15481.	32073.
13850.	20063.	28488.
14613.	21267.	35573.
15742.	24677.	41548.
17793.	25241.	46137.
18219.	26774.	49884.
29455.	36819.	71546.
29605.	37006.	51808.
15742.	19677.	27548.
15776.	19720.	27608.
19544.	24430.	34203.
14094.	17617.	24664.
8954.	11192.	15669.
7698.	9622.	13471.
8159.	10199.	14278.
7721.	9651.	13512.

20 SUBJECTIVE INFLOW FORECASTS (CFS) FOR RUSSELL (315)

F00	F50	F95
4807.	8412.	18412.
4173.	7800.	17303.
4525.	7409.	17419.
4781.	6617.	13617.
4461.	7484.	18807.
4277.	7484.	16484.
4369.	7645.	17645.
5683.	9944.	17944.
5878.	10287.	20287.
8448.	10560.	24784.
9922.	17403.	24364.
10721.	14651.	20512.
8160.	10200.	14280.
7400.	9249.	12949.
8840.	11050.	15470.
6143.	7679.	10751.
3654.	4568.	6395.
4300.	5375.	7524.
2986.	3732.	5225.
2018.	2522.	3531.

20 SUBJECTIVE INFLOW FORECASTS (CFS) FOR THURMOND (310)

F00	F50	F95
2856.	3570.	7997.
4285.	5356.	11198.
8606.	10758.	25061.
15532.	19415.	39181.
19888.	24860.	45804.
25462.	34327.	67058.
31289.	46611.	85256.
40469.	50587.	99821.
32587.	40734.	84027.
19634.	24543.	64360.
10876.	13595.	38033.

7799.	9749.	23649.
10761.	13451.	18832.
4884.	6105.	8547.
29153.	36441.	51018.
16154.	20193.	28270.
4723.	5903.	8264.
4815.	6018.	8426.
5276.	6595.	9232.
4031.	5039.	7054.

APPENDIX D

An Example of Turbine Outage Schedule File APG3

```
H,3,032591,042091
R,2,032091,033091
R,4,033091,041091
T,7,032091,040191
T,2,032091,040191
```

APPENDIX E

Output File Generated by SAVRES in Section 3.1 (Normal Operations)

NORMAL OPERATION TRADEOFF

(ENERGY-TARGET) STATS. MWH PER WEEK NO.	MAX.	AVG.	(ELEVATION-TARGET) STATISTICS - FEET HARTWELL MAX.	HARTWELL AVG.	RUSSELL MAX.	RUSSELL AVG.	THURMOND MAX.	THURMOND AVG.
1	14814.3	9680.0	0.03	0.01	0.01	0.00	0.02	0.01
	0.0	0.0	-0.01	-0.01	0.00	0.00	0.00	0.00
2	12428.5	7895.2	0.74	0.32	0.07	0.04	0.30	0.11
	0.0	0.0	0.00	0.00	0.00	0.00	0.00	0.00
3	296.6	197.0	3.79	2.03	0.37	0.25	0.99	0.68
	0.0	0.0	0.00	0.00	0.00	0.00	0.00	0.00
4	36.4	4.5	3.87	2.08	0.37	0.26	0.98	0.69
	0.0	0.0	0.00	0.00	0.00	0.00	0.00	0.00

NORMAL OPERATION TRADEOFF

(ENERGY-TARGET) STATS. MWH PER WEEK NO.	MAX.	AVG.	(ELEVATION-TARGET) STATISTICS - FEET HARTWELL MAX.	HARTWELL AVG.	RUSSELL MAX.	RUSSELL AVG.	THURMOND MAX.	THURMOND AVG.
1	14811.1	9688.6	0.02	0.00	0.00	0.00	0.02	0.00
	0.0	0.0	-0.01	-0.01	0.00	0.00	-0.02	0.00
2	14810.0	9612.3	0.04	0.02	0.01	0.00	0.02	0.01
	0.0	0.0	-0.03	-0.01	0.00	0.00	-0.01	0.00
3	14447.4	9283.3	0.17	0.07	0.02	0.01	0.07	0.03
	0.0	0.0	-0.04	-0.04	0.00	0.00	-0.01	-0.01
4	12428.1	7895.0	0.74	0.32	0.07	0.04	0.30	0.11
	0.0	0.0	0.00	0.00	0.00	0.00	0.00	0.00

S U M M A R Y   S E Q U E N C E S
NORMAL OPERATION CONDITIONS
TRADEOFF POINT 1

HARTWELL ELEV-FT	HARTWELL GEN-HRS	HARTWELL MWH	RUSSELL ELEV-FT	RUSSELL GEN-HRS	RUSSELL MWH	THURMOND ELEV-FT	THURMOND GEN-HRS	THURMOND MWH
660.00	27.84	11014.06	475.00	34.38	11378.75	330.00	52.97	16278.67
660.00	26.72	10571.07	475.00	33.06	10937.75	330.00	54.50	16742.35
660.00	26.56	10507.62	475.00	32.65	10806.48	330.00	52.11	16016.80
660.01	23.79	9411.48	475.00	37.64	9740.36	330.00	40.49	12482.24
660.00	23.37	9245.80	475.00	37.42	9681.28	330.00	41.22	12705.31
660.00	23.53	9309.97	475.00	37.86	9795.71	330.00	40.41	12458.12
659.99	24.39	9647.64	475.00	39.02	10095.96	330.00	42.99	13243.42
660.02	19.38	7664.91	475.00	30.14	7799.16	330.02	31.90	9870.24
660.01	19.50	7714.08	475.00	24.07	7966.41	330.01	31.90	9869.42
659.99	18.36	7264.87	475.00	22.33	7388.74	329.99	31.90	9868.02
660.00			475.00			330.00		

DETAILED SEQUENCES
STARTING DATE: 5/ 6/1991 MONDAY

WEEK 1

HARTWELL

PERCENTILES:	5.00%	MEAN	95.00%
BEGINNING STORAGE (BCF):	111.04	111.04	111.04
ENDING STORAGE (BCF):	109.06	111.04	113.05
BEGINNING ELEVATION (FT):	660.00	660.00	660.00
ENDING ELEVATION (FT):	659.18	660.00	660.82

MEAN INFLOW (CFS): 4944.58

TURBINE NO.:	1	2	3	4	5
PEAK POWER (MW):	75.90	75.90	75.90	75.90	92.00
OUTFLOW (CFS):	5718.58	5718.58	5718.58	5718.58	6970.54

PEAK GENERATION (HRS):	27.84	OFF-PEAK GEN. (HRS):	0.00
PEAK ENERGY (MWH):	11014.06	OFF-PEAK ENERGY (MWH):	0.00
TOTAL POWER OUTPUT (MW):	395.60		
TURBINE OUTFLOW (CFS):	29844.84		
SPILLWAY OUTFLOW (CFS):	0.00		

RUSSELL

PERCENTILES:	5.00%	MEAN	95.00%
BEGINNING STORAGE (BCF):	44.70	44.70	44.70
ENDING STORAGE (BCF):	43.90	44.70	45.51
BEGINNING ELEVATION (FT):	475.00	475.00	475.00
ENDING ELEVATION (FT):	474.30	475.00	475.69

MEAN INFLOW (CFS): 1192.67

TURBINE NO.:	1	2	3	4
TURBINE POWER (MW):	86.25	86.25	86.07	72.44
OUTFLOW (CFS):	7765.61	7765.61	7765.61	6703.17

PEAK GENERATION (HRS):	34.38	OFF-PEAK GEN. (HRS):	0.00
PEAK ENERGY (MWH):	11378.75	OFF-PEAK ENERGY (MWH):	0.00
TOTAL POWER OUTPUT (MW):	331.00		
TURBINE OUTFLOW (CFS):	30000.00		
SPILLWAY OUTFLOW (CFS):	0.00		

THURMOND

PERCENTILES:	5.00%	MEAN	95.00%
BEGINNING STORAGE (BCF):	109.46	109.46	109.46
ENDING STORAGE (BCF):	106.39	109.46	112.59
BEGINNING ELEVATION (FT):	330.00	330.00	330.00
ENDING ELEVATION (FT):	329.02	330.00	330.98

MEAN INFLOW (CFS): 3426.92

TURBINE NO.:	1	2	3	4	5	6	7
TURBINE POWER (MW):	44.55	44.54	44.52	44.50	44.48	44.44	37.10
OUTFLOW (CFS):	4400.75	4399.47	4397.89	4395.85	4393.13	4389.29	3622.25
SERVICE UNITS (MW):	1.00	0.00					
OUTFLOW (CFS):	104.39	0.00					

PEAK GENERATION (HRS):	52.97	OFF-PEAK GEN. (HRS):	0.00
PEAK ENERGY (MWH):	16110.67	OFF-PEAK ENERGY (MWH):	0.00
TOTAL POWER OUTPUT (MW):	304.14		
TURBINE OUTFLOW (CFS):	29998.63		
SPILLWAY OUTFLOW (CFS):	0.00		

---------------------------- W E E K 2 ----------------------------------
5/ 6/1991

H A R T W E L L

PERCENTILES:	5.00%	MEAN	95.00%		
BEGINNING STORAGE (BCF):	109.06	111.04	113.05		
ENDING STORAGE (BCF):	108.82	111.04	113.29		
BEGINNING ELEVATION (FT):	659.18	660.00	660.82		
ENDING ELEVATION (FT):	659.08	660.00	660.92		
MEAN INFLOW (CFS): 4749.32					
TURBINE NO.:	1	2	3	4	5
PEAK POWER (MW):	75.90	75.90	75.90	75.90	92.00
OUTFLOW (CFS):	5718.59	5718.59	5718.59	5718.59	6970.55

PEAK GENERATION (HRS): 26.72 OFF-PEAK GEN. (HRS): 0.00
PEAK ENERGY (MWH): 10571.07 OFF-PEAK ENERGY (MWH): 0.00
TOTAL POWER OUTPUT (MW): 395.60
TURBINE OUTFLOW (CFS): 29844.91
SPILLWAY OUTFLOW (CFS): 0.00

R U S S E L L

PERCENTILES:	5.00%	MEAN	95.00%	
BEGINNING STORAGE (BCF):	43.90	44.70	45.51	
ENDING STORAGE (BCF):	43.85	44.70	45.57	
BEGINNING ELEVATION (FT):	474.30	475.00	475.69	
ENDING ELEVATION (FT):	474.26	475.00	475.74	
MEAN INFLOW (CFS): 1155.97				
TURBINE NO.:	1	2	3	4
TURBINE POWER (MW):	86.25	86.19	86.19	72.26
OUTFLOW (CFS):	7765.60	7765.60	7765.60	6703.19

PEAK GENERATION (HRS): 33.06 OFF-PEAK GEN. (HRS): 0.00
PEAK ENERGY (MWH): 10937.75 OFF-PEAK ENERGY (MWH): 0.00
TOTAL POWER OUTPUT (MW): 330.88
TURBINE OUTFLOW (CFS): 30000.00
SPILLWAY OUTFLOW (CFS): 0.00

T H U R M O N D

PERCENTILES:	5.00%	MEAN	95.00%				
BEGINNING STORAGE (BCF):	106.39	109.46	112.59				
ENDING STORAGE (BCF):	105.70	109.46	113.30				
BEGINNING ELEVATION (FT):	329.02	330.00	330.98				
ENDING ELEVATION (FT):	328.79	330.00	331.21				
MEAN INFLOW (CFS): 3928.12							
TURBINE NO.:	1	2	3	4	5	6	7
TURBINE POWER (MW):	44.55	44.54	44.52	44.50	44.48	44.44	37.10
OUTFLOW (CFS):	4400.75	4399.47	4397.89	4395.85	4393.13	4389.29	3622.25
SERVICE UNITS (MW):	1.00	0.00					
OUTFLOW (CFS):	104.39	0.00					

PEAK GENERATION (HRS): 54.50 OFF-PEAK GEN. (HRS): 0.00
PEAK ENERGY (MWH): 16574.35 OFF-PEAK ENERGY (MWH): 0.00
TOTAL POWER OUTPUT (MW): 304.14
TURBINE OUTFLOW (CFS): 29998.64
SPILLWAY OUTFLOW (CFS): 0.00

---------------------------- W E E K 3 ----------------------------------
5/ 6/1991

H A R T W E L L

PERCENTILES:	5.00%	MEAN	95.00%		
BEGINNING STORAGE (BCF):	108.82	111.04	113.29		
ENDING STORAGE (BCF):	108.61	111.06	113.54		
BEGINNING ELEVATION (FT):	659.08	660.00	660.92		
ENDING ELEVATION (FT):	658.99	660.01	661.01		
MEAN INFLOW (CFS): 4744.63					
TURBINE NO.:	1	2	3	4	5
PEAK POWER (MW):	75.90	75.90	75.90	75.90	92.00
OUTFLOW (CFS):	5718.57	5718.57	5718.57	5718.57	6970.53
PEAK GENERATION (HRS):	26.56	OFF-PEAK GEN. (HRS):	0.00		
PEAK ENERGY (MWH):	10507.62	OFF-PEAK ENERGY (MWH):	0.00		
TOTAL POWER OUTPUT (MW):	395.60				
TURBINE OUTFLOW (CFS):	29844.80				
SPILLWAY OUTFLOW (CFS):	0.00				

R U S S E L L

PERCENTILES:	5.00%	MEAN	95.00%	
BEGINNING STORAGE (BCF):	43.85	44.70	45.57	
ENDING STORAGE (BCF):	43.89	44.70	45.53	
BEGINNING ELEVATION (FT):	474.26	475.00	475.74	
ENDING ELEVATION (FT):	474.29	475.00	475.71	
MEAN INFLOW (CFS): 1113.10				
TURBINE NO.:	1	2	3	4
TURBINE POWER (MW):	86.25	86.25	86.25	72.25
OUTFLOW (CFS):	7765.68	7765.68	7765.68	6702.97
PEAK GENERATION (HRS):	32.65	OFF-PEAK GEN. (HRS):	0.00	
PEAK ENERGY (MWH):	10806.48	OFF-PEAK ENERGY (MWH):	0.00	
TOTAL POWER OUTPUT (MW):	330.99			
TURBINE OUTFLOW (CFS):	30000.00			
SPILLWAY OUTFLOW (CFS):	0.00			

T H U R M O N D

PERCENTILES:	5.00%	MEAN	95.00%				
BEGINNING STORAGE (BCF):	105.70	109.46	113.30				
ENDING STORAGE (BCF):	105.40	109.46	113.62				
BEGINNING ELEVATION (FT):	328.79	330.00	331.21				
ENDING ELEVATION (FT):	328.70	330.00	331.31				
MEAN INFLOW (CFS): 3587.78							
TURBINE NO.:	1	2	3	4	5	6	7
TURBINE POWER (MW):	44.55	44.54	44.52	44.51	44.48	44.45	37.10
OUTFLOW (CFS):	4400.73	4399.46	4397.87	4395.84	4393.12	4389.29	3622.32
SERVICE UNITS (MW):	1.00	0.00					
OUTFLOW (CFS):	104.39	0.00					
PEAK GENERATION (HRS):	52.11	OFF-PEAK GEN. (HRS):	0.00				
PEAK ENERGY (MWH):	15848.80	OFF-PEAK ENERGY (MWH):	0.00				
TOTAL POWER OUTPUT (MW):	304.14						
TURBINE OUTFLOW (CFS):	29998.64						
SPILLWAY OUTFLOW (CFS):	0.00						

```
---------------------------- W E E K  4 ----------------------------------
                              5/ 6/1991

H A R T W E L L
PERCENTILES:                     5.00%    MEAN     95.00%
BEGINNING STORAGE (BCF):        108.61   111.06   113.54
ENDING STORAGE (BCF):           109.21   111.04   112.89
BEGINNING ELEVATION (FT):       658.99   660.01   661.01
ENDING ELEVATION (FT):          659.24   660.00   660.75
MEAN INFLOW (CFS):    4198.97
TURBINE NO.:               1        2        3        4        5
PEAK POWER (MW):       75.90    75.90    75.90    75.90    92.00
OUTFLOW (CFS):       5718.34  5718.34  5718.34  5718.34  6970.24
PEAK GENERATION (HRS):     23.79  OFF-PEAK GEN. (HRS):          0.00
PEAK ENERGY (MWH):       9411.48  OFF-PEAK ENERGY (MWH):        0.00
TOTAL POWER OUTPUT (MW):  395.60
TURBINE OUTFLOW (CFS):  29843.58
SPILLWAY OUTFLOW (CFS):     0.00

R U S S E L L
PERCENTILES:                     5.00%    MEAN     95.00%
BEGINNING STORAGE (BCF):         43.89    44.70    45.53
ENDING STORAGE (BCF):            44.03    44.70    45.38
BEGINNING ELEVATION (FT):       474.29   475.00   475.71
ENDING ELEVATION (FT):          474.42   475.00   475.58
MEAN INFLOW (CFS):     992.49
TURBINE NO.:               1        2        3        4
TURBINE POWER (MW):    86.25     0.00    86.25    86.25
OUTFLOW (CFS):       7765.84     0.00  7765.84  7765.84
PEAK GENERATION (HRS):     37.64  OFF-PEAK GEN. (HRS):          0.00
PEAK ENERGY (MWH):       9740.36  OFF-PEAK ENERGY (MWH):        0.00
TOTAL POWER OUTPUT (MW):  258.75
TURBINE OUTFLOW (CFS):  23297.52
SPILLWAY OUTFLOW (CFS):     0.00

T H U R M O N D
PERCENTILES:                     5.00%    MEAN     95.00%
BEGINNING STORAGE (BCF):        105.40   109.46   113.62
ENDING STORAGE (BCF):           107.86   109.46   111.07
BEGINNING ELEVATION (FT):       328.70   330.00   331.31
ENDING ELEVATION (FT):          329.49   330.00   330.51
MEAN INFLOW (CFS):    2108.43
TURBINE NO.:               1        2        3        4        5        6        7
TURBINE POWER (MW):    44.55    44.54    44.52    44.51    44.48    44.45    37.10
OUTFLOW (CFS):       4400.72  4399.45  4397.86  4395.83  4393.12  4389.28  3622.38
SERVICE UNITS (MW):     1.00     0.00
OUTFLOW (CFS):        104.39     0.00
PEAK GENERATION (HRS):     40.49  OFF-PEAK GEN. (HRS):          0.00
PEAK ENERGY (MWH):      12314.25  OFF-PEAK ENERGY (MWH):        0.00
TOTAL POWER OUTPUT (MW):  304.14
TURBINE OUTFLOW (CFS):  29998.64
SPILLWAY OUTFLOW (CFS):     0.00
```

WEEK 5

5/ 6/1991

HARTWELL

PERCENTILES:	5.00%	MEAN	95.00%		
BEGINNING STORAGE (BCF):	109.21	111.04	112.89		
ENDING STORAGE (BCF):	109.29	111.04	112.81		
BEGINNING ELEVATION (FT):	659.24	660.00	660.75		
ENDING ELEVATION (FT):	659.28	660.00	660.72		
MEAN INFLOW (CFS):	4152.44				
TURBINE NO.:	1	2	3	4	5
PEAK POWER (MW):	75.90	75.90	75.90	75.90	92.00
OUTFLOW (CFS):	5718.58	5718.58	5718.58	5718.58	6970.54
PEAK GENERATION (HRS):	23.37	OFF-PEAK GEN. (HRS):	0.00		
PEAK ENERGY (MWH):	9245.80	OFF-PEAK ENERGY (MWH):	0.00		
TOTAL POWER OUTPUT (MW):	395.60				
TURBINE OUTFLOW (CFS):	29844.86				
SPILLWAY OUTFLOW (CFS):	0.00				

RUSSELL

PERCENTILES:	5.00%	MEAN	95.00%	
BEGINNING STORAGE (BCF):	44.03	44.70	45.38	
ENDING STORAGE (BCF):	43.97	44.70	45.44	
BEGINNING ELEVATION (FT):	474.42	475.00	475.58	
ENDING ELEVATION (FT):	474.37	475.00	475.63	
MEAN INFLOW (CFS):	1036.62			
TURBINE NO.:	1	2	3	4
TURBINE POWER (MW):	86.25	0.00	86.25	86.25
OUTFLOW (CFS):	7765.77	0.00	7765.77	7765.77
PEAK GENERATION (HRS):	37.42	OFF-PEAK GEN. (HRS):	0.00	
PEAK ENERGY (MWH):	9681.28	OFF-PEAK ENERGY (MWH):	0.00	
TOTAL POWER OUTPUT (MW):	258.75			
TURBINE OUTFLOW (CFS):	23297.29			
SPILLWAY OUTFLOW (CFS):	0.00			

THURMOND

PERCENTILES:	5.00%	MEAN	95.00%				
BEGINNING STORAGE (BCF):	107.86	109.46	111.07				
ENDING STORAGE (BCF):	107.30	109.46	111.64				
BEGINNING ELEVATION (FT):	329.49	330.00	330.51				
ENDING ELEVATION (FT):	329.31	330.00	330.69				
MEAN INFLOW (CFS):	2273.63						
TURBINE NO.:	1	2	3	4	5	6	7
TURBINE POWER (MW):	44.55	44.54	44.52	44.50	44.48	44.44	37.10
OUTFLOW (CFS):	4400.75	4399.47	4397.88	4395.85	4393.13	4389.29	3622.27
SERVICE UNITS (MW):	1.00	0.00					
OUTFLOW (CFS):	104.39	0.00					
PEAK GENERATION (HRS):	41.22	OFF-PEAK GEN. (HRS):	0.00				
PEAK ENERGY (MWH):	12537.31	OFF-PEAK ENERGY (MWH):	0.00				
TOTAL POWER OUTPUT (MW):	304.14						
TURBINE OUTFLOW (CFS):	29998.64						
SPILLWAY OUTFLOW (CFS):	0.00						

--------------------------- W E E K 6 ---------------------------------
5/ 6/1991

H A R T W E L L

PERCENTILES:	5.00%	MEAN	95.00%
BEGINNING STORAGE (BCF):	109.29	111.04	112.81
ENDING STORAGE (BCF):	108.77	111.03	113.31
BEGINNING ELEVATION (FT):	659.28	660.00	660.72
ENDING ELEVATION (FT):	659.06	659.99	660.92

MEAN INFLOW (CFS): 4151.64

TURBINE NO.:	1	2	3	4	5
PEAK POWER (MW):	75.90	75.90	75.90	75.90	92.00
OUTFLOW (CFS):	5718.58	5718.58	5718.58	5718.58	6970.54

PEAK GENERATION (HRS): 23.53 OFF-PEAK GEN. (HRS): 0.00
PEAK ENERGY (MWH): 9309.97 OFF-PEAK ENERGY (MWH): 0.00
TOTAL POWER OUTPUT (MW): 395.60
TURBINE OUTFLOW (CFS): 29844.84
SPILLWAY OUTFLOW (CFS): 0.00

R U S S E L L

PERCENTILES:	5.00%	MEAN	95.00%
BEGINNING STORAGE (BCF):	43.97	44.70	45.44
ENDING STORAGE (BCF):	43.72	44.70	45.69
BEGINNING ELEVATION (FT):	474.37	475.00	475.63
ENDING ELEVATION (FT):	474.15	475.00	475.85

MEAN INFLOW (CFS): 1067.37

TURBINE NO.:	1	2	3	4
TURBINE POWER (MW):	86.25	0.00	86.25	86.25
OUTFLOW (CFS):	7765.78	0.00	7765.78	7765.78

PEAK GENERATION (HRS): 37.86 OFF-PEAK GEN. (HRS): 0.00
PEAK ENERGY (MWH): 9795.71 OFF-PEAK ENERGY (MWH): 0.00
TOTAL POWER OUTPUT (MW): 258.75
TURBINE OUTFLOW (CFS): 23297.34
SPILLWAY OUTFLOW (CFS): 0.00

T H U R M O N D

PERCENTILES:	5.00%	MEAN	95.00%
BEGINNING STORAGE (BCF):	107.30	109.46	111.64
ENDING STORAGE (BCF):	107.64	109.45	111.28
BEGINNING ELEVATION (FT):	329.31	330.00	330.69
ENDING ELEVATION (FT):	329.42	330.00	330.57

MEAN INFLOW (CFS): 2055.96

TURBINE NO.:	1	2	3	4	5	6	7
TURBINE POWER (MW):	44.55	44.54	44.52	44.51	44.48	44.44	37.10
OUTFLOW (CFS):	4400.74	4399.47	4397.88	4395.85	4393.13	4389.29	3622.28
SERVICE UNITS (MW):	1.00	0.00					
OUTFLOW (CFS):	104.39	0.00					

PEAK GENERATION (HRS): 40.41 OFF-PEAK GEN. (HRS): 0.00
PEAK ENERGY (MWH): 12290.12 OFF-PEAK ENERGY (MWH): 0.00
TOTAL POWER OUTPUT (MW): 304.14
TURBINE OUTFLOW (CFS): 29998.63
SPILLWAY OUTFLOW (CFS): 0.00

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--------------------------- W E E K  7 --------------------------------
                            5/ 6/1991

HARTWELL
PERCENTILES:                   5.00%    MEAN     95.00%
BEGINNING STORAGE (BCF):      108.77   111.03   113.31
ENDING STORAGE (BCF):         107.62   111.09   114.64
BEGINNING ELEVATION (FT):     659.06   659.99   660.92
ENDING ELEVATION (FT):        658.58   660.02   661.45
MEAN INFLOW (CFS):   4446.36
TURBINE NO.:               1       2       3       4       5
PEAK POWER (MW):       75.90   75.90   75.90   75.90   92.00
OUTFLOW (CFS):       5718.84 5718.84 5718.84 5718.84 6970.86
PEAK GENERATION (HRS):      24.39  OFF-PEAK GEN. (HRS):        0.00
PEAK ENERGY (MWH):        9647.64  OFF-PEAK ENERGY (MWH):      0.00
TOTAL POWER OUTPUT (MW):   395.60
TURBINE OUTFLOW (CFS):   29846.21
SPILLWAY OUTFLOW (CFS):      0.00

RUSSELL
PERCENTILES:                   5.00%    MEAN     95.00%
BEGINNING STORAGE (BCF):       43.72    44.70    45.69
ENDING STORAGE (BCF):          43.53    44.71    45.91
BEGINNING ELEVATION (FT):     474.15   475.00   475.85
ENDING ELEVATION (FT):        473.98   475.00   476.03
MEAN INFLOW (CFS):   1087.38
TURBINE NO.:               1       2       3       4
TURBINE POWER (MW):    86.25    0.00   86.25   86.25
OUTFLOW (CFS):       7765.73    0.00 7765.73 7765.73
PEAK GENERATION (HRS):      39.02  OFF-PEAK GEN. (HRS):        0.00
PEAK ENERGY (MWH):       10095.96  OFF-PEAK ENERGY (MWH):      0.00
TOTAL POWER OUTPUT (MW):   258.75
TURBINE OUTFLOW (CFS):   23297.19
SPILLWAY OUTFLOW (CFS):      0.00

THURMOND
PERCENTILES:                   5.00%    MEAN     95.00%
BEGINNING STORAGE (BCF):      107.64   109.45   111.28
ENDING STORAGE (BCF):         106.31   109.51   112.77
BEGINNING ELEVATION (FT):     329.42   330.00   330.57
ENDING ELEVATION (FT):        328.99   330.02   331.04
MEAN INFLOW (CFS):   2475.86
TURBINE NO.:               1       2       3       4       5       6       7
TURBINE POWER (MW):    44.55   44.54   44.52   44.50   44.48   44.44   37.10
OUTFLOW (CFS):       4400.76 4399.48 4397.90 4395.86 4393.14 4389.30 3622.19
SERVICE UNITS (MW):     1.00    0.00
OUTFLOW (CFS):        104.40    0.00
PEAK GENERATION (HRS):      42.99  OFF-PEAK GEN. (HRS):        0.00
PEAK ENERGY (MWH):       13075.42  OFF-PEAK ENERGY (MWH):      0.00
TOTAL POWER OUTPUT (MW):   304.13
TURBINE OUTFLOW (CFS):   29998.64
SPILLWAY OUTFLOW (CFS):      0.00
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---------------------------  W E E K  8  --------------------------------
                              5/ 6/1991

H A R T W E L L
PERCENTILES:                    5.00%     MEAN      95.00%
BEGINNING STORAGE (BCF):       107.62    111.09    114.64
ENDING STORAGE (BCF):          108.76    111.06    113.39
BEGINNING ELEVATION (FT):      658.58    660.02    661.45
ENDING ELEVATION (FT):         659.05    660.01    660.95
MEAN INFLOW (CFS):   3378.58
TURBINE NO.:                1         2         3         4         5
PEAK POWER (MW):        75.90     75.90     75.90     75.90     92.00
OUTFLOW (CFS):        5717.83 5717.83 5717.83 5717.83 6969.60
PEAK GENERATION (HRS):      19.38  OFF-PEAK GEN. (HRS):          0.00
PEAK ENERGY (MWH):        7664.91  OFF-PEAK ENERGY (MWH):        0.00
TOTAL POWER OUTPUT (MW):   395.60
TURBINE OUTFLOW (CFS):   29840.90
SPILLWAY OUTFLOW (CFS):      0.00

R U S S E L L
PERCENTILES:                    5.00%     MEAN      95.00%
BEGINNING STORAGE (BCF):        43.53     44.71     45.91
ENDING STORAGE (BCF):           44.09     44.70     45.33
BEGINNING ELEVATION (FT):      473.98    475.00    476.03
ENDING ELEVATION (FT):         474.47    475.00    475.53
MEAN INFLOW (CFS):    733.54
TURBINE NO.:                1         2         3         4
TURBINE POWER (MW):     86.25      0.00     86.25     86.25
OUTFLOW (CFS):        7766.32      0.00 7766.32 7766.32
PEAK GENERATION (HRS):      30.14  OFF-PEAK GEN. (HRS):          0.00
PEAK ENERGY (MWH):        7799.16  OFF-PEAK ENERGY (MWH):        0.00
TOTAL POWER OUTPUT (MW):   258.75
TURBINE OUTFLOW (CFS):   23298.95
SPILLWAY OUTFLOW (CFS):      0.00

T H U R M O N D
PERCENTILES:                    5.00%     MEAN      95.00%
BEGINNING STORAGE (BCF):       106.31    109.51    112.77
ENDING STORAGE (BCF):          106.55    109.48    112.46
BEGINNING ELEVATION (FT):      328.99    330.02    331.04
ENDING ELEVATION (FT):         329.07    330.01    330.94
MEAN INFLOW (CFS):   1568.59
TURBINE NO.:                1         2         3         4         5         6         7
TURBINE POWER (MW):     44.55     44.54     44.53     44.51     44.48     44.45     37.11
OUTFLOW (CFS):        4400.61 4399.34 4397.76 4395.73 4393.03 4389.21 3622.94
SERVICE UNITS (MW):      1.00      0.00
OUTFLOW (CFS):         104.38      0.00
PEAK GENERATION (HRS):      31.90  OFF-PEAK GEN. (HRS):          0.00
PEAK ENERGY (MWH):        9702.24  OFF-PEAK ENERGY (MWH):        0.00
TOTAL POWER OUTPUT (MW):   304.17
TURBINE OUTFLOW (CFS):   29998.62
SPILLWAY OUTFLOW (CFS):      0.00
```

WEEK 10
5/ 6/1991

HARTWELL

PERCENTILES:	5.00%	MEAN	95.00%			
BEGINNING STORAGE (BCF):	108.37	111.02	113.70			
ENDING STORAGE (BCF):	108.21	111.05	113.93			
BEGINNING ELEVATION (FT):	658.89	659.99	661.08			
ENDING ELEVATION (FT):	658.83	660.00	661.17			

MEAN INFLOW (CFS):	3311.82				
TURBINE NO.:	1	2	3	4	5
PEAK POWER (MW):	75.90	75.90	75.90	75.90	92.00
OUTFLOW (CFS):	5718.97	5718.97	5718.97	5718.97	6971.03

PEAK GENERATION (HRS):	18.36	OFF-PEAK GEN. (HRS):	0.00
PEAK ENERGY (MWH):	7264.87	OFF-PEAK ENERGY (MWH):	0.00
TOTAL POWER OUTPUT (MW):	395.60		
TURBINE OUTFLOW (CFS):	29846.91		
SPILLWAY OUTFLOW (CFS):	0.00		

RUSSELL

PERCENTILES:	5.00%	MEAN	95.00%
BEGINNING STORAGE (BCF):	43.92	44.70	45.49
ENDING STORAGE (BCF):	44.16	44.70	45.24
BEGINNING ELEVATION (FT):	474.32	475.00	475.67
ENDING ELEVATION (FT):	474.53	475.00	475.46

MEAN INFLOW (CFS):	728.40			
TURBINE NO.:	1	2	3	4
TURBINE POWER (MW):	86.14	86.25	86.25	72.29
OUTFLOW (CFS):	7765.11	7765.11	7765.11	6704.67

PEAK GENERATION (HRS):	22.33	OFF-PEAK GEN. (HRS):	0.00
PEAK ENERGY (MWH):	7388.74	OFF-PEAK ENERGY (MWH):	0.00
TOTAL POWER OUTPUT (MW):	330.93		
TURBINE OUTFLOW (CFS):	30000.00		
SPILLWAY OUTFLOW (CFS):	0.00		

THURMOND

PERCENTILES:	5.00%	MEAN	95.00%
BEGINNING STORAGE (BCF):	106.16	109.42	112.73
ENDING STORAGE (BCF):	105.37	109.44	113.61
BEGINNING ELEVATION (FT):	328.94	329.99	331.03
ENDING ELEVATION (FT):	328.69	330.00	331.30

MEAN INFLOW (CFS):	1856.35						
TURBINE NO.:	1	2	3	4	5	6	7
TURBINE POWER (MW):	44.55	44.53	44.52	44.50	44.48	44.44	37.09
OUTFLOW (CFS):	4400.86	4399.58	4397.99	4395.95	4393.22	4389.36	3621.69
SERVICE UNITS (MW):	1.00	0.00					
OUTFLOW (CFS):	104.40	0.00					

PEAK GENERATION (HRS):	31.90	OFF-PEAK GEN. (HRS):	0.00
PEAK ENERGY (MWH):	9700.02	OFF-PEAK ENERGY (MWH):	0.00
TOTAL POWER OUTPUT (MW):	304.11		
TURBINE OUTFLOW (CFS):	29998.65		
SPILLWAY OUTFLOW (CFS):	0.00		

APPENDIX F

Output File Generated by SAVRES in Section 3.2 (Drought Operations)

DROUGHT OPERATION TRADEOFFS

NO.	THURMOND AVG. DISCH. CFS	SYSTEM ENERGY MWH/WK.	HARTWELL MIN.	HARTWELL WEEK	RUSSELL MIN.	RUSSELL WEEK	THURMOND MIN.	THURMOND WEEK
			RESERVOIR ELEVATION STATISTICS - FEET					
1	5799.95	23869.	650.95	11	473.08	10	320.99	11
2	4727.21	19882.	652.25	11	473.35	9	322.29	11
3	4085.00	17505.	653.02	11	473.49	9	323.05	11
4	3599.76	15716.	653.59	11	473.50	1	323.63	11

S U M M A R Y   S E Q U E N C E S
DROUGHT OPERATION CONDITIONS
TRADEOFF POINT 1

HARTWELL			RUSSELL			THURMOND		
ELEV-FT	GEN-HRS	MWH	ELEV-FT	GEN-HRS	MWH	ELEV-FT	GEN-HRS	MWH
655.00	15.28	5894.42	473.50	14.21	4818.44	325.00	31.88	9171.40
654.68	16.42	6324.11	473.79	19.53	6640.76	324.43	31.87	9129.79
654.39	16.34	6282.63	473.71	19.29	6564.54	324.14	31.87	9110.91
654.05	16.08	6180.22	473.63	19.02	6481.35	323.79	31.87	9085.86
653.64	15.92	6097.60	473.53	18.77	6406.39	323.38	31.87	9056.41
653.23	16.35	6246.37	473.42	19.26	6583.11	322.96	31.87	9027.16
652.80	16.05	6117.75	473.31	19.05	6521.89	322.54	31.87	8997.24
652.34	15.04	5718.40	473.19	17.98	6163.62	322.09	31.87	8965.01
651.94	17.94	6804.49	473.09	20.04	6880.97	321.71	31.87	8937.74
651.43	17.74	6707.60	473.07	19.41	6677.58	321.33	31.86	8911.32
650.95			473.08			320.99		

D E T A I L E D   S E Q U E N C E S
STARTING DATE: 8/19/1991 MONDAY

--------------------------- W E E K 1 ---------------------------

H A R T W E L L

PERCENTILES:	50.00%	MEAN	50.00%
BEGINNING STORAGE (BCF):	99.41	99.41	99.41
ENDING STORAGE (BCF):	98.70	98.70	98.70
BEGINNING ELEVATION (FT):	655.00	655.00	655.00
ENDING ELEVATION (FT):	654.68	654.68	654.68

MEAN INFLOW (CFS): 1562.45

TURBINE NO.:	1	2	3	4	5
PEAK POWER (MW):	78.40	78.35	78.29	78.21	72.52
OUTFLOW (CFS):	6111.17	6107.36	6102.41	6095.65	5583.04

PEAK GENERATION (HRS):	15.28	OFF-PEAK GEN. (HRS):	0.00
PEAK ENERGY (MWH):	5894.42	OFF-PEAK ENERGY (MWH):	0.00
TOTAL POWER OUTPUT (MW):	385.77		
TURBINE OUTFLOW (CFS):	29999.63		
SPILLWAY OUTFLOW (CFS):	0.00		

R U S S E L L

PERCENTILES:	50.00%	MEAN	50.00%
BEGINNING STORAGE (BCF):	42.99	42.99	42.99
ENDING STORAGE (BCF):	43.31	43.31	43.31
BEGINNING ELEVATION (FT):	473.50	473.50	473.50
ENDING ELEVATION (FT):	473.79	473.79	473.79

MEAN INFLOW (CFS): 343.45

TURBINE NO.:	1	2	3	4
TURBINE POWER (MW):	93.74	93.74	82.76	68.75
OUTFLOW (CFS):	8166.54	8166.54	7353.08	6313.93

PEAK GENERATION (HRS):	14.21	OFF-PEAK GEN. (HRS):	0.00
PEAK ENERGY (MWH):	4818.44	OFF-PEAK ENERGY (MWH):	0.00
TOTAL POWER OUTPUT (MW):	338.99		
TURBINE OUTFLOW (CFS):	30000.09		
SPILLWAY OUTFLOW (CFS):	0.00		

T H U R M O N D

PERCENTILES:	50.00%	MEAN	50.00%
BEGINNING STORAGE (BCF):	94.47	94.47	94.47
ENDING STORAGE (BCF):	92.88	92.88	92.88
BEGINNING ELEVATION (FT):	325.00	325.00	325.00
ENDING ELEVATION (FT):	324.43	324.43	324.43

MEAN INFLOW (CFS): 625.67

TURBINE NO.:	1	2	3	4	5	6	7
TURBINE POWER (MW):	47.64	47.60	47.53	47.43	47.23	45.03	0.00
OUTFLOW (CFS):	5101.70	5092.97	5080.40	5060.37	5021.51	4644.01	0.00
SERVICE UNITS (MW):	1.00	0.00					
OUTFLOW (CFS):	107.76	0.00					

PEAK GENERATION (HRS):	31.88	OFF-PEAK GEN. (HRS):	0.00
PEAK ENERGY (MWH):	9003.40	OFF-PEAK ENERGY (MWH):	0.00
TOTAL POWER OUTPUT (MW):	282.46		
TURBINE OUTFLOW (CFS):	30000.96		
SPILLWAY OUTFLOW (CFS):	0.00		

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---------------------------- W E E K  2 ---------------------------------
                             8/19/1991

H A R T W E L L
PERCENTILES:                     50.00%    MEAN     50.00%
BEGINNING STORAGE (BCF):          98.70    98.70     98.70
ENDING STORAGE (BCF):             98.07    98.07     98.07
BEGINNING ELEVATION (FT):        654.68   654.68    654.68
ENDING ELEVATION (FT):           654.39   654.39    654.39
MEAN INFLOW (CFS):    1890.16
TURBINE NO.:                1        2        3        4        5
PEAK POWER (MW):        78.30    78.25    78.19    78.11    72.20
OUTFLOW (CFS):        6115.09  6111.12  6105.94  6098.84  5568.62
PEAK GENERATION (HRS):      16.42  OFF-PEAK GEN. (HRS):         0.00
PEAK ENERGY (MWH):        6324.11  OFF-PEAK ENERGY (MWH):       0.00
TOTAL POWER OUTPUT (MW):   385.04
TURBINE OUTFLOW (CFS):   29999.62
SPILLWAY OUTFLOW (CFS):      0.00

R U S S E L L
PERCENTILES:                     50.00%    MEAN     50.00%
BEGINNING STORAGE (BCF):          43.31    43.31     43.31
ENDING STORAGE (BCF):             43.23    43.23     43.23
BEGINNING ELEVATION (FT):        473.79   473.79    473.79
ENDING ELEVATION (FT):           473.71   473.71    473.71
MEAN INFLOW (CFS):     420.79
TURBINE NO.:                1        2        3        4
TURBINE POWER (MW):     93.74    93.74    93.74    58.74
OUTFLOW (CFS):        8146.70  8146.70  8146.70  5559.93
PEAK GENERATION (HRS):      19.53  OFF-PEAK GEN. (HRS):         0.00
PEAK ENERGY (MWH):        6640.76  OFF-PEAK ENERGY (MWH):       0.00
TOTAL POWER OUTPUT (MW):   339.96
TURBINE OUTFLOW (CFS):   30000.02
SPILLWAY OUTFLOW (CFS):      0.00

T H U R M O N D
PERCENTILES:                     50.00%    MEAN     50.00%
BEGINNING STORAGE (BCF):          92.88    92.88     92.88
ENDING STORAGE (BCF):             92.05    92.05     92.05
BEGINNING ELEVATION (FT):        324.43   324.43    324.43
ENDING ELEVATION (FT):           324.14   324.14    324.14
MEAN INFLOW (CFS):     937.09
TURBINE NO.:                1        2        3        4        5        6        7
TURBINE POWER (MW):     47.46    47.41    47.34    47.23    47.01    44.75     0.00
OUTFLOW (CFS):        5106.26  5096.75  5083.06  5061.25  5019.05  4637.11     0.00
SERVICE UNITS (MW):      1.00     0.00
OUTFLOW (CFS):         108.16     0.00
PEAK GENERATION (HRS):      31.87  OFF-PEAK GEN. (HRS):         0.00
PEAK ENERGY (MWH):        8961.79  OFF-PEAK ENERGY (MWH):       0.00
TOTAL POWER OUTPUT (MW):   281.19
TURBINE OUTFLOW (CFS):   30003.49
SPILLWAY OUTFLOW (CFS):      0.00
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---------------------------  W E E K  3  ---------------------------------
                              8/19/1991

H A R T W E L L
PERCENTILES:                     50.00%     MEAN      50.00%
BEGINNING STORAGE (BCF):         98.07      98.07     98.07
ENDING STORAGE (BCF):            97.33      97.33     97.33
BEGINNING ELEVATION (FT):        654.39     654.39    654.39
ENDING ELEVATION (FT):           654.05     654.05    654.05
MEAN INFLOW (CFS):     1685.06
TURBINE NO.:                 1        2        3        4        5
PEAK POWER (MW):         77.74    77.70    77.65    77.57    73.86
OUTFLOW (CFS):         6078.94  6075.42  6070.82  6064.49  5711.29
PEAK GENERATION (HRS):       16.34  OFF-PEAK GEN. (HRS):        0.00
PEAK ENERGY (MWH):         6282.63  OFF-PEAK ENERGY (MWH):      0.00
TOTAL POWER OUTPUT (MW):   384.52
TURBINE OUTFLOW (CFS):   30000.96
SPILLWAY OUTFLOW (CFS):      0.00

R U S S E L L
PERCENTILES:                     50.00%     MEAN      50.00%
BEGINNING STORAGE (BCF):         43.23      43.23     43.23
ENDING STORAGE (BCF):            43.13      43.13     43.13
BEGINNING ELEVATION (FT):        473.71     473.71    473.71
ENDING ELEVATION (FT):           473.63     473.63    473.63
MEAN INFLOW (CFS):     367.63
TURBINE NO.:                 1        2        3        4
TURBINE POWER (MW):      93.74    93.74    93.74    59.13
OUTFLOW (CFS):         8138.80  8138.80  8138.80  5583.60
PEAK GENERATION (HRS):       19.29  OFF-PEAK GEN. (HRS):        0.00
PEAK ENERGY (MWH):         6564.54  OFF-PEAK ENERGY (MWH):      0.00
TOTAL POWER OUTPUT (MW):   340.35
TURBINE OUTFLOW (CFS):   30000.00
SPILLWAY OUTFLOW (CFS):      0.00

T H U R M O N D
PERCENTILES:                     50.00%     MEAN      50.00%
BEGINNING STORAGE (BCF):         92.05      92.05     92.05
ENDING STORAGE (BCF):            91.10      91.10     91.10
BEGINNING ELEVATION (FT):        324.14     324.14    324.14
ENDING ELEVATION (FT):           323.79     323.79    323.79
MEAN INFLOW (CFS):     783.50
TURBINE NO.:                 1        2        3        4        5        6        7
TURBINE POWER (MW):      47.36    47.31    47.24    47.12    46.89    44.65     0.00
OUTFLOW (CFS):         5107.73  5097.81  5083.54  5060.80  5016.85  4632.52     0.00
SERVICE UNITS (MW):       1.00     0.00
OUTFLOW (CFS):          108.36     0.00
PEAK GENERATION (HRS):       31.87  OFF-PEAK GEN. (HRS):        0.00
PEAK ENERGY (MWH):         8942.91  OFF-PEAK ENERGY (MWH):      0.00
TOTAL POWER OUTPUT (MW):   280.57
TURBINE OUTFLOW (CFS):   29999.25
SPILLWAY OUTFLOW (CFS):      0.00
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---------------------------  W E E K  4  --------------------------------
                              8/19/1991

 H A R T W E L L
 PERCENTILES:                     50.00%    MEAN      50.00%
 BEGINNING STORAGE (BCF):         97.33     97.33     97.33
 ENDING STORAGE (BCF):            96.44     96.44     96.44
 BEGINNING ELEVATION (FT):       654.05    654.05    654.05
 ENDING ELEVATION (FT):          653.64    653.64    653.64
 MEAN INFLOW (CFS):    1396.62
 TURBINE NO.:                 1        2        3        4        5
 PEAK POWER (MW):         74.96    74.95    74.95    74.94    84.58
 OUTFLOW (CFS):         6047.38  6044.29  6040.23  6034.63  5833.47
 PEAK GENERATION (HRS):        16.08  OFF-PEAK GEN. (HRS):        0.00
 PEAK ENERGY (MWH):          6180.22  OFF-PEAK ENERGY (MWH):      0.00
 TOTAL POWER OUTPUT (MW):    384.39
 TURBINE OUTFLOW (CFS):    30000.01
 SPILLWAY OUTFLOW (CFS):       0.00

 R U S S E L L
 PERCENTILES:                     50.00%    MEAN      50.00%
 BEGINNING STORAGE (BCF):         43.13     43.13     43.13
 ENDING STORAGE (BCF):            43.02     43.02     43.02
 BEGINNING ELEVATION (FT):       473.63    473.63    473.63
 ENDING ELEVATION (FT):          473.53    473.53    473.53
 MEAN INFLOW (CFS):     332.25
 TURBINE NO.:                 1        2        3        4
 TURBINE POWER (MW):      93.74    93.74    93.16    60.15
 OUTFLOW (CFS):         8129.90  8129.90  8087.26  5652.95
 PEAK GENERATION (HRS):        19.02  OFF-PEAK GEN. (HRS):        0.00
 PEAK ENERGY (MWH):          6481.35  OFF-PEAK ENERGY (MWH):      0.00
 TOTAL POWER OUTPUT (MW):    340.79
 TURBINE OUTFLOW (CFS):    30000.01
 SPILLWAY OUTFLOW (CFS):       0.00

 T H U R M O N D
 PERCENTILES:                     50.00%    MEAN      50.00%
 BEGINNING STORAGE (BCF):         91.10     91.10     91.10
 ENDING STORAGE (BCF):            89.97     89.97     89.97
 BEGINNING ELEVATION (FT):       323.79    323.79    323.79
 ENDING ELEVATION (FT):          323.38    323.38    323.38
 MEAN INFLOW (CFS):     541.82
 TURBINE NO.:                 1        2        3        4        5        6        7
 TURBINE POWER (MW):      47.25    47.19    47.12    47.00    46.76    44.49     0.00
 OUTFLOW (CFS):         5110.39  5100.00  5085.04  5061.21  5015.23  4628.46     0.00
 SERVICE UNITS (MW):       1.00     0.00
 OUTFLOW (CFS):          108.61     0.00
 PEAK GENERATION (HRS):        31.87  OFF-PEAK GEN. (HRS):        0.00
 PEAK ENERGY (MWH):          8917.86  OFF-PEAK ENERGY (MWH):      0.00
 TOTAL POWER OUTPUT (MW):    279.81
 TURBINE OUTFLOW (CFS):    30000.33
 SPILLWAY OUTFLOW (CFS):       0.00
```

WEEK 5
8/19/1991

H A R T W E L L

PERCENTILES:	50.00%	MEAN	50.00%				
BEGINNING STORAGE (BCF):	96.44	96.44	96.44				
ENDING STORAGE (BCF):	95.54	95.54	95.54				
BEGINNING ELEVATION (FT):	653.64	653.64	653.64				
ENDING ELEVATION (FT):	653.23	653.23	653.23				
MEAN INFLOW (CFS):	1360.95						
TURBINE NO.:	1	2	3	4	5		
PEAK POWER (MW):	75.90	75.88	75.86	75.82	79.66		
OUTFLOW (CFS):	5965.24	5963.28	5960.71	5957.13	6153.69		
PEAK GENERATION (HRS):	15.92	OFF-PEAK GEN. (HRS):	0.00				
PEAK ENERGY (MWH):	6097.60	OFF-PEAK ENERGY (MWH):	0.00				
TOTAL POWER OUTPUT (MW):	383.13						
TURBINE OUTFLOW (CFS):	30000.05						
SPILLWAY OUTFLOW (CFS):	0.00						

R U S S E L L

PERCENTILES:	50.00%	MEAN	50.00%	
BEGINNING STORAGE (BCF):	43.02	43.02	43.02	
ENDING STORAGE (BCF):	42.90	42.90	42.90	
BEGINNING ELEVATION (FT):	473.53	473.53	473.53	
ENDING ELEVATION (FT):	473.42	473.42	473.42	
MEAN INFLOW (CFS):	311.55			
TURBINE NO.:	1	2	3	4
TURBINE POWER (MW):	93.74	93.74	93.74	60.09
OUTFLOW (CFS):	8119.43	8119.43	8119.43	5641.71
PEAK GENERATION (HRS):	18.77	OFF-PEAK GEN. (HRS):	0.00	
PEAK ENERGY (MWH):	6406.39	OFF-PEAK ENERGY (MWH):	0.00	
TOTAL POWER OUTPUT (MW):	341.30			
TURBINE OUTFLOW (CFS):	30000.00			
SPILLWAY OUTFLOW (CFS):	0.00			

T H U R M O N D

PERCENTILES:	50.00%	MEAN	50.00%				
BEGINNING STORAGE (BCF):	89.97	89.97	89.97				
ENDING STORAGE (BCF):	88.84	88.84	88.84				
BEGINNING ELEVATION (FT):	323.38	323.38	323.38				
ENDING ELEVATION (FT):	322.96	322.96	322.96				
MEAN INFLOW (CFS):	574.74						
TURBINE NO.:	1	2	3	4	5	6	7
TURBINE POWER (MW):	47.11	47.06	46.98	46.85	46.60	44.30	0.00
OUTFLOW (CFS):	5113.49	5102.53	5086.74	5061.62	5013.21	4622.80	0.00
SERVICE UNITS (MW):	1.00	0.00					
OUTFLOW (CFS):	108.91	0.00					
PEAK GENERATION (HRS):	31.87	OFF-PEAK GEN. (HRS):	0.00				
PEAK ENERGY (MWH):	8888.41	OFF-PEAK ENERGY (MWH):	0.00				
TOTAL POWER OUTPUT (MW):	278.90						
TURBINE OUTFLOW (CFS):	30000.38						
SPILLWAY OUTFLOW (CFS):	0.00						

--------------------------- WEEK 6 --------------------------------
8/19/1991

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H A R T W E L L
PERCENTILES:                     50.00%    MEAN     50.00%
BEGINNING STORAGE (BCF):         95.54     95.54    95.54
ENDING STORAGE (BCF):            94.62     94.62    94.62
BEGINNING ELEVATION (FT):        653.23    653.23   653.23
ENDING ELEVATION (FT):           652.80    652.80   652.80
MEAN INFLOW (CFS):      1401.19
TURBINE NO.:                  1       2       3       4       5
PEAK POWER (MW):          76.88   76.84   76.79   76.72   74.81
OUTFLOW (CFS):          6132.68 6127.91 6121.60 6112.81 5505.01
PEAK GENERATION (HRS):        16.35  OFF-PEAK GEN. (HRS):          0.00
PEAK ENERGY (MWH):          6246.37  OFF-PEAK ENERGY (MWH):        0.00
TOTAL POWER OUTPUT (MW):    382.04
TURBINE OUTFLOW (CFS):    30000.02
SPILLWAY OUTFLOW (CFS):       0.00

R U S S E L L
PERCENTILES:                     50.00%    MEAN     50.00%
BEGINNING STORAGE (BCF):         42.90     42.90    42.90
ENDING STORAGE (BCF):            42.77     42.77    42.77
BEGINNING ELEVATION (FT):        473.42    473.42   473.42
ENDING ELEVATION (FT):           473.31    473.31   473.31
MEAN INFLOW (CFS):       314.93
TURBINE NO.:                  1       2       3       4
TURBINE POWER (MW):       93.74   92.96   93.13   61.99
OUTFLOW (CFS):          8108.99 8051.38 8064.28 5775.36
PEAK GENERATION (HRS):        19.26  OFF-PEAK GEN. (HRS):          0.00
PEAK ENERGY (MWH):          6583.11  OFF-PEAK ENERGY (MWH):        0.00
TOTAL POWER OUTPUT (MW):    341.82
TURBINE OUTFLOW (CFS):    30000.01
SPILLWAY OUTFLOW (CFS):       0.00

T H U R M O N D
PERCENTILES:                     50.00%    MEAN     50.00%
BEGINNING STORAGE (BCF):         88.84     88.84    88.84
ENDING STORAGE (BCF):            87.71     87.71    87.71
BEGINNING ELEVATION (FT):        322.96    322.96   322.96
ENDING ELEVATION (FT):           322.54    322.54   322.54
MEAN INFLOW (CFS):       501.40
TURBINE NO.:                  1       2       3       4       5       6       7
TURBINE POWER (MW):       46.97   46.92   46.83   46.70   46.44   44.11    0.00
OUTFLOW (CFS):          5116.52 5104.98 5088.36 5061.92 5011.06 4615.73    0.00
SERVICE UNITS (MW):        1.00    0.00
OUTFLOW (CFS):           109.21    0.00
PEAK GENERATION (HRS):        31.87  OFF-PEAK GEN. (HRS):          0.00
PEAK ENERGY (MWH):          8859.16  OFF-PEAK ENERGY (MWH):        0.00
TOTAL POWER OUTPUT (MW):    277.98
TURBINE OUTFLOW (CFS):    29998.58
SPILLWAY OUTFLOW (CFS):       0.00
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WEEK 7
8/19/1991

HARTWELL

PERCENTILES:	50.00%	MEAN	50.00%		
BEGINNING STORAGE (BCF):	94.62	94.62	94.62		
ENDING STORAGE (BCF):	93.65	93.65	93.65		
BEGINNING ELEVATION (FT):	652.80	652.80	652.80		
ENDING ELEVATION (FT):	652.34	652.34	652.34		
MEAN INFLOW (CFS):	1254.75				
TURBINE NO.:	1	2	3	4	5
PEAK POWER (MW):	76.62	76.58	76.53	76.46	74.91
OUTFLOW (CFS):	6137.79	6132.77	6126.10	6116.77	5486.58
PEAK GENERATION (HRS):	16.05	OFF-PEAK GEN. (HRS):	0.00		
PEAK ENERGY (MWH):	6117.75	OFF-PEAK ENERGY (MWH):	0.00		
TOTAL POWER OUTPUT (MW):	381.10				
TURBINE OUTFLOW (CFS):	30000.02				
SPILLWAY OUTFLOW (CFS):	0.00				

RUSSELL

PERCENTILES:	50.00%	MEAN	50.00%	
BEGINNING STORAGE (BCF):	42.77	42.77	42.77	
ENDING STORAGE (BCF):	42.64	42.64	42.64	
BEGINNING ELEVATION (FT):	473.31	473.31	473.31	
ENDING ELEVATION (FT):	473.19	473.19	473.19	
MEAN INFLOW (CFS):	312.53			
TURBINE NO.:	1	2	3	4
TURBINE POWER (MW):	93.74	93.74	93.35	61.50
OUTFLOW (CFS):	8098.78	8098.78	8070.07	5732.38
PEAK GENERATION (HRS):	19.05	OFF-PEAK GEN. (HRS):	0.00	
PEAK ENERGY (MWH):	6521.89	OFF-PEAK ENERGY (MWH):	0.00	
TOTAL POWER OUTPUT (MW):	342.33			
TURBINE OUTFLOW (CFS):	30000.00			
SPILLWAY OUTFLOW (CFS):	0.00			

THURMOND

PERCENTILES:	50.00%	MEAN	50.00%				
BEGINNING STORAGE (BCF):	87.71	87.71	87.71				
ENDING STORAGE (BCF):	86.51	86.51	86.51				
BEGINNING ELEVATION (FT):	322.54	322.54	322.54				
ENDING ELEVATION (FT):	322.09	322.09	322.09				
MEAN INFLOW (CFS):	414.12						
TURBINE NO.:	1	2	3	4	5	6	7
TURBINE POWER (MW):	46.84	46.78	46.69	46.55	46.28	43.92	0.00
OUTFLOW (CFS):	5119.60	5107.47	5090.02	5062.26	5008.94	4610.03	0.00
SERVICE UNITS (MW):	1.00	0.00					
OUTFLOW (CFS):	109.51	0.00					
PEAK GENERATION (HRS):	31.87	OFF-PEAK GEN. (HRS):	0.00				
PEAK ENERGY (MWH):	8829.24	OFF-PEAK ENERGY (MWH):	0.00				
TOTAL POWER OUTPUT (MW):	277.05						
TURBINE OUTFLOW (CFS):	29998.31						
SPILLWAY OUTFLOW (CFS):	0.00						

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---------------------------- W E E K  8 ---------------------------------
                              8/19/1991

H A R T W E L L
PERCENTILES:                   50.00%    MEAN      50.00%
BEGINNING STORAGE (BCF):       93.65     93.65     93.65
ENDING STORAGE (BCF):          92.82     92.82     92.82
BEGINNING ELEVATION (FT):     652.34    652.34    652.34
ENDING ELEVATION (FT):        651.94    651.94    651.94
MEAN INFLOW (CFS):    1325.97
TURBINE NO.:               1       2       3       4       5
PEAK POWER (MW):       76.31   76.27   76.22   76.15   75.16
OUTFLOW (CFS):       6143.22 6137.92 6130.86 6120.92 5467.09
PEAK GENERATION (HRS):      15.04  OFF-PEAK GEN. (HRS):          0.00
PEAK ENERGY (MWH):        5718.40  OFF-PEAK ENERGY (MWH):        0.00
TOTAL POWER OUTPUT (MW):   380.11
TURBINE OUTFLOW (CFS):   30000.02
SPILLWAY OUTFLOW (CFS):      0.00

R U S S E L L
PERCENTILES:                   50.00%    MEAN      50.00%
BEGINNING STORAGE (BCF):       42.64     42.64     42.64
ENDING STORAGE (BCF):          42.52     42.52     42.52
BEGINNING ELEVATION (FT):     473.19    473.19    473.19
ENDING ELEVATION (FT):        473.09    473.09    473.09
MEAN INFLOW (CFS):     331.68
TURBINE NO.:               1       2       3       4
TURBINE POWER (MW):    93.68   93.75   93.75   61.69
OUTFLOW (CFS):       8083.31 8088.67 8088.67 5737.02
PEAK GENERATION (HRS):      17.98  OFF-PEAK GEN. (HRS):          0.00
PEAK ENERGY (MWH):        6163.62  OFF-PEAK ENERGY (MWH):        0.00
TOTAL POWER OUTPUT (MW):   342.87
TURBINE OUTFLOW (CFS):   29997.65
SPILLWAY OUTFLOW (CFS):      0.00

T H U R M O N D
PERCENTILES:                   50.00%    MEAN      50.00%
BEGINNING STORAGE (BCF):       86.51     86.51     86.51
ENDING STORAGE (BCF):          85.51     85.51     85.51
BEGINNING ELEVATION (FT):     322.09    322.09    322.09
ENDING ELEVATION (FT):        321.71    321.71    321.71
MEAN INFLOW (CFS):     929.55
TURBINE NO.:               1       2       3       4       5       6       7
TURBINE POWER (MW):    46.69   46.62   46.53   46.39   46.10   43.72    0.00
OUTFLOW (CFS):       5122.86 5110.11 5091.75 5062.57 5006.61 4604.08    0.00
SERVICE UNITS (MW):     1.00    0.00
OUTFLOW (CFS):        109.84    0.00
PEAK GENERATION (HRS):      31.87  OFF-PEAK GEN. (HRS):          0.00
PEAK ENERGY (MWH):        8797.01  OFF-PEAK ENERGY (MWH):        0.00
TOTAL POWER OUTPUT (MW):   276.05
TURBINE OUTFLOW (CFS):   29997.99
SPILLWAY OUTFLOW (CFS):      0.00
```

--------------------------- W E E K 9 ---------------------------------

8/19/1991

H A R T W E L L

PERCENTILES:	50.00%	MEAN	50.00%
BEGINNING STORAGE (BCF):	92.82	92.82	92.82
ENDING STORAGE (BCF):	91.76	91.76	91.76
BEGINNING ELEVATION (FT):	651.94	651.94	651.94
ENDING ELEVATION (FT):	651.43	651.43	651.43

MEAN INFLOW (CFS): 1448.87

TURBINE NO.:	1	2	3	4	5
PEAK POWER (MW):	76.10	76.06	76.01	75.93	75.15
OUTFLOW (CFS):	6147.80	6142.27	6134.87	6124.40	5450.68

PEAK GENERATION (HRS): 17.94 OFF-PEAK GEN. (HRS): 0.00

PEAK ENERGY (MWH): 6804.49 OFF-PEAK ENERGY (MWH): 0.00

TOTAL POWER OUTPUT (MW): 379.25

TURBINE OUTFLOW (CFS): 30000.02

SPILLWAY OUTFLOW (CFS): 0.00

R U S S E L L

PERCENTILES:	50.00%	MEAN	50.00%
BEGINNING STORAGE (BCF):	42.52	42.52	42.52
ENDING STORAGE (BCF):	42.50	42.50	42.50
BEGINNING ELEVATION (FT):	473.09	473.09	473.09
ENDING ELEVATION (FT):	473.07	473.07	473.07

MEAN INFLOW (CFS): 345.17

TURBINE NO.:	1	2	3	4
TURBINE POWER (MW):	93.74	93.74	93.74	62.10
OUTFLOW (CFS):	8079.01	8079.01	8079.01	5762.97

PEAK GENERATION (HRS): 20.04 OFF-PEAK GEN. (HRS): 0.00

PEAK ENERGY (MWH): 6880.97 OFF-PEAK ENERGY (MWH): 0.00

TOTAL POWER OUTPUT (MW): 343.32

TURBINE OUTFLOW (CFS): 30000.00

SPILLWAY OUTFLOW (CFS): 0.00

T H U R M O N D

PERCENTILES:	50.00%	MEAN	50.00%
BEGINNING STORAGE (BCF):	85.51	85.51	85.51
ENDING STORAGE (BCF):	84.55	84.55	84.55
BEGINNING ELEVATION (FT):	321.71	321.71	321.71
ENDING ELEVATION (FT):	321.33	321.33	321.33

MEAN INFLOW (CFS): 632.08

TURBINE NO.:	1	2	3	4	5	6	7
TURBINE POWER (MW):	46.56	46.49	46.40	46.25	45.95	43.55	0.00
OUTFLOW (CFS):	5125.59	5112.30	5093.17	5062.80	5004.63	4599.21	0.00
SERVICE UNITS (MW):	1.00	0.00					
OUTFLOW (CFS):	110.13	0.00					

PEAK GENERATION (HRS): 31.87 OFF-PEAK GEN. (HRS): 0.00

PEAK ENERGY (MWH): 8769.74 OFF-PEAK ENERGY (MWH): 0.00

TOTAL POWER OUTPUT (MW): 275.21

TURBINE OUTFLOW (CFS): 29997.70

SPILLWAY OUTFLOW (CFS): 0.00

W E E K 10
8/19/1991

H A R T W E L L

PERCENTILES:	50.00%	MEAN	50.00%
BEGINNING STORAGE (BCF):	91.76	91.76	91.76
ENDING STORAGE (BCF):	90.77	90.77	90.77
BEGINNING ELEVATION (FT):	651.43	651.43	651.43
ENDING ELEVATION (FT):	650.95	650.95	650.95

MEAN INFLOW (CFS): 1525.46

TURBINE NO.:	1	2	3	4	5
PEAK POWER (MW):	76.04	75.99	75.94	75.85	74.24
OUTFLOW (CFS):	6153.72	6147.86	6140.01	6128.83	5429.59

PEAK GENERATION (HRS):	17.74	OFF-PEAK GEN. (HRS):	0.00
PEAK ENERGY (MWH):	6707.60	OFF-PEAK ENERGY (MWH):	0.00
TOTAL POWER OUTPUT (MW):	378.06		
TURBINE OUTFLOW (CFS):	30000.02		
SPILLWAY OUTFLOW (CFS):	0.00		

R U S S E L L

PERCENTILES:	50.00%	MEAN	50.00%
BEGINNING STORAGE (BCF):	42.50	42.50	42.50
ENDING STORAGE (BCF):	42.51	42.51	42.51
BEGINNING ELEVATION (FT):	473.07	473.07	473.07
ENDING ELEVATION (FT):	473.08	473.08	473.08

MEAN INFLOW (CFS): 314.58

TURBINE NO.:	1	2	3	4
TURBINE POWER (MW):	93.74	93.74	93.74	62.72
OUTFLOW (CFS):	8066.61	8066.61	8066.61	5800.19

PEAK GENERATION (HRS):	19.41	OFF-PEAK GEN. (HRS):	0.00
PEAK ENERGY (MWH):	6677.58	OFF-PEAK ENERGY (MWH):	0.00
TOTAL POWER OUTPUT (MW):	343.94		
TURBINE OUTFLOW (CFS):	30000.00		
SPILLWAY OUTFLOW (CFS):	0.00		

T H U R M O N D

PERCENTILES:	50.00%	MEAN	50.00%
BEGINNING STORAGE (BCF):	84.55	84.55	84.55
ENDING STORAGE (BCF):	83.67	83.67	83.67
BEGINNING ELEVATION (FT):	321.33	321.33	321.33
ENDING ELEVATION (FT):	320.99	320.99	320.99

MEAN INFLOW (CFS): 880.73

TURBINE NO.:	1	2	3	4	5	6	7
TURBINE POWER (MW):	46.44	46.37	46.27	46.12	45.81	43.39	0.00
OUTFLOW (CFS):	5128.19	5114.37	5094.51	5062.99	5002.69	4594.68	0.00
SERVICE UNITS (MW):	1.00	0.00					
OUTFLOW (CFS):	110.40	0.00					

PEAK GENERATION (HRS):	31.86	OFF-PEAK GEN. (HRS):	0.00
PEAK ENERGY (MWH):	8743.32	OFF-PEAK ENERGY (MWH):	0.00
TOTAL POWER OUTPUT (MW):	274.39		
TURBINE OUTFLOW (CFS):	29997.43		
SPILLWAY OUTFLOW (CFS):	0.00		

S U M M A R Y   S E Q U E N C E S
DROUGHT OPERATION CONDITIONS
TRADEOFF POINT 4

HARTWELL ELEV-FT	HARTWELL GEN-HRS	HARTWELL MWH	RUSSELL ELEV-FT	RUSSELL GEN-HRS	RUSSELL MWH	THURMOND ELEV-FT	THURMOND GEN-HRS	THURMOND MWH
655.00	11.53	4446.89	473.50	10.00	3389.85	325.00	19.56	5691.67
654.86	10.02	3863.73	473.83	12.31	4177.58	324.75	19.55	5680.09
654.89	11.14	4294.76	473.84	13.42	4558.86	324.65	19.55	5675.49
654.81	10.90	4199.86	473.82	13.15	4469.78	324.56	19.55	5671.42
654.66	10.75	4140.16	473.78	12.90	4386.51	324.40	19.55	5665.99
654.50	11.07	4257.51	473.74	13.24	4504.69	324.25	19.55	5659.09
654.35	10.70	4115.30	473.70	12.96	4410.09	324.09	19.55	5651.96
654.16	10.00	3842.00	473.65	12.16	4143.91	323.90	19.55	5643.60
654.04	14.06	5395.83	473.62	15.31	5218.28	323.79	19.55	5638.44
653.74	10.07	3858.64	473.69	11.05	3767.94	323.73	19.55	5636.41
653.66			473.76			323.57		

DETAILED SEQUENCES

STARTING DATE: 8/19/1991 MONDAY

--------------------------- WEEK 1 ---------------------------------

HARTWELL

PERCENTILES:	50.00%	MEAN	50.00%		
BEGINNING STORAGE (BCF):	99.41	99.41	99.41		
ENDING STORAGE (BCF):	99.11	99.11	99.11		
BEGINNING ELEVATION (FT):	655.00	655.00	655.00		
ENDING ELEVATION (FT):	654.86	654.86	654.86		
MEAN INFLOW (CFS):	1562.45				
TURBINE NO.:	1	2	3	4	5
PEAK POWER (MW):	78.40	78.35	78.29	78.21	72.52
OUTFLOW (CFS):	6111.17	6107.36	6102.41	6095.65	5583.04

PEAK GENERATION (HRS): 11.53 OFF-PEAK GEN. (HRS): 0.00
PEAK ENERGY (MWH): 4446.89 OFF-PEAK ENERGY (MWH): 0.00
TOTAL POWER OUTPUT (MW): 385.77
TURBINE OUTFLOW (CFS): 29999.63
SPILLWAY OUTFLOW (CFS): 0.00

RUSSELL

PERCENTILES:	50.00%	MEAN	50.00%	
BEGINNING STORAGE (BCF):	42.99	42.99	42.99	
ENDING STORAGE (BCF):	43.36	43.36	43.36	
BEGINNING ELEVATION (FT):	473.50	473.50	473.50	
ENDING ELEVATION (FT):	473.83	473.83	473.83	
MEAN INFLOW (CFS):	343.45			
TURBINE NO.:	1	2	3	4
TURBINE POWER (MW):	93.74	93.74	82.76	68.75
OUTFLOW (CFS):	8166.54	8166.54	7353.08	6313.93

PEAK GENERATION (HRS): 10.00 OFF-PEAK GEN. (HRS): 0.00
PEAK ENERGY (MWH): 3389.85 OFF-PEAK ENERGY (MWH): 0.00
TOTAL POWER OUTPUT (MW): 338.99
TURBINE OUTFLOW (CFS): 30000.09
SPILLWAY OUTFLOW (CFS): 0.00

THURMOND

PERCENTILES:	50.00%	MEAN	50.00%				
BEGINNING STORAGE (BCF):	94.47	94.47	94.47				
ENDING STORAGE (BCF):	93.75	93.75	93.75				
BEGINNING ELEVATION (FT):	325.00	325.00	325.00				
ENDING ELEVATION (FT):	324.75	324.75	324.75				
MEAN INFLOW (CFS):	625.67						
TURBINE NO.:	1	2	3	4	5	6	7
TURBINE POWER (MW):	47.64	47.60	47.53	47.43	47.23	45.03	0.00
OUTFLOW (CFS):	5101.70	5092.97	5080.40	5060.37	5021.51	4644.01	0.00
SERVICE UNITS (MW):	1.00	0.00					
OUTFLOW (CFS):	107.76	0.00					

PEAK GENERATION (HRS): 19.56 OFF-PEAK GEN. (HRS): 0.00
PEAK ENERGY (MWH): 5523.67 OFF-PEAK ENERGY (MWH): 0.00
TOTAL POWER OUTPUT (MW): 282.46
TURBINE OUTFLOW (CFS): 30000.96
SPILLWAY OUTFLOW (CFS): 0.00

---------------------------- W E E K 2 ----------------------------

8/19/1991

H A R T W E L L

PERCENTILES:		50.00%	MEAN	50.00%			
BEGINNING STORAGE (BCF):		99.11	99.11	99.11			
ENDING STORAGE (BCF):		99.17	99.17	99.17			
BEGINNING ELEVATION (FT):		654.86	654.86	654.86			
ENDING ELEVATION (FT):		654.89	654.89	654.89			
MEAN INFLOW (CFS):	1890.16						
TURBINE NO.:	1	2	3	4	5		
PEAK POWER (MW):	78.35	78.31	78.25	78.17	72.38		
OUTFLOW (CFS):	6112.84	6108.97	6103.91	6097.01	5576.89		
PEAK GENERATION (HRS):		10.02	OFF-PEAK GEN. (HRS):			0.00	
PEAK ENERGY (MWH):		3863.73	OFF-PEAK ENERGY (MWH):			0.00	
TOTAL POWER OUTPUT (MW):	385.46						
TURBINE OUTFLOW (CFS):	29999.63						
SPILLWAY OUTFLOW (CFS):		0.00					

R U S S E L L

PERCENTILES:		50.00%	MEAN	50.00%			
BEGINNING STORAGE (BCF):		43.36	43.36	43.36			
ENDING STORAGE (BCF):		43.37	43.37	43.37			
BEGINNING ELEVATION (FT):		473.83	473.83	473.83			
ENDING ELEVATION (FT):		473.84	473.84	473.84			
MEAN INFLOW (CFS):	420.79						
TURBINE NO.:	1	2	3	4			
TURBINE POWER (MW):	93.74	93.74	93.74	58.26			
OUTFLOW (CFS):	8156.43	8156.43	8156.43	5530.72			
PEAK GENERATION (HRS):		12.31	OFF-PEAK GEN. (HRS):			0.00	
PEAK ENERGY (MWH):		4177.58	OFF-PEAK ENERGY (MWH):			0.00	
TOTAL POWER OUTPUT (MW):	339.48						
TURBINE OUTFLOW (CFS):	30000.02						
SPILLWAY OUTFLOW (CFS):		0.00					

T H U R M O N D

PERCENTILES:		50.00%	MEAN	50.00%			
BEGINNING STORAGE (BCF):		93.75	93.75	93.75			
ENDING STORAGE (BCF):		93.47	93.47	93.47			
BEGINNING ELEVATION (FT):		324.75	324.75	324.75			
ENDING ELEVATION (FT):		324.65	324.65	324.65			
MEAN INFLOW (CFS):	937.09						
TURBINE NO.:	1	2	3	4	5	6	7
TURBINE POWER (MW):	47.56	47.51	47.44	47.34	47.13	44.91	0.00
OUTFLOW (CFS):	5103.75	5094.68	5081.60	5060.78	5020.41	4640.88	0.00
SERVICE UNITS (MW):	1.00	0.00					
OUTFLOW (CFS):	107.94	0.00					
PEAK GENERATION (HRS):		19.55	OFF-PEAK GEN. (HRS):			0.00	
PEAK ENERGY (MWH):		5512.09	OFF-PEAK ENERGY (MWH):			0.00	
TOTAL POWER OUTPUT (MW):	281.89						
TURBINE OUTFLOW (CFS):	30002.10						
SPILLWAY OUTFLOW (CFS):		0.00					

--------------------------- WEEK 3 ---------------------------------
8/19/1991

HARTWELL

PERCENTILES:		50.00%	MEAN	50.00%			
BEGINNING STORAGE (BCF):		99.17	99.17	99.17			
ENDING STORAGE (BCF):		98.99	98.99	98.99			
BEGINNING ELEVATION (FT):		654.89	654.89	654.89			
ENDING ELEVATION (FT):		654.81	654.81	654.81			
MEAN INFLOW (CFS):	1685.06						
TURBINE NO.:	1	2	3	4	5		
PEAK POWER (MW):	78.36	78.32	78.26	78.18	72.41		
OUTFLOW (CFS):	6112.51	6108.65	6103.62	6096.75	5578.09		
PEAK GENERATION (HRS):	11.14	OFF-PEAK GEN. (HRS):			0.00		
PEAK ENERGY (MWH):	4294.76	OFF-PEAK ENERGY (MWH):			0.00		
TOTAL POWER OUTPUT (MW):	385.52						
TURBINE OUTFLOW (CFS):	29999.63						
SPILLWAY OUTFLOW (CFS):	0.00						

RUSSELL

PERCENTILES:		50.00%	MEAN	50.00%			
BEGINNING STORAGE (BCF):		43.37	43.37	43.37			
ENDING STORAGE (BCF):		43.34	43.34	43.34			
BEGINNING ELEVATION (FT):		473.84	473.84	473.84			
ENDING ELEVATION (FT):		473.82	473.82	473.82			
MEAN INFLOW (CFS):	367.63						
TURBINE NO.:	1	2	3	4			
TURBINE POWER (MW):	93.74	93.74	93.74	58.48			
OUTFLOW (CFS):	8152.11	8152.11	8152.11	5543.69			
PEAK GENERATION (HRS):	13.42	OFF-PEAK GEN. (HRS):			0.00		
PEAK ENERGY (MWH):	4558.86	OFF-PEAK ENERGY (MWH):			0.00		
TOTAL POWER OUTPUT (MW):	339.69						
TURBINE OUTFLOW (CFS):	30000.01						
SPILLWAY OUTFLOW (CFS):	0.00						

THURMOND

PERCENTILES:		50.00%	MEAN	50.00%			
BEGINNING STORAGE (BCF):		93.47	93.47	93.47			
ENDING STORAGE (BCF):		93.22	93.22	93.22			
BEGINNING ELEVATION (FT):		324.65	324.65	324.65			
ENDING ELEVATION (FT):		324.56	324.56	324.56			
MEAN INFLOW (CFS):	783.50						
TURBINE NO.:	1	2	3	4	5	6	7
TURBINE POWER (MW):	47.52	47.48	47.41	47.30	47.09	44.86	0.00
OUTFLOW (CFS):	5104.56	5095.35	5082.08	5060.93	5019.98	4639.65	0.00
SERVICE UNITS (MW):	1.00	0.00					
OUTFLOW (CFS):	108.01	0.00					
PEAK GENERATION (HRS):	19.55	OFF-PEAK GEN. (HRS):			0.00		
PEAK ENERGY (MWH):	5507.49	OFF-PEAK ENERGY (MWH):			0.00		
TOTAL POWER OUTPUT (MW):	281.66						
TURBINE OUTFLOW (CFS):	30002.55						
SPILLWAY OUTFLOW (CFS):	0.00						

---------------------------- WEEK 4 ----------------------------
8/19/1991

HARTWELL

PERCENTILES:	50.00%	MEAN	50.00%		
BEGINNING STORAGE (BCF):	98.99	98.99	98.99		
ENDING STORAGE (BCF):	98.65	98.65	98.65		
BEGINNING ELEVATION (FT):	654.81	654.81	654.81		
ENDING ELEVATION (FT):	654.66	654.66	654.66		
MEAN INFLOW (CFS): 1396.62					
TURBINE NO.:	1	2	3	4	5
PEAK POWER (MW):	78.34	78.29	78.23	78.15	72.33
OUTFLOW (CFS):	6113.55	6109.64	6104.55	6097.59	5574.30

PEAK GENERATION (HRS): 10.90 OFF-PEAK GEN. (HRS): 0.00
PEAK ENERGY (MWH): 4199.86 OFF-PEAK ENERGY (MWH): 0.00
TOTAL POWER OUTPUT (MW): 385.33
TURBINE OUTFLOW (CFS): 29999.63
SPILLWAY OUTFLOW (CFS): 0.00

RUSSELL

PERCENTILES:	50.00%	MEAN	50.00%	
BEGINNING STORAGE (BCF):	43.34	43.34	43.34	
ENDING STORAGE (BCF):	43.30	43.30	43.30	
BEGINNING ELEVATION (FT):	473.82	473.82	473.82	
ENDING ELEVATION (FT):	473.78	473.78	473.78	
MEAN INFLOW (CFS): 332.25				
TURBINE NO.:	1	2	3	4
TURBINE POWER (MW):	93.74	93.74	93.74	58.59
OUTFLOW (CFS):	8149.71	8149.71	8149.71	5550.88

PEAK GENERATION (HRS): 13.15 OFF-PEAK GEN. (HRS): 0.00
PEAK ENERGY (MWH): 4469.78 OFF-PEAK ENERGY (MWH): 0.00
TOTAL POWER OUTPUT (MW): 339.81
TURBINE OUTFLOW (CFS): 30000.02
SPILLWAY OUTFLOW (CFS): 0.00

THURMOND

PERCENTILES:	50.00%	MEAN	50.00%				
BEGINNING STORAGE (BCF):	93.22	93.22	93.22				
ENDING STORAGE (BCF):	92.79	92.79	92.79				
BEGINNING ELEVATION (FT):	324.56	324.56	324.56				
ENDING ELEVATION (FT):	324.40	324.40	324.40				
MEAN INFLOW (CFS): 541.82							
TURBINE NO.:	1	2	3	4	5	6	7
TURBINE POWER (MW):	47.50	47.45	47.38	47.27	47.06	44.81	0.00
OUTFLOW (CFS):	5105.28	5095.95	5082.50	5061.07	5019.58	4638.57	0.00
SERVICE UNITS (MW):	1.00	0.00					
OUTFLOW (CFS):	108.07	0.00					

PEAK GENERATION (HRS): 19.55 OFF-PEAK GEN. (HRS): 0.00
PEAK ENERGY (MWH): 5503.42 OFF-PEAK ENERGY (MWH): 0.00
TOTAL POWER OUTPUT (MW): 281.46
TURBINE OUTFLOW (CFS): 30002.95
SPILLWAY OUTFLOW (CFS): 0.00

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---------------------------  W E E K  5  --------------------------------
                              8/19/1991

H A R T W E L L
PERCENTILES:                    50.00%     MEAN      50.00%
BEGINNING STORAGE (BCF):        98.65      98.65     98.65
ENDING STORAGE (BCF):           98.32      98.32     98.32
BEGINNING ELEVATION (FT):      654.66     654.66    654.66
ENDING ELEVATION (FT):         654.50     654.50    654.50
MEAN INFLOW (CFS):    1360.95
TURBINE NO.:                 1       2       3       4       5
PEAK POWER (MW):         78.29   78.24   77.64   77.57   73.32
OUTFLOW (CFS):         6115.40 6111.42 6060.45 6054.09 5659.04
PEAK GENERATION (HRS):      10.75  OFF-PEAK GEN. (HRS):          0.00
PEAK ENERGY (MWH):        4140.16  OFF-PEAK ENERGY (MWH):        0.00
TOTAL POWER OUTPUT (MW):   385.07
TURBINE OUTFLOW (CFS):   30000.40
SPILLWAY OUTFLOW (CFS):      0.00

R U S S E L L
PERCENTILES:                    50.00%     MEAN      50.00%
BEGINNING STORAGE (BCF):        43.30      43.30     43.30
ENDING STORAGE (BCF):           43.26      43.26     43.26
BEGINNING ELEVATION (FT):      473.78     473.78    473.78
ENDING ELEVATION (FT):         473.74     473.74    473.74
MEAN INFLOW (CFS):     311.55
TURBINE NO.:                 1       2       3       4
TURBINE POWER (MW):      93.74   93.74   93.74   58.79
OUTFLOW (CFS):         8145.71 8145.71 8145.71 5562.88
PEAK GENERATION (HRS):      12.90  OFF-PEAK GEN. (HRS):          0.00
PEAK ENERGY (MWH):        4386.51  OFF-PEAK ENERGY (MWH):        0.00
TOTAL POWER OUTPUT (MW):   340.01
TURBINE OUTFLOW (CFS):   30000.01
SPILLWAY OUTFLOW (CFS):      0.00

T H U R M O N D
PERCENTILES:                    50.00%     MEAN      50.00%
BEGINNING STORAGE (BCF):        92.79      92.79     92.79
ENDING STORAGE (BCF):           92.35      92.35     92.35
BEGINNING ELEVATION (FT):      324.40     324.40    324.40
ENDING ELEVATION (FT):         324.25     324.25    324.25
MEAN INFLOW (CFS):     574.74
TURBINE NO.:                 1       2       3       4       5       6       7
TURBINE POWER (MW):      47.45   47.40   47.33   47.22   47.00   44.78    0.00
OUTFLOW (CFS):         5105.69 5096.15 5082.40 5060.50 5018.13 4636.53    0.00
SERVICE UNITS (MW):       1.00    0.00
OUTFLOW (CFS):          108.18    0.00
PEAK GENERATION (HRS):      19.55  OFF-PEAK GEN. (HRS):          0.00
PEAK ENERGY (MWH):        5497.99  OFF-PEAK ENERGY (MWH):        0.00
TOTAL POWER OUTPUT (MW):   281.16
TURBINE OUTFLOW (CFS):   29999.40
SPILLWAY OUTFLOW (CFS):      0.00
```

WEEK 6

8/19/1991

HARTWELL

PERCENTILES:	50.00%	MEAN	50.00%		
BEGINNING STORAGE (BCF):	98.32	98.32	98.32		
ENDING STORAGE (BCF):	97.97	97.97	97.97		
BEGINNING ELEVATION (FT):	654.50	654.50	654.50		
ENDING ELEVATION (FT):	654.35	654.35	654.35		
MEAN INFLOW (CFS):	1401.19				
TURBINE NO.:	1	2	3	4	5
PEAK POWER (MW):	77.81	77.77	77.72	77.64	73.82
OUTFLOW (CFS):	6080.54	6077.04	6072.47	6066.19	5704.59
PEAK GENERATION (HRS):	11.07	OFF-PEAK GEN. (HRS):	0.00		
PEAK ENERGY (MWH):	4257.51	OFF-PEAK ENERGY (MWH):	0.00		
TOTAL POWER OUTPUT (MW):	384.76				
TURBINE OUTFLOW (CFS):	30000.82				
SPILLWAY OUTFLOW (CFS):	0.00				

RUSSELL

PERCENTILES:	50.00%	MEAN	50.00%	
BEGINNING STORAGE (BCF):	43.26	43.26	43.26	
ENDING STORAGE (BCF):	43.21	43.21	43.21	
BEGINNING ELEVATION (FT):	473.74	473.74	473.74	
ENDING ELEVATION (FT):	473.70	473.70	473.70	
MEAN INFLOW (CFS):	314.93			
TURBINE NO.:	1	2	3	4
TURBINE POWER (MW):	93.74	93.74	93.74	58.99
OUTFLOW (CFS):	8141.68	8141.68	8141.68	5574.98
PEAK GENERATION (HRS):	13.24	OFF-PEAK GEN. (HRS):	0.00	
PEAK ENERGY (MWH):	4504.69	OFF-PEAK ENERGY (MWH):	0.00	
TOTAL POWER OUTPUT (MW):	340.20			
TURBINE OUTFLOW (CFS):	30000.00			
SPILLWAY OUTFLOW (CFS):	0.00			

THURMOND

PERCENTILES:	50.00%	MEAN	50.00%				
BEGINNING STORAGE (BCF):	92.35	92.35	92.35				
ENDING STORAGE (BCF):	91.91	91.91	91.91				
BEGINNING ELEVATION (FT):	324.25	324.25	324.25				
ENDING ELEVATION (FT):	324.09	324.09	324.09				
MEAN INFLOW (CFS):	501.40						
TURBINE NO.:	1	2	3	4	5	6	7
TURBINE POWER (MW):	47.39	47.35	47.27	47.16	46.94	44.70	0.00
OUTFLOW (CFS):	5106.88	5097.12	5083.07	5060.67	5017.38	4634.19	0.00
SERVICE UNITS (MW):	1.00	0.00					
OUTFLOW (CFS):	108.29	0.00					
PEAK GENERATION (HRS):	19.55	OFF-PEAK GEN. (HRS):	0.00				
PEAK ENERGY (MWH):	5491.09	OFF-PEAK ENERGY (MWH):	0.00				
TOTAL POWER OUTPUT (MW):	280.82						
TURBINE OUTFLOW (CFS):	29999.32						
SPILLWAY OUTFLOW (CFS):	0.00						

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----------------------------  W E E K  7  ---------------------------------
                               8/19/1991

H A R T W E L L
PERCENTILES:                    50.00%     MEAN      50.00%
BEGINNING STORAGE (BCF):        97.97      97.97     97.97
ENDING STORAGE (BCF):           97.57      97.57     97.57
BEGINNING ELEVATION (FT):      654.35     654.35    654.35
ENDING ELEVATION (FT):         654.16     654.16    654.16
MEAN INFLOW (CFS):   1254.75
TURBINE NO.:                1        2        3        4        5
PEAK POWER (MW):        77.65    77.61    77.56    77.48    74.14
OUTFLOW (CFS):        6072.76  6069.33  6064.85  6058.69  5735.67
PEAK GENERATION (HRS):       10.70  OFF-PEAK GEN. (HRS):          0.00
PEAK ENERGY (MWH):         4115.30  OFF-PEAK ENERGY (MWH):        0.00
TOTAL POWER OUTPUT (MW):    384.43
TURBINE OUTFLOW (CFS):    30001.30
SPILLWAY OUTFLOW (CFS):       0.00

R U S S E L L
PERCENTILES:                    50.00%     MEAN      50.00%
BEGINNING STORAGE (BCF):        43.21      43.21     43.21
ENDING STORAGE (BCF):           43.16      43.16     43.16
BEGINNING ELEVATION (FT):      473.70     473.70    473.70
ENDING ELEVATION (FT):         473.65     473.65    473.65
MEAN INFLOW (CFS):    312.53
TURBINE NO.:                1        2        3        4
TURBINE POWER (MW):     93.74    93.74    93.74    59.20
OUTFLOW (CFS):        8137.45  8137.45  8137.45  5587.66
PEAK GENERATION (HRS):       12.96  OFF-PEAK GEN. (HRS):          0.00
PEAK ENERGY (MWH):         4410.09  OFF-PEAK ENERGY (MWH):        0.00
TOTAL POWER OUTPUT (MW):    340.41
TURBINE OUTFLOW (CFS):    30000.00
SPILLWAY OUTFLOW (CFS):       0.00

T H U R M O N D
PERCENTILES:                    50.00%     MEAN      50.00%
BEGINNING STORAGE (BCF):        91.91      91.91     91.91
ENDING STORAGE (BCF):           91.38      91.38     91.38
BEGINNING ELEVATION (FT):      324.09     324.09    324.09
ENDING ELEVATION (FT):         323.90     323.90    323.90
MEAN INFLOW (CFS):    414.12
TURBINE NO.:                1        2        3        4        5        6        7
TURBINE POWER (MW):     47.34    47.29    47.22    47.10    46.87    44.63     0.00
OUTFLOW (CFS):        5108.11  5098.13  5083.75  5060.85  5016.61  4631.79     0.00
SERVICE UNITS (MW):      1.00     0.00
OUTFLOW (CFS):         108.40     0.00
PEAK GENERATION (HRS):       19.55  OFF-PEAK GEN. (HRS):          0.00
PEAK ENERGY (MWH):         5483.96  OFF-PEAK ENERGY (MWH):        0.00
TOTAL POWER OUTPUT (MW):    280.46
TURBINE OUTFLOW (CFS):    29999.22
SPILLWAY OUTFLOW (CFS):       0.00
```

WEEK 8

8/19/1991

HARTWELL

PERCENTILES:		50.00%	MEAN	50.00%	
BEGINNING STORAGE (BCF):		97.57	97.57	97.57	
ENDING STORAGE (BCF):		97.29	97.29	97.29	
BEGINNING ELEVATION (FT):		654.16	654.16	654.16	
ENDING ELEVATION (FT):		654.04	654.04	654.04	
MEAN INFLOW (CFS):	1325.97				
TURBINE NO.:	1	2	3	4	5
PEAK POWER (MW):	77.49	77.45	77.40	77.33	74.38
OUTFLOW (CFS):	6066.25	6062.86	6058.42	6052.28	5762.01

PEAK GENERATION (HRS):	10.00	OFF-PEAK GEN. (HRS):	0.00
PEAK ENERGY (MWH):	3842.00	OFF-PEAK ENERGY (MWH):	0.00
TOTAL POWER OUTPUT (MW):	384.04		
TURBINE OUTFLOW (CFS):	30001.83		
SPILLWAY OUTFLOW (CFS):	0.00		

RUSSELL

PERCENTILES:		50.00%	MEAN	50.00%
BEGINNING STORAGE (BCF):		43.16	43.16	43.16
ENDING STORAGE (BCF):		43.13	43.13	43.13
BEGINNING ELEVATION (FT):		473.65	473.65	473.65
ENDING ELEVATION (FT):		473.62	473.62	473.62
MEAN INFLOW (CFS):	331.68			
TURBINE NO.:	1	2	3	4
TURBINE POWER (MW):	93.74	93.74	93.74	59.43
OUTFLOW (CFS):	8132.64	8132.64	8132.64	5602.10

PEAK GENERATION (HRS):	12.16	OFF-PEAK GEN. (HRS):	0.00
PEAK ENERGY (MWH):	4143.91	OFF-PEAK ENERGY (MWH):	0.00
TOTAL POWER OUTPUT (MW):	340.65		
TURBINE OUTFLOW (CFS):	30000.00		
SPILLWAY OUTFLOW (CFS):	0.00		

THURMOND

PERCENTILES:		50.00%	MEAN	50.00%			
BEGINNING STORAGE (BCF):		91.38	91.38	91.38			
ENDING STORAGE (BCF):		91.08	91.08	91.08			
BEGINNING ELEVATION (FT):		323.90	323.90	323.90			
ENDING ELEVATION (FT):		323.79	323.79	323.79			
MEAN INFLOW (CFS):	929.55						
TURBINE NO.:	1	2	3	4	5	6	7
TURBINE POWER (MW):	47.28	47.23	47.15	47.04	46.80	44.54	0.00
OUTFLOW (CFS):	5109.54	5099.30	5084.55	5061.05	5015.69	4628.99	0.00
SERVICE UNITS (MW):	1.00	0.00					
OUTFLOW (CFS):	108.53	0.00					

PEAK GENERATION (HRS):	19.55	OFF-PEAK GEN. (HRS):	0.00
PEAK ENERGY (MWH):	5475.60	OFF-PEAK ENERGY (MWH):	0.00
TOTAL POWER OUTPUT (MW):	280.04		
TURBINE OUTFLOW (CFS):	29999.13		
SPILLWAY OUTFLOW (CFS):	0.00		

------------------------- W E E K 9 -------------------------
8/19/1991

H A R T W E L L

PERCENTILES:	50.00%	MEAN	50.00%
BEGINNING STORAGE (BCF):	97.29	97.29	97.29
ENDING STORAGE (BCF):	96.65	96.65	96.65
BEGINNING ELEVATION (FT):	654.04	654.04	654.04
ENDING ELEVATION (FT):	653.74	653.74	653.74

MEAN INFLOW (CFS): 1448.87

TURBINE NO.:	1	2	3	4	5
PEAK POWER (MW):	77.34	77.30	77.25	77.18	74.71
OUTFLOW (CFS):	6058.38	6055.08	6050.75	6044.77	5791.11

PEAK GENERATION (HRS):	14.06	OFF-PEAK GEN. (HRS):	0.00
PEAK ENERGY (MWH):	5395.83	OFF-PEAK ENERGY (MWH):	0.00
TOTAL POWER OUTPUT (MW):	383.78		
TURBINE OUTFLOW (CFS):	30000.08		
SPILLWAY OUTFLOW (CFS):	0.00		

R U S S E L L

PERCENTILES:	50.00%	MEAN	50.00%
BEGINNING STORAGE (BCF):	43.13	43.13	43.13
ENDING STORAGE (BCF):	43.20	43.20	43.20
BEGINNING ELEVATION (FT):	473.62	473.62	473.62
ENDING ELEVATION (FT):	473.69	473.69	473.69

MEAN INFLOW (CFS): 345.17

TURBINE NO.:	1	2	3	4
TURBINE POWER (MW):	93.74	93.74	93.74	59.58
OUTFLOW (CFS):	8129.55	8129.55	8129.55	5611.34

PEAK GENERATION (HRS):	15.31	OFF-PEAK GEN. (HRS):	0.00
PEAK ENERGY (MWH):	5218.28	OFF-PEAK ENERGY (MWH):	0.00
TOTAL POWER OUTPUT (MW):	340.80		
TURBINE OUTFLOW (CFS):	30000.00		
SPILLWAY OUTFLOW (CFS):	0.00		

T H U R M O N D

PERCENTILES:	50.00%	MEAN	50.00%
BEGINNING STORAGE (BCF):	91.08	91.08	91.08
ENDING STORAGE (BCF):	90.94	90.94	90.94
BEGINNING ELEVATION (FT):	323.79	323.79	323.79
ENDING ELEVATION (FT):	323.73	323.73	323.73

MEAN INFLOW (CFS): 632.08

TURBINE NO.:	1	2	3	4	5	6	7
TURBINE POWER (MW):	47.24	47.19	47.12	47.00	46.76	44.49	0.00
OUTFLOW (CFS):	5110.43	5100.03	5085.06	5061.22	5015.21	4628.39	0.00
SERVICE UNITS (MW):	1.00	0.00					
OUTFLOW (CFS):	108.61	0.00					

PEAK GENERATION (HRS):	19.55	OFF-PEAK GEN. (HRS):	0.00
PEAK ENERGY (MWH):	5470.44	OFF-PEAK ENERGY (MWH):	0.00
TOTAL POWER OUTPUT (MW):	279.80		
TURBINE OUTFLOW (CFS):	30000.34		
SPILLWAY OUTFLOW (CFS):	0.00		

W E E K 10
8/19/1991

H A R T W E L L
PERCENTILES: 50.00% MEAN 50.00%
BEGINNING STORAGE (BCF): 96.65 96.65 96.65
ENDING STORAGE (BCF): 96.49 96.49 96.49
BEGINNING ELEVATION (FT): 653.74 653.74 653.74
ENDING ELEVATION (FT): 653.66 653.66 653.66
MEAN INFLOW (CFS): 1525.46
TURBINE NO.: 1 2 3 4 5
PEAK POWER (MW): 75.66 75.64 75.62 75.59 80.84
OUTFLOW (CFS): 5926.57 5925.25 5923.50 5921.09 6303.68
PEAK GENERATION (HRS): 10.07 OFF-PEAK GEN. (HRS): 0.00
PEAK ENERGY (MWH): 3858.64 OFF-PEAK ENERGY (MWH): 0.00
TOTAL POWER OUTPUT (MW): 383.36
TURBINE OUTFLOW (CFS): 30000.08
SPILLWAY OUTFLOW (CFS): 0.00

R U S S E L L
PERCENTILES: 50.00% MEAN 50.00%
BEGINNING STORAGE (BCF): 43.20 43.20 43.20
ENDING STORAGE (BCF): 43.28 43.28 43.28
BEGINNING ELEVATION (FT): 473.69 473.69 473.69
ENDING ELEVATION (FT): 473.76 473.76 473.76
MEAN INFLOW (CFS): 314.58
TURBINE NO.: 1 2 3 4
TURBINE POWER (MW): 93.74 93.74 93.74 59.80
OUTFLOW (CFS): 8125.30 8125.30 8125.30 5624.11
PEAK GENERATION (HRS): 11.05 OFF-PEAK GEN. (HRS): 0.00
PEAK ENERGY (MWH): 3767.94 OFF-PEAK ENERGY (MWH): 0.00
TOTAL POWER OUTPUT (MW): 341.01
TURBINE OUTFLOW (CFS): 30000.00
SPILLWAY OUTFLOW (CFS): 0.00

T H U R M O N D
PERCENTILES: 50.00% MEAN 50.00%
BEGINNING STORAGE (BCF): 90.94 90.94 90.94
ENDING STORAGE (BCF): 90.49 90.49 90.49
BEGINNING ELEVATION (FT): 323.73 323.73 323.73
ENDING ELEVATION (FT): 323.57 323.57 323.57
MEAN INFLOW (CFS): 880.73
TURBINE NO.: 1 2 3 4 5 6 7
TURBINE POWER (MW): 47.23 47.18 47.10 46.98 46.74 44.47 0.00
OUTFLOW (CFS): 5110.78 5100.32 5085.25 5061.26 5014.98 4627.74 0.00
SERVICE UNITS (MW): 1.00 0.00
OUTFLOW (CFS): 108.65 0.00
PEAK GENERATION (HRS): 19.55 OFF-PEAK GEN. (HRS): 0.00
PEAK ENERGY (MWH): 5468.41 OFF-PEAK ENERGY (MWH): 0.00
TOTAL POWER OUTPUT (MW): 279.69
TURBINE OUTFLOW (CFS): 30000.34
SPILLWAY OUTFLOW (CFS): 0.00

APPENDIX G

Output File Generated by SAVRES in Section 3.3.1 (Flood Operations)

FLOOD OPERATION TRADEOFFS

NO.	THURMOND DISCH. CFS	SYSTEM ENERGY MWH/DAY	RESERVOIR STATISTICS (MAXIMUM VALUES) HARTWELL FEET	HARTWELL CFS	RUSSELL FEET	RUSSELL CFS	THURMOND FEET	THURMOND CFS
1	20000.	10800.	665.17	20000.	480.16	20000.	335.18	20103.
2	25000.	13565.	664.59	25000.	479.53	25000.	334.60	25104.
3	30000.	16103.	663.98	30000.	478.99	30000.	334.00	30106.
4	35000.	18789.	663.39	32793.	478.37	33348.	333.41	35106.
5	40000.	19529.	663.18	32896.	478.13	33354.	333.20	37538.

S U M M A R Y   S E Q U E N C E S
FLOOD OPERATION CONDITIONS - DAILY
TRADEOFF POINT 4

HARTWELL ELEV-FT	HARTWELL CFS	HARTWELL MWH	RUSSELL ELEV-FT	RUSSELL CFS	RUSSELL MWH	THURMOND ELEV-FT	THURMOND CFS	THURMOND MWH
660.00	20830.	6555.57	475.00	30675.	8280.43	330.00	35102.	8179.58
660.00	19455.	6122.75	475.00	28615.	7724.41	330.00	35102.	8179.36
659.99	16583.	5218.79	474.99	24509.	6615.89	329.99	35102.	8179.12
660.06	13038.	4104.96	475.06	18518.	4998.69	330.07	35102.	8183.52
660.23	10651.	3357.15	475.23	16426.	4434.05	330.23	35103.	8193.59
660.48	8808.	2780.77	475.48	11784.	3180.80	330.49	35103.	8209.16
660.91	5511.	1744.72	475.90	6236.	1683.36	330.92	35106.	8232.69
661.52	4773.	1517.06	476.51	5248.	1416.54	331.53	35102.	8271.08
662.27	9232.	2948.10	477.26	11810.	3187.49	332.29	35105.	8319.36
662.91	15694.	5032.07	477.90	21913.	5914.04	332.93	35106.	8358.56
663.39			478.37			333.41		

D E T A I L E D   S E Q U E N C E S

STARTING DATE: 2/11/1991 MONDAY

--------------------------- D A Y 1 ---------------------------------

H A R T W E L L

PERCENTILES:	5.00%	MEAN	95.00%
BEGINNING STORAGE (BCF):	111.04	111.04	111.04
ENDING STORAGE (BCF):	110.51	111.03	111.56
BEGINNING ELEVATION (FT):	660.00	660.00	660.00
ENDING ELEVATION (FT):	659.78	660.00	660.21

MEAN INFLOW (CFS): 20735.68

TURBINE NO.:	1	2	3	4	5
PEAK POWER (MW):	82.50	82.50	82.50	82.50	100.00
OUTFLOW (CFS):	6280.29	6280.29	6280.29	6280.29	7670.03

PEAK GENERATION (HRS):	15.00	OFF-PEAK GEN. (HRS):	0.25
PEAK ENERGY (MWH):	6449.96	OFF-PEAK ENERGY (MWH):	105.62

TOTAL POWER OUTPUT (MW): 430.00
TURBINE OUTFLOW (CFS): 32791.20
SPILLWAY OUTFLOW (CFS): 0.00

R U S S E L L

PERCENTILES:	5.00%	MEAN	95.00%
BEGINNING STORAGE (BCF):	44.70	44.70	44.70
ENDING STORAGE (BCF):	44.02	44.70	45.38
BEGINNING ELEVATION (FT):	475.00	475.00	475.00
ENDING ELEVATION (FT):	474.41	475.00	475.58

MEAN INFLOW (CFS): 9801.02

TURBINE NO.:	1	2	3	4
TURBINE POWER (MW):	93.75	93.75	93.75	93.75
OUTFLOW (CFS):	8335.20	8335.20	8335.20	8335.00

PEAK GENERATION (HRS):	15.00	OFF-PEAK GEN. (HRS):	7.08
PEAK ENERGY (MWH):	5624.96	OFF-PEAK ENERGY (MWH):	2655.47

TOTAL POWER OUTPUT (MW): 375.00
TURBINE OUTFLOW (CFS): 33340.59
SPILLWAY OUTFLOW (CFS): 0.00

T H U R M O N D

PERCENTILES:	5.00%	MEAN	95.00%
BEGINNING STORAGE (BCF):	109.46	109.46	109.46
ENDING STORAGE (BCF):	109.07	109.45	109.82
BEGINNING ELEVATION (FT):	330.00	330.00	330.00
ENDING ELEVATION (FT):	329.88	330.00	330.12

MEAN INFLOW (CFS): 4322.99

TURBINE NO.:	1	2	3	4	5	6	7
TURBINE POWER (MW):	48.87	48.85	48.83	48.80	48.75	48.66	47.05
OUTFLOW (CFS):	5057.02	5054.18	5050.35	5044.85	5036.09	5019.11	4735.78
SERVICE UNITS (MW):	1.00	0.00					
OUTFLOW (CFS):	105.03	0.00					

PEAK GENERATION (HRS):	15.00	OFF-PEAK GEN. (HRS):	9.00
PEAK ENERGY (MWH):	5097.24	OFF-PEAK ENERGY (MWH):	3058.34

TOTAL POWER OUTPUT (MW): 339.82
TURBINE OUTFLOW (CFS): 34997.37
SPILLWAY OUTFLOW (CFS): 0.00

---------------------------- D A Y 2 ----------------------------------
2/12/1991 TUESDAY

H A R T W E L L

PERCENTILES:	5.00%	MEAN	95.00%		
BEGINNING STORAGE (BCF):	110.51	111.03	111.56		
ENDING STORAGE (BCF):	110.04	111.02	112.01		
BEGINNING ELEVATION (FT):	659.78	660.00	660.21		
ENDING ELEVATION (FT):	659.59	659.99	660.40		

MEAN INFLOW (CFS): 19323.77

TURBINE NO.:	1	2	3	4	5
PEAK POWER (MW):	82.50	82.50	82.50	82.50	100.00
OUTFLOW (CFS):	6280.42	6280.42	6280.42	6280.42	7670.18

PEAK GENERATION (HRS): 14.24 OFF-PEAK GEN. (HRS): 0.00
PEAK ENERGY (MWH): 6122.75 OFF-PEAK ENERGY (MWH): 0.00
TOTAL POWER OUTPUT (MW): 430.00
TURBINE OUTFLOW (CFS): 32791.84
SPILLWAY OUTFLOW (CFS): 0.00

R U S S E L L

PERCENTILES:	5.00%	MEAN	95.00%
BEGINNING STORAGE (BCF):	44.02	44.70	45.38
ENDING STORAGE (BCF):	44.03	44.69	45.36
BEGINNING ELEVATION (FT):	474.41	475.00	475.58
ENDING ELEVATION (FT):	474.42	474.99	475.56

MEAN INFLOW (CFS): 9097.47

TURBINE NO.:	1	2	3	4
TURBINE POWER (MW):	93.75	93.75	93.75	93.75
OUTFLOW (CFS):	8335.17	8335.17	8335.17	8334.97

PEAK GENERATION (HRS): 15.00 OFF-PEAK GEN. (HRS): 5.60
PEAK ENERGY (MWH): 5624.96 OFF-PEAK ENERGY (MWH): 2099.45
TOTAL POWER OUTPUT (MW): 375.00
TURBINE OUTFLOW (CFS): 33340.48
SPILLWAY OUTFLOW (CFS): 0.00

T H U R M O N D

PERCENTILES:	5.00%	MEAN	95.00%
BEGINNING STORAGE (BCF):	109.07	109.45	109.82
ENDING STORAGE (BCF):	108.79	109.43	110.08
BEGINNING ELEVATION (FT):	329.88	330.00	330.12
ENDING ELEVATION (FT):	329.79	329.99	330.20

MEAN INFLOW (CFS): 6321.32

TURBINE NO.:	1	2	3	4	5	6	7
TURBINE POWER (MW):	48.86	48.85	48.83	48.80	48.75	48.66	47.05
OUTFLOW (CFS):	5057.04	5054.20	5050.37	5044.86	5036.09	5019.09	4735.73
SERVICE UNITS (MW):	1.00	0.00					
OUTFLOW (CFS):	105.03	0.00					

PEAK GENERATION (HRS): 15.00 OFF-PEAK GEN. (HRS): 9.00
PEAK ENERGY (MWH): 5097.10 OFF-PEAK ENERGY (MWH): 3058.26
TOTAL POWER OUTPUT (MW): 339.81
TURBINE OUTFLOW (CFS): 34997.38
SPILLWAY OUTFLOW (CFS): 0.00

------------------------------ D A Y 3 ------------------------------

2/13/1991 WEDNESDAY

H A R T W E L L

PERCENTILES:	5.00%	MEAN	95.00%
BEGINNING STORAGE (BCF):	110.04	111.02	112.01
ENDING STORAGE (BCF):	110.04	111.20	112.37
BEGINNING ELEVATION (FT):	659.59	659.99	660.40
ENDING ELEVATION (FT):	659.59	660.06	660.54

MEAN INFLOW (CFS): 18619.80

TURBINE NO.:	1	2	3	4	5
PEAK POWER (MW):	82.50	82.50	82.50	82.50	100.00
OUTFLOW (CFS):	6280.62	6280.62	6280.62	6280.62	7670.44

PEAK GENERATION (HRS): 12.14 OFF-PEAK GEN. (HRS): 0.00
PEAK ENERGY (MWH): 5218.79 OFF-PEAK ENERGY (MWH): 0.00
TOTAL POWER OUTPUT (MW): 430.00
TURBINE OUTFLOW (CFS): 32792.93
SPILLWAY OUTFLOW (CFS): 0.00

R U S S E L L

PERCENTILES:	5.00%	MEAN	95.00%
BEGINNING STORAGE (BCF):	44.03	44.69	45.36
ENDING STORAGE (BCF):	44.03	44.78	45.53
BEGINNING ELEVATION (FT):	474.42	474.99	475.56
ENDING ELEVATION (FT):	474.42	475.06	475.71

MEAN INFLOW (CFS): 8889.83

TURBINE NO.:	1	2	3	4
TURBINE POWER (MW):	93.75	93.75	93.75	93.75
OUTFLOW (CFS):	8335.25	8335.25	8335.25	8335.06

PEAK GENERATION (HRS): 15.00 OFF-PEAK GEN. (HRS): 2.64
PEAK ENERGY (MWH): 5624.96 OFF-PEAK ENERGY (MWH): 990.93
TOTAL POWER OUTPUT (MW): 375.00
TURBINE OUTFLOW (CFS): 33340.81
SPILLWAY OUTFLOW (CFS): 0.00

T H U R M O N D

PERCENTILES:	5.00%	MEAN	95.00%
BEGINNING STORAGE (BCF):	108.79	109.43	110.08
ENDING STORAGE (BCF):	108.22	109.66	111.11
BEGINNING ELEVATION (FT):	329.79	329.99	330.20
ENDING ELEVATION (FT):	329.61	330.07	330.52

MEAN INFLOW (CFS): 13228.82

TURBINE NO.:	1	2	3	4	5	6	7
TURBINE POWER (MW):	48.86	48.85	48.83	48.80	48.75	48.66	47.05
OUTFLOW (CFS):	5057.07	5054.23	5050.39	5044.87	5036.09	5019.06	4735.66
SERVICE UNITS (MW):	1.00	0.00					
OUTFLOW (CFS):	105.03	0.00					

PEAK GENERATION (HRS): 15.00 OFF-PEAK GEN. (HRS): 9.00
PEAK ENERGY (MWH): 5096.95 OFF-PEAK ENERGY (MWH): 3058.17
TOTAL POWER OUTPUT (MW): 339.80
TURBINE OUTFLOW (CFS): 34997.37
SPILLWAY OUTFLOW (CFS): 0.00

--------------------------- D A Y 4 --------------------------------
2/14/1991 THURSDAY

H A R T W E L L

PERCENTILES:	5.00%	MEAN	95.00%
BEGINNING STORAGE (BCF):	110.04	111.20	112.37
ENDING STORAGE (BCF):	110.26	111.60	112.95
BEGINNING ELEVATION (FT):	659.59	660.06	660.54
ENDING ELEVATION (FT):	659.68	660.23	660.78

MEAN INFLOW (CFS): 17683.37

TURBINE NO.:	1	2	3	4	5
PEAK POWER (MW):	82.50	82.50	82.50	82.50	100.00
OUTFLOW (CFS):	6277.70	6277.70	6277.70	6277.70	7666.79

PEAK GENERATION (HRS):	9.55	OFF-PEAK GEN. (HRS):	0.00
PEAK ENERGY (MWH):	4104.96	OFF-PEAK ENERGY (MWH):	0.00
TOTAL POWER OUTPUT (MW):	430.00		
TURBINE OUTFLOW (CFS):	32777.59		
SPILLWAY OUTFLOW (CFS):	0.00		

R U S S E L L

PERCENTILES:	5.00%	MEAN	95.00%
BEGINNING STORAGE (BCF):	44.03	44.78	45.53
ENDING STORAGE (BCF):	44.33	44.97	45.61
BEGINNING ELEVATION (FT):	474.42	475.06	475.71
ENDING ELEVATION (FT):	474.68	475.23	475.78

MEAN INFLOW (CFS): 7678.24

TURBINE NO.:	1	2	3	4
TURBINE POWER (MW):	93.75	93.75	93.75	93.75
OUTFLOW (CFS):	8335.22	8335.22	8335.22	8335.03

PEAK GENERATION (HRS):	13.33	OFF-PEAK GEN. (HRS):	0.00
PEAK ENERGY (MWH):	4998.69	OFF-PEAK ENERGY (MWH):	0.00
TOTAL POWER OUTPUT (MW):	375.00		
TURBINE OUTFLOW (CFS):	33340.68		
SPILLWAY OUTFLOW (CFS):	0.00		

T H U R M O N D

PERCENTILES:	5.00%	MEAN	95.00%
BEGINNING STORAGE (BCF):	108.22	109.66	111.11
ENDING STORAGE (BCF):	108.30	110.18	112.09
BEGINNING ELEVATION (FT):	329.61	330.07	330.52
ENDING ELEVATION (FT):	329.63	330.23	330.83

MEAN INFLOW (CFS): 22629.52

TURBINE NO.:	1	2	3	4	5	6	7
TURBINE POWER (MW):	48.89	48.87	48.85	48.82	48.78	48.69	47.08
OUTFLOW (CFS):	5056.54	5053.76	5050.01	5044.63	5036.06	5019.48	4737.00
SERVICE UNITS (MW):	1.00	0.00					
OUTFLOW (CFS):	104.99	0.00					

PEAK GENERATION (HRS):	15.00	OFF-PEAK GEN. (HRS):	9.00
PEAK ENERGY (MWH):	5099.70	OFF-PEAK ENERGY (MWH):	3059.82
TOTAL POWER OUTPUT (MW):	339.98		
TURBINE OUTFLOW (CFS):	34997.48		
SPILLWAY OUTFLOW (CFS):	0.00		

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---------------------------   D A Y    5   ---------------------------------
                           2/15/1991 FRIDAY

 H A R T W E L L
 PERCENTILES:                    5.00%     MEAN      95.00%
 BEGINNING STORAGE (BCF):       110.26    111.60    112.95
 ENDING STORAGE (BCF):          110.65    112.22    113.81
 BEGINNING ELEVATION (FT):      659.68    660.23    660.78
 ENDING ELEVATION (FT):         659.84    660.48    661.13
 MEAN INFLOW (CFS):  17867.77
 TURBINE NO.:                1        2        3        4        5
 PEAK POWER (MW):          82.50    82.50    82.50    82.50   100.00
 OUTFLOW (CFS):          6271.07  6271.07  6271.07  6271.07  7658.53
 PEAK GENERATION (HRS):        7.81  OFF-PEAK GEN. (HRS):          0.00
 PEAK ENERGY (MWH):         3357.15  OFF-PEAK ENERGY (MWH):        0.00
 TOTAL POWER OUTPUT (MW):   430.00
 TURBINE OUTFLOW (CFS):   32742.80
 SPILLWAY OUTFLOW (CFS):      0.00

 R U S S E L L
 PERCENTILES:                    5.00%     MEAN      95.00%
 BEGINNING STORAGE (BCF):        44.33     44.97     45.61
 ENDING STORAGE (BCF):           44.31     45.26     46.23
 BEGINNING ELEVATION (FT):      474.68    475.23    475.78
 ENDING ELEVATION (FT):         474.66    475.48    476.30
 MEAN INFLOW (CFS):   9192.83
 TURBINE NO.:                1        2        3        4
 TURBINE POWER (MW):       93.75    93.75    93.75    93.75
 OUTFLOW (CFS):          8335.32  8335.32  8335.32  8335.12
 PEAK GENERATION (HRS):       11.82  OFF-PEAK GEN. (HRS):          0.00
 PEAK ENERGY (MWH):         4434.05  OFF-PEAK ENERGY (MWH):        0.00
 TOTAL POWER OUTPUT (MW):   375.00
 TURBINE OUTFLOW (CFS):   33341.07
 SPILLWAY OUTFLOW (CFS):      0.00

 T H U R M O N D
 PERCENTILES:                    5.00%     MEAN      95.00%
 BEGINNING STORAGE (BCF):       108.30    110.18    112.09
 ENDING STORAGE (BCF):          108.91    111.00    113.11
 BEGINNING ELEVATION (FT):      329.63    330.23    330.83
 ENDING ELEVATION (FT):         329.83    330.49    331.15
 MEAN INFLOW (CFS):  28115.64
 TURBINE NO.:                1        2        3        4        5        6        7
 TURBINE POWER (MW):       48.94    48.93    48.91    48.88    48.84    48.75    47.16
 OUTFLOW (CFS):          5055.29  5052.67  5049.12  5044.04  5035.96  5020.39  4740.27
 SERVICE UNITS (MW):        1.00     0.00
 OUTFLOW (CFS):           104.88     0.00
 PEAK GENERATION (HRS):       15.00  OFF-PEAK GEN. (HRS):          9.00
 PEAK ENERGY (MWH):         5106.00  OFF-PEAK ENERGY (MWH):     3063.60
 TOTAL POWER OUTPUT (MW):   340.40
 TURBINE OUTFLOW (CFS):   34997.74
 SPILLWAY OUTFLOW (CFS):      0.00
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---------------------------- D A Y 6 ----------------------------------

2/16/1991 SATURDAY

H A R T W E L L

PERCENTILES:		5.00%	MEAN	95.00%	
BEGINNING STORAGE (BCF):		110.65	112.22	113.81	
ENDING STORAGE (BCF):		111.84	113.27	114.72	
BEGINNING ELEVATION (FT):		659.84	660.48	661.13	
ENDING ELEVATION (FT):		660.33	660.91	661.49	
MEAN INFLOW (CFS): 20965.98					
TURBINE NO.:	1	2	3	4	5
PEAK POWER (MW):	82.50	82.50	82.50	82.50	100.00
OUTFLOW (CFS):	6260.80	6260.80	6260.80	6260.80	7645.73
PEAK GENERATION (HRS):		0.00	OFF-PEAK GEN. (HRS):		6.47
PEAK ENERGY (MWH):		0.00	OFF-PEAK ENERGY (MWH):		2780.77
TOTAL POWER OUTPUT (MW):	430.00				
TURBINE OUTFLOW (CFS):	32688.92				
SPILLWAY OUTFLOW (CFS):		0.00			

R U S S E L L

PERCENTILES:		5.00%	MEAN	95.00%
BEGINNING STORAGE (BCF):		44.31	45.26	46.23
ENDING STORAGE (BCF):		44.89	45.76	46.64
BEGINNING ELEVATION (FT):		474.66	475.48	476.30
ENDING ELEVATION (FT):		475.16	475.90	476.64
MEAN INFLOW (CFS): 8738.43				
TURBINE NO.:	1	2	3	4
TURBINE POWER (MW):	93.75	93.75	93.75	93.75
OUTFLOW (CFS):	8335.42	8335.42	8335.42	8335.23
PEAK GENERATION (HRS):		0.00	OFF-PEAK GEN. (HRS):	8.48
PEAK ENERGY (MWH):		0.00	OFF-PEAK ENERGY (MWH):	3180.80
TOTAL POWER OUTPUT (MW):	375.00			
TURBINE OUTFLOW (CFS):	33341.50			
SPILLWAY OUTFLOW (CFS):		0.00		

T H U R M O N D

PERCENTILES:		5.00%	MEAN	95.00%			
BEGINNING STORAGE (BCF):		108.91	111.00	113.11			
ENDING STORAGE (BCF):		109.49	112.38	115.30			
BEGINNING ELEVATION (FT):		329.83	330.49	331.15			
ENDING ELEVATION (FT):		330.01	330.92	331.82			
MEAN INFLOW (CFS): 39248.34							
TURBINE NO.:	1	2	3	4	5	6	7
TURBINE POWER (MW):	49.02	49.01	48.99	48.97	48.93	48.85	47.28
OUTFLOW (CFS):	5053.29	5050.89	5047.66	5043.03	5035.71	5021.73	4745.81
SERVICE UNITS (MW):	1.00	0.00					
OUTFLOW (CFS):	104.71	0.00					
PEAK GENERATION (HRS):		0.00	OFF-PEAK GEN. (HRS):		24.00		
PEAK ENERGY (MWH):		0.00	OFF-PEAK ENERGY (MWH):		8185.16		
TOTAL POWER OUTPUT (MW):	341.05						
TURBINE OUTFLOW (CFS):	34998.12						
SPILLWAY OUTFLOW (CFS):		0.00					

DAY 7

2/17/1991 SUNDAY

HARTWELL

PERCENTILES:	5.00%	MEAN	95.00%
BEGINNING STORAGE (BCF):	111.84	113.27	114.72
ENDING STORAGE (BCF):	112.94	114.79	116.66
BEGINNING ELEVATION (FT):	660.33	660.91	661.49
ENDING ELEVATION (FT):	660.77	661.52	662.26

MEAN INFLOW (CFS): 23099.49

TURBINE NO.:	1	2	3	4	5
PEAK POWER (MW):	82.50	82.50	82.50	82.50	100.00
OUTFLOW (CFS):	6243.67	6243.67	6243.67	6243.67	7624.40

PEAK GENERATION (HRS):	0.00	OFF-PEAK GEN. (HRS):	4.06
PEAK ENERGY (MWH):	0.00	OFF-PEAK ENERGY (MWH):	1744.72
TOTAL POWER OUTPUT (MW):	430.00		
TURBINE OUTFLOW (CFS):	32599.10		
SPILLWAY OUTFLOW (CFS):	0.00		

RUSSELL

PERCENTILES:	5.00%	MEAN	95.00%
BEGINNING STORAGE (BCF):	44.89	45.76	46.64
ENDING STORAGE (BCF):	45.46	46.48	47.51
BEGINNING ELEVATION (FT):	475.16	475.90	476.64
ENDING ELEVATION (FT):	475.65	476.51	477.36

MEAN INFLOW (CFS): 9073.10

TURBINE NO.:	1	2	3	4
TURBINE POWER (MW):	93.75	93.75	93.75	93.75
OUTFLOW (CFS):	8335.61	8335.61	8335.61	8335.42

PEAK GENERATION (HRS):	0.00	OFF-PEAK GEN. (HRS):	4.49
PEAK ENERGY (MWH):	0.00	OFF-PEAK ENERGY (MWH):	1683.36
TOTAL POWER OUTPUT (MW):	375.00		
TURBINE OUTFLOW (CFS):	33342.26		
SPILLWAY OUTFLOW (CFS):	0.00		

THURMOND

PERCENTILES:	5.00%	MEAN	95.00%
BEGINNING STORAGE (BCF):	109.49	112.38	115.30
ENDING STORAGE (BCF):	111.05	114.36	117.73
BEGINNING ELEVATION (FT):	330.01	330.92	331.82
ENDING ELEVATION (FT):	330.50	331.53	332.56

MEAN INFLOW (CFS): 51825.59

TURBINE NO.:	1	2	3	4	5	6	7
TURBINE POWER (MW):	49.16	49.15	49.13	49.11	49.08	49.02	47.38
OUTFLOW (CFS):	5052.33	5050.31	5047.60	5043.73	5037.67	5026.33	4743.83
SERVICE UNITS (MW):	1.00	0.00					
OUTFLOW (CFS):	104.45	0.00					

PEAK GENERATION (HRS):	0.00	OFF-PEAK GEN. (HRS):	24.00
PEAK ENERGY (MWH):	0.00	OFF-PEAK ENERGY (MWH):	8208.69
TOTAL POWER OUTPUT (MW):	342.03		
TURBINE OUTFLOW (CFS):	35001.80		
SPILLWAY OUTFLOW (CFS):	0.00		

---------------------------- D A Y 8 ---------------------------------
2/18/1991 MONDAY

H A R T W E L L

PERCENTILES:	5.00%	MEAN	95.00%		
BEGINNING STORAGE (BCF):	112.94	114.79	116.66		
ENDING STORAGE (BCF):	114.50	116.69	118.91		
BEGINNING ELEVATION (FT):	660.77	661.52	662.26		
ENDING ELEVATION (FT):	661.40	662.27	663.14		
MEAN INFLOW (CFS): 26741.33					
TURBINE NO.:	1	2	3	4	5
PEAK POWER (MW):	82.50	82.50	82.50	82.50	100.00
OUTFLOW (CFS):	6219.39	6219.39	6219.39	6219.39	7594.14

PEAK GENERATION (HRS): 3.53 OFF-PEAK GEN. (HRS): 0.00
PEAK ENERGY (MWH): 1517.06 OFF-PEAK ENERGY (MWH): 0.00
TOTAL POWER OUTPUT (MW): 430.00
TURBINE OUTFLOW (CFS): 32471.69
SPILLWAY OUTFLOW (CFS): 0.00

R U S S E L L

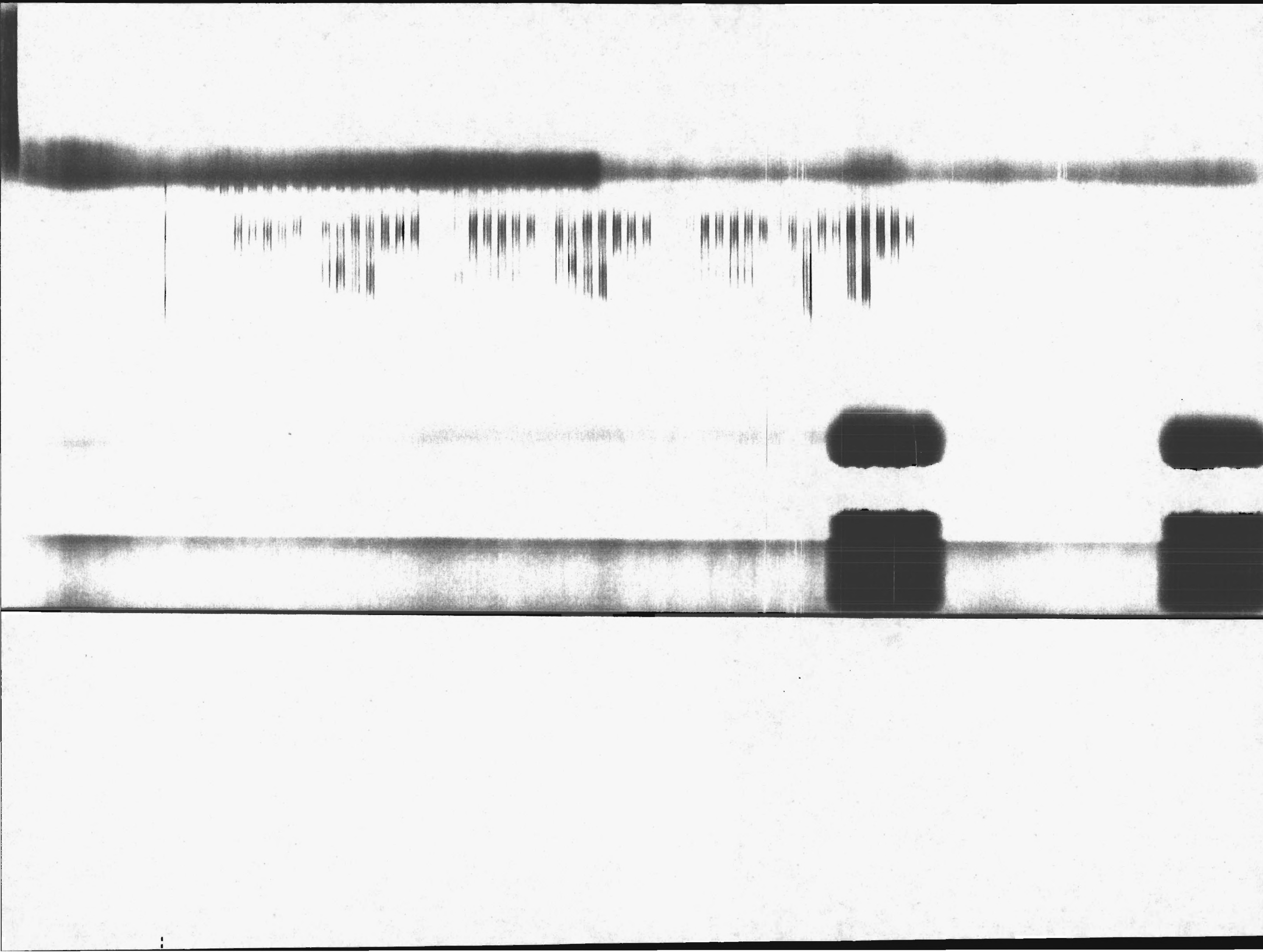
PERCENTILES:	5.00%	MEAN	95.00%	
BEGINNING STORAGE (BCF):	45.46	46.48	47.51	
ENDING STORAGE (BCF):	46.34	47.38	48.44	
BEGINNING ELEVATION (FT):	475.65	476.51	477.36	
ENDING ELEVATION (FT):	476.39	477.26	478.12	
MEAN INFLOW (CFS): 10920.84				
TURBINE NO.:	1	2	3	4
TURBINE POWER (MW):	93.75	93.75	93.75	93.75
OUTFLOW (CFS):	8336.05	8336.05	8336.05	8335.86

PEAK GENERATION (HRS): 3.78 OFF-PEAK GEN. (HRS): 0.00
PEAK ENERGY (MWH): 1416.54 OFF-PEAK ENERGY (MWH): 0.00
TOTAL POWER OUTPUT (MW): 375.00
TURBINE OUTFLOW (CFS): 33344.02
SPILLWAY OUTFLOW (CFS): 0.00

T H U R M O N D

PERCENTILES:	5.00%	MEAN	95.00%				
BEGINNING STORAGE (BCF):	111.05	114.36	117.73				
ENDING STORAGE (BCF):	112.37	116.83	121.41				
BEGINNING ELEVATION (FT):	330.50	331.53	332.56				
ENDING ELEVATION (FT):	330.91	332.29	333.67				
MEAN INFLOW (CFS): 58510.02							
TURBINE NO.:	1	2	3	4	5	6	7
TURBINE POWER (MW):	49.35	49.34	49.33	49.32	49.29	49.25	47.74
OUTFLOW (CFS):	5045.66	5044.18	5042.21	5039.43	5035.18	5027.59	4763.82
SERVICE UNITS (MW):	1.00	0.00					
OUTFLOW (CFS):	104.05	0.00					

PEAK GENERATION (HRS): 15.00 OFF-PEAK GEN. (HRS): 9.00
PEAK ENERGY (MWH): 5154.42 OFF-PEAK ENERGY (MWH): 3092.65
TOTAL POWER OUTPUT (MW): 343.63
TURBINE OUTFLOW (CFS): 34998.06
SPILLWAY OUTFLOW (CFS): 0.00



---------------------------- D A Y 10 ----------------------------

2/20/1991 WEDNESDAY

H A R T W E L L

PERCENTILES:	5.00%	MEAN	95.00%
BEGINNING STORAGE (BCF):	115.57	118.33	121.12
ENDING STORAGE (BCF):	116.42	119.56	122.75
BEGINNING ELEVATION (FT):	661.83	662.91	663.99
ENDING ELEVATION (FT):	662.16	663.39	664.60

MEAN INFLOW (CFS): 29958.67

TURBINE NO.:	1	2	3	4	5
PEAK POWER (MW):	82.50	82.50	82.50	82.50	100.00
OUTFLOW (CFS):	6164.71	6164.71	6164.71	6164.71	7526.02

PEAK GENERATION (HRS):	11.70	OFF-PEAK GEN. (HRS):	0.00
PEAK ENERGY (MWH):	5032.07	OFF-PEAK ENERGY (MWH):	0.00
TOTAL POWER OUTPUT (MW):	430.00		
TURBINE OUTFLOW (CFS):	32184.84		
SPILLWAY OUTFLOW (CFS):	0.00		

R U S S E L L

PERCENTILES:	5.00%	MEAN	95.00%
BEGINNING STORAGE (BCF):	46.86	48.16	49.49
ENDING STORAGE (BCF):	46.96	48.75	50.58
BEGINNING ELEVATION (FT):	476.82	477.90	478.97
ENDING ELEVATION (FT):	476.91	478.37	479.83

MEAN INFLOW (CFS): 13024.42

TURBINE NO.:	1	2	3	4
TURBINE POWER (MW):	93.75	93.75	93.75	93.75
OUTFLOW (CFS):	8336.68	8336.68	8336.68	8336.49

PEAK GENERATION (HRS):	15.00	OFF-PEAK GEN. (HRS):	0.77
PEAK ENERGY (MWH):	5624.96	OFF-PEAK ENERGY (MWH):	289.08
TOTAL POWER OUTPUT (MW):	375.00		
TURBINE OUTFLOW (CFS):	33346.54		
SPILLWAY OUTFLOW (CFS):	0.00		

T H U R M O N D

PERCENTILES:	5.00%	MEAN	95.00%
BEGINNING STORAGE (BCF):	114.39	118.96	123.63
ENDING STORAGE (BCF):	115.37	120.56	125.89
BEGINNING ELEVATION (FT):	331.54	332.93	334.32
ENDING ELEVATION (FT):	331.84	333.41	334.98

MEAN INFLOW (CFS): 31732.71

TURBINE NO.:	1	2	3	4	5	6	7
TURBINE POWER (MW):	49.76	49.75	49.75	49.75	49.74	49.74	48.78
OUTFLOW (CFS):	5025.61	5025.26	5024.83	5024.26	5023.50	5022.43	4856.90
SERVICE UNITS (MW):	1.00	0.00					
OUTFLOW (CFS):	103.14	0.00					

PEAK GENERATION (HRS):	15.00	OFF-PEAK GEN. (HRS):	9.00
PEAK ENERGY (MWH):	5209.10	OFF-PEAK ENERGY (MWH):	3125.46
TOTAL POWER OUTPUT (MW):	347.27		
TURBINE OUTFLOW (CFS):	35002.80		
SPILLWAY OUTFLOW (CFS):	0.00		

APPENDIX H

Output File Generated by SAVRES in Section 3.3.2 (Flood Operations)

FLOOD OPERATION TRADEOFFS

	THURMOND	SYSTEM	RESERVOIR STATISTICS (MAXIMUM VALUES)					
	DISCH.	ENERGY	HARTWELL		RUSSELL		THURMOND	
NO.	CFS	MWH/DAY	FEET	CFS	FEET	CFS	FEET	CFS
1	40000.	26738.	664.84	32166.	480.77	44636.	336.00	60802.
2	46000.	26740.	664.84	32166.	480.77	44715.	335.96	59214.
3	52000.	26740.	664.84	32166.	480.78	52000.	335.89	57311.
4	58000.	26740.	664.84	32166.	480.73	58000.	335.81	58000.
5	64000.	26740.	664.84	32166.	480.64	64000.	335.72	64000.
6	70000.	26740.	664.84	32166.	480.61	66883.	335.61	70000.

S U M M A R Y   S E Q U E N C E S
FLOOD OPERATION CONDITIONS - DAILY
TRADEOFF POINT 1

HARTWELL			RUSSELL			THURMOND		
ELEV-FT	CFS	MWH	ELEV-FT	CFS	MWH	ELEV-FT	CFS	MWH
663.00	22581.	7244.71	478.00	33341.	8999.94	333.00	35606.	8423.84
663.63	22685.	7307.16	478.62	33253.	8999.94	333.17	35520.	8423.84
664.16	22484.	7266.46	479.14	33202.	8999.94	333.43	35384.	8423.85
664.64	19638.	6366.05	479.63	28613.	7749.63	334.06	35072.	8423.85

D E T A I L E D   S E Q U E N C E S
STARTING DATE: 2/11/1991 MONDAY

---------------------------- D A Y   1 ----------------------------------

H A R T W E L L

PERCENTILES:	5.00%	MEAN	95.00%
BEGINNING STORAGE (BCF):	118.56	118.56	118.56
ENDING STORAGE (BCF):	119.14	120.19	121.25
BEGINNING ELEVATION (FT):	663.00	663.00	663.00
ENDING ELEVATION (FT):	663.23	663.63	664.03

MEAN INFLOW (CFS): 41471.36

TURBINE NO.:	1	2	3	4	5
PEAK POWER (MW):	82.50	82.50	82.50	82.50	100.00
OUTFLOW (CFS):	6161.15	6161.15	6161.15	6161.15	7521.59

PEAK GENERATION (HRS): 15.00 OFF-PEAK GEN. (HRS): 1.85
PEAK ENERGY (MWH): 6449.96 OFF-PEAK ENERGY (MWH): 794.75
TOTAL POWER OUTPUT (MW): 430.00
TURBINE OUTFLOW (CFS): 32166.18
SPILLWAY OUTFLOW (CFS): 0.00

R U S S E L L

PERCENTILES:	5.00%	MEAN	95.00%
BEGINNING STORAGE (BCF):	48.29	48.29	48.29
ENDING STORAGE (BCF):	47.70	49.05	50.43
BEGINNING ELEVATION (FT):	478.00	478.00	478.00
ENDING ELEVATION (FT):	477.52	478.62	479.71

MEAN INFLOW (CFS): 19602.04

TURBINE NO.:	1	2	3	4
TURBINE POWER (MW):	93.75	93.75	93.75	93.75
OUTFLOW (CFS):	8335.25	8335.25	8335.25	8335.05

PEAK GENERATION (HRS): 15.00 OFF-PEAK GEN. (HRS): 9.00
PEAK ENERGY (MWH): 5624.96 OFF-PEAK ENERGY (MWH): 3374.98
TOTAL POWER OUTPUT (MW): 375.00
TURBINE OUTFLOW (CFS): 33340.79
SPILLWAY OUTFLOW (CFS): 0.00

T H U R M O N D

PERCENTILES:	5.00%	MEAN	95.00%
BEGINNING STORAGE (BCF):	119.18	119.18	119.18
ENDING STORAGE (BCF):	118.99	119.73	120.48
BEGINNING ELEVATION (FT):	333.00	333.00	333.00
ENDING ELEVATION (FT):	332.94	333.17	333.39

MEAN INFLOW (CFS): 8645.99

TURBINE NO.:	1	2	3	4	5	6	7
TURBINE POWER (MW):	50.00	50.00	50.00	50.00	50.00	50.00	49.99
OUTFLOW (CFS):	5072.06	5072.06	5072.06	5072.06	5072.06	5072.06	5070.84
SERVICE UNITS (MW):	1.00	0.00					
OUTFLOW (CFS):	103.15	0.00					

PEAK GENERATION (HRS): 15.00 OFF-PEAK GEN. (HRS): 9.00
PEAK ENERGY (MWH): 5249.90 OFF-PEAK ENERGY (MWH): 3149.94
TOTAL POWER OUTPUT (MW): 349.99
TURBINE OUTFLOW (CFS): 35503.18
SPILLWAY OUTFLOW (CFS): 0.00

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---------------------------- D A Y   2 ----------------------------------
                         2/12/1991 TUESDAY

H A R T W E L L
PERCENTILES:                      5.00%     MEAN      95.00%
BEGINNING STORAGE (BCF):        119.14    120.19    121.25
ENDING STORAGE (BCF):           119.40    121.57    123.77
BEGINNING ELEVATION (FT):       663.23    663.63    664.03
ENDING ELEVATION (FT):          663.32    664.16    664.99
MEAN INFLOW (CFS):  38647.54
TURBINE NO.:                 1         2         3         4         5
PEAK POWER (MW):         82.50     82.50     82.50     82.50    100.00
OUTFLOW (CFS):         6136.77   6136.77   6136.77   6136.77   7491.22
PEAK GENERATION (HRS):        15.00  OFF-PEAK GEN. (HRS):          1.99
PEAK ENERGY (MWH):          6449.96  OFF-PEAK ENERGY (MWH):      857.20
TOTAL POWER OUTPUT (MW):     430.00
TURBINE OUTFLOW (CFS):     32038.29
SPILLWAY OUTFLOW (CFS):        0.00

R U S S E L L
PERCENTILES:                      5.00%     MEAN      95.00%
BEGINNING STORAGE (BCF):         47.70     49.05     50.43
ENDING STORAGE (BCF):            48.32     49.71     51.13
BEGINNING ELEVATION (FT):       477.52    478.62    479.71
ENDING ELEVATION (FT):          478.03    479.14    480.26
MEAN INFLOW (CFS):  18194.95
TURBINE NO.:                 1         2         3         4
TURBINE POWER (MW):      93.75     93.75     93.75     93.75
OUTFLOW (CFS):         8313.19   8313.19   8313.19   8313.00
PEAK GENERATION (HRS):        15.00  OFF-PEAK GEN. (HRS):          9.00
PEAK ENERGY (MWH):          5624.96  OFF-PEAK ENERGY (MWH):     3374.98
TOTAL POWER OUTPUT (MW):     375.00
TURBINE OUTFLOW (CFS):     33252.58
SPILLWAY OUTFLOW (CFS):        0.00

T H U R M O N D
PERCENTILES:                      5.00%     MEAN      95.00%
BEGINNING STORAGE (BCF):        118.99    119.73    120.48
ENDING STORAGE (BCF):           119.44    120.63    121.83
BEGINNING ELEVATION (FT):       332.94    333.17    333.39
ENDING ELEVATION (FT):          333.08    333.43    333.79
MEAN INFLOW (CFS):  12642.64
TURBINE NO.:                 1         2         3         4         5         6         7
TURBINE POWER (MW):      50.00     50.00     50.00     50.00     50.00     50.00     49.99
OUTFLOW (CFS):         5059.78   5059.78   5059.78   5059.78   5059.78   5059.78   5058.58
SERVICE UNITS (MW):       1.00      0.00
OUTFLOW (CFS):          103.04      0.00
PEAK GENERATION (HRS):        15.00  OFF-PEAK GEN. (HRS):          9.00
PEAK ENERGY (MWH):          5249.90  OFF-PEAK ENERGY (MWH):     3149.94
TOTAL POWER OUTPUT (MW):     349.99
TURBINE OUTFLOW (CFS):     35417.23
SPILLWAY OUTFLOW (CFS):        0.00
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--------------------------- D A Y 3 ---------------------------------

2/13/1991 WEDNESDAY

H A R T W E L L

PERCENTILES:	5.00%	MEAN	95.00%
BEGINNING STORAGE (BCF):	119.40	121.57	123.77
ENDING STORAGE (BCF):	120.06	122.85	125.68
BEGINNING ELEVATION (FT):	663.32	664.16	664.99
ENDING ELEVATION (FT):	663.58	664.64	665.69

MEAN INFLOW (CFS): 37239.59

TURBINE NO.:	1	2	3	4	5
PEAK POWER (MW):	82.50	82.50	82.50	82.50	100.00
OUTFLOW (CFS):	6116.55	6116.55	6116.55	6116.55	7466.03

PEAK GENERATION (HRS): 15.00 OFF-PEAK GEN. (HRS): 1.90
PEAK ENERGY (MWH): 6449.96 OFF-PEAK ENERGY (MWH): 816.50
TOTAL POWER OUTPUT (MW): 430.00
TURBINE OUTFLOW (CFS): 31932.23
SPILLWAY OUTFLOW (CFS): 0.00

R U S S E L L

PERCENTILES:	5.00%	MEAN	95.00%
BEGINNING STORAGE (BCF):	48.32	49.71	51.13
ENDING STORAGE (BCF):	48.66	50.32	52.02
BEGINNING ELEVATION (FT):	478.03	479.14	480.26
ENDING ELEVATION (FT):	478.30	479.63	480.95

MEAN INFLOW (CFS): 17779.66

TURBINE NO.:	1	2	3	4
TURBINE POWER (MW):	93.75	93.75	93.75	93.75
OUTFLOW (CFS):	8300.51	8300.51	8300.51	8300.32

PEAK GENERATION (HRS): 15.00 OFF-PEAK GEN. (HRS): 9.00
PEAK ENERGY (MWH): 5624.96 OFF-PEAK ENERGY (MWH): 3374.98
TOTAL POWER OUTPUT (MW): 375.00
TURBINE OUTFLOW (CFS): 33201.83
SPILLWAY OUTFLOW (CFS): 0.00

T H U R M O N D

PERCENTILES:	5.00%	MEAN	95.00%
BEGINNING STORAGE (BCF):	119.44	120.63	121.83
ENDING STORAGE (BCF):	119.98	122.73	125.52
BEGINNING ELEVATION (FT):	333.08	333.43	333.79
ENDING ELEVATION (FT):	333.24	334.06	334.88

MEAN INFLOW (CFS): 26457.65

TURBINE NO.:	1	2	3	4	5	6	7
TURBINE POWER (MW):	50.00	50.00	50.00	50.00	50.00	50.00	49.99
OUTFLOW (CFS):	5040.37	5040.37	5040.37	5040.37	5040.37	5040.37	5039.20
SERVICE UNITS (MW):	1.00	0.00					
OUTFLOW (CFS):	102.85	0.00					

PEAK GENERATION (HRS): 15.00 OFF-PEAK GEN. (HRS): 9.00
PEAK ENERGY (MWH): 5249.90 OFF-PEAK ENERGY (MWH): 3149.94
TOTAL POWER OUTPUT (MW): 349.99
TURBINE OUTFLOW (CFS): 35281.43
SPILLWAY OUTFLOW (CFS): 0.00

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--------------------------- D A Y   4 ---------------------------------
                    2/14/1991 THURSDAY

H A R T W E L L
PERCENTILES:                    5.00%     MEAN      95.00%
BEGINNING STORAGE (BCF):      120.06    122.85    125.68
ENDING STORAGE (BCF):         121.50    124.21    126.95
BEGINNING ELEVATION (FT):     663.58    664.64    665.69
ENDING ELEVATION (FT):        664.13    665.15    666.17
MEAN INFLOW (CFS):  35366.73
TURBINE NO.:                1       2       3       4       5
PEAK POWER (MW):        82.50   82.50   82.50   82.50  100.00
OUTFLOW (CFS):        6098.15 6098.15 6098.15 6098.15 7443.12
PEAK GENERATION (HRS):        14.80  OFF-PEAK GEN. (HRS):          0.00
PEAK ENERGY (MWH):          6366.05  OFF-PEAK ENERGY (MWH):        0.00
TOTAL POWER OUTPUT (MW):     430.00
TURBINE OUTFLOW (CFS):     31835.71
SPILLWAY OUTFLOW (CFS):        0.00

R U S S E L L
PERCENTILES:                    5.00%     MEAN      95.00%
BEGINNING STORAGE (BCF):       48.66     50.32     52.02
ENDING STORAGE (BCF):          49.57     50.87     52.19
BEGINNING ELEVATION (FT):     478.30    479.63    480.95
ENDING ELEVATION (FT):        479.03    480.06    481.08
MEAN INFLOW (CFS):  15356.48
TURBINE NO.:                1       2       3       4
TURBINE POWER (MW):     93.75   93.75   93.75   93.75
OUTFLOW (CFS):        8307.43 8307.43 8307.43 8307.24
PEAK GENERATION (HRS):        15.00  OFF-PEAK GEN. (HRS):          5.67
PEAK ENERGY (MWH):          5624.96  OFF-PEAK ENERGY (MWH):     2124.67
TOTAL POWER OUTPUT (MW):     375.00
TURBINE OUTFLOW (CFS):     33229.54
SPILLWAY OUTFLOW (CFS):        0.00

T H U R M O N D
PERCENTILES:                    5.00%     MEAN      95.00%
BEGINNING STORAGE (BCF):      119.98    122.73    125.52
ENDING STORAGE (BCF):         122.39    126.08    129.85
BEGINNING ELEVATION (FT):     333.24    334.06    334.88
ENDING ELEVATION (FT):        333.96    335.04    336.13
MEAN INFLOW (CFS):  45259.04
TURBINE NO.:                1       2       3       4       5       6       7
TURBINE POWER (MW):     50.00   50.00   50.00   50.00   50.00   50.00   49.99
OUTFLOW (CFS):        4995.77 4995.77 4995.77 4995.77 4995.77 4995.77 4994.67
SERVICE UNITS (MW):      1.00    0.00
OUTFLOW (CFS):         102.42    0.00
PEAK GENERATION (HRS):        15.00  OFF-PEAK GEN. (HRS):          9.00
PEAK ENERGY (MWH):          5249.91  OFF-PEAK ENERGY (MWH):     3149.94
TOTAL POWER OUTPUT (MW):     349.99
TURBINE OUTFLOW (CFS):     34969.29
SPILLWAY OUTFLOW (CFS):        0.00

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S U M M A R Y   S E Q U E N C E S
FLOOD OPERATION CONDITIONS - 4 HRS
TRADEOFF POINT 1

HARTWELL			RUSSELL			THURMOND		
ELEV-FT	CFS	MWH	ELEV-FT	CFS	MWH	ELEV-FT	CFS	MWH
664.64	31836.	1719.99	479.63	33229.	1499.99	334.06	35072.	1403.98
664.66	31832.	1719.99	479.78	33234.	1499.99	334.24	34982.	1403.98
664.68	31828.	1719.99	479.94	33240.	1499.99	334.43	34892.	1403.98
664.70	31824.	1719.99	480.10	40000.	1499.99	334.61	34803.	1403.98
664.72	31821.	1719.99	480.18	40000.	1499.99	334.82	34702.	1403.98
664.74	31817.	1719.99	480.26	36511.	1499.99	335.03	40000.	1403.98
664.75	31813.	1719.99	480.38	38153.	1499.99	335.21	40000.	1403.98
664.78	31809.	1719.99	480.51	40565.	1499.99	335.44	46823.	1403.97
664.80	31804.	1719.99	480.62	42774.	1499.99	335.64	53924.	1403.97
664.82	31800.	1719.99	480.70	44619.	1499.99	335.83	60850.	1403.97
664.84			480.77			336.00		

D E T A I L E D   S E Q U E N C E S

--------------------------- 2/14/1991 THURSDAY ---------------------------
HOURS 0 - 4

H A R T W E L L

PERCENTILES:	5.00%	MEAN	95.00%
BEGINNING STORAGE (BCF):	120.06	122.85	125.68
ENDING STORAGE (BCF):	119.99	122.90	125.86
BEGINNING ELEVATION (FT):	663.58	664.64	665.69
ENDING ELEVATION (FT):	663.55	664.66	665.76

MEAN INFLOW (CFS): 35366.73

TURBINE NO.:	1	2	3	4	5
PEAK POWER (MW):	82.50	82.50	82.50	82.50	100.00
OUTFLOW (CFS):	6098.16	6098.16	6098.16	6098.16	7443.13

PEAK GENERATION (HRS): 0.00 OFF-PEAK GEN. (HRS): 4.00
PEAK ENERGY (MWH): 0.00 OFF-PEAK ENERGY (MWH): 1719.99
TOTAL POWER OUTPUT (MW): 430.00
TURBINE OUTFLOW (CFS): 31835.78
SPILLWAY OUTFLOW (CFS): 0.00

R U S S E L L

PERCENTILES:	5.00%	MEAN	95.00%
BEGINNING STORAGE (BCF):	48.66	50.32	52.02
ENDING STORAGE (BCF):	48.81	50.52	52.27
BEGINNING ELEVATION (FT):	478.30	479.63	480.95
ENDING ELEVATION (FT):	478.42	479.78	481.14

MEAN INFLOW (CFS): 15356.48

TURBINE NO.:	1	2	3	4
TURBINE POWER (MW):	93.75	93.75	93.75	93.75
OUTFLOW (CFS):	8307.40	8307.40	8307.40	8307.21

PEAK GENERATION (HRS): 0.00 OFF-PEAK GEN. (HRS): 4.00
PEAK ENERGY (MWH): 0.00 OFF-PEAK ENERGY (MWH): 1499.99
TOTAL POWER OUTPUT (MW): 375.00
TURBINE OUTFLOW (CFS): 33229.39
SPILLWAY OUTFLOW (CFS): 0.00

T H U R M O N D

PERCENTILES:	5.00%	MEAN	95.00%
BEGINNING STORAGE (BCF):	119.98	122.73	125.52
ENDING STORAGE (BCF):	120.33	123.35	126.42
BEGINNING ELEVATION (FT):	333.24	334.06	334.88
ENDING ELEVATION (FT):	333.35	334.24	335.14

MEAN INFLOW (CFS): 45259.04

TURBINE NO.:	1	2	3	4	5	6	7
TURBINE POWER (MW):	50.00	50.00	50.00	50.00	50.00	50.00	49.99
OUTFLOW (CFS):	4995.77	4995.77	4995.77	4995.77	4995.77	4995.77	4994.67
SERVICE UNITS (MW):	1.00	0.00					
OUTFLOW (CFS):	102.42	0.00					

PEAK GENERATION (HRS): 0.00 OFF-PEAK GEN. (HRS): 4.00
PEAK ENERGY (MWH): 0.00 OFF-PEAK ENERGY (MWH): 1399.98
TOTAL POWER OUTPUT (MW): 349.99
TURBINE OUTFLOW (CFS): 34969.29
SPILLWAY OUTFLOW (CFS): 0.00

---------------------------- 2/14/1991 THURSDAY --------------------------------

HOURS 4 - 8

H A R T W E L L

PERCENTILES:	5.00%	MEAN	95.00%
BEGINNING STORAGE (BCF):	119.99	122.90	125.86
ENDING STORAGE (BCF):	119.92	122.95	126.03
BEGINNING ELEVATION (FT):	663.55	664.66	665.76
ENDING ELEVATION (FT):	663.52	664.68	665.83

MEAN INFLOW (CFS): 35366.73

TURBINE NO.:	1	2	3	4	5
PEAK POWER (MW):	82.50	82.50	82.50	82.50	100.00
OUTFLOW (CFS):	6097.44	6097.44	6097.44	6097.44	7442.23

PEAK GENERATION (HRS): 1.00 OFF-PEAK GEN. (HRS): 3.00
PEAK ENERGY (MWH): 430.00 OFF-PEAK ENERGY (MWH): 1289.99
TOTAL POWER OUTPUT (MW): 430.00
TURBINE OUTFLOW (CFS): 31831.97
SPILLWAY OUTFLOW (CFS): 0.00

R U S S E L L

PERCENTILES:	5.00%	MEAN	95.00%
BEGINNING STORAGE (BCF):	48.81	50.52	52.27
ENDING STORAGE (BCF):	48.97	50.72	52.52
BEGINNING ELEVATION (FT):	478.42	479.78	481.14
ENDING ELEVATION (FT):	478.55	479.94	481.33

MEAN INFLOW (CFS): 15356.48

TURBINE NO.:	1	2	3	4
TURBINE POWER (MW):	93.75	93.75	93.75	93.75
OUTFLOW (CFS):	8308.65	8308.65	8308.65	8308.46

PEAK GENERATION (HRS): 1.00 OFF-PEAK GEN. (HRS): 3.00
PEAK ENERGY (MWH): 375.00 OFF-PEAK ENERGY (MWH): 1124.99
TOTAL POWER OUTPUT (MW): 375.00
TURBINE OUTFLOW (CFS): 33234.41
SPILLWAY OUTFLOW (CFS): 0.00

T H U R M O N D

PERCENTILES:	5.00%	MEAN	95.00%
BEGINNING STORAGE (BCF):	120.33	123.35	126.42
ENDING STORAGE (BCF):	120.71	123.98	127.30
BEGINNING ELEVATION (FT):	333.35	334.24	335.14
ENDING ELEVATION (FT):	333.46	334.43	335.39

MEAN INFLOW (CFS): 45259.04

TURBINE NO.:	1	2	3	4	5	6	7
TURBINE POWER (MW):	50.00	50.00	50.00	50.00	50.00	50.00	49.99
OUTFLOW (CFS):	4982.90	4982.90	4982.90	4982.90	4982.90	4982.90	4981.81
SERVICE UNITS (MW):	1.00	0.00					
OUTFLOW (CFS):	102.30	0.00					

PEAK GENERATION (HRS): 1.00 OFF-PEAK GEN. (HRS): 3.00
PEAK ENERGY (MWH): 349.99 OFF-PEAK ENERGY (MWH): 1049.98
TOTAL POWER OUTPUT (MW): 349.99
TURBINE OUTFLOW (CFS): 34879.21
SPILLWAY OUTFLOW (CFS): 0.00

---------------------------- 2/14/1991 THURSDAY --------------------------------
HOURS 8 - 12

HARTWELL

PERCENTILES:	5.00%	MEAN	95.00%
BEGINNING STORAGE (BCF):	119.92	122.95	126.03
ENDING STORAGE (BCF):	119.85	123.00	126.20
BEGINNING ELEVATION (FT):	663.52	664.68	665.83
ENDING ELEVATION (FT):	663.50	664.70	665.89

MEAN INFLOW (CFS): 35366.73

TURBINE NO.:	1	2	3	4	5
PEAK POWER (MW):	82.50	82.50	82.50	82.50	100.00
OUTFLOW (CFS):	6096.71	6096.71	6096.71	6096.71	7441.32

PEAK GENERATION (HRS): 4.00 OFF-PEAK GEN. (HRS): 0.00
PEAK ENERGY (MWH): 1719.99 OFF-PEAK ENERGY (MWH): 0.00
TOTAL POWER OUTPUT (MW): 430.00
TURBINE OUTFLOW (CFS): 31828.15
SPILLWAY OUTFLOW (CFS): 0.00

RUSSELL

PERCENTILES:	5.00%	MEAN	95.00%
BEGINNING STORAGE (BCF):	48.97	50.72	52.52
ENDING STORAGE (BCF):	49.12	50.93	52.77
BEGINNING ELEVATION (FT):	478.55	479.94	481.33
ENDING ELEVATION (FT):	478.67	480.10	481.52

MEAN INFLOW (CFS): 15356.48

TURBINE NO.:	1	2	3	4
TURBINE POWER (MW):	93.75	93.75	93.75	93.75
OUTFLOW (CFS):	8309.93	8309.93	8309.93	8309.74

PEAK GENERATION (HRS): 4.00 OFF-PEAK GEN. (HRS): 0.00
PEAK ENERGY (MWH): 1499.99 OFF-PEAK ENERGY (MWH): 0.00
TOTAL POWER OUTPUT (MW): 375.00
TURBINE OUTFLOW (CFS): 33239.55
SPILLWAY OUTFLOW (CFS): 0.00

THURMOND

PERCENTILES:	5.00%	MEAN	95.00%
BEGINNING STORAGE (BCF):	120.71	123.98	127.30
ENDING STORAGE (BCF):	121.11	124.61	128.17
BEGINNING ELEVATION (FT):	333.46	334.43	335.39
ENDING ELEVATION (FT):	333.58	334.61	335.64

MEAN INFLOW (CFS): 45259.04

TURBINE NO.:	1	2	3	4	5	6	7
TURBINE POWER (MW):	50.00	50.00	50.00	50.00	50.00	50.00	49.99
OUTFLOW (CFS):	4970.14	4970.14	4970.14	4970.14	4970.14	4970.14	4969.07
SERVICE UNITS (MW):	1.00	0.00					
OUTFLOW (CFS):	102.17	0.00					

PEAK GENERATION (HRS): 4.00 OFF-PEAK GEN. (HRS): 0.00
PEAK ENERGY (MWH): 1399.98 OFF-PEAK ENERGY (MWH): 0.00
TOTAL POWER OUTPUT (MW): 349.99
TURBINE OUTFLOW (CFS): 34789.90
SPILLWAY OUTFLOW (CFS): 0.00

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---------------------------- 2/14/1991 THURSDAY -------------------------------
                              HOURS 12 - 16

HARTWELL
PERCENTILES:                  5.00%    MEAN     95.00%
BEGINNING STORAGE (BCF):     119.85   123.00   126.20
ENDING STORAGE (BCF):        119.79   123.05   126.37
BEGINNING ELEVATION (FT):    663.50   664.70   665.89
ENDING ELEVATION (FT):       663.48   664.72   665.95
MEAN INFLOW (CFS):  35366.73
TURBINE NO.:                1       2       3       4       5
PEAK POWER (MW):        82.50   82.50   82.50   82.50  100.00
OUTFLOW (CFS):        6095.98 6095.98 6095.98 6095.98 7440.41
PEAK GENERATION (HRS):        4.00  OFF-PEAK GEN. (HRS):         0.00
PEAK ENERGY (MWH):         1719.99  OFF-PEAK ENERGY (MWH):       0.00
TOTAL POWER OUTPUT (MW):    430.00
TURBINE OUTFLOW (CFS):    31824.33
SPILLWAY OUTFLOW (CFS):       0.00

RUSSELL
PERCENTILES:                  5.00%    MEAN     95.00%
BEGINNING STORAGE (BCF):      49.12    50.93    52.77
ENDING STORAGE (BCF):         49.18    51.03    52.92
BEGINNING ELEVATION (FT):    478.67   480.10   481.52
ENDING ELEVATION (FT):       478.72   480.18   481.64
MEAN INFLOW (CFS):  15356.48
TURBINE NO.:                1       2       3       4
TURBINE POWER (MW):     93.75   93.75   93.75   93.75
OUTFLOW (CFS):        8311.26 8311.26 8311.26 8311.07
PEAK GENERATION (HRS):        4.00  OFF-PEAK GEN. (HRS):         0.00
PEAK ENERGY (MWH):         1499.99  OFF-PEAK ENERGY (MWH):       0.00
TOTAL POWER OUTPUT (MW):    375.00
TURBINE OUTFLOW (CFS):    33244.86
SPILLWAY OUTFLOW (CFS):    6755.14

THURMOND
PERCENTILES:                  5.00%    MEAN     95.00%
BEGINNING STORAGE (BCF):     121.11   124.61   128.17
ENDING STORAGE (BCF):        121.62   125.33   129.12
BEGINNING ELEVATION (FT):    333.58   334.61   335.64
ENDING ELEVATION (FT):       333.73   334.82   335.92
MEAN INFLOW (CFS):  45259.04
TURBINE NO.:                1       2       3       4       5       6       7
TURBINE POWER (MW):     50.00   50.00   50.00   50.00   50.00   50.00   49.99
OUTFLOW (CFS):        4957.47 4957.47 4957.47 4957.47 4957.47 4957.47 4956.42
SERVICE UNITS (MW):      1.00    0.00
OUTFLOW (CFS):         102.05    0.00
PEAK GENERATION (HRS):        4.00  OFF-PEAK GEN. (HRS):         0.00
PEAK ENERGY (MWH):         1399.98  OFF-PEAK ENERGY (MWH):       0.00
TOTAL POWER OUTPUT (MW):    349.99
TURBINE OUTFLOW (CFS):    34701.26
SPILLWAY OUTFLOW (CFS):       0.00
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---------------------------- 2/14/1991 THURSDAY -------------------------------
HOURS 16 - 20

H A R T W E L L

PERCENTILES:	5.00%	MEAN	95.00%
BEGINNING STORAGE (BCF):	119.79	123.05	126.37
ENDING STORAGE (BCF):	119.74	123.10	126.53
BEGINNING ELEVATION (FT):	663.48	664.72	665.95
ENDING ELEVATION (FT):	663.45	664.74	666.01

MEAN INFLOW (CFS): 35366.73

TURBINE NO.:	1	2	3	4	5
PEAK POWER (MW):	82.50	82.50	82.50	82.50	100.00
OUTFLOW (CFS):	6095.25	6095.25	6095.25	6095.25	7439.50

PEAK GENERATION (HRS):	4.00	OFF-PEAK GEN. (HRS):	0.00
PEAK ENERGY (MWH):	1719.99	OFF-PEAK ENERGY (MWH):	0.00
TOTAL POWER OUTPUT (MW):	430.00		
TURBINE OUTFLOW (CFS):	31820.50		
SPILLWAY OUTFLOW (CFS):	0.00		

R U S S E L L

PERCENTILES:	5.00%	MEAN	95.00%
BEGINNING STORAGE (BCF):	49.18	51.03	52.92
ENDING STORAGE (BCF):	49.24	51.13	53.07
BEGINNING ELEVATION (FT):	478.72	480.18	481.64
ENDING ELEVATION (FT):	478.77	480.26	481.75

MEAN INFLOW (CFS): 15356.48

TURBINE NO.:	1	2	3	4
TURBINE POWER (MW):	93.75	93.75	93.75	93.75
OUTFLOW (CFS):	8317.69	8317.69	8317.69	8317.50

PEAK GENERATION (HRS):	4.00	OFF-PEAK GEN. (HRS):	0.00
PEAK ENERGY (MWH):	1499.99	OFF-PEAK ENERGY (MWH):	0.00
TOTAL POWER OUTPUT (MW):	375.00		
TURBINE OUTFLOW (CFS):	33270.57		
SPILLWAY OUTFLOW (CFS):	6729.43		

T H U R M O N D

PERCENTILES:	5.00%	MEAN	95.00%
BEGINNING STORAGE (BCF):	121.62	125.33	129.12
ENDING STORAGE (BCF):	122.15	126.06	130.05
BEGINNING ELEVATION (FT):	333.73	334.82	335.92
ENDING ELEVATION (FT):	333.89	335.03	336.19

MEAN INFLOW (CFS): 45259.04

TURBINE NO.:	1	2	3	4	5	6	7
TURBINE POWER (MW):	50.00	50.00	50.00	50.00	50.00	50.00	49.99
OUTFLOW (CFS):	4943.02	4943.02	4943.02	4943.02	4943.02	4943.02	4941.98
SERVICE UNITS (MW):	1.00	0.00					
OUTFLOW (CFS):	101.91	0.00					

PEAK GENERATION (HRS):	4.00	OFF-PEAK GEN. (HRS):	0.00
PEAK ENERGY (MWH):	1399.98	OFF-PEAK ENERGY (MWH):	0.00
TOTAL POWER OUTPUT (MW):	349.99		
TURBINE OUTFLOW (CFS):	34600.09		
SPILLWAY OUTFLOW (CFS):	0.00		

2/14/1991 THURSDAY
HOURS 20 - 24

H A R T W E L L

PERCENTILES:	5.00%	MEAN	95.00%
BEGINNING STORAGE (BCF):	119.74	123.10	126.53
ENDING STORAGE (BCF):	119.68	123.15	126.69
BEGINNING ELEVATION (FT):	663.45	664.74	666.01
ENDING ELEVATION (FT):	663.43	664.75	666.07

MEAN INFLOW (CFS): 35366.73

TURBINE NO.:	1	2	3	4	5
PEAK POWER (MW):	82.50	82.50	82.50	82.50	100.00
OUTFLOW (CFS):	6094.52	6094.52	6094.52	6094.52	7438.60

PEAK GENERATION (HRS):	2.00	OFF-PEAK GEN. (HRS):	2.00
PEAK ENERGY (MWH):	859.99	OFF-PEAK ENERGY (MWH):	859.99
TOTAL POWER OUTPUT (MW):	430.00		
TURBINE OUTFLOW (CFS):	31816.68		
SPILLWAY OUTFLOW (CFS):	0.00		

R U S S E L L

PERCENTILES:	5.00%	MEAN	95.00%
BEGINNING STORAGE (BCF):	49.24	51.13	53.07
ENDING STORAGE (BCF):	49.35	51.29	53.27
BEGINNING ELEVATION (FT):	478.77	480.26	481.75
ENDING ELEVATION (FT):	478.85	480.38	481.90

MEAN INFLOW (CFS): 15356.48

TURBINE NO.:	1	2	3	4
TURBINE POWER (MW):	93.75	93.75	93.75	93.75
OUTFLOW (CFS):	8323.73	8323.73	8323.73	8323.54

PEAK GENERATION (HRS):	2.00	OFF-PEAK GEN. (HRS):	2.00
PEAK ENERGY (MWH):	749.99	OFF-PEAK ENERGY (MWH):	749.99
TOTAL POWER OUTPUT (MW):	375.00		
TURBINE OUTFLOW (CFS):	33294.72		
SPILLWAY OUTFLOW (CFS):	3216.46		

T H U R M O N D

PERCENTILES:	5.00%	MEAN	95.00%
BEGINNING STORAGE (BCF):	122.15	126.06	130.05
ENDING STORAGE (BCF):	122.56	126.66	130.85
BEGINNING ELEVATION (FT):	333.89	335.03	336.19
ENDING ELEVATION (FT):	334.01	335.21	336.41

MEAN INFLOW (CFS): 45259.04

TURBINE NO.:	1	2	3	4	5	6	7
TURBINE POWER (MW):	50.00	50.00	50.00	50.00	50.00	50.00	49.99
OUTFLOW (CFS):	4992.75	4992.75	4992.75	4992.75	4992.75	4992.75	4991.65
SERVICE UNITS (MW):	1.00	0.00					
OUTFLOW (CFS):	102.39	0.00					

PEAK GENERATION (HRS):	2.00	OFF-PEAK GEN. (HRS):	2.00
PEAK ENERGY (MWH):	699.99	OFF-PEAK ENERGY (MWH):	699.99
TOTAL POWER OUTPUT (MW):	349.99		
TURBINE OUTFLOW (CFS):	34948.12		
SPILLWAY OUTFLOW (CFS):	4949.48		

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---------------------------  2/15/1991 FRIDAY  -------------------------------
                             HOURS  0 -  4

 H A R T W E L L
 PERCENTILES:                     5.00%     MEAN      95.00%
 BEGINNING STORAGE (BCF):       119.68    123.15    126.69
 ENDING STORAGE (BCF):          119.62    123.21    126.87
 BEGINNING ELEVATION (FT):      663.43    664.75    666.07
 ENDING ELEVATION (FT):         663.41    664.78    666.13
 MEAN INFLOW (CFS):  35735.54
 TURBINE NO.:                1        2        3        4       5
 PEAK POWER (MW):        82.50    82.50    82.50    82.50  100.00
 OUTFLOW (CFS):        6093.79  6093.79  6093.79  6093.79 7437.69
 PEAK GENERATION (HRS):          0.00  OFF-PEAK GEN. (HRS):          4.00
 PEAK ENERGY (MWH):              0.00  OFF-PEAK ENERGY (MWH):     1719.99
 TOTAL POWER OUTPUT (MW):    430.00
 TURBINE OUTFLOW (CFS):    31812.85
 SPILLWAY OUTFLOW (CFS):       0.00

 R U S S E L L
 PERCENTILES:                     5.00%     MEAN      95.00%
 BEGINNING STORAGE (BCF):        49.35     51.29     53.27
 ENDING STORAGE (BCF):           49.42     51.46     53.55
 BEGINNING ELEVATION (FT):      478.85    480.38    481.90
 ENDING ELEVATION (FT):         478.91    480.51    482.11
 MEAN INFLOW (CFS):  18385.66
 TURBINE NO.:                1        2        3        4
 TURBINE POWER (MW):     93.75    93.75    93.75    93.75
 OUTFLOW (CFS):        8326.94  8326.94  8326.94  8326.75
 PEAK GENERATION (HRS):          0.00  OFF-PEAK GEN. (HRS):          4.00
 PEAK ENERGY (MWH):              0.00  OFF-PEAK ENERGY (MWH):     1499.99
 TOTAL POWER OUTPUT (MW):    375.00
 TURBINE OUTFLOW (CFS):    33307.58
 SPILLWAY OUTFLOW (CFS):    4845.32

 T H U R M O N D
 PERCENTILES:                     5.00%     MEAN      95.00%
 BEGINNING STORAGE (BCF):       122.56    126.66    130.85
 ENDING STORAGE (BCF):          123.16    127.45    131.83
 BEGINNING ELEVATION (FT):      334.01    335.21    336.41
 ENDING ELEVATION (FT):         334.18    335.44    336.69
 MEAN INFLOW (CFS):  56231.29
 TURBINE NO.:                1        2        3        4        5        6        7
 TURBINE POWER (MW):     50.00    50.00    50.00    50.00    50.00    50.00    49.99
 OUTFLOW (CFS):        4981.48  4981.48  4981.48  4981.48  4981.48  4981.48  4980.39
 SERVICE UNITS (MW):      1.00     0.00
 OUTFLOW (CFS):         102.28     0.00
 PEAK GENERATION (HRS):          0.00  OFF-PEAK GEN. (HRS):          4.00
 PEAK ENERGY (MWH):              0.00  OFF-PEAK ENERGY (MWH):     1399.98
 TOTAL POWER OUTPUT (MW):    349.99
 TURBINE OUTFLOW (CFS):    34869.26
 SPILLWAY OUTFLOW (CFS):    5028.45
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---------------------------- 2/15/1991 FRIDAY --------------------------------
HOURS 4 - 8

H A R T W E L L

PERCENTILES:		5.00%	MEAN	95.00%			
BEGINNING STORAGE (BCF):		119.62	123.21	126.87			
ENDING STORAGE (BCF):		119.56	123.27	127.05			
BEGINNING ELEVATION (FT):		663.41	664.78	666.13			
ENDING ELEVATION (FT):		663.39	664.80	666.20			
MEAN INFLOW (CFS): 35735.54							
TURBINE NO.:	1	2	3	4	5		
PEAK POWER (MW):	82.50	82.50	82.50	82.50	100.00		
OUTFLOW (CFS):	6092.99	6092.99	6092.99	6092.99	7436.69		
PEAK GENERATION (HRS):	1.00	OFF-PEAK GEN. (HRS):	3.00				
PEAK ENERGY (MWH):	430.00	OFF-PEAK ENERGY (MWH):	1289.99				
TOTAL POWER OUTPUT (MW):	430.00						
TURBINE OUTFLOW (CFS):	31808.63						
SPILLWAY OUTFLOW (CFS):	0.00						

R U S S E L L

PERCENTILES:		5.00%	MEAN	95.00%			
BEGINNING STORAGE (BCF):		49.42	51.46	53.55			
ENDING STORAGE (BCF):		49.46	51.60	53.80			
BEGINNING ELEVATION (FT):		478.91	480.51	482.11			
ENDING ELEVATION (FT):		478.94	480.62	482.30			
MEAN INFLOW (CFS): 18385.66							
TURBINE NO.:	1	2	3	4			
TURBINE POWER (MW):	93.75	93.75	93.75	93.75			
OUTFLOW (CFS):	8331.89	8331.89	8331.89	8331.70			
PEAK GENERATION (HRS):	1.00	OFF-PEAK GEN. (HRS):	3.00				
PEAK ENERGY (MWH):	375.00	OFF-PEAK ENERGY (MWH):	1124.99				
TOTAL POWER OUTPUT (MW):	375.00						
TURBINE OUTFLOW (CFS):	33327.37						
SPILLWAY OUTFLOW (CFS):	7238.04						

T H U R M O N D

PERCENTILES:		5.00%	MEAN	95.00%			
BEGINNING STORAGE (BCF):		123.16	127.45	131.83			
ENDING STORAGE (BCF):		123.70	128.17	132.73			
BEGINNING ELEVATION (FT):		334.18	335.44	336.69			
ENDING ELEVATION (FT):		334.34	335.64	336.95			
MEAN INFLOW (CFS): 56231.29							
TURBINE NO.:	1	2	3	4	5	6	7
TURBINE POWER (MW):	50.00	50.00	50.00	50.00	50.00	50.00	49.99
OUTFLOW (CFS):	5040.26	5040.26	5040.26	5040.26	5040.26	5040.26	5039.10
SERVICE UNITS (MW):	1.00	0.00					
OUTFLOW (CFS):	102.85	0.00					
PEAK GENERATION (HRS):	1.00	OFF-PEAK GEN. (HRS):	3.00				
PEAK ENERGY (MWH):	349.99	OFF-PEAK ENERGY (MWH):	1049.98				
TOTAL POWER OUTPUT (MW):	349.99						
TURBINE OUTFLOW (CFS):	35280.69						
SPILLWAY OUTFLOW (CFS):	11439.79						

---------------------------- 2/15/1991 FRIDAY --------------------------------
HOURS 8 - 12

H A R T W E L L

PERCENTILES:	5.00%	MEAN	95.00%
BEGINNING STORAGE (BCF):	119.56	123.27	127.05
ENDING STORAGE (BCF):	119.50	123.32	127.22
BEGINNING ELEVATION (FT):	663.39	664.80	666.20
ENDING ELEVATION (FT):	663.36	664.82	666.26

MEAN INFLOW (CFS): 35735.54

TURBINE NO.:	1	2	3	4	5
PEAK POWER (MW):	82.50	82.50	82.50	82.50	100.00
OUTFLOW (CFS):	6092.18	6092.18	6092.18	6092.18	7435.68

PEAK GENERATION (HRS): 4.00 OFF-PEAK GEN. (HRS): 0.00
PEAK ENERGY (MWH): 1719.99 OFF-PEAK ENERGY (MWH): 0.00
TOTAL POWER OUTPUT (MW): 430.00
TURBINE OUTFLOW (CFS): 31804.41
SPILLWAY OUTFLOW (CFS): 0.00

R U S S E L L

PERCENTILES:	5.00%	MEAN	95.00%
BEGINNING STORAGE (BCF):	49.46	51.60	53.80
ENDING STORAGE (BCF):	49.47	51.70	54.00
BEGINNING ELEVATION (FT):	478.94	480.62	482.30
ENDING ELEVATION (FT):	478.95	480.70	482.45

MEAN INFLOW (CFS): 18385.66

TURBINE NO.:	1	2	3	4
TURBINE POWER (MW):	93.75	93.75	93.75	93.75
OUTFLOW (CFS):	8337.29	8337.29	8337.29	8337.10

PEAK GENERATION (HRS): 4.00 OFF-PEAK GEN. (HRS): 0.00
PEAK ENERGY (MWH): 1499.99 OFF-PEAK ENERGY (MWH): 0.00
TOTAL POWER OUTPUT (MW): 375.00
TURBINE OUTFLOW (CFS): 33348.99
SPILLWAY OUTFLOW (CFS): 9425.03

T H U R M O N D

PERCENTILES:	5.00%	MEAN	95.00%
BEGINNING STORAGE (BCF):	123.70	128.17	132.73
ENDING STORAGE (BCF):	124.19	128.82	133.56
BEGINNING ELEVATION (FT):	334.34	335.64	336.95
ENDING ELEVATION (FT):	334.49	335.83	337.18

MEAN INFLOW (CFS): 56231.29

TURBINE NO.:	1	2	3	4	5	6	7
TURBINE POWER (MW):	50.00	50.00	50.00	50.00	50.00	50.00	49.99
OUTFLOW (CFS):	5103.66	5103.66	5103.66	5103.66	5103.66	5103.66	5102.40
SERVICE UNITS (MW):	1.00	0.00					
OUTFLOW (CFS):	103.45	0.00					

PEAK GENERATION (HRS): 4.00 OFF-PEAK GEN. (HRS): 0.00
PEAK ENERGY (MWH): 1399.97 OFF-PEAK ENERGY (MWH): 0.00
TOTAL POWER OUTPUT (MW): 349.99
TURBINE OUTFLOW (CFS): 35724.35
SPILLWAY OUTFLOW (CFS): 18096.37

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---------------------------  2/15/1991 FRIDAY  ------------------------------
                             HOURS 12 - 16

 H A R T W E L L
 PERCENTILES:                   5.00%     MEAN      95.00%
 BEGINNING STORAGE (BCF):      119.50    123.32    127.22
 ENDING STORAGE (BCF):         119.45    123.38    127.39
 BEGINNING ELEVATION (FT):     663.36    664.82    666.26
 ENDING ELEVATION (FT):        663.34    664.84    666.33
 MEAN INFLOW (CFS): 35735.54
 TURBINE NO.:                1        2        3        4       5
 PEAK POWER (MW):        82.50    82.50    82.50    82.50  100.00
 OUTFLOW (CFS):        6091.37  6091.37  6091.37  6091.37 7434.68
 PEAK GENERATION (HRS):       4.00  OFF-PEAK GEN. (HRS):         0.00
 PEAK ENERGY (MWH):        1719.99  OFF-PEAK ENERGY (MWH):       0.00
 TOTAL POWER OUTPUT (MW):   430.00
 TURBINE OUTFLOW (CFS):   31800.17
 SPILLWAY OUTFLOW (CFS):      0.00

 R U S S E L L
 PERCENTILES:                   5.00%     MEAN      95.00%
 BEGINNING STORAGE (BCF):       49.47     51.70     54.00
 ENDING STORAGE (BCF):          49.46     51.78     54.18
 BEGINNING ELEVATION (FT):     478.95    480.70    482.45
 ENDING ELEVATION (FT):        478.94    480.77    482.58
 MEAN INFLOW (CFS): 18385.66
 TURBINE NO.:                1        2        3        4
 TURBINE POWER (MW):     93.75    93.75    93.75    93.75
 OUTFLOW (CFS):        8343.05  8343.05  8343.05  8342.86
 PEAK GENERATION (HRS):       4.00  OFF-PEAK GEN. (HRS):         0.00
 PEAK ENERGY (MWH):        1499.99  OFF-PEAK ENERGY (MWH):       0.00
 TOTAL POWER OUTPUT (MW):   375.00
 TURBINE OUTFLOW (CFS):   33372.01
 SPILLWAY OUTFLOW (CFS):  11247.20

 T H U R M O N D
 PERCENTILES:                   5.00%     MEAN      95.00%
 BEGINNING STORAGE (BCF):      124.19    128.82    133.56
 ENDING STORAGE (BCF):         124.60    129.39    134.30
 BEGINNING ELEVATION (FT):     334.49    335.83    337.18
 ENDING ELEVATION (FT):        334.61    336.00    337.39
 MEAN INFLOW (CFS): 56231.29
 TURBINE NO.:                1        2        3        4        5        6        7
 TURBINE POWER (MW):     50.00    50.00    50.00    50.00    50.00    50.00    49.99
 OUTFLOW (CFS):        5162.94  5162.94  5162.94  5162.94  5162.94  5162.94  5161.59
 SERVICE UNITS (MW):      1.00     0.00
 OUTFLOW (CFS):         103.99     0.00
 PEAK GENERATION (HRS):       4.00  OFF-PEAK GEN. (HRS):         0.00
 PEAK ENERGY (MWH):        1399.97  OFF-PEAK ENERGY (MWH):       0.00
 TOTAL POWER OUTPUT (MW):   349.99
 TURBINE OUTFLOW (CFS):   36139.24
 SPILLWAY OUTFLOW (CFS):  24606.58

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