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14. ABSTRACT
A combined optimization-simulation procedure was developed and applied to identify the optimal conservation pool storage allocation problem is formulated and solved as a constrained nonlinear programming (NLP) problem with multiple objectives. The Box-Complex algorithm is coupled with an existing generalized reservoir simulation model to seek a solution to the NLP problem. The solutions are refined by an iterative simulation process that allows input from planners and engineers who are involved in management of this system.

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US Army Corps of Engineers
Institute for Water Resources
Hydrologic Engineering Center
609 Second Street
Davis, CA 95616

(530) 756-1104
(530) 756-8250 FAX
www.hec.usace.army.mil

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Operation Policy Analysis: Sam Rayburn Reservoir

By David T. Ford[1], A. M. ASCE; Ralph Garland[2], M. ASCE;
and, Charles Sullivan[3], M. ASCE

Setting

The Sam Rayburn Reservoir System includes two reservoirs in series: Sam Rayburn Reservoir on the Angelina River and B. A. Steinhagen Lake and Town Bluff Dam (Dam B Reservoir), on the Neches River in eastern Texas. These reservoirs are operated by the U.S. Army Corps of Engineers. The system components are shown in Figure 1.

Operation of Sam Rayburn Reservoir provides flood control, power generation, water supply, water quality maintenance, and recreation. Runoff from approximately 3,449 square miles (8,940 km^2) drains into the reservoir. The total storage volume of the reservoir is 5,610,000 acre-feet; 2,898,500 acre-feet of the volume are allocated to conservation purposes, and the remainder is allocated to flood control. The installed capacity of the two hydropower units at the reservoir is 52,000 kW, and the "dependable" capacity currently is estimated to be 49,000 kW.

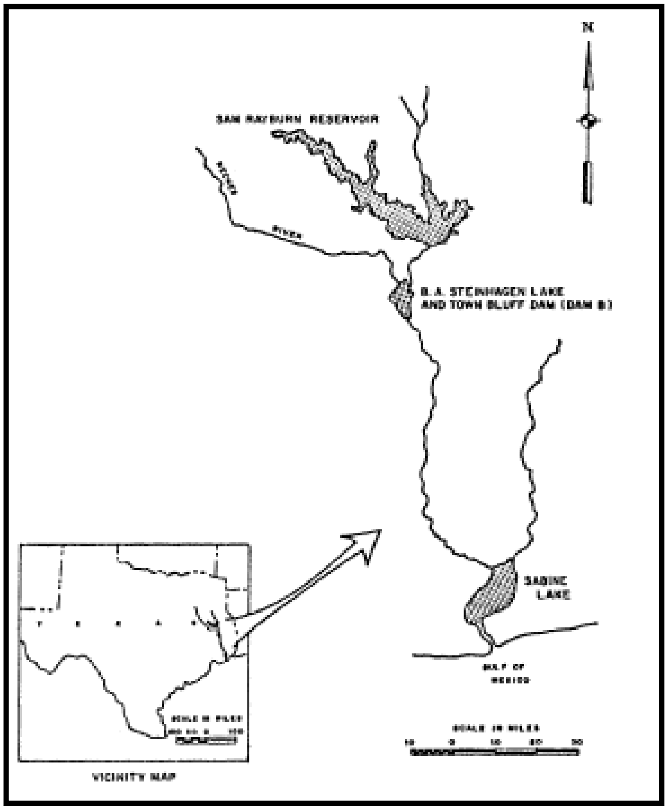

Figure 1. Sam Rayburn Reservoir System Components

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[1] Hydraulic Engineer, U. S. Army Corps of Engineers, Hydrologic Engineering Center, 609 Second St., Davis, CA 95616.

[2] Hydraulic Engineer, U. S. Army Corps of Engineers, Fort Worth District, Fort Worth, TX.

[3] Hydraulic Engineer, U. S. Army Corps of Engineers, Southwestern Division, Dallas, TX.

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Dam B Reservoir was constructed and is operated primarily for reregulation of releases from Sam Rayburn Reservoir. The reservoir is operated also for water supply and for recreation. Total storage available is 306,400 acre-feet (377,938,835 m^3).

Additional detailed information on Sam Rayburn Reservoir is presented in Reference 8. Information on B. A. Steinhagen Lake and Dam B Reservoir is available in Reference 6.

Current Operation Problems

Due to the proximity of the reservoir system to the Gulf of Mexico, maintenance of sufficient discharge downstream of the Dam B Reservoir is critical to prevention of saltwater intrusion. This intrusion is detrimental because water is withdrawn from the Neches River for irrigation and for municipal and industrial water supply. The average maximum monthly discharge rates for recent years are shown in Table 1. Historically, a saltwater barrier has been installed downstream from the Dam B Reservoir during periods of little runoff because releases are reduced during these periods. With such a barrier in place, the downstream discharge requirement is reduced by approximately 1,000 cfs (28 m^3/s) because the need for water to prevent saltwater intrusion is eliminated. Subsequent discharge that exceeds the demand by approximately 2,000 cfs (56 m^3/s) causes the barrier to be "washed-out." Thus one of the operation problems is to select an operation policy that minimizes the number of times that a saltwater barrier must be installed.

Table 1. Water Supply Demand Schedule: Sam Rayburn Reservoir System

Month	Average Maximum Monthly Demand (cubic feet per second)*
January	250
February	300
March	700
April	1,100
May	1,400
June	1,700
July	1,400
August	800
September	450
October	350
November	300
December	250

*1 cfs = 0.028 m^3/s

Selection of operation rules that will yield the optimal hydropower production from Rayburn Reservoir is the second operation problem considered. The minimum acceptable energy output is defined in a contract between the Sam Rayburn Dam Electric Cooperative, Inc., and the Federal Government. The contract states:

> **. . .** *the government agrees, to the extent that water is available in the McGee Bend Reservoir (now Sam Rayburn Reservoir) above elevation 149, to make*

> *releases . . . as required for the generation of power, with such releases at least sufficient to generate power equivalent to 42,000 kilowatts for a minimum period of 75 hours per month for each of the six monthly periods from mid-April through mid-October of each year (8).*

Additional useable power often can be generated, and, if so, is purchased by a private utility. Thus a dependable power output must be defined, and operating rules must be selected to provide the power with high reliability. The operation rules also should yield as much additional useable power as possible.

The facilities for recreation at Sam Rayburn Reservoir and at Dam B Reservoir pose another operation constraint: the reservoirs should be operated in such a way that the pool elevation fluctuations are not intolerable to those using the facilities.

In addition to other previously mentioned purposes, Sam Rayburn Reservoir and Dam B Reservoir are regulated to provide flood control downstream. The channel capacity downstream of Dam B Reservoir is approximately 20,000 cfs (560 m^3/s), so the reservoirs are operated to maintain flows at or below this capacity if possible.

Solution Methodology

A combined simulation-optimization approach is employed to select an optimal operation policy for Sam Rayburn Reservoir System. This methodology is shown schematically in Figure 2. The simulation model is a single reservoir model that accounts for water use throughout the system, satisfying all demands when possible and allocating the available water according to specific priorities when conflicts exist. The simulation model is linked with a nonlinear programming algorithm that selects automatically the optimal operation policy for the reservoir system for the given data and with a user-specified objective function. A weighted combination of ten indices of operation efficiency can be used to define this objective function. The operation policy that is identified as the optimal policy by the nonlinear programming algorithm is smoothed using engineering judgment based on experience with operation of the system, and system response with this smoothed policy is simulated. This step is repeated as necessary to obtain an acceptable operation policy. The general approach was suggested by Jacoby and Loucks (11).

Alternative techniques for selection of an optimal allocation of available storage have been proposed and were considered, including applications of linear programming (13), network flow programming (14, 15) and dynamic programming (1, 4, 16). However, as Yeh et al. (16) point out, *". . . there appears to exist no general algorithm"*. Each application of these mathematical programming techniques has required some development and research to select and to program the most efficient solution procedure. In this study, time constraints and budget limitations precluded such research and development, so a readily available, generalized simulation program was combined with readily available computer code for the nonlinear programming algorithm (12). This approach provides the important capability to simulate in detail the operation of reservoir system with a model that can easily be used independent of this optimization algorithm.

Simulation Model. The operation of the Sam Rayburn Reservoir System is modeled with the Reservoir Yield Program developed by the Hydrologic Engineering Center (HEC), with modifications to simulate accurately the operation of this particular system and to model the format of the operation policy traditionally used with this reservoir system. The Reservoir Yield Program simulates the conservation operation of a reservoir system that includes one reservoir and one downstream control point. Constraints on discharge can be specified at the reservoir and at the control point. The model is designed for analysis of operation with a long time interval, such as one month. The methods of computation in the Reservoir Yield Program follow closely the procedures traditionally employed in hand computations. For each computation period, the reservoir release equals the maximum minimum flow requirement for all system purposes unless this conflicts with maximum permissible flows. In that case, the reservoir release is restricted to the minimum maximum permissible flow. Absolute control over the release is exercised by full reservoir and empty reservoir limitations. Power is assumed to be generated from reservoir releases up to plant capacity, with power head determined by successive approximations to account for variation of head with discharge. Flows are translated from the reservoir outlet to the downstream control point in a single period without routing. Further detailed description of the methods of computation employed in the Reservoir Yield Program is presented in Reference 7.

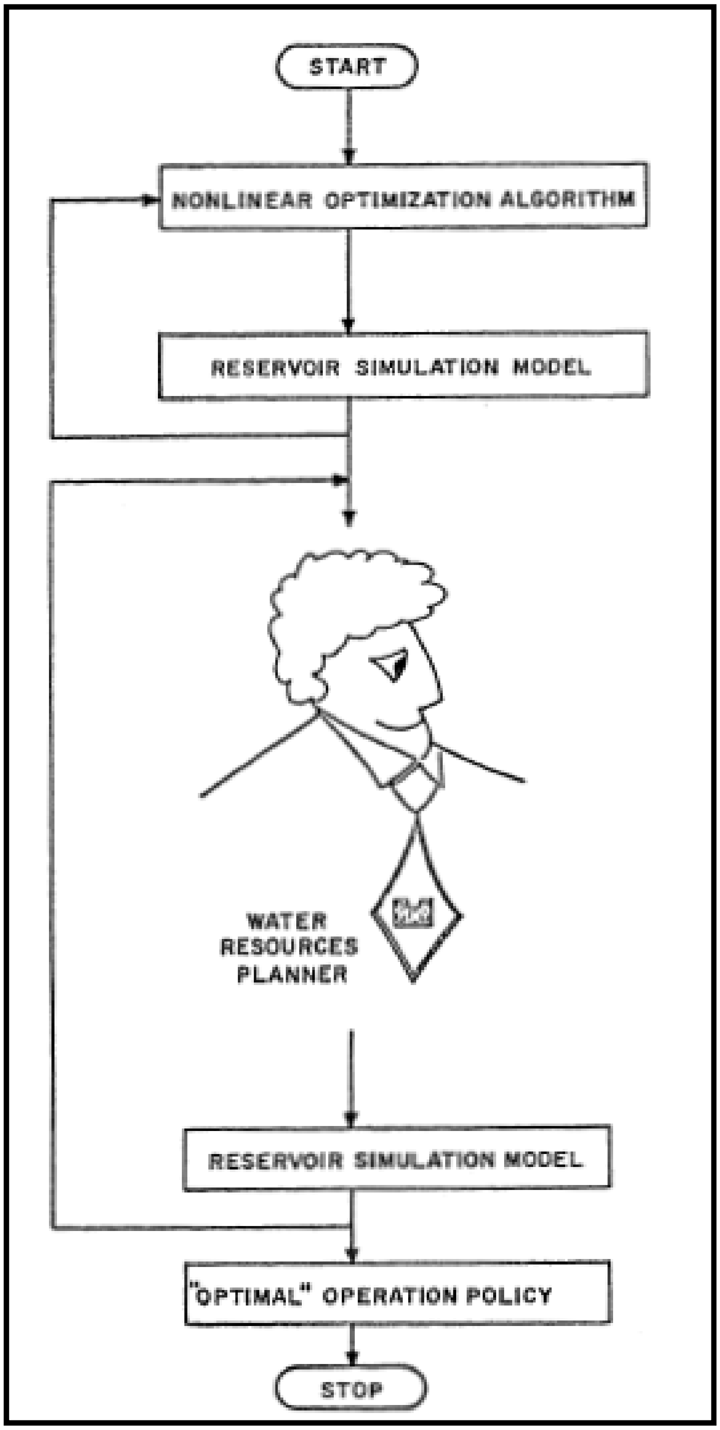

Figure 2. Schematic of Solution Methodology

Operation of the Sam Rayburn Reservoir System can be simulated adequately for the purposes of the study using the Reservoir Yield Program with a monthly computation interval because Dam B Reservoir has no significant monthly carry-over storage capacity. Dam B Reservoir can be represented as a control point, with average monthly outflow considered equal to average monthly inflow, and all water requirements downstream of Dam B Reservoir can be modeled as requirements at the control point.

Modifications to the Reservoir Yield Program required for simulation of the operation of the Sam Rayburn Reservoir System include the following: (1) modifications to employ a storage level concept in operation of Sam Rayburn Reservoir; (2) modifications to reflect the installation of a downstream saltwater barrier when the volume of water in storage in Sam Rayburn Reservoir falls below a specified value; (3) modifications to allow specification of power requirements and downstream discharge requirements as a function of storage in Sam Rayburn Reservoir; and (4) modifications to alter the system operation goals so releases required to satisfy minimum power generation requirement at Sam Rayburn Reservoir will have highest priority as required by contract.

Use of storage levels for specification of the operation rules for Sam Rayburn Reservoir is accepted practice at that reservoir, so modification of the program to employ the levels is necessary if practicable operation rules are to be selected. Incorporation of storage levels for operation of Sam Rayburn Reservoir is accomplished by defining the conservation storage volume allocated to each of the four imaginary zones illustrated in Figure 3. At the beginning of each period of simulation, the current level is determined by comparing the beginning-of-period storage value with these bounds, and the at-site power requirements and downstream discharge requirements are set, as shown in Table 2. The Reservoir Yield Program is executed as before.

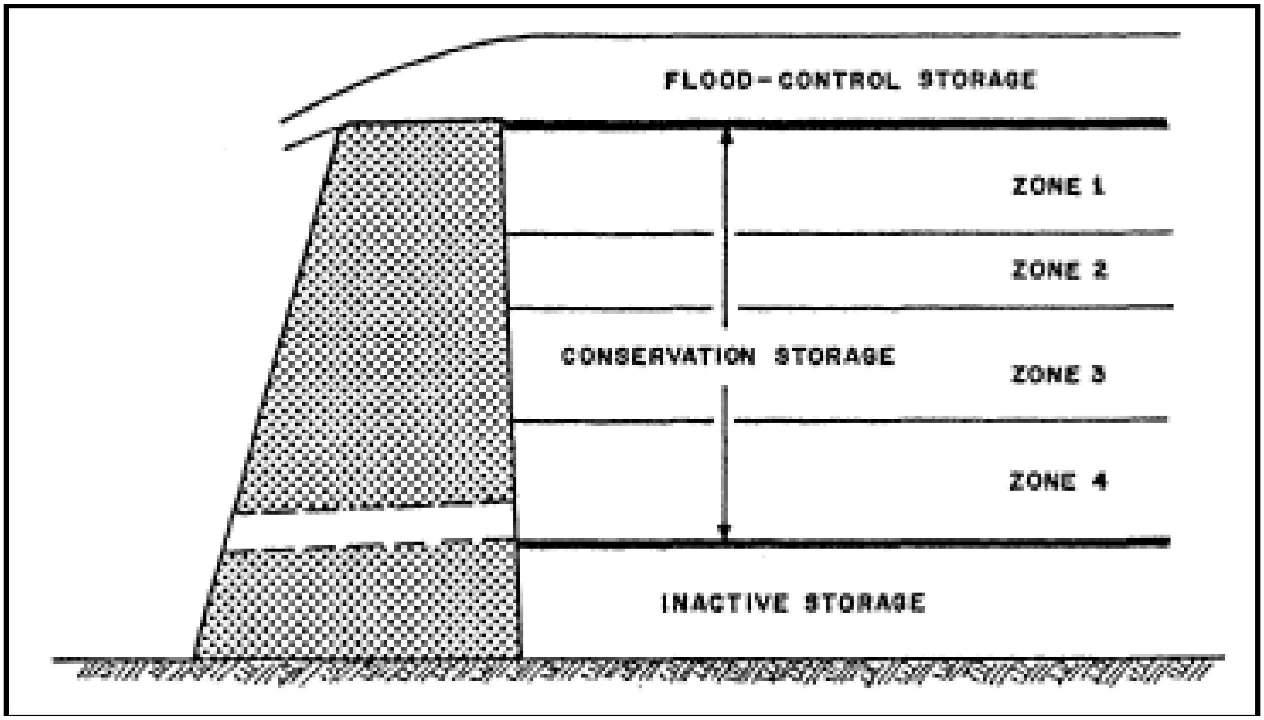

Figure 3. Imaginary Reservoir Storage Zones

Additional modifications to the Reservoir Yield Program provide for simulation of installation and failure of a saltwater barrier downstream from Dam B Reservoir. Installation of the barrier is assumed to occur when storage in Sam Rayburn Reservoir falls to Level 3 or 4 and remains in either level for three months (thus simulating a time lag for decision and for installation of the barrier). When the barrier is not in place, downstream discharge targets are increased to prevent saltwater intrusion, as shown in Table 2. When the barrier is installed, the targets are fixed at the

Table 2. Power and Discharge Requirements: Sam Rayburn Reservoir System

Level*	Power Requirement at Rayburn Reservoir	Discharge Requirement Below Dam
1	20% plant factor	Water supply demand plus flow to prevent saltwater intrusion
2	75 hours of generation (approximately 10% plant factor)	Water supply demand plus flow to prevent saltwater intrusion
3	75 hours of generation; 15 April thru 15 October No requirement in other months	Water supply demand
4	75 hours of generation; 15 April thru 15 October No requirement in other months	No specific operation requirement; shortages declared if discharge fails to meet demands of Level 3

*Note that the convention of numbering levels for this study does not correspond to the convention in other reservoir simulation programs developed yb the Hydrologic Engineering Center (9, 10).

actual water supply demand until the barrier is "washed-out" by excessive discharge. This excessive discharge is defined as 2,000 cfs (56 m^3/s) or the downstream requirement plus 1,000 cfs (28 m^3/s), whichever is larger.

To model adequately the priorities of releases in the Sam Rayburn Reservoir System (priorities which are contrary to those incorporated in the Reservoir Yield Program), the algorithm that selects the release for each period is modified to give highest priority to satisfaction of the minimum power requirement at Sam Rayburn Reservoir, as required by contract. With the modification, releases necessary to generate the required power, rather than certain minimum flow requirements, are given first priority.

Optimization Model. To determine the optimal operation policy for the Sam Rayburn Reservoir System, the reservoir operation problem is formulated as a constrained nonlinear programming (NLP) problem. The decision variables in this optimization problem are the volumes of conservation storage to be allocated to each of the four operation levels. These decision variables are subject to upper and lower bounds; the volume allocated to each level must be greater than zero and must not exceed the total volume of conservation storage available. Also, the sum of the volumes allocated to the four levels must equal the total conservation storage available. The storage allocation currently varies seasonally, with seasons defined on the basis of significant change in rainfall pattern as follows: 1) March-April; 2) May-June; 3) July-September; and, 4) October-February.

The optimization problem may be expressed mathematically as:

$$\text{minimize } f(\mathrm{X}) \quad (1)$$

$$\text{subject to } 0 \le x_{i,j} \le STMX - STMN \quad (2)$$

$$\sum_{i=1}^{4} x_{i,j} = STMX - STMN;\ j = 1,2,3,4 \quad (3)$$

where:

x = a vector of all decision variables $x_{i,j}$
i = the index of storage levels
j = the index of seasons
STMX = total storage volume at the top of the conservation pool
STMN = total storage volume at the bottom of the conservation pool

If desired, this formulation can be modified to allow monthly variation of the storage allocation. The objective function, $f(X)$, is evaluated by executing the modified Reservoir Yield Program with specified values of the decision variables.

The Box-Complex algorithm (Equation 3) is employed to solve the constrained nonlinear programming problem. This algorithm is a multivariate, constrained, random-search technique that seeks the minimum (or maximum) of a general nonlinear function subject to explicit upper and lower bounds on the decision variables (Equation 2) and to nonlinear constraints on the decision variables (Equation 3). With the Box-Complex algorithm, a set of feasible solutions to the optimization problem is generated at random, the objective function is evaluated for each, the "worst" solution is discarded, a new solution is determined with a projection technique, and the process is repeated until convergence criteria are satisfied.

Multiple Objective Analysis. The efficiency of operation of the Sam Rayburn Reservoir System cannot be measured solely in economic terms, in terms of power generation, or in terms of failure to satisfy discharge requirements. These and other indices of operation efficiency, must be considered when selecting the optimal operating policy, and the trade-offs must be considered when selecting the optimal policy. For example, if the storage is allocated to maximize the average annual energy generated, the number of times that the saltwater barrier must be installed may be unacceptable. On the other hand, if storage is allocated to minimize the number of times the barrier must be installed; the energy generated decreases and may fall below an acceptable level. Neither solution is likely to be acceptable in terms of overall system operation goals, so some compromise solution must be selected.

A weighting method of multiobjective programming is employed to quantify the relative importance of various operation objectives (5). With this technique, the mathematical objective function for the NLP problem is defined as:

$$f(X) = \sum_{k=1}^{p} \omega_k z_k(X) \quad \text{.......} \quad (4)$$

where:

$z_k(X)$ = the value of index k of operation efficiency with decision variables X
p = the total number of indices
ω_k = the weight assigned to index k

The optimization problem then is to minimize $f(X)$, the weighted sum of the efficiency indices. Ten indices of system operation efficiency are included in the objective function available for selection of the best operation rules for Sam Rayburn Reservoir. These are listed in Table 3. In application only, functions 3, 5, 8, 9, and 10 are utilized for selection of the best-compromise

Table 3. Possible Objective Function Terms for Sam Rayburn Reservoir Operation Analysis

Function	Description
1	Energy shortage index[1,2]
2	Downstream discharge shortage index[1]
3	Number of times saltwater barrier is installed in period of analysis
4	Number of times saltwater barrier fails (is washed-out) in period of analysis
5	Average annual energy shortage[2]
6	Average annual downstream discharge shortage
7	Average monthly conservation pool elevation fluctuation
8	Average annual energy
9	Number of times conservation pool is emptied
10	Number of times downstream discharge shortage occurs

[1] Each shortage index is computed by summing the squares of the annual shortage ratios and multiplying by (100/number of years of analysis). The annual shortage ratio is expressed as the ratio of the-annual shortage divided by the annual requirement.

[2] Energy shortage is equivalent to "power" shortage computed by the Reservoir Yield Program. For this study, shortage is defined as follows: Shortage = maximum (0., Level 1 energy requirement minus energy generated).

operation study,with weights defined on the basis of analysis of optimal system operation for the objectives individually. The approach is conceptually similar to the Step Method suggested by Benayoun, et al. (2).

Selected Operation Rules. Using the analytical tools described herein and data provided by the Fort Worth District and by the Southwestern Division of the U.S. Corps of Engineers, best-compromise operation rules for the Sam Rayburn Reservoir System were determined for several alternative objective functions with different combinations of downstream demands, power requirements, and discharge necessary to prevent saltwater intrusion. System operation indices for several of these alternative policies are summarized in Table 4. Prior to selection of a policy for actual operation of the reservoir, these alternative storage allocation policies were reviewed by personnel of the Fort Worth District and Southwestern Division, U.S. Corps at Engineers, by personnel of the Lower Neches Valley Authority (a Texas river authority), and by personnel of the Department of Energy (Southwestern Power Administration). As a consequence of this review, several smoothed, compromise solutions were identified, and the system operation was simulated with the Reservoir Yield Program to evaluate the effectiveness of each. These results are also shown in Table 4. Figure 4 illustrates the storage allocation of one of these operation policies.

Conclusions

From the perspective of the water resources planner, the most important conclusion that may be drawn from this study is that certain analytical techniques presented in the literature are applicable to practical resource management problems. The Sam Rayburn Reservoir operation problem is solved as a nonlinear programming problem, using an accepted simulation model to evaluate the objective function for each set of operation rules. The nonlinear programming algorithm employed is a simple, readily available technique. A multi-objective programming technique is used to develop an objective function that, in some sense, quantifies the importance of various system purposes.

Table 4. Summary of Selected Operation Efficiency

Operation Objective	Plant Factor (percentage)	Downstream Demand Schedule	Discharge to Prevent Saltwater Intrusion (cubic feet per second)	Number of Times Saltwater Barrier is Installed	Average Annual Energy Shortage (thousand kilowatts-hour)	Average Monthly Conservation Pool Elevation Fluctuation (in feet)	Average Annual Energy (thousand kilowatt-hours)	Number of Times Conservation Pool is Emptied	Number of Months in which Downstream Shortage Occurs
Maximize	20	Maximum	1,000	57	34,265	.69	115,073	0	110
average annual	20	Average	1,000	49	33,120	.56	115,972	0	32
energy	25	Maximum	1,000	57	47,634	.69	115,095	0	114
Minimize energy shortage	20	Maximum	1,000	25	15,735	1.03	113,632	31	32
	20	Average	1,000	13	13,007	.93	113,971	31	17
	25	Maximum	1,000	20	27,624	1.10	112,689	60	58
Minimize barrier installation	20	Maximum	1,000	8	25,670	1.01	113,529	19	31
	20	Average	1,000	1	25,856	.73	114,467	4	12
Compromise	20	Maximum	1,000	14	26,656	.93	114,250	0	28
	20	Average	1,000	6	24,857	.75	114,570	0	9
	20	Average	1,000	6	23,356	.81	114,411	0	4

Note: Values shown are for 2,551-year analysis period; 1 cfs = 0.028 m^3/s; 1 foot = 0.305 meters

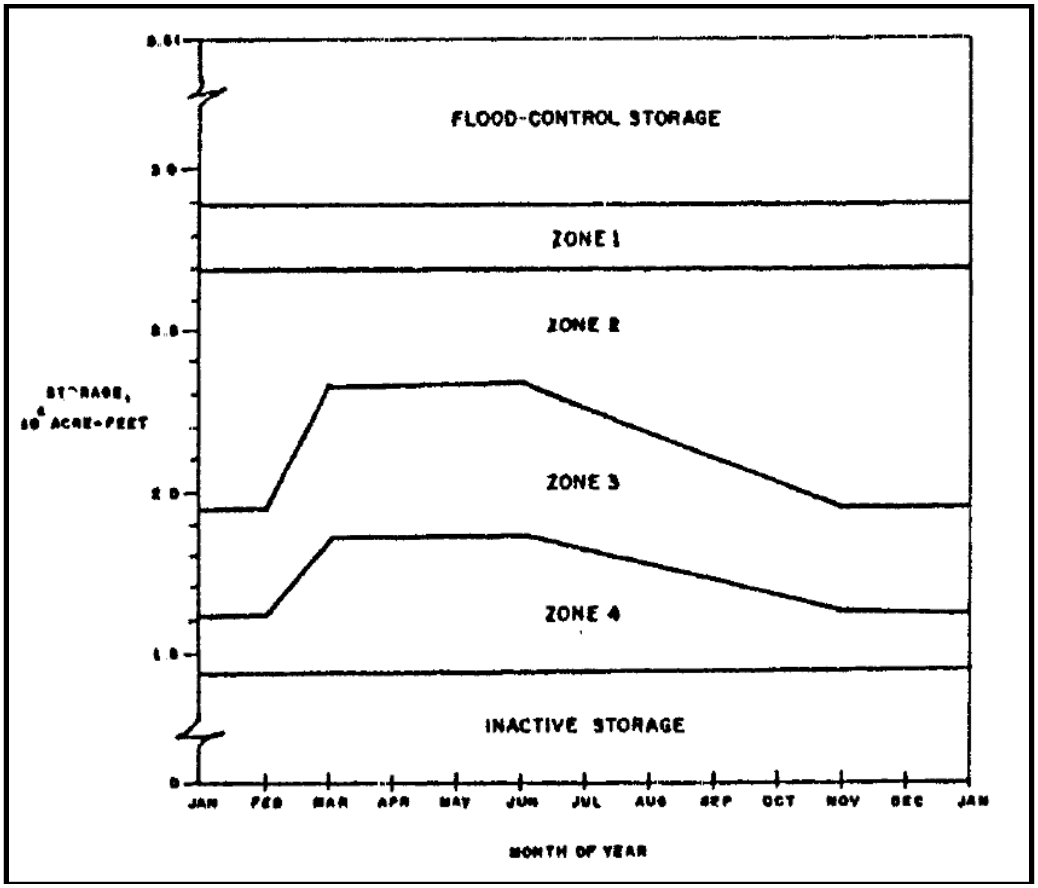

Figure 4. Seasonal Reservoir Storage Allocation

From the perspective of the water resources system analyst, two important conclusions may be drawn from this study. The first is that planners and engineers involved in planning and managing water resources projects will accept application of systems analysis techniques to problems they face if such applications can be demonstrated to: (1) provide additional information for use in decision making; (2) reduce the time, money, or computer memory requirements for plan formulation or evaluation; or (3) increase the project benefits by identifying solutions that satisfy the practical constraints on operation and are sufficiently resilient to respond to changing conditions. Integrated use of a nonlinear programming formulation with the Reservoir Yield Program for simulation of system operation, followed by an interactive smoothing process that allows input from the water managers satisfies these requirements.

In the process of developing operation rules for Sam Rayburn Reservoir, Corps personnel who are involved daily with the operation were consulted in the definition of the problem, in identification of the critical characteristics of the system that should be modeled, and in evaluation of the solutions developed by application of the optimization-simulation methodology. The results of the initial simulations of system operations were reviewed carefully by Corps District and Division personnel to assure that the modified reservoir simulation program adequately modeled the system operation. This leads logically to the second conclusion: the resource managers/system operators must be included in the policy formulation-evaluation "DO-Loop" at many points.

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Notation

The following symbols are used in this paper:

f = total objective function;
p = total number of objective functions;
STMN = total storage volume at bottom of conservation pool;
STMX = total storage volume at top of conservation pool;
ω = weight assigned to objective functions;
x = decision variable;
X = vector of all decision variables; and
z = objective function.

Subscripts

i = index of reservoir conservation storage levels;
j = index of seasons; and
k = index of objective functions.

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