REAL TIME RESERVOIR OPERATION (VALIDATION PHASE) A CASE STUDY

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Abstract

The LP formulation with the selected set of penalties is run in the validation phase. There are two sub-phases in the validation phase. In the first sub-phase, three years corresponding to the flood, normal, and drought years are considered. The performance of these years is measured by the reservoir storage at the end of monsoon season and peak flow at d/s flood control point. In the second sub-phase, eight extreme floods from the history of the reservoir are chosen. The performances of these floods are measured by peak flow at d/s flood control point during each of the floods. The real time operation is done for three time intervals, viz. 24, 12 and 6 hours.

***Keywords**: Real time reservoir operation, validation phase*

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1. INTRODUCTION

Most of the living beings are affected by either too less or too much of water compared to the normal requirement. As the scarcity of water is a grave concern for management, so also the excess of it. The former situation leads to drought, and the latter to flood. Both are equally alarming. Structural and non-structural measures are required to mitigate these disaster situations (*Mays and Tung*, 1992). One of the major structural measures is construction of a dam across the river. Reservoir, created by construction of dam, can tackle both the situations, viz., drought and flood. It is natural for the beneficiaries of a reservoir to extract as much benefit as possible from a single or multi-reservoir system.

At present, most of the reservoirs are for multipurpose, even though some of them were originally conceived for single purpose. The various purposes of reservoir include irrigation, hydropower, drinking water supply, low-flow augmentation, navigation, aquaculture etc. All these purposes come under the category of conservative purpose. The management of any of the conservative purposes is similar in nature, viz., to utilize the available water of the reservoir judiciously. The reservoir, built for flood control purpose on the other hand, uses the available empty space of reservoir to absorb the flood. In the case of such flood control reservoir, it is operated for flood control and conservative purposes during some periods (for example, monsoon period in India) and is operated for only conservative purposes during rest of the year. Hence, it is more difficult to operate a multipurpose flood control reservoir than a reservoir with conservative purposes alone.

2. METHODOLOGY

The following LP formulation is used in validation phases, which is very similar to the calibration phase. The only difference lies in the use of Muskingum equation. Conventional Muskingum equation was used in calibration phase in the previous paper, where as more accurate extended Muskingum equation is used in this validation phase. This LP formulation is used for operation intervals of 24 hours, 12 hours and 6 hours. For illustration, the formulation is discussed for the operation interval of 24 hours. The LP formulation is as follows.

Minimize

$$Z = \sum_{t=1}^{L} [P_{LS}\ LS_t + P_{US}\ US_t + P_{QI}\ QI_t + P_{QD}\ QD_t + P_{ROAI}\ ROAI_t + P_{ROAD}\ ROAD_t + P_{ROEI}\ ROEI_t + P_{ROED}\ ROED_t] \quad (1)$$

$$S_2 + CF * RPS_2/2 = CF\,[I_1 + I_2]/2 - CF\,[IR_1 + IR_2]/2 - CF * RPS_1/2 + S_1 \quad (2)$$

$$S_t + CF\,[RPS_{t-1} + RPS_t]/2 - S_{t-1} = CF\,[I_{t-1} + I_t]/2 - CF\,[IR_{t-1} + IR_t]/2 \qquad t = 3,4,....,L \quad (3)$$

$$S_t - US_t + LS_t = RCS_t \qquad t = 2,3....,L \quad (4)$$

$$Q_2 - C_1^H\ RPS_2 = C_0^K\ DC_1 + C_0^H\ RPS_1 + C_1^K\ DC_2 + C_2\, Q_1 \tag{5}$$

$$Q_t - C_0^H\ RPS_{t-1} - C_1^H\ RPS_t - C_2\ Q_{t-1} = C_0^K\ DC_{t-1} + C_1^K\ DC_t \tag{6}$$

$$t = 3,4,...., L$$

$$Q_t - QI_t - QD_t = 0 \qquad t = 2, 3, ...,L \tag{7}$$

$$RPS_2 - [ROAI_1 + ROEI_1] + [ROAD_1 + ROED_1] = RPS_1 \tag{8}$$

$$RPS_t - [ROAI_{t-1} + ROEI_{t-1}] + [ROAD_{t-1} + ROED_{t-1}] - RPS_{t-1} = 0 \qquad t = 3, 4....L \tag{9}$$

$$RPSMIN \le RPS_t \le RPSMAX \qquad t = 2,3, ...,L \tag{10}$$

$$QD_t \le NDF \qquad t = 2,3, ...,L \tag{11}$$

$$ROAI_t \le ROAIMAX;\ \ ROAD_t \le ROADMAX \qquad t = 1,2, ...,L-1 \tag{12}$$

$$S_{DSL} \le S_t \le S_{FRL} \qquad t = 2,3, ...,L \tag{13}$$

Non-negative constraints on US_t, LS_t, QI_t, QD_t, $ROAI_t$, $ROAD_t$, $ROEI_t$, *and* $ROED_t$. $t = 2,3, ...,L$ (14)

Where
Z is the objective function.
LS_t is the deviation of reservoir storage below the recommended rule curve storage at beginning of time period t.
US_t is the deviation of reservoir storage above the recommended rule curve storage at beginning of time period t.
QI_t is the difference between flow at Naraj and non-damaging flow at beginning of time period t, when the flow is more than non-damaging flow,.
QD_t is the flow at Naraj at beginning of time period t, when the flow is less than or equal to non-damaging flow.
$ROAI_t$ is the increase of release from reservoir (summation of release for power and spill) within acceptable safe limit during time period t.
$ROAD_t$ is the decrease of release from reservoir within acceptable safe limit during time period t.
$ROEI_t$ is the increase of release from reservoir beyond acceptable safe limit during time period t.
$ROED_t$ is the decrease of release from reservoir beyond acceptable safe limit during time period t.
P_{LS}, P_{US}, P_{QI}, P_{QD} are the relative penalties for unit change of *LS, US, QI, QD* respectively.
P_{ROEI}, P_{ROED}, P_{ROAI}, P_{ROAD} are the relative penalties for unit change of *ROEI, ROED, ROAI, ROAD* respectively.
S_t is the reservoir storage volume at beginning of time period t.
CF is the conversion factor to convert from rate to volume of any variable.
RPS_t is the summation of release from reservoir for power and spill at beginning of time period t.
I_t is inflow into the reservoir at beginning of time period t.
IR_t is the release from reservoir for irrigation at beginning of time period t.
RCS_t is the recommended rule curve storage at beginning of time period t.
Q_t is the flow at Naraj at beginning of time period t.
DC_t is d/s catchment contribution at beginning of time period t.
C_0^H is the Muskingum coefficient for release from Hirakud at beginning of time period.
C_1^H is the Muskingum coefficient for release from Hirakud at end of time period.
C_0^K is the Muskingum coefficient for d/s catchment contribution at beginning of time period.
C_1^K is the Muskingum coefficient for d/s catchment contribution at end of time period.
C_2 is the Muskingum coefficient for flow at Naraj at end of time period.
RPSMIN is the minimum required release from reservoir for power and spill.
RPSMAX is the maximum release capacity from reservoir for power and spill.
ROAIMAX is the safe limit of increase of release from reservoir during a specific time period.
ROADMAX is the safe limit of decrease of release from reservoir during a specific time period.
S_{DSL} is the reservoir storage at dead storage level.
S_{FRL} is the reservoir storage at full reservoir level.
t is the time period.
L is the operating horizon for each iteration of the LP model.

3. VALIDATION PHASE

The performance of the three calibration floods during calibration phase is compared and a suitable set of penalties ($P_{QD} : P_{US} : P_{ROAI} : P_{ROAD} : P_{QI}, P_{LS}, P_{ROEI}, P_{ROED}$ :: 1 : 3 : 1 : 1 : 8) for objective function of the LP formulation is selected. This set of penalties is applied in other situations to check the model performance in this validation phase. The situations for validation are taken in two ways; (i) the quantity of inflow into the reservoir for the whole monsoon of a year and (ii) the severity of floods. In the first category, the years with extremely high, extremely low, and normal quantity of inflow into the reservoir are selected for validation. In second category, severe floods are selected for validation.

The extended Muskingum coefficients for various routing period are obtained for Hirakud Project (Baliarsingh, 2000) by following the procedure given by M. H. Khan (Khan, 1993) and are placed in table-2. The data from 1972 to 1995 is considered for validation phase as the measurement of d/s catchment contribution was started from 1972 onwards. During this period, the total quantity of inflow into the reservoir in monsoon season is extremely high in the year 1994, extremely low in the year 1979, and close to the average in the year of 1984. These quantities are 73.9, 10.5, and 33.3 TMCM respectively. The average inflow into the reservoir in monsoon season during 1972-1995 is 31 TMCM. So these years are selected for validation and referred as validation year 1, 2, and 3 respectively henceforth.

The most severe floods among 43 floods during 1972 to 1995 are selected in a similar way as done in calibration phase. The details of these most severe floods are shown in the Table-1. There is no occurrence of flood during ninth block period in these years. Eight floods in the remaining eight block periods are selected for validation phase. These floods from first to eighth block periods are referred henceforth as validation floods 1 to 8 respectively.

4. RESULTS AND DISCUSSION OF VALIDATION PHASE

This phase is divided into two stages. In first stage (section 4.1), the results of three validation years are discussed and in the second stage (section 4.2), the result of eight validation floods are discussed. The variable rule curve (rule curve for drought, normal, and flood situation) is recommended for Hirakud reservoir and is given in Fig.3 of the previous paper. The various rule curves are followed according to the type of year, i.e., the rule curve corresponding to drought situation is to be followed in the drought year and so also for normal and flood year. These types of year are characterized by total monsoon inflow into the reservoir, the classification of which is made as follow.

From the historical data, it is observed that the maximum and minimum total quantity of inflow into the reservoir in a monsoon season is 86 and 10.5 TMCM respectively. The average value during these years is 31 TMCM. In a 100 points scale, 10.5, 31, and 86 TMCM are considered as 10, 50, and 90 points respectively. 10 points beyond 90 are reserved for more severe flood year than the year with 86 TMCM of total inflow into the reservoir. Similarly, 10 points on the lower side are reserved for more severe drought year than the year with 10.5 TMCM. A year is considered to be a drought year if the total inflow into the reservoir is less than 33 on 100 point scale, a normal year if it is between 33 and 67 and a flood year if it is above 67.

The relationship of the total inflow into the reservoir and points in 100 point scale is determined by regression analysis with the data as 10, 50, 90 points corresponding to 10.5, 31, 86 TMCM and is given in equation 6.18.

$$Y = 0.0108*X^2 - 0.1344*X + 10.766 \qquad (15)$$

Where
Y is total inflow into the reservoir in the monsoon in TMCM
X is point in 100 point scale.

By following the above points system and the equation-15, it is found that the year with total inflow into the reservoir below 18 TMCM is drought year, 18 to 50.25 TMCM is normal year and above 50.25 TMCM is flood year.

The reservoir is operated in this study by the LP model (equation-1 to equation-14) for all the three validation years and eight validation floods. Six years of data, i.e., 1973, 1976, 1977, 1980, 1982, and 1994, are used for validation floods. In the following two sub-sections, the results of validation years and validation floods are discussed independently.

4.1 Validation Years

As discussed in section 3, the years 1979, 1984, and 1994 are selected for validation purpose as drought, normal, and flood years respectively. The penalties for various components in objective function of LP formulation, as obtained in calibration phase, $P_{QD} : P_{US} : P_{ROAI} : P_{ROAD} : P_{QI}$, P_{LS}, P_{ROEI}, P_{ROED} :: 1 : 3 : 1 : 1 : 8, are used for the validation phase. The procedure of real time reservoir operation by adaptive planning, as explained in previous paper, is used in the validation phase also. For this purpose, forecasted inflows and d/s catchment contribution are required for five days at each time step. However, the data, generated by any forecasting model, will have error and uncertainty associated with the forecasts. Therefore, in the present case, the observed data is used as forecast. This will give good insight into the performance evaluation of the operating policy by avoiding the forecasted data with its uncertainty nature. It may be noted that the proposed optimization model can easily incorporate the forecasted data obtained from any forecasting approach.

The performance of the reservoir operation is evaluated by the reservoir storage achieved on 1st October and the peak flow at Naraj during the operation. It is expected to achieve the full reservoir level i.e., 7.197 TMCM by 1st October and the peak flow at Naraj should be always less than non-damaging flow of 25.5 thousand cumecs. The performance of reservoir operation by the LP formulation for the years 1979, 1984, and 1994 is shown in the Table-3. The reservoir operation is done at an interval of 24 hours in this case. The reservoir reached the full reservoir level by 1st October with the proposed model for each of these three validation years.

Regarding the maximum flow at Naraj during these years, the peak flow during 1979 and 1984 is less than non-damaging flow, but during 1994, it is 29.19 thousand cumecs. The performance of the proposed model is compared with the performance of Hirakud authority in the same Table 3. The reservoir storage during 1979 and 1984 is much below than 7.197 TMCM, but it is full only during 1994 by the operation procedure followed by Hirakud Authority. The peak flow at Naraj during the operation by Hirakud authority is more than that of during the operation by the proposed model.

The reservoir storage for each time period obtained from optimization model are compared with recommended variable rule curve for the validation years. Since the deviation above the recommended storage (P_{US}) is given lower penalty, the reservoir storage obtained from the model is always above the recommended storage. This implies that, the reservoir has higher storage after meeting the flood control obligations. However in the drought year (1979) as the inflow into the reservoir is very low, the storage level has gone below the recommended rule curve for certain period. Routed daily flow rate at Naraj obtained from the model for all the three validation years. It can be observed that only for two days in 1994, the flow rate has exceeded the non-damaging flow of 25.5 thousand cumecs. In all other periods the flow at Naraj was maintained below 25.5 thousand cumecs by the model.

4.2 Validation Floods

Eight validation floods as shown in eight block periods (Table-1) were considered for validation. These floods occurred during six different years: Two each in 1973 and 1994, and one each in 1976, 1977, 1980, and 1982. The reservoir is operated once in 24 hours by the proposed LP model for filling during the monsoon period, from 1st July to 1st October. During flood, the reservoir operation is also done once in 12 hours and once in 6 hours along with once in 24 hours to compare the performance of operation at various operation durations. The forecasted data (in the present case, observed flows are considered as forecasted data) for 5 days is used irrespective of frequency of operation. The reservoir storage as per the rule curve in a particular type of year is followed as discussed before. The reservoir operation is done by the proposed model as follows during all the above six years for comparison purpose.

The reservoir is assumed to be at dead storage level on 1st July. The LP model (equation-1 to equation-14) is run once in 24 hours with advance five days data of inflow into the reservoir and d/s catchment contribution. The recommended variable rule curve as per the type of year (drought, normal, or flood) is followed. The release from reservoir for next five days will be obtained by running the LP model. Only the release for first day is implemented. Again, the LP model is run for the next day with the forecasted data of next five days. In this way, operation of reservoir continues up to the first day of any flood duration. During the flood, the release decision is made for next period, where the duration of period is 24 hours, 12 hours, or 6 hours. However, during the flood also the data of advance five days is used by LP model. For example, for 6 hours duration operation, the number of periods that considered in the optimization model is 20. At the end of flood, the water level in reservoir is reached at three different levels for the various durations of operation. After the flood, the reservoir is operated once in 24 hours only with each of these three levels achieved at the end of flood. In this way, the operation is continued till 1st October. The duration of operation is named by the duration of reservoir operation during the flood.

Comparison of performance of the reservoir operation by the proposed LP model with an interval of 24 hours, 12 hours, and 6 hours during the flood and by Hirakud authority is shown in Table-4. The performance is evaluated by peak flow at Naraj during the flood. The peak flow at Naraj obtained by proposed optimization model is less than that obtained by Hirakud authority in eight floods except the validation flood numbers 3 and 8 for all operation durations. For the validation flood number 3, peak flow obtained by proposed model with 24 hours operation duration is 24.76 thousand cumecs, which is more than that obtained by Hirakud authority of 22.93 thousand cumecs. For the validation flood number 8, the peaks obtained are 36.5 and 36.0 thousand cumecs respectively and the difference is quite small. Among the different operation durations, peak flow by 24 hours operation is always more than the peak flow achieved by either 12 or 6 hours operation. The performance of 12 hours and 6 hours operation is not consistant. The peak at Naraj obtained by 6 hours operation is either same or less than that obtained by 12 hours operation during most of the flood (5 validation floods). The time of occurrences of peak flow at Naraj during the floods by each of the models are also shown in Table-4. The time difference of occurrence of peak during the operation by each model differs maximum by one day for flood numbers 2, 5, 6 and it varies from one day to five days for the other floods. In each of the floods, peak flow at Naraj occurs during the flood.

The reservoir is brought to full reservoir level at the end of monsoon season for each of these six years by the reservoir operation with proposed optimization model irrespective of time of operational duration. The reservoir was also actually filled up by the method adopted by Hirakud authority in five years except in 1982 in which it was brought up to 6.329 TMCM. So the optimization model is meeting the performance criteria of filling the reservoir by 1st October for all the flood events.

5. CONCLUSIONS

The real time operation of the Hirakud reservoir is proposed to be done by the LP formulation given by equation-1 to equation-14. The penalties for different components of objective function in LP formulation are determined in the calibration phase. The ratio of penalties $P_{QD} : P_{US} : P_{ROAI} : P_{ROAD} : P_{QI}, P_{LS}, P_{ROEI}, P_{ROED}$ :: 1 : 3 : 1 : 1 : 8 is found suitable during calibration. This ratio of penalties is validated by reservoir operation during 3 years and also for 8 severe floods. The performance during validation phase is quite satisfactory. So this ratio is recommended for future use during reservoir operation.

Among the three operation durations chosen during validation phase, the reservoir operation by 6 hours is preferable for flood control purpose. In all the cases, the performance by 6 hours operation duration is better than that by 24 hours duration.

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Table 1: Data of Severe Floods Among Forty-three Floods form 1972 to 1995 in Ten Days Block Period-Wise.

Duration of block period	1st July - 10th July	11th July - 20th July	21st July - 31th July	1st Aug - 10th Aug	11th Aug - 20th Aug	21st Aug - 31st Aug	1st Sep - 10th Sep	11th Sep - 20th Sep	21st Sep - 30th Sep
Block period No.	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
Duration of occurrence	09/07/73 - 17/07/73	08/07/94 - 19/07/94	20/07/94 - 25/07/94	07/08/77 - 11/08/77	11/08/76 - 18/08/76	30/08/82 - 04/09/82	02/09/73 - 06/09/73	19/09/80 - 30/09/80	No flood during ninth block period
Peak inflow into the reservoir (T. Cumecs)	18.4	25.8	19.8	18.0	21.4	26.9	18.8	37.8	
Peak calculated d/s catchment contribution (T. Cumecs)	16.7	15.9	09.6	10.1	20.6	44.9	12.1	11.3	

Table 2: Parameters of Extended Muskingum Method.

Routing interval (Hours)	Coefficients of extended Muskingum equation				
	C_0^H	C_0^K	C_1^H	C_1^K	C_2
24	0.513	1.138	0.082	-0.092	0.509
12	0.236	0.691	-0.164	-0.180	0.855
06	0.107	0.656	-0.100	-0.436	0.958

Table 3: Comparison of Performance of Reservoir Operation by Hirakud Authority and Proposed Optimization Model for Three Validation Years.

Approach	Performance	Validation Years		
		1979	1984	1994
Proposed optimization (LP) model (24 Hours operation duration)	Reservoir storage on 1st of october (TMCM)	7.197	7.197	7.197
	Peak flow at Naraj during whole monsoon season (T. Cumecs)	12.27	18.68	29.19
Operation by Hirakud authority	Reservoir storage on 1st of October(TMCM)	4.824	6.692	7.197
	Peak flow at Naraj during whole monsoon season (T. Cumecs)	18.9	25.05	30.63

Table 4: Comparison of Performance of Reservoir Operation by Hirakud Authority and Proposed Model for Eight Validation Floods.

Validation flood number.	Duration of flood	Occurrence of peak inflow into the reservoir	Operation model	Performance during flood	
				Peak flow at Naraj (T. Cumecs)	Time of occurrence
1	09/07/73 to 17/07/73	10/07/73 (12 hours)	Hirakud authority	23.60	15/07/73 (00 hours)
			Proposed model (24 Hours)	19.52	16/07/73 (00 hours)
			Proposed model (12 Hours)	18.90	16/07/73 (00 hours)
			Proposed model (06 Hours)	18.53	16/07/73 (06 hours)
2	08/07/94 to 19/07/94	11/07/94 (09 hours)	Hirakud authority	29.03	13/07/94 (18 hours)
			Proposed model (24 Hours)	26.95	14/07/94 (00 hours)
			Proposed model (12 Hours)	26.00	13/07/94 (00 hours)
			Proposed model (06 Hours)	22.15	13/07/94 (06 hours)
3	20/07/94 to 25/07/94	21/07/94 (03 hours)	Hirakud authority	22.93	23/07/94 (09 hours)
			Proposed model (24 Hours)	24.76	20/07/94 (00 hours)
			Proposed model (12 Hours)	16.10	20/07/94 (00 hours)
			Proposed model (06 Hours)	16.30	20/07/94 (00 hours)
4	07/08/77 to 11/08/77	08/08/77 (06 hours)	Hirakud authority	17.80	11/08/77 (21 hours)
			Proposed model (24 Hours)	14.90	09/08/77 (00 hours)
			Proposed model (12 Hours)	13.80	07/08/77 (00 hours)
			Proposed model (06 Hours)	13.80	07/08/77 (00 hours)
5	11/08/76 to 18/08/76	15/08/76 (15 hours)	Hirakud authority	25.90	15/08/76 (00 hours)
			Proposed model (24 Hours)	20.90	15/08/76 (00 hours)
			Proposed model (12 Hours)	17.80	15/08/76 (12 hours)
			Proposed model (06 Hours)	17.60	16/08/76 (00 hours)
6	30/08/82 to 04/09/82	31/08/82 (09 hours)	Hirakud authority	44.90	31/08/82 (15 hours)
			Proposed model (24 Hours)	31.60	31/08/82 (00 hours)
			Proposed model (12 Hours)	27.60	31/08/82 (00 hours)
			Proposed model (06 Hours)	27.70	01/09/82 (00 hours)
7	02/09/73 to 06/09/73	03/09/73 (06 hours)	Hirakud authority	23.43	06/09/73 (18 hours)
			Proposed model (24 Hours)	14.20	06/09/73 (00 hours)
			Proposed model (12 Hours)	13.20	02/09/73 (00 hours)
			Proposed model (06 Hours)	13.20	02/09/73 (00 hours)
8	19/09/80 to 30/09/80	20/09/80 (12 hours)	Hirakud authority	36.00	22/09/80 (05 hours)
			Proposed model (24 Hours)	36.50	20/09/80 (00 hours)
			Proposed model (12 Hours)	33.50	20/09/80 (00 hours)
			Proposed model (06 Hours)	33.70	20/09/80 (18 hours)