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Real-time multipurpose reservoir operation: a case study

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Abstract A real-time operational methodology has been developed for multipurpose reservoir operation for irrigation and hydropower generation with application to the Bhadra reservoir system in the state of Karnataka, India. The methodology consists of three phases of computer modelling. In the first phase, the optimal release policy for a given initial storage and inflow is determined using a stochastic dynamic programming (SDP) model. Streamflow forecasting using an adaptive AutoRegressive Integrated Moving Average (ARIMA) model constitutes the second phase. A real-time simulation model is developed in the third phase using the forecast inflows of phase 2 and the operating policy of phase 1. A comparison of the optimal monthly real-time operation with the historical operation demonstrates the relevance, applicability and the relative advantage of the proposed methodology.

Exploitation en temps réel d'un reservoir à buts multiples: étude d'un cas

Résumé Une méthodologie de l'exploitation en réel temps a été mis au point pour la gestion d'un réservoir à buts multiples pour l'irrigation et la production d'hydro-électricité avec application au système de réservoirs du Bhadra au Karnataka, en Inde. La méthodologie se compose de trois phases de modèles. Dans la première phase, la politique de lâchures optimales pour un situation donné de la réserve et un apport donné est déterminé en utilisant le modèle de Programme Stochastique Dynamique (SDP). On prévoir le débit arrivant dans la réservoir en employant un modèle pourant s'ajuster du type de l'adaptif Auto Regressif à Moyenne Mobile Integrée (ARIMA), ceci constitue la deuxième phase. Un modèle de simulation en temps réel a été mis au point pour la troisième phase qui utilise la prévision de débits de la deuxième phase et la politique d'exploitation de la première phase. Un comparaison de l'optimum mensuel dans l'exploitation en temps réel avec l'exploitation telle qu'elle a été faite montre la valeur, les facilités d'application et les avantages

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relatifs de la méthodologie proposée.

INTRODUCTION

Optimum development of water resources for irrigation and hydropower generation is a high priority consideration in the economic development of most of the developing countries, as food and energy continue to be among the most pressing needs. It is therefore important to operate existing multipurpose projects at their maximum efficiency. Determination of the optimum mode of operation of existing multipurpose reservoir systems is extremely relevant and the present paper is an exercise towards this goal.

The development of systems analysis techniques and their application to real-time reservoir operations have only been recently reported. Sigvaldason (1976) proposed a conceptual simulation model for the real-time operation of a multipurpose multi-reservoir system using a penalty function approach. Yaziagil *et al.* (1983) extended this simulation approach and presented a unified screening (linear programming) model for the Green River Basin system. An automated control strategy has been developed for the short term operation of a multipurpose reservoir system (Jamieson & Wilkinson, 1972). This strategy was mainly adopted for flood control purposes and its applicability is limited to simple reservoir systems only. Chu & Yeh (1978) developed a nonlinear programming algorithm for real-time hourly operation of a single reservoir system with the objective of maximizing the sum of hourly power generation over a period of one day subject to constraints on hourly power schedules, daily flow requirements of water supply and limitations on the facilities.

Becker *et al.* (1976) postulated monthly, daily and hourly real-time operation models for the Central Valley Project. The monthly model outputs were used in the daily model and the daily model outputs were in turn used in the hourly model. The monthly model used the combined linear programming and dynamic programming approach (Becker & Yeh, 1974) and the daily model used only linear programming. Yeh *et al.* (1979) also developed the hourly operation model for the Central Valley Project. In this model, the technique of incremental dynamic programming with successive approximations was used, for which the initial policy had been developed by linear programming. In all these models for the Central Valley Project, the forecasting of inflows was carried out using a computer simulation model developed by Burnash *et al.* (1973).

Ambrosino *et al.* (1984) described a sequential procedure for real-time reservoir operation management and compared its performance with the Alternative Stochastic Optimization (ASO) method of Croley (1974). In this approach, the release decision was based on present storage and present and future release targets.

Dagli & Miles (1980) proposed an adaptive planning model for the operation of a multipurpose water resource system. In this method, at any time *t*, the forecast values for the inflows during the planning periods (the next 12 months) were obtained using a forecasting model developed by

Roesner & Yevdjevich (1966) and, using these forecast values, a deterministic nonlinear programming model was solved to obtain an operating policy for time $t + 1$. The procedure was repeated for period $t + 1$ and so on. The main disadvantage of this approach is that the optimization model has to run as many times as the number of periods in the operating horizon of the reservoir. Bras *et al.* (1983) proposed an adaptive closed loop control algorithm which uses stochastic dynamic programming to derive real-time operating policies for the High Aswan Dam. This model is highly non-stationary and takes relatively more computer time to reach the steady state. Pre-emptive goal programming was applied for real-time daily operation of a multipurpose multi-reservoir system by Can & Houck (1984). In their later paper, Can & Houck (1985) discussed the implication of the problems due to the use of imperfect forecast information in real-time operation models.

In spite of the considerable work done in real-time reservoir operation, very few attempts have been made to evolve reservoir operating policies for real-time operation taking into account variability of the inflows.

Present Study

In this paper, a real-time operation methodology based on stochastic optimization and inflow forecasting is proposed taking an existing multi-purpose reservoir system, namely the Bhadra reservoir system in Karnataka State, India, as a case. The reservoir is operated for irrigation and hydro-power production, irrigation being the primary purpose. The hydropower is generated both by irrigation release (through canal turbines) and by river releases (through the river bed turbines), wherever possible. The objective of the study is to apply the proposed methodology to evolve operating policies which show potential for a distinct increase in the total annual hydropower production subject to the condition that irrigation requirements be met as in the past. The operating policy considered thus maximizes the annual hydro-power production subject to best meeting the present irrigation demands.

The proposed real-time operation methodology consists of three phases of computer modelling. In the first phase, the optimal release policy for given initial conditions at the start of a given period is determined using Stochastic Dynamic Programming (SDP). Streamflow forecasting using an adaptive AutoRegressive Integrated Moving Average (ARIMA) model constitutes the second phase. With the forecast inflows and the optimal release policies from the SDP model solution, a real-time simulation model is developed in the third phase. A comparison of the optimal monthly real-time operation with the historical operation of the Bhadra reservoir system demonstrates the relevance, applicability and relative advantage of the proposed methodology.

SYSTEM FOR STUDY

The Bhadra reservoir project is a multipurpose river valley project in the Krishna basin being operated for irrigation and hydropower generation. The reservoir has a gross capacity of 2025 M m^3 with an active storage of 1784 M m^3. Fig. 1 shows a schematic diagram of the configuration of the project. Two canals, one on each side of the reservoir, carry releases for irrigation. Three sets of turbines, named as the left turbine, right turbine and the bed turbine (Fig. 1), generate hydropower. Water released for irrigation can be used for hydropower by the left and the right turbines, whereas river release alone can produce power from the bed turbine.

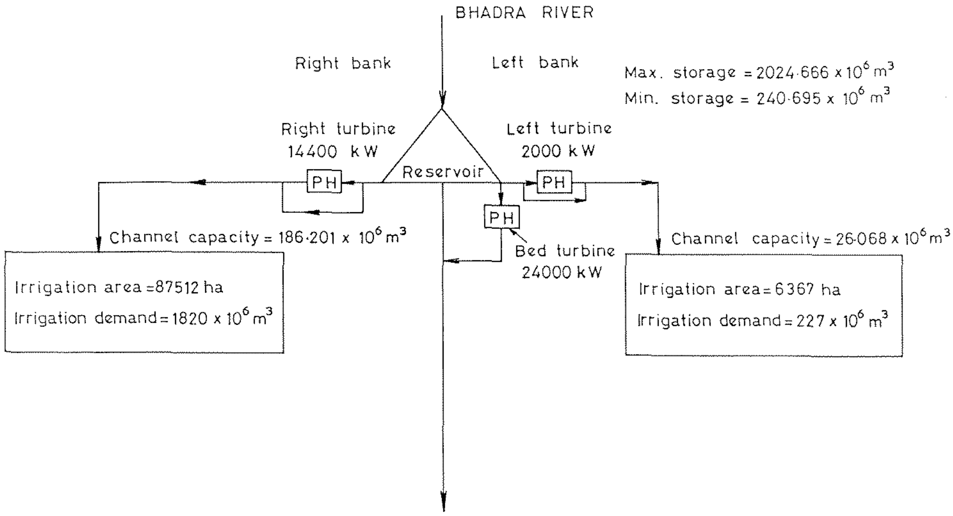

Fig. 1 *Schematic diagram of Bhadra reservoir project.*

Data

Monthly streamflow data at the reservoir site for 52 water years (1930–1931 to 1981–1982, water year beginning 1 June and ending 31 May), and monthly withdrawal data for 11 water years (1971–1972 to 1981–1982) were used in this study. A constant downstream river release of 8.565 M m^3 per month was allowed in all months for the purpose of fish and wildlife preservation.

Evaporation loss data for the period from 1970–1971 to 1981–1982 were used in deriving the relationship between the evaporation and average storage in each month by least squares fitting.

Irrigation demand

Monthly irrigation demands for the Bhadra reservoir project were computed earlier (Vedula *et al.,* 1986) based on the guidelines given by the Water Management Division (1971) of the Ministry of Agriculture, Government of India, and the actual canal withdrawals. In the computation of the demands, both the crop requirements and the actual withdrawals made for the canals were considered, as the actual cropping pattern will not always be in conformity with the design. For the purpose of the present study, the higher of the computed crop water requirements at the canal head and the average of the actual canal withdrawals in each month are taken as the demands in the model. These are given in Table 1.

Table 1 *Irrigation demands* at the canal head in M m^3*

Month	*Left bank demand*	*Right bank demand*	*Total demand*
Jun	8.9	111.0	119.9
Jul	15.0	121.8	136.8
Aug	21.1	179.5	200.6
Sep	22.3	173.5	195.8
Oct	24.3	178.9	203.2
Nov	21.2	168.5	189.7
Dec	8.0	101.4	109.4
Jan	16.5	120.8	137.3
Feb	21.2	158.9	180.1
Mar	22.7	174.6	197.3
Apr	24.0	173.9	197.9
May	21.3	157.3	178.6
Totals	226.5	1820.1	2046.6

* *as per Vedula & Mohan (1986).*

Bed turbine operation

There are some practical considerations in the operation of the bed turbine. If the bed turbine is operated at full capacity in any month as soon as the reservoir level rises above the minimum prescribed for its feasible operation, the reservoir level in the subsequent month may drop down to such an extent that the bed turbine itself would have to be shut off. Also the release made through the bed turbine is, in a sense, a loss from the reservoir storage and may lead to an irrigation shortage in a future month. Such a difficulty is not met in the case of the left and right turbines as the canal water, released for the purpose of irrigation, generates power from them anyway. A strategic operation of the bed turbine is therefore proposed keeping these considerations as follows.

Power can be generated from the bed turbine as long as the reservoir level, H, is above a minimum value, $H_{\min}$, prescribed for its operation. In the procedure considered herein, the bed turbine is operated at full capacity at and above a chosen reservoir level, H_o ($H_o > H_{\min}$). For any level H between $H_{\min}$ and H_o, the bed turbine is operated only at part (α_c) of its capacity in a linear manner as follows:

$$\alpha_c = (H - H_{\min}) \,/\, (H_o - H_{\min}) \qquad (1)$$

Also considered is the possibility of operating the bed turbine at only a fraction, p_c, of its full capacity at and above the reservoir level H_o. In this case also, the operation below the level H_o and above $H_{\min}$ is governed by the proportionality factor α_c via equation (1). Thus the bed turbine is brought from zero capacity operation to its full capacity (p_c = 1.0) or to its specified capacity (p_c < 1.0) operation, as the case may be, in a linear manner as the reservoir level rises from H_{min} to the specified or chosen level H_o. The required amount of water, QB', is released to the bed turbine to satisfy this condition.

Therefore:

$$QB' = \alpha_c \, QB \, p_c \tag{2}$$

where QB is the discharge required to operate the bed turbine at its full capacity with reservoir level H. The lower the value H_o, the higher is the power generation from the bed turbine and the greater is the likelihood of irrigation shortage in the subsequent months.

Based on this, preliminary simulation runs (Vedula *et al.*, 1986) indicated two procedures among a total of thirteen (Mohan, 1983) for the bed turbine operation. These two correspond to p_c = 1.0 (referred to here as PROC I) and p_c = 0.75 (PROC II), with H_o corresponding to the maximum water level in the reservoir, H_{max}.

These procedures regulate the flow through the bed turbine every month for power generation keeping in view possible irrigation shortages in future periods consequent on operating the bed turbine at its full capacity whenever possible.

The procedures PROC I and PROC II specify the manner in which the bed turbine is to be operated for a given reservoir level. It is to be noted, however, that these do not indicate in any way how the reservoir system should be operated either for irrigation or for power production from the left and right turbines. This latter issue is to be resolved by the reservoir operating policy.

RESERVOIR OPERATING POLICY

A steady state reservoir operating policy for each month for known values of inflow and initial storage in the reservoir was obtained using SDP following Loucks *et al.* (1981).

The inflows were assumed to follow a discrete Markov process. The inflow transition probability P^t_{ij} is the probability that inflow would be in state j in period t + 1 given that it is in state i in period t. The operating policy derived from the SDP model is a set of rules specifying the storage at the beginning of the next period for each combination of initial storage and inflow for the current period thus specifying the release for the current period.

The objective of the model is to obtain the steady state value of the maximized annual system performance through the solution of the SDP model. The total number of time periods over which the model runs is T. Let $f^n_t(k,i)$ denote the maximum value of the cumulative system performance from time period T to the present time, t (n stages remaining) given the initial storage state k and inflow state i for time period t. The general recursive relationship for any time period t between 1 and T is:

$$f_t^n(k,i) = \underset{l}{\text{maximum}} \left[B_{kilt} + \sum_j P_{ij}^t f_{t+1}^{n-1}(l,j) \right] \qquad k,i \ ; \ l \text{ feasible} \tag{3}$$

and the storage continuity equation is:

$$R_{kilt} = S_{kt} - S_{l,t+1} + Q_{it} - EL_{klt} \tag{4}$$

where:

- i, j are indices of characteristic inflows in time periods t and $t + 1$ respectively;
- k, l are indices of characteristic storages at beginning and end of time period t respectively;
- n is the number of time periods remaining until the end of the operation horizon;
- t is time period or stage;
- Q_{it} is characteristic streamflow in state i in time period t;
- $S_{l,t+1}$ is characteristic final storage in state l in time period t;
- S_{kt} is characteristic initial storage in state k in time period t;
- R_{kilt} is the release during time period t that results from an initial storage S_{kt}, an inflow Q_{it} and final storage $S_{l,t+1}$;
- EL_{klt} is evaporation loss based on initial storage state k and final storage state l in time period t; and
- B_{kilt} is the system performance value for initial storage state k, inflow state i and final storage state l in time period t.

Solution of the recursive relation proceeds for $t = T, T - 1, ...$ until the algorithm converges to a steady state. When the steady state condition is reached, the expected annual system performance $[f_t^{n+12}(k,i) - f_t^n(k,i)]$ reaches a constant value for all states k, i and for all t. The steady state condition is obtained because the system performance values (B_{kilt}) and the transition probabilities (P_{ij}^t) remain the same every year.

Months were considered as stages in the model. The storage volumes and inflows were divided into finite sets of discrete storage and inflow intervals. Based on the historic inflow data from 1930–1931 to 1981–1982, monthly inflows were discretized into five states (i = 1, 2, ...5). From the observed data of 12 years (1970–1971 to 1981–1982), the initial and final storage volumes were discretized into 10 states each (k = 1, 2, ..10; l = 1, 2, ...10) in each month. The mid point values of the class intervals were taken as the characteristic values in the computations.

The total hydropower production in the system (from the left, right and bed turbines together) was taken as a measure of the system performance, B_{kilt}, with the requirement that irrigation demands be met to the extent possible. The system performance values (total power production), B_{kilt}, were computed for all feasible combination of inflows (5 states), initial and final storages (of 10 states each), for PROC I and PROC II by simulation.

Model solution

The system performance values along with the transition probabilities of inflows form the input to the stochastic dynamic programming model. Optimal solutions (optimal releases for irrigation and power) were obtained for PROC I and PROC II. The optimal solution obtained with B_{kilt} values computed via PROC I is hereafter referred to as POLICY I, and the solution via PROC II as POLICY II. The release policy converged to a steady state form in both cases at the end of six years (72 months) from the start of computations. The policy gives, in each case, the optimal final storage volume index (l^*) for each combination of k and i and for each month t.

REAL TIME OPERATION

In order to be able to use the steady state policy as a release policy for a real-time operation of the reservoir, knowledge of the current month's inflow at the beginning of each month is essential. To circumvent this, Loucks *et al.* (1981) proposed a methodology to derive an optimal steady state policy that does not depend on the inflow of the current period by identifying either a final storage volume target subject to limitations on the releases or reservoir releases subject to limitations on final storage volumes. A more direct alternative, however, is to forecast the inflow of the current period. This latter approach is adopted in the present study through a streamflow forecasting model.

A $(4, 0, 0) \times (0, 1, 1)_{12}$ multiplicative seasonal AutoRegressive Integrated Moving Average (ARIMA) model was fitted (Mohan, 1987) to the Bhadra reservoir streamflow series following the methodology explained by Box & Jenkins (1976). The forecasting model and the operating policies derived from the SDP model were used in combination to develop the real-time simulation model for the operation of the reservoir.

REAL-TIME SIMULATION

Simulation

The simulation takes into account the forecast inflows to determine the optimal releases for the given initial storage and inflow in any month. The actual releases are then made accordingly, and, at the end of the month, the final storage is computed with the observed inflow for that month. The observed inflow is also used to update the information for forecasting the next period's inflow. This procedure is repeated in the model for all the months of the simulation. The block diagram shown in Fig. 2 illustrates the methodology.

Validation

The proposed simulation model has been validated for its application in real-

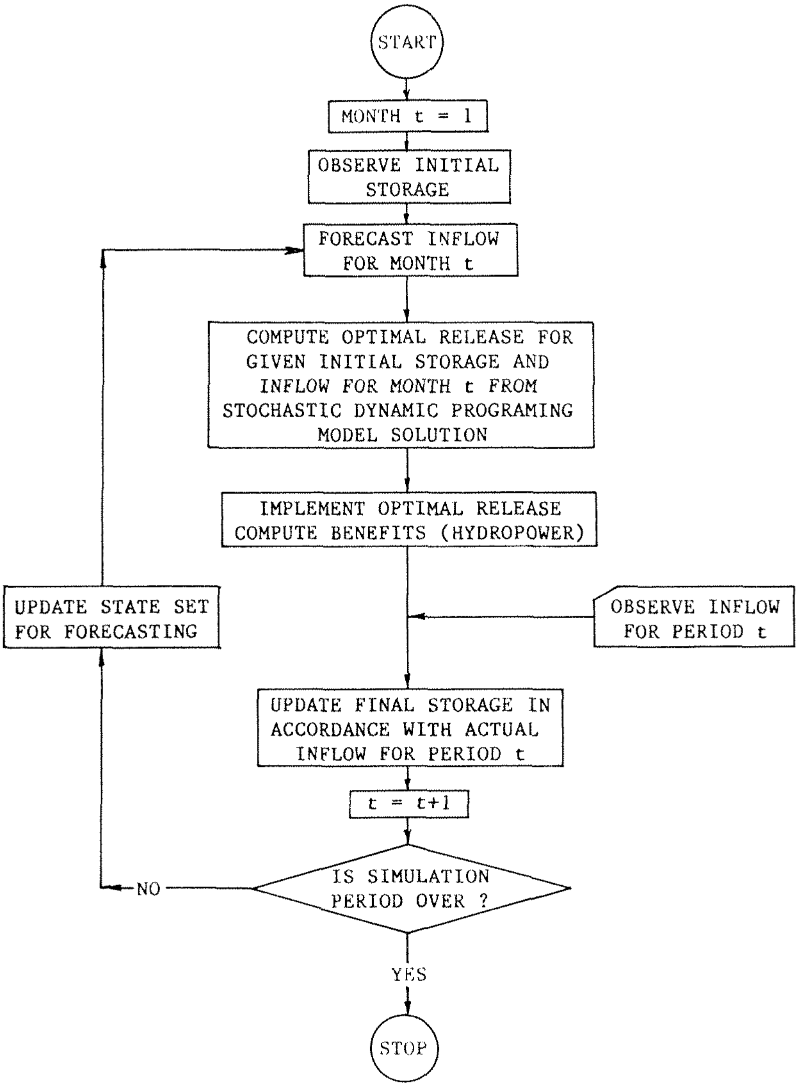

Fig. 2 Block diagram for real-time simulation.

time operation. The model has been used to simulate the reservoir operation over a 11 year period from 1971–1972 to 1981–1982 (water years) using the two different policies (POLICY I & POLICY II). This period was chosen based on the availability of data on actual power production. In the forecasting model used in the present study, the parameters were estimated based on 41 years of historic data (1930–1931 to 1970–1971) prior to the start of the simulation. The starting month for simulation was taken as June and the actual observed initial storage for June 1971, equal to 460.78 M m^3, was taken as the initial storage for the start of simulation for both POLICY I and POLICY II.

The monthly and yearly performance of the two policies of operation and their comparison with actual realizations are discussed below based on the irrigation supplies, the bed turbine power production and the total power production from all turbines.

Monthly performance

A scale of performance based on the magnitude of any irrigation shortage and its frequency of occurrence has been used to assess the irrigation performance. The suggested scale is shown in Table 2, where the percent irrigation shortage (IS) refers to the average percentage of the monthly deficits (from the corresponding demands), averaged over those months in which deficit occurred, over the 11 year period. The frequency of occurrence of the deficit in any given month is expressed as the percentage of the number of such deficit months to the total (FIS). From the results of simulation runs, the average percentage of irrigation shortage and its frequency are tabulated in Table 3, which also shows the quantities based on data of the historical operation over these 11 years. The performance indicators for each case are also given in Table 3.

It can be seen that the actual operation experienced irrigation shortage (with reference to the demands used in the present study) in all the months over the 11 year period considered. On the other hand, POLICY I and POLICY II show better performance (indicated by A1) during the first eight months (June to January) than the actual operation (with indicators of performance worse than A1). This shows that the average performance with either of the two policies is better than the actual performance during the months of the important kharif season (June to November). Also the performance indicator for the month of February shows a better performance (A2) if either of the policies was used, compared to the actual performance (C1). During March, April and May however, POLICY I results in a performance better than or as good as POLICY II, but actual performance was even better than that of POLICY I. However, in these months, the actual operation itself was not good with 22 to 34% irrigation shortage and with the frequency varying from 20 to 36%.

The inflows during two among the 11 years considered are only 53%

Table 2 *Classification of irrigation shortage and its frequency*

Percent irrigation shortage (IS)	*Class*	*Percent frequency of irrigation shortage (FIS)*	*Class*
$0 \leqslant IS \leqslant 5$	A	$0 \leqslant FIS \leqslant 20$	1
$5 < IS \leqslant 20$	B	$20 < FIS \leqslant 40$	2
$20 < IS \leqslant 40$	C	$40 < FIS \leqslant 60$	3
$40 < IS \leqslant 60$	D	$60 < FIS \leqslant 80$	4
$60 < IS \leqslant 80$	E	$80 < FIS \leqslant 100$	5
$80 < IS \leqslant 100$	F		

Table 3 *Monthly comparison of irrigation releases by simulation*

Month	Historic operation			Runs with forecast inflows					
				POLICY I			POLICY II		
	IS*	FIS†	Class	IS*	FIS†	Class	IS*	FIS†	Class
Jun	57.2	100.0	D5	0.0	0.0	A1	0.0	0.0	A1
Jul	13.6	64.0	B4	0.0	0.0	A1	0.0	0.0	A1
Aug	2.5	60.0	A3	0.0	0.0	A1	0.0	0.0	A1
Sep	3.9	50.0	A3	0.0	0.0	A1	0.0	0.0	A1
Oct	5.3	30.0	B2	0.0	0.0	A1	0.0	0.0	A1
Nov	8.9	50.0	B3	0.0	0.0	A1	0.0	0.0	A1
Dec	50.9.	100.0	D5	0.0	0.0	A1	0.0	0.0	A1
Jan	11.6	45.4	B3	0.0	0.0	A1	0.0	0.0	A1
Feb	28.0	20.0	C1	2.5	36.4	A2	2.9	36.4	A2
Mar	26.3	27.3	C2	32.6	54.4	C3	32.8	63.6	C4
Apr	21.9	20.0	C1	56.6	81.8	D5	62.7	54.5	E3
May	33.8	36.4	C2	71.9	54.5	E3	66.3	45.5	E3

* *average of percent irrigation shortage;*
† *frequency of irrigation shortage.*

and 61% of the average annual flow (in the other 9 years, they are higher than 80%) resulting in severe irrigation shortage during the months of April and May in both the years in simulation. The policies show higher deficits than actual experience on an average during the months of March, April and May. Considering that the demands imposed in the model are the higher of the computed requirements and the actual withdrawals, the irrigation shortages in these months are not considered as severe as they may look from the cropping point of view, because the actual withdrawals in the months of March, April and May were higher than the requirements by 7, 17 and 44% respectively. The overall irrigation performance is assessed thus: that POLICY I and POLICY II perform better during the months of June to February compared with the actual operation and, in the other months, the performance is just as good or as bad as that of the actual operation. No further restrictions on the operation of the bed turbine are therefore considered warranted.

A comparison of simulation results in respect of bed power production and total power production, from all the turbines, shows a distinct improvement due to the operating procedures adopted in the simulation runs. The average monthly power production from the bed turbine and the total production from all the turbines are plotted against each month in Figs 3 and 4 respectively. It can be seen from Fig. 4 that both the policies result in higher amount of total power production than in the actual operation in all the months. The average monthly power production from the bed turbine, as can be seen from Fig. 3, is also higher than the actual value in 8 out of 12 months with both policies, 9 out of 12 months with POLICY II and 10 out of 12 months with POLICY I. Thus the simulation model with forecast inflows yields better results than the actual realization (both from the point of view of irrigation releases and hydropower production).

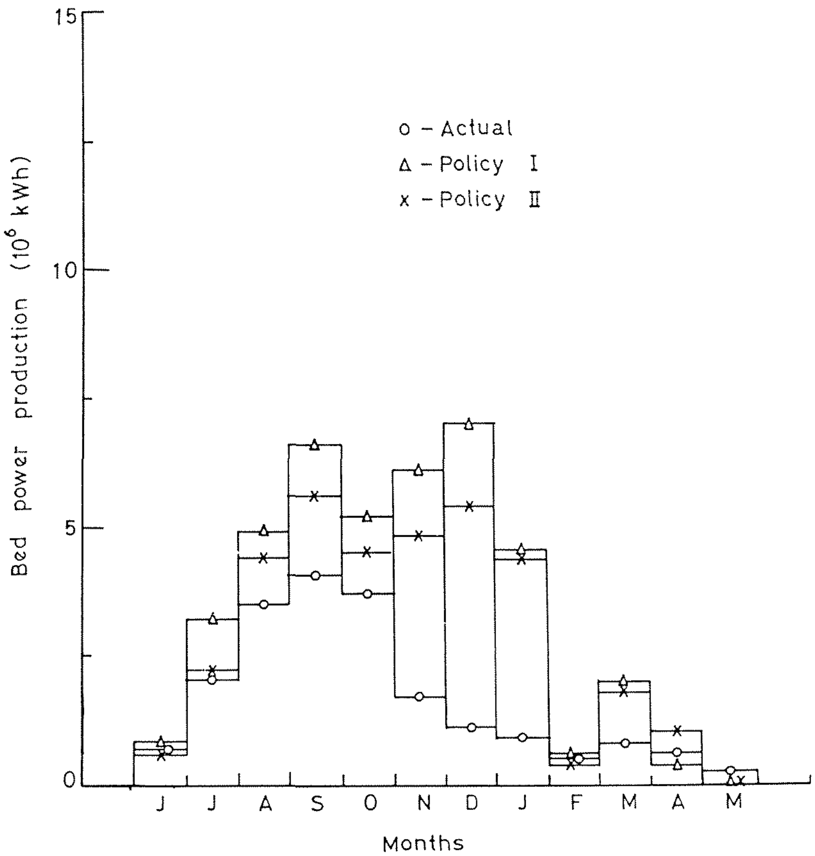

Fig. 3 Comparison of average power production monthwise.

Yearly performance

Table 4 gives the average annual values of different performance variables from simulation runs with POLICY I and II along with their actual realizations. From Table 4, it can be seen that the percentage deviations of irrigation releases from the actual values are only 3.3% and 1.6% for POLICY I and POLICY II, respectively. On the other hand, the power production from the bed turbine results in an increase of 89% and 60% for policies I and II, respectively, when compared with actual realizations. The corresponding total power production from all the turbines results in a substantial increase compared to the actual values of 57% and 52% for policies I and II, respectively. It was also found that both the policies resulted in lower evaporation loss than has actually been experienced.

The detailed simulation results for the 11 years are presented in Table 5 along with their corresponding actual values. Irrigation deficits occur during eight years out of the 11 years considered; but the magnitudes of the average percentage deficit over these years are only 5.3% and 3.5% for policies I and II, respectively.

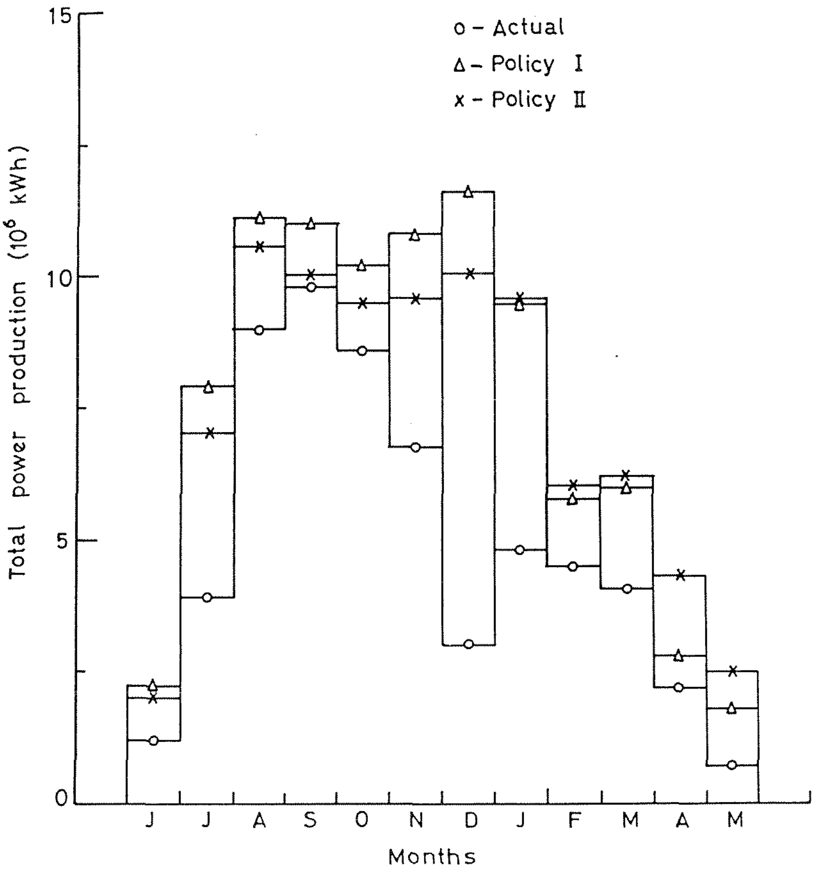

Fig. 4 *Comparison of total power production monthwise.*

Table 4 *Comparison of simulation results with historical operation*

Quantity	*Average annual value*		
	Actual	*POLICY I*	*POLICY II*
Irrigation releases (IR) ($M\,m^3$)	*1912.0*	*1848.2*	*1882.0*
Percent deviation of IR from actual	-	*3.3*	*1.6*
Evaporation loss ($M\,m^3$)	*124.8*	*97.4*	*99.6*
Bed power production (10^6 kW h)	*21.2*	*40.2*	*34.0*
Total power production (10^6 kW h)	*57.1*	*89.7*	*86.9*

With respect to the bed turbine power production, Table 5 shows that both policies produce higher power than the actual value in 10 out of 11 years. POLICY I results in a better performance in all the years whereas POLICY II gives better results in 10 out of 11 years when compared with actual realizations.

Table 5 *Yearly comparison of simulation results*

Year	Total irrigation releases (M m^3)					Bed turbine power production (10^6 kW h)			Total power production (10^6 kW h)		
	Actual	POLICY I	Percent deviation from actual	POLICY II	Percent deviation from actual	Actual	POLICY I	POLICY II	Actual	POLICY I	POLICY II
1971-1972	1991.7	1893.0	-4.9	1893.0	-4.9	13.3	33.7	33.3	60.9	94.0	93.0
1972-1973	1475.7	1608.7	9.0	1608.7	9.0	7.7	18.5	17.9	33.3	60.3	62.4
1973-1974	1885.2	1893.0	0.4	1886.3	0.1	3.8	23.5	21.3	42.5	77.6	76.4
1974-1975	1958.1	1899.0	-3.0	1898.1	-3.1	0.8	31.2	26.6	33.5	88.7	84.4
1975-1976	1994.6	1967.0	-1.4	1967.0	-1.4	33.6	61.2	50.3	77.9	113.2	105.4
1976-1977	1647.1	1607.3	-2.4	1608.7	-2.3	1.5	20.8	20.2	21.9	60.2	66.1
1977-1978	1921.1	1784.0	-7.1	1903.6	-0.9	2.0	32.0	26.1	21.5	82.0	81.7
1978-1979	1943.8	1871.9	-3.7	2041.7	6.3	46.8	61.9	51.2	98.8	101.5	100.8
1979-1980	2013.1	1893.0	-6.0	1893.0	-6.0	22.1	33.6	22.8	46.6	90.9	84.5
1980-1981	2027.0	2041.0	0.7	1961.4	-3.3	50.3	70.1	55.0	96.4	115.0	100.1
1981-1982	2174.5	1871.9	-13.9	2041.0	-6.0	51.5	55.3	49.6	94.1	103.7	102.8

In terms of the total power production from all three turbines, it is seen from Table 5 that both policies I and II give better results than the actual achievements in all the years of comparison. It is observed that POLICY II produces better results than POLICY I in terms of total power production during the two low inflow years, 1972–1973 and 1976–1977, of the 11 year period; and in all the other years, POLICY I gives higher power production than POLICY II.

CONCLUDING REMARKS

A real-time operation methodology was developed and two potential reservoir operating policies were identified for the Bhadra reservoir system in Karnataka State. These policies yield a substantial increase (of 52–57% a year) in power production as demonstrated in the study. This is a significant result considering the frequent and acute power shortage which the state of Karnataka experiences from time to time. The trade-off for this in terms of irrigation shortage is almost negligible (varying from 1.6 to 3.3% depending on the policy used) when compared with the average (actual) annual releases over the 11 year period.

The present (existing) operation appears to be over-conservative in holding water in the reservoir during the dry season and not effectively utilizing it for better power production. This is being done, presumably, with the apprehension of having to face possible irrigation shortage in the subsequent months till the onset of the monsoon, especially because of increased evaporation loss during the season. This study shows that, from the point of view of a long term strategy, such an apprehension, leading to a reservoir operation at the expense of hydropower, is not well founded.

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