YIELD MODEL FOR SCREENING MULTIPURPOSE RESERVOIR SYSTEMS

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ABSTRACT: A screening model for selecting and sizing potential reservoirs and hydroplants on a river basin is presented. The system is designed to meet annual irrigation and hydropower demands at prescribed levels of reliability. The model is developed with a focus on considerations that are important to the Indian decision makers. A linked simulation-optimization framework is used for formulation. Sizing of reservoirs and hydroplants, and evaluation of objective function and constraints and their derivatives are done as part of simulation. For sizing reservoirs, a new sequent trough algorithm is used that considers evaporation losses automatically. Generator capacities are determined by maximizing the local net revenues produced from hydropower generation. Derivatives are evaluated using automatic differentiation that produces exact derivatives with minimal human effort. The resulting formulation is applied to Par, Auranga, Ambica, and Purna river basins located in India. Comparison of model solutions with those of the state agency shows that the present formulation leads to a reduction in the system storage and cost of its development.

INTRODUCTION

Water planners in India have traditionally relied on simulations for planning reservoir and hydroplant sites for development (Jacoby and Loucks 1972; Chaturvedi and Srivastava 1981; *Preliminary* 1991). Simulations are attractive for planning purposes because they offer direct insight into the interaction of the components of the reservoir system. In addition, they can realistically address the oddities in reservoir operation arising due to concerns related to water rights, water quality, and other factors. However, simulation models explore only a limited set of scenarios, and despite considerable effort, may not provide superior or optimal solutions with respect to a management criteria. Therefore, it is desirable to use a modeling approach that has the flexibility of representation of simulation models and efficient state space exploration of formal optimization models. Linked simulation-optimization models such as those of Bredehoeft and Young (1970), Lall and Miller (1988), and Lall (1995) combine the modeling flexibility of simulation with the exploratory power of optimization algorithms and therefore are more effective in the Indian contexts. In this paper, the algorithm of Lall and Miller (1988) and Lall (1995) is further improved, and additional factors are considered for its application in an Indian context.

General review of reservoir operation and management literature can be obtained in Yeh (1985). Stedinger et al. (1983) provided a review of screening algorithms for multiple reservoir systems. They concluded that the yield model of Loucks et al. (1981) produces a reasonable solution in terms of yield reliabilities realized for the reservoir system. Lall and Miller (1988) presented a nonlinear formulation in the spirit of the yield model using a linked simulation-optimization framework. The essence of their formulation is that the capacity of the reservoir and generator depend upon the sequence of inflows and releases from the reservoir. This dependence can be functionalized and evaluated independently using monthly simulations with respect to annual target yields. The optimization model then needs to consider only annual releases for different purposes. Lall and Miller used a modified sequent peak (MSP) algorithm for determining storage capacities that improves the estimate of storage capacity by iterating throughout the entire operation period to calculate the evaporation loss. As a further refinement to the MSP, Lall (1995) presented a two-step procedure that is direct and does not need iteration. The procedure first determines the storage capacity of the reservoir without considering evaporation losses using the sequent peak algorithm of Loucks et al. (1981). This reservoir is then simulated backward in time to calculate the evaporation loss for each storage state in the critical period. The correct storage capacity is obtained by adding the accumulated loss to the previous estimate of storage. Sinha (1996) applied this algorithm to the river basins in India and discovered that Lall's algorithm can produce storage capacities that are inadequate to meet the demands if the evaporation losses are severe. To eliminate this possibility, in this paper a new sequent trough algorithm (STA) for sizing reservoirs is presented that considers evaporation losses automatically. Readers may note that the STA in its original form (Rippl 1883; Klemeš 1979a,b) does not consider evaporation losses. Other algorithmic improvements offered on the yield model of Lall and Miller include formulation of annual firm energy as a constraint and application of automatic differentiation (Sinha and Bischof 1998) for obtaining derivatives for the functions considered in the formulation. The formulation is applied to the Par, Auranga, Ambica, and Purna river basins in India, and the solutions obtained are compared with those of the National Water Development Agency (NWDA) in India.

MODELING CRITERIA

The objective of the study is to determine a set of optimal storage capacities for the candidate set of reservoirs that minimizes the system cost. The system cost is defined as the sum of the annualized total cost of reservoir construction, land acquisition, and projected operation and maintenance at each of the sites. The operation and maintenance costs and the associated discounting factors are built into coefficient $c1_s$.

Fig. 1 shows the potential reservoir sites in Par, Auranga, Ambica, and Purna river basins. Some of the reservoirs located in the neighboring region have received adverse publicity, as their construction has resulted in large displacement of the people from the area. This has made land acquisition (for construction) difficult, invited local protests, delayed completion of projects, and escalated the cost many times over the planned outlays. The government of India is concerned and is keen on minimizing such losses. Consequently, in this study, land acquisition is also included in the system cost. The goal of the present study is to reduce this component and the overall cost;

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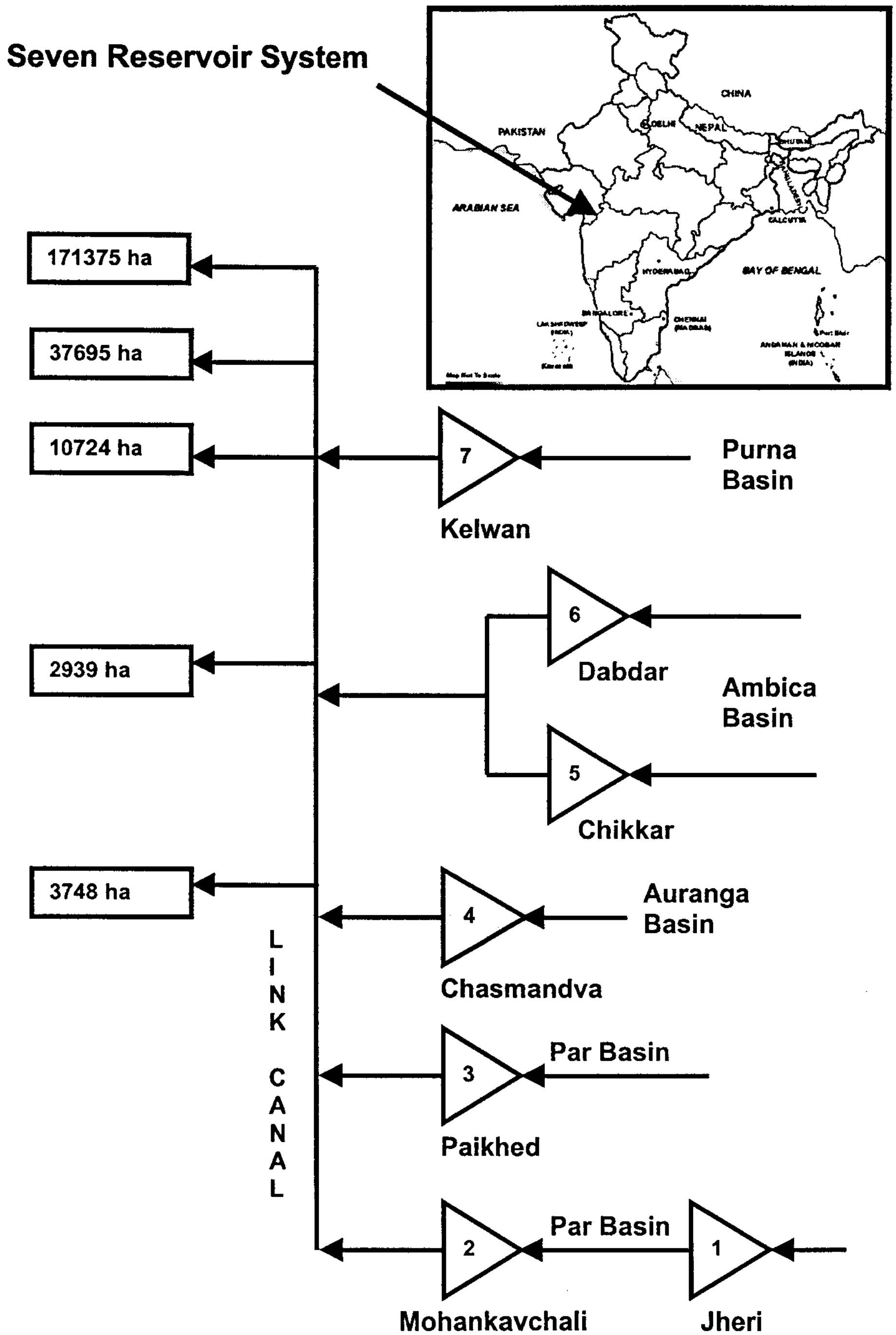

FIG. 1. Schematic Diagram of Reservoir System

hence minimization of the total system cost is considered as the objective of the formulation.

The reservoir and generator capacities are solved subject to a set of constraints. These constraints specify (1) limits on the total reservoir capacity for each site; (2) filling the reservoir subsequent to its emptying; (3) maintaining prescribed ratios of dead storage to total storage at each site; (4) meeting target irrigation demands for the system and individual irrigation area with the prescribed dependability; and (5) meeting annual firm energy demand.

Hydropower generation is considered on a self-sustaining basis. That is, the local net revenue accrued from hydropower generation should be positive to justify the installation of a hydroplant. The main assumption in optimizing the hydropower at the reservoir (local) level is that the power grid can utilize the power produced locally at any time. In India, chronic power shortages are typical, and the energy sector is supply limited; thus this is a reasonable assumption. Irrigation release is also available for hydropower generation. Consistent with the typical policy followed in India, 75% reliability for irrigation demand is considered. This is defined as meeting the target demand in any of the 76 years out of the 100 years and at least 50% of the target demand in the remaining years of operation.

MODEL FORMULATION

The model is formulated in the context of the reservoir system located in the western part of India in the states of Maharastra and Gujarat (Fig. 1). There are seven reservoirs in the system with two of these (Jheri and Mohankavchali) in series and the remaining (Paikhed, Chasmandva, Chikkar, Dabdar, and Kelwan) in parallel. The catchment areas for these reservoirs are 425, 206, 315, 89, 323, 482, and 733 km^2, respectively. The proposed reservoir system envisages transfer of surplus water from the west flowing rivers shown in Fig. 1 to the water deficit areas in northern Gujarat. A link canal is proposed to carry the water from these reservoirs to the target irrigation areas in Gujarat in addition to irrigating the intermediate command areas.

The irrigation areas are grouped into five zones (Fig. 1). Simulation of reservoirs for historical streamflow data of 34 years is considered. Annual yield reliability is considered as a decision variable for each year of operation, and annual yields from each reservoir are considered to meet the target yield of the system. The monthly demand at each irrigation area is computed by applying monthly demand fractions to the annual demands. In this study, the following three questions need to be answered:

1. Which of the reservoir sites can be developed economically?
2. What should their sizes be?
3. What should be the capacity of the generator that can be installed at various sites on a self-sustaining basis?

The yield definitions correspond to those in Loucks et al. (1981). The decision variables are defined symbolically as follows:

- D_s—dead storage at reservoir site s
- I_{si}—firm annual irrigation yield from site s to irrigation area (zone) i
- qf_{ys}—degree of failure expressed as fraction of the irrigation yields from the site s in the year y

The model is formulated in a linked simulation-optimization framework (Fig. 2). At an iteration of the optimization model, the values of the decision variables are known. Using these values, monthly releases are computed, and the required reservoir capacity is evaluated through system simulation using historical inflows. Then the corresponding values of the objective function, constraints, and their derivatives with respect to the decision variables are evaluated. If the current iteration satisfies the optimality criteria, then the optimization process terminates, or else a new iteration is generated, and the procedure is repeated until an optimal solution is found. The optimality criteria are (1) satisfying the Karush-Kuhn-Tucker condition; or (2) insufficient improvement in the value of the objective function over a specified number of iterations (Zhou and Tits 1992).

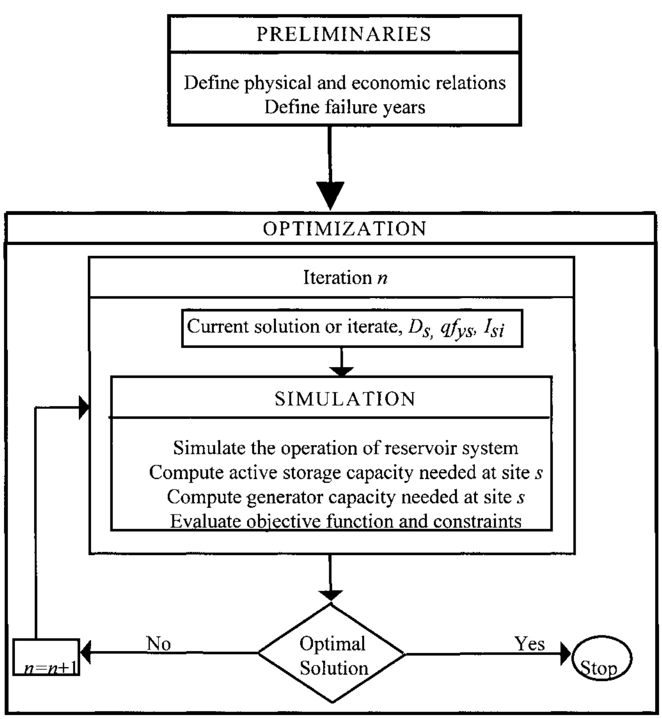

FIG. 2. Model Framework

Reservoir Simulation

The components of the simulation model are the sequent trough algorithm, network connections, generator sizing algorithm, and evaluation of functions and their derivatives with respect to the decision variables. A schematic representation of the reservoir system is shown in Fig. 1. Reservoirs are numbered sequentially from upstream to downstream. The algorithm proceeds sequentially from upstream to downstream sites. The total inflow into a downstream site is evaluated as the sum of local inflow and upstream spills or diversions. The simulation procedure proceeds one reservoir at a time, from upstream to downstream sites, to determine the active and total storage capacities, the generator size, and the net revenue from hydropower at each site. The model formulated leads to a sequential screening algorithm, with trade-off in reservoir operation satisfied by a simultaneous examination of the reduced gradients with respect to all decision variables and constraints.

Active Storage Capacity Determination

Fig. 3 illustrates the new STA that considers losses automatically while sizing reservoirs. The total monthly inflow into a reservoir site s is calculated as the sum of the natural incremental inflow and the fraction $\delta_{s's}$ of the releases (irrigation + spill + hydrorelease) from any upstream reservoirs s' that are passed through to this site. The fraction $\delta_{s's}$ is a predefined parameter. The monthly release required is determined as the sum of target annual yield I_{si} times the annual dependability $(1 - qf_{ys})$ times the monthly demand fractions c_{it} for calendar month for irrigation area i. Then a backward sweep in time $(T, \ldots, 2, 1, 0)$ is made to calculate the maximum deficit accumulated over the simulation. This determines the active storage capacity $SA_{s,t}$. Evaporation is approximated by taking the average surface area of the reservoir over a month. Finally, a forward sweep is made to identify the maximum storage of the reservoir during the fill cycles to investigate if the reservoir is capable of refilling. Compared with the MSP algorithm (Lall and Miller 1988), which makes multiple sweeps through the operation period, the STA sweeps through the operation period only once to determine the storage capacity. This results in a faster algorithm as the dimensionality of the matrices that needs to be inverted over a monthly simulation embedded in the optimization is drastically reduced.

Generator Capacity Determination

Determination of generator capacity begins after the calculation of storage capacity. The algorithm used for sizing the generator follows that in Lall and Miller (1988). It is reproduced here for completeness. The optimal hydropower generator size G_s is determined by first computing the total release HT_{st} possible through the hydropower plant at site s in month t and then the corresponding possible power production P_{st}. This monthly power is then treated as candidate generator sizes, and the one with the highest net annual revenue is selected as the optimal generator size.

The total possible release HT_{st} is defined as the sum of release for hydropower (if made) and irrigation through the hy-

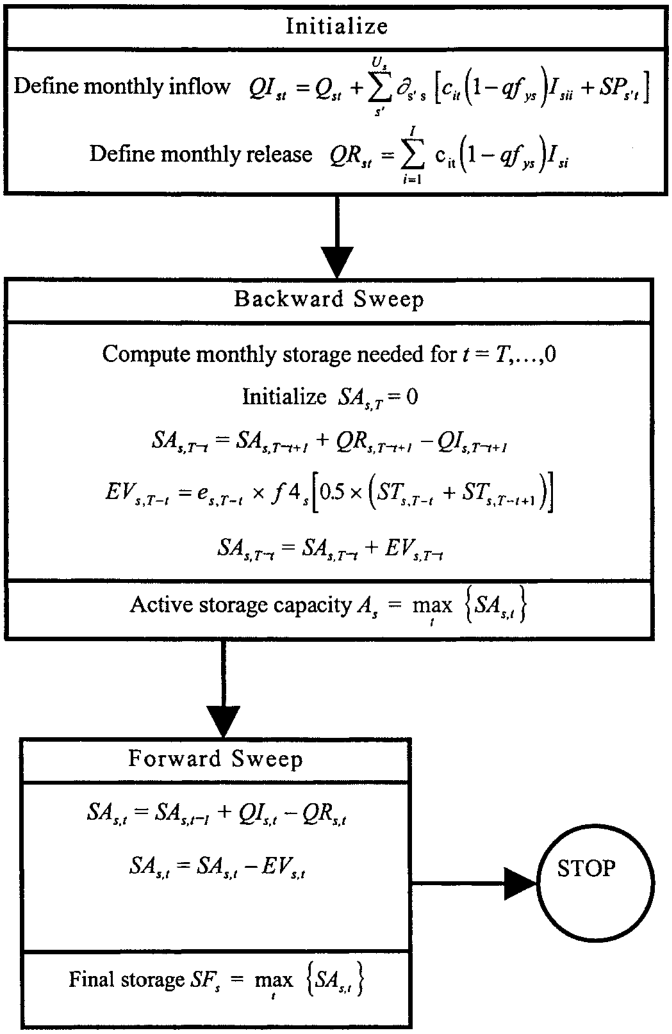

FIG. 3. STA

droplant, and any available surplus release that can be routed through the hydroplant plant. The possible power production is expressed as

$$P_{st} = c_p \times HT_{st} \times f2_s(ST_{st}) \tag{1}$$

where ST_{st} = total storage state defined as the combination of dead and active storage state; c_p = factor for conversion to power in megawatts (MW); and $f2_s$ defines the functional relation between available head and storage for reservoir s. The set of possible power production P_{st} is then converted into an ordered set P_{sO} and is defined as

$$P_{sO} = \{P_{s1}, P_{s2}, \ldots, P_{sT} | P_{s1} \le P_{s2} \le \cdots \le P_{sT}\} \tag{2}$$

Note that the subscript T in P_{sT} in (2) does not indicate the actual month; instead it is the rank of the ordered array $P_{sO'}$. Each value of the ordered set is then considered a candidate value for the optimal generator size G_s. The actual power production $P_{so'}$ for each rank (from the ordered set) is then the minimum of P_{so} and G_s (here, the candidate generator size). Then, for o equal to some o', and G_s equal to $P_{so'}$, the annual cost $ACH_{so'}$ and annual revenue $ARH_{so'}$ from hydropower are given as

$$ACH_s = c3_s P_{so'}^{c4_s} \tag{3}$$

$$ARH_s = \frac{R_{1s} \times C_e}{NY} \left\{(T - o')P_{so'} + \sum_{o=1}^{o'} P_{so}\right\} \tag{4}$$

$$NAR_s = ARH_s - ACH_s \tag{5}$$

where $c3_s$ and $c4_s$ = coefficient and exponent for a relation between annual generator cost and generator size, respectively; R_{1s} = revenue per megawatthour (MW·h); C_e = coefficient to convert to MW·h (number of generation hours per month); NY = total number of years considered for operation; and T = total number of months. The discounting factor is built into the coefficient $c3_s$.

The net annual revenue $NAR_{so'}$ from hydropower at site s is obtained as the difference between $ARH_{so'}$ and $ACH_{so'}$, given that G_s is equal to $P_{so'}$. The $NAR_{so'}$ are then calculated at each o' incremented from 1 to T, and the procedure is terminated as soon as the computed value NAR_s at o' is less than the value of NAR_s at $(o' - 1)$. The o^* is defined as $(o' - 1)$ and the optimum hydropower plant size G_s as P_{so^*}. Finally, if the optimal value of net annual revenue NAR_s is negative, the optimal hydropower plant capacity and cost and revenue are defined as zero.

Objective Function

The objective of the model is to minimize the annualized cost of reservoir and hydropower system construction. The total cost includes the cost of construction, operation, maintenance, and land acquisition. The parameter $c1_s$ accounts for the construction, operation, and maintenance components of the overall cost. Mathematically the objective function is written as follows:

$$\min Z = \sum_{s=1}^{S} (c1_s T_s^{c2_s} + f1_s(T_s)) \tag{6}$$

where $c2_s$ = exponent for the cost function; T_s = total storage capacity; and $f1_s$ = function relation between cost of land acquisition and storage capacity at site s.

Constraints

Total Storage Capacity (TSC)

The TSC T_s at site s is represented as the sum of dead and active storage capacity of the reservoir. It is required that T_s should lie between some specified upper $T_{s,\max}$ and lower $T_{s,\min}$ bound

$$T_{s,\min} \le T_s \le T_{s,\max}, \quad s = 1, \ldots, S \tag{7}$$

Reservoir Refill Constraint (RFC)

This constraint is imposed to ensure that each reservoir can be filled at least once duing the simulation. The maximum active storage for each reservoir over the simulation is required to be greater than or equal to the reservoir storage capacity

$$\max_t(SA_{s,t} + D_s) - T_s \ge 0, \quad s = 1, \ldots, S, \quad t \in \{m2 + 1, m2\} \tag{8}$$

Alternatively, this requirement can also be satisfied by setting the final storage at the end of the simulation equal to the initial storage. We are not sure if this is a better approach.

Dead Storage Constraint (DSC)

Dead storage is necessary to (1) take care of the sedimentation requirements in the reservoir; (2) ensure a firm head for hydropower production; and (3) provide an adequate head to deliver water into the main canal. It is prescribed as a fraction of the total reservoir storage

$$DR_{s,\min} \le \frac{D_s}{T_s} \le DR_{s,\max}, \quad s = 1, \ldots, S \tag{9}$$

where $DR_{s,\min}$ and $DR_{s,\max}$ = limits on the fraction of dead storage.

Irrigation Demand Dependability (IDD)

The irrigation demand for each demand area i must be satisfied with the prescribed dependability. Let NF by the maximum number of years that can be failed in NY years of simulation to achieve the prescribed dependability. The annual yield $AY_{i,y}$ for each irrigation area i can be written as follows:

$$AY_{i,y} = \sum_{i \in S_i}^{S_i} (1 - qf_{ys})I_{s,i} \tag{10}$$

where S_i = number of reservoirs supplying the irrigation area i. Let TI_i be the target irrigation requirement for area i. Let DI_i be the lower bound for yield in failure years set at 50% of the target yield for area i. Then the dependability constraint may be written as follows:

$$\min_y\{AY_{i,y}\} \ge DI_i, \quad y \in N_f \tag{11}$$

$$\min_y\{AY_{i,y}\} \ge TI_i, \quad y \in N_{nf} \tag{12}$$

where N_{nf} = set of years in which there is no failure of the target yield for area i; and N_f = set of years in which yield failure occurs for area i. Failure years are identified as part of the simulation by determining the years for which the calculated annual yield is less than the target yield.

System Yield Dependability (SYD)

This constraint accounts for the hydrological heterogeneity of the reservoir system in time and space. In a heterogeneous reservoir system, irrigation areas can experience different failure years because correlation between inflows at various sites may not be strong. Hence, it is important to ensure that the reservoir system as a whole supplies the target yield with the prescribed dependability.

Let TY be the target system yield and DY the lower bound for system yield in failure years set at 50% of the target yield. Now, consider that the array of system annual yield SAY_y values is sorted in ascending order. Then the dependability constraint may be written as follows:

$$\min_y\{SAY_y\} \ge DY, \quad y \in NT_f \tag{13}$$

$$\min_y\{SAY_y\} \ge TY, \quad y \in NT_{nf} \tag{14}$$

where NT_{nf} = set of years in which there is no failure of the target yield; and NT_f = set of years in which system yield failure occurs over the simulation. The set of failure years is identified as part of simulation.

Firm Energy Constraint (FEC)

Firm energy is defined as the minimum energy available in each year of operation. This function is evaluated after the determination of the optimal generator size at each site. Let $P_{s,t}$ be the possible power generation at site s in month t. Then the power generated by an optimally sized generator is given by

$$PS_{s,t} = \min\{P_{s,t}, G_s\} \tag{15}$$

where G_s = optimal generator capacity at site s. The FEC is expressed as

$$FE \ge TFE \tag{16}$$

where FE = firm energy provided by the system; and TFE = target firm energy desired by the system. The expression for FE can be written as follows:

$$FE = 12 \times \sum_{s=1}^{S} \min_t\{PS_{s,t}\} \tag{17}$$

where $PS_{s,t}$ = hydropower generated at site s in month t.

MODEL SOLUTION AND APPLICATION

The objective function and constraints depend nonlinearly on the decision variables, so a nonlinear programming algorithm is required to solve the formulation. The feasible sequential quadratic programming algorithm of Zhou and Tits (1992) is used to solve the formulation. Automatic differentiation is used to evaluate the derivatives of functions in the formulation. Automatic differentiation is a nonapproximative method allowing fast and exact evaluation of derivatives of any degree, and this results in faster optimization. In general, depending on the particular approach chosen, automatic differentiation approaches can compute derivatives with lower arithmetic complexity than that required by the approximate divided differences method. Details of automatic differentiation and its application to the yield model presented in this paper can be obtained in Sinha and Bischof (1998).

Table 1 summarizes the parameters for each of the reservoir sites. An inflow record of 34 years was used. The target irrigation yield is set at 1,304 million cubic meters (MCM) and target firm energy is set at 15,000 MW·h for the application presented. The problem formulated resulted in 276 ($7D_s$, $31I_{si}$, $S \times NY = 238qf_{ys}$) decision variables and 34 (7 TSC, 7 RRC, 7 DSC, 10 IDD, 2 SYD, 1 FEC) constraints. The application took between 50 and 70 min of central processor time on a CDC 4600 workstation computer for the seven-reservoir system. The CDC 4600 is roughly comparable to the SUN, Sparc 1+ workstation in processing speed. Computer memory requirement (double precision arithmetic) for this problem varied between 6.0 MB and 6.5 MB.

Table 2 presents the results from this application. The optimal objective function value is 5,663.10 million rupees (MRs). It is seen that all reservoir sites are developed to meet the irrigation and hydropower requirements. The active storage capacity required at a site depends directly upon the inflow sequence and the prescribed reliability for target yield. The 75% dependable inflows at the Jheri (240 MCM), Paikhed (208 MCM), and Kelwan (197 MCM) reservoir sites are higher than that available at the Chasmandva reservoir site (80 MCM). Consequently, storage capacity for the Chasmandva site is the least. The optimal dead storage at the Mohankavchali site has remained at its lower bound set at 192 MCM. The provision of relatively high dead storage at the Mohankavchali is primarily to ensure an adequate head for irrigating the command areas as the link canal takes off from this site. Optimal dead storage for Jheri, Paikhed, Dabdar, and Kelwan reservoirs is slightly higher than their lower bounds to satisfy the system energy requirements. It can be seen from Table 2 that the storage capacity for the Mohankavchali reservoir is the greatest and for the Chasmandva reservoir, it is the least. Consequently, the cost incurred in developing the Mohankavchali reservoir site is the highest, whereas for Chasmandva it is the lowest. The land acquisition cost at each of the sites depends upon the total storage capacity and the shape of the storage area function. The storage area functions for Chasmandva and Chikkar reservoirs are relatively steeper (Table 1), implying that for a unit rise in storage capacity, submergence at Chasmandva site is greater than the remaining reservoirs. Because the optimization algorithm minimizes the cost of land acquisition at each site as well, storage capacity at the

TABLE 1. Parameter Values for Par-Tapi-Narmada Link

Parameter	Reservoir 1	2	3	4	5	6	7
$c1_s$	9.5831	13.3941	17.7474	57.2025	37.9747	44.3855	27.9629
$c2_s$	0.7281	0.6954	0.7149	0.5978	0.5744	0.5266	0.5813
$c3_s$	0.15	0.15	0.15	0.15	0.15	0.15	0.15
$c4_s$	1.0	1.0	1.0	1.0	1.0	1.0	1.0
$c5_s$	23.19	23.19	23.19	23.19	23.19	23.19	23.19
$c6_s$	1.0	1.0	1.0	1.0	1.0	1.0	1.0
$c7_s$	1.50	1.50	1.50	1.50	1.50	1.50	1.50
$c8_s$	1.0	1.0	1.0	1.0	1.0	1.0	1.0
$c9_s$	31.7317	41.3637	20.9023	27.4761	26.8752	30.9121	44.6217
$c10_s$	0.6037	0.5882	0.6828	0.6772	0.6730	0.6776	0.6351
$c11_s$	186.95	97.16	168.42	187.61	166.95	123.26	118.46
$c12_s$	0.0464	0.0672	0.0691	0.0325	0.0382	0.0523	0.0545
$D_{s,\min}$	15	192	11	3	12	17	27
$D_{s,\max}$	50	250	60	20	30	50	70
$T_{s,\min}$	15	192	11	3	12	17	27
$T_{s,\max}$	250	400	300	100	150	250	350

Note: Annual reservoir cost (Rs/MCM) = $c1_s T_s^{c2_s}$; generator cost (MRs/MW) = $c5_s G_s^{c6_s}$; land acquisition cost (MRs/ha) = $c3_s AR_s^{c4_s}$; surface area (ha/MCM) = $c9_s SA_s^{c10_s}$; hydropower revenue (Rs/KW·h) = $c7_s P_s^{c8_s}$; reduced level (m) = $c11_s SA_s^{c12_s}$.

TABLE 2. Summary Results for Seven-Reservoir System

Category (1)	Reservoirs: Jheri (2)	Mohankavchali (3)	Paikhed (4)	Chasmandva (5)	Chikkar (6)	Dabdar (7)	Kelwan (8)	System (9)
Dead storage (MCM)	15.30	192.00	17.10	3.00	12.00	17.06	27.66	284.12
Active storage (MCM)	189.80	186.64	213.77	33.49	90.27	165.99	232.55	1,112.53
Total storage (MCM)	205.10	378.64	230.87	36.49	102.27	183.05	260.21	1,396.65
Storage cost (MRs)	462.38	831.61	868.64	491.23	542.03	689.84	709.07	4,594.80
Irrigation yield (MCM)	260.89	241.29	291.02	54.50	129.27	233.37	303.42	1,513.76
Submergence area (ha)	789.68	1,359.20	858.88	313.99	605.25	1,055.00	1,526.00	6,508.71
Land acquisition cost (MRs)	118.45	203.88	128.83	47.09	90.78	158.25	229.00	976.30
Generator size (MW)	8.93	1.56	11.22	1.42	3.40	6.15	6.94	39.65
Firm energy (MW·h)	—	—	—	—	—	—	—	20,729.43
Generator cost (MRs)	20.73	3.61	26.03	3.30	7.88	14.26	16.10	91.93
Hydro benefits (MRs)	57.38	7.77	73.49	8.65	22.26	39.79	44.41	253.78
Net hydro benefits (MRs)	36.64	4.15	47.22	5.04	14.35	25.41	28.22	161.05
Total cost (MRs)	601.56	1,039.10	1,023.50	541.62	640.72	862.36	954.20	5,663.10

Chasmandva reservoir site is low. For other sites, the land acquisition cost shows a direct dependence on the reservoir capacity. Note that the optimal annual yields from each reservoir as shown in Table 2 are available only for the nonfailure years. An examination of the model solution shows that the reservoir system fails to meet the prescribed annual irrigation requirement in the 2nd, 8th, 11th, 12th, 13th, 23rd, and 25th year of operation. Incidentally, these are also the deficit years in the historic inflow record for the Par, Auranga, Ambica, and Purna system.

DISCUSSION

Indian water planners usually apply mass curve diagrams to determine storage capacity for the reservoir. In the present study, a numerical implementation of the mass curve diagram, the modified STA, is used to determine the capacity of a reservoir. As the STA is solved as part of the optimization process, the optimal reservoir capacities obtained are actually trade-offs between q_{ys} and I_{si} values. In the formulation, total system yield reliability and yield are explicitly considered and are then integrated over the individual reservoir sites; thus cross-reservoir trade-offs are also considered.

The NWDA in India investigated the feasibility of the reservoir system to meet the target irrigation demands (*Preliminary* 1991). The NWDA developed yield capacity curves for each site and then selected a point on the curve that offered acceptable yield per unit capacity. As the NWDA procedure precluded an integrated operation of the reservoir system, it produced conservative storage capacities compared with the present model (Table 3). In the present study, joint operation of reservoirs resulted in the realization of a more cost-effective solution through a trade-off among the costs of reservoir sites. From Table 1, it is clear that Chasmandva is the costliest site for development, so the reduction in cost achieved for this site after optimization is the largest. Table 3 shows a marginal increase in the storage capacity at Jheri, Mohankavchali, and Paikhed sites. However, for the remaining sites and for the system overall, the capacities have decreased. Thus, while the NWDA approach resulted in 1,524 MCM of storage, the yield model required 1,397 MCM of storage—a savings of 8.35% of storage. The savings in cost achieved is 9.44%. The reduction in land submergence achieved is 8.05%.

The NWDA procedure for sizing generators is usually based on the average head and release available for hydropower generation. Although no data are available for comparison, it can be safely said that the present algorithm for sizing generators offers a better solution as it is based on sound economics. Table 2 shows that for all the hydropower plant sites, the net annual revenue is positive, which implies that for the given sequence of release available, the hydropower plants can be profitably developed by maximizing the local net revenues.

The NWDA model implicitly presumes that if yields from each reservoir site are available at the prescribed dependability of 75%, target yield from the system is also available at the same level. However, this may not be the case if the hydrology of the system is not homogeneous and can result in the realization of lower reliability of yields. To eliminate such an oc-

TABLE 3. Comparison of Results Obtained by NWDA Model and Yield Model for Seven-Reservoir System

Item (1)	Jheri (2)	Mohankavchali (3)	Paikhed (4)	Chasmandva (5)	Chikkar (6)	Dabdar (7)	Kelwan (8)	System (9)	Improvement (%) (10)
Storage capacity (MCM)									
NWDA model	203.00	372.00	220.00	80.00	142.00	223.00	284.00	1,524.00	—
Yield model	205.10	378.64	230.87	36.49	102.27	183.05	260.21	1,396.65	8.35
Storage cost (MRs)									
NWDA model	458.77	821.23	838.94	785.38	654.28	765.34	745.93	5,069.89	—
Yield model	462.38	831.61	868.64	491.23	542.03	689.84	709.07	4,594.80	9.44
Land submergence (ha)									
NWDA model	784.38	1,344.66	830.99	534.23	754.82	1,205.98	1,613.05	7,068.12	—
Yield model	789.68	1,359.20	858.88	313.99	605.25	1,055.00	1,526.00	6,508.71	8.05
Land acquisition cost (MRs)									
NWDA model	117.66	201.69	124.65	80.13	113.22	180.89	241.96	1,060.22	—
Yield model	118.45	203.88	128.83	47.09	90.78	158.25	229.00	976.30	8.05

curance, suitable constraints are incorporated in the present formulation.

CONCLUSIONS

The objective of the work is to present a realistic and efficient representation of the screening problem related to a multipurpose reservoir system. The focus is on a formulation that captures the policy and interests of local planners in India. A linked simulation-optimization framework is used to derive such a formulation. In this formulation, mass balance equations and the decisions variables, like release and storage, are not explicitly considered but are satisfied implicitly through the simulation. Consequently, the growth in memory and computational requirement to solve the formulation is linear with the increase in the length of inflow record. The screening algorithm presented here represents the following improvements over the optimization model presented by Lall and Miller (1988) for sizing multipurpose reservoir systems:

1. A new STA for reservoir sizing that considers evaporation losses automatically
2. Considerations of annual yield reliability as a decision variable
3. Consideration of annual firm energy as a constraint in the formulation
4. Application of automatic differentiation to obtain exact derivatives for the nonlinear functions used in the formulation (Sinha and Bischof 1998)

Reservoir planners in India typically conduct a number of simulations for various levels of irrigation yields and hydropower generation to assess the impact of variation in the development level on the reservoir system economics. An optimal solution is determined by following some heuristics and expert judgements. In the approach presented, these heuristics are replaced by a formal search algorithm that integrates the local objectives of planning.

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APPENDIX I. REFERENCES

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APPENDIX II. NOTATIONS

The following symbols are used in this paper:

A_s = active storage capacity at site s;
ACH_s = annual cost of hydropower at site s;
ARH_s = annual revenue accrued from hydropower production at site s;
$AY_{i,y}$ = annual yield for irrigation area i in year y;
C_e = coefficient to convert hydropower from MW to MW·h;
c_{it} = monthly demand fraction at area i in period t;
c_p = factor for conversion to power (MW);
D_s = dead storage at reservoir site s;
$D_{s,\max}$ = upper bound on dead storage at site s;
$D_{s,\min}$ = lower bound on dead storage at site s;
$EV_{s,t}$ = volume of evaporation loss at site s in month t;
FE = firm energy provided by system;
$f1_s$ = function relation between land acquisition cost and storage capacity at site s;
G_s = generator capacity at site s;
HT_{st} = total release HT_{st} possible through hydroplant at site s and month t;
I_{si} = firm annual irrigation yield from site s to irrigation demand zone i;
$K_{s,t}$ = critical period fill-up at site s in month t;

$m1_s$ = beginning of critical period at site s;
$m2_s$ = end of critical period at site s;
NAR_s = net annual revenue from hydropower production at site s;
NF = maximum permissible number of failure years;
NY = total number of years considered for operation;
P_{sO} = array of ordered power; O represents rank;
P_{st} = power production at site s in month t;
$Q_{s,t}$ = inflow into site s in month t;
qf_{ys} = degree (fraction of failure of irrigation yields from site s in year y;
$R_{s,t}$ = release from reservoir at site s in month t;
R_{1s} = revenue per megawatthour;
$SA_{s,t}$ = active storage at site s in period t;
SAY_y = system annual yield in year y;
SF_s = maximum storage recorded subsequent to emptying reservoir at site s;
SP_{st} = spill from reservoir at site s in month t;
ST_{st} = total storage state at site s;
s' = index for reservoirs upstream of site s;
T = operation period;
T_s = total storage capacity at site s;
$T_{s,\max}$ = upper bound on total storage capacity at site s;
$T_{s,\min}$ = lower bound on total storage capacity at site s;
TFE = target firm energy desired by system; and
U_s = number of reservoirs upstream of site s.