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OPTIMAL RESERVOIR OPERATING POLICIES – A STOCHASTIC DYNAMIC PROGRAMMING APPROACH

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Abstract: Efficient reservoir operation is necessary to meet the various water supply requirements. Reservoir operation involves uncertainty which needs to be considered in deriving the reservoir operating policies. Reservoir operating policies are sequences of release decisions across time period as a function of the state of the system. The state of the system is defined by the reservoir storage at the beginning of the time period and inflow during that period. In the present study, Stochastic Dynamic Programming (SDP) model has been developed to derive the optimal operating policy for a single reservoir with multiple objectives. Two objectives have been considered in developing the SDP model. The first objective relates to minimization of deviation of release and the corresponding demand while the second objective deals with minimization of deviation of storage and its target value. In the SDP model reported here, the expected sum of the weighted absolute deviations in respect of the above mentioned objectives is minimized for determining the optimal operating policies. The uncertainty of reservoir inflow is incorporated into the SDP model in the form of transition probabilities of inflow using the concept of Markov chains. The developed model has been solved under three scenarios using three weightage sets to absolute value of the deviations under different demand conditions.

Keywords: Reservoir, Stochastic Dynamic Programming, Markovchains

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INTRODUCTION

Reservoir operation is a continuous decision making process to determine the water level of reservoir and releases from it across time period. It is one of the most challenging tasks in water resource because water resources are limited and fluctuated by nature. A large volume of water may be available during rainy season but there is scarcity of water in the other dry seasons. As such, proper planning and operation need to be done to meet the various water resource demands and requirements. These demands and requirements encompass irrigation, hydropower, flood control, consumptive use, industrial requirements and so on. Optimal policies in respect of reservoir operation in the form of charts, tables etc. are to be given to the operator for implementation.

There is a substantial body of literature for optimization techniques to water resource system planning and operations. A dynamic programming application in water resources was carried out by Yakowitz (1982). Traditional optimization technique including linear programming and dynamic programming has been used in deriving operating policy. Revelle (1999) solved a single reservoir system using linear programming model. Chandramouli and Umamahesh (2003), Trezosand Yeh (1989), Kelman et al. (1990) have considered the inflows as a stochastic process and developed several stochastic models and applied them successfully. Stochastic dynamic programming is widely used in deriving the policy of a single reservoir when inflows are considered as stochastic because it has a much smaller computational effort (including computing time and memory) as compared to stochastic linear programming.

METHODOLOGY:

Stochastic dynamic programming model.

Stochastic dynamic programming is an optimization technique based on Bellman's principle of optimality. It has been widely used in water resource due to its ability to tackle both linear and nonlinear constraints and objective function. To derive the reservoir operating policy using stochastic dynamic model, reservoir capacity and the historical data of inflow should be available. Decision variables such as reservoir storage, inflow and release are discretized into various class intervals to simplify the computation. Each class intervals have a representative value taken as the midpoint of upper and lower bounds. Stages here refer to the monthly time period at which the decisions need to be taken. Storage at the beginning of time period t and inflow during period t are treated as state variables.

Let Q_t represent the inflow into the reservoir in time period t. This Q_t is discretized into various class intervals and any value within that range of class interval is represented by a representative value. Let i and j be the indexes represent the class interval of inflow

in period t and t+1 and let Q_{it} and Q_{jt+1} be their respective representative values.

Similarly for storage, let k be the class interval of storage at the beginning of time period t and l be the class interval of storage at the beginning of time period t+1and let S_{kt} and S_{lt+1}be their representative value.

For the initial storage volume S_{kt}, inflow Q_{it} and final storage volume S_{lt+1} neglecting all loses in time period t, the release R_{kilt} is define by the continuity equation.

$R_{kilt} = S_{kt} + Q_{it} - S_{lt+1.}$

For the next time period, the final storage will become the initial storage and the procedure will repeat for all the remaining time period.

The objective function is minimization of the expected sum of weighted absolute deviation of the release from the demand and the storage from its target value in each time period. Three different scenariosare considered by varying the weightage of release and storage values depending on the various demands.

Model formulation:

A Stochastic optimization model with multiple objectives is developed for identifying the optimal operating policy of a single reservoir.

Minimize: $E\ [W_1|(R_t-D_t)\ |+ W_2|(S_t-T_{st})|\ ]$

Subject to:

$$R_{kilt} = S_{kt} + Q_{it} - S_{lt+1}$$

$$S_{min} \leq S_t \leq S_{max}$$

$$R_{min} \leq R_t \leq R_{max}$$

Where E is the expected sum, R_t is the release in time period t, D_t is the demand in period t, S_t is the storage in period t, T_{st} is the target storage in period t, S_{min} is the dead storage and S_{max} is the capacity, W_1 and W_2 are the weightage factors given for release and storage respectively.

In the first scenario, an equal weightage factors is given to both release and storage where the demand for release consist of only irrigation demand.

In the second scenario, a weightage factor of 0.7 is given for release and 0.3 for storage where the demands for release consist of both hydropower and irrigation demands.

In the third scenario, a weightage factor of 0.8 is given for release and 0.2 for storage where the demand for release consists of drinking water supply as well as hydropower and irrigations requirements.

As mentioned above E refers to the expected value over all time periods. Let F_t^n be the total expected value with n periods to go including the current time period t. Then the backward recursive equation can be expressed as:

$$F_t^n (k,i) = \text{Minimize} \left[E + \sum_j P_{ij}^t f_{t+1}^{n-1} (l,j) \right]$$

Where P_{ij}^t is the probability of inflow Q_{t+1} belong to class interval j in time period t+1 given Q_t belong to i in time period t

Above equation is solved recursively until a steady state solution is reached. The steady state is reached when the expected annual system remain constant for all combination of k, i and t.

$$f_t^{n+T}(k, i) - f_t^{n}(k, i) = \text{constant}$$

Data collection:

Data of 20 years are available having a monthly time periods. The database is divided into 12 time periods considering each month as a time periods. In the present study, the first time periods start from June and end in May. The data has been collected for Srisailam reservoir.

Discretization of storage:

The active storage is discretized into ten class interval in each time period. Associated with each class interval we have a representative value taken as the average of lower and upper bound as shown in the Table 8.

Discretization of inflow:

Discretization of inflow is done based on the historical available data. The flow data available is for 22 years having monthly time periods. Based on the actual value that have been realized in the historical data inflow is discretized into five class interval. Each of the class intervals in a time period t is represented by a particular representative value of the inflows. The representative flow under each class interval is taken to be the average of the lower and upper bounds. The representative flows are given in Table 9.

Transitional probabilities:

The uncertainties of inflow are incorporated into the Stochastic Dynamic Programming (SDP) model using the transitional probabilities of inflows. The transitional probabilities are derived using the assumption of Markov chain.Markov chainis a stochastic process with the property that the value of process Q_t at time t depends on its value t-1 and not on the sequence of other values (Q_{t-2}, Q_{t-3},….. Q_0) that the process passed through in arriving at Q_{t-1} , where Q_t refers to inflow during time period t.

$P\ [Q_t/\ Q_{t-1},\ Q_{t-2}\ldots Q_0) = P[Q_t/Q_{t-1}]$.

Transition probabilities are used to measure the dependence of inflow during period t+1 on the inflow during period t. The transition probabilities P_{ij}^{t} is define as the probability that the inflow in time period t+1 will be in class interval j given that the inflow in period t lies in class interval i.

$P_{ij}^{t} = P\ [Q_{t+1}=j\ /\ Q_t=i]$

The transition probabilities are estimated from the historical data by the Relative Frequency Approach. It is estimated by counting the number of times the generated flows of these two seasons t and t+1 fall within the prescribed class intervals.

It is given by P_{ij}^{t} = (Number of times the flow in season t is in the i^{th} class interval and at the same time the flow in season (t +1) is in the j^{th} interval)/ (Number of times the flow in season t is in i^{th} class interval). In computations when t=12, (t+1) is taken equal to 1.

Typical transition probability matrixes for some months are shown below:

Table1: Transitional Probability Matrix from June to July

0.11	**0.63**	**0.21**	**0.05**	**0**
0.04	0.65	0.27	0.04	0
0.22	0.43	0.35	0	0
0	0.5	0.19	0.12	0.19
0	0.5	0.5	0	0

Table2: Transitional Probability Matrix from July to August

0.3	**0.31**	**0.39**	**0**	**0**
0.09	0.51	0.27	0.1	0.03
0	0.26	0.34	0.13	0.27
0	0.61	0	0.39	0
0	0	1	0	0

Table 3: Transitional Probability Matrix from August to September

0.62	**0.19**	**0.19**	**0**	**0**
0.1	0.57	0.16	0.17	0
0	0.45	0.41	0.05	0.09
0	0.34	0.55	0	0.11
0	0	0.5	0.5	0

Table 4: Transitional Probability Matrix from September to October.

0.52	**0.48**	**0**	**0**	**0**
0.36	0.5	0.11	0	0.03
0	0.52	0.4	0.08	0
0.23	0.51	0.13	0.13	0
0	0.48	0	0.26	0.26

Table 5: Transitional probability matrix from October to November

0.69	**0.31**	**0**	**0**	**0**
0.28	0.56	0.08	0.03	0.05
0.07	0.65	0.14	0.14	0
0	0	1	0	0
0	0	0	0	1

Table 6: Transitional probability matrix from November to December

0.97	**0.03**	**0**	**0**	**0**
0.79	0.15	0.03	0	0.03
0	1	0	0	0
0.22	0.52	0.26	0	0
0	0.23	0	0.77	0

Table 7: Transitional probability matrix from December to January

0.06	**0.65**	**0.25**	**0.02**	**0.02**
0.06	0.08	0.43	0.43	0
0	0	0.23	0	0.77
0	0.5	0	0	0.5
0	0	0	0	1

Table 8: Representative storage during each time period (*acre feet*)

TIME PERIOD/ REPRESENTATIVE STORAGE STATES	1	2	3	4	5	6	7	8	9	10
JUNE	295	405	515	625	735	845	955	1065	1175	1285
JUL	315	465	615	765	915	1065	1215	1365	1515	1665
AUG	330	510	690	870	1050	1230	1410	1590	1770	1950
SEPT	330	510	690	870	1050	1230	1410	1590	1770	1950
OCT	330	510	690	870	1050	1230	1410	1590	1770	1950
NOV	330	510	690	870	1050	1230	1410	1590	1770	1950
DEC	330	510	690	870	1050	1230	1410	1590	1770	1950
JAN	330	510	690	870	1050	1230	1410	1590	1770	1950
FEB	330	510	690	870	1050	1230	1410	1590	1770	1950
MARCH	320	480	640	800	960	1120	1280	1440	1600	1760
APRIL	310	450	590	730	870	1010	1150	1290	1430	1570
MAY	300	420	540	660	780	900	1020	1140	1260	1380

Table 9: Representative inflows during each time period (*acre feet*)

TIMEPERIOD/ REPRESENTATIVE INFLOW STATE	1	2	3	4	5
JUN	80	240	400	560	720
JUL	250	750	1250	1750	2250
AUG	200	600	1000	1400	1800
SEP	85	255	425	595	765
OCT	80	240	400	560	720
NOV	40	120	200	280	360
DEC	35	105	175	245	315
JAN	8	24	40	56	72
FEB	4	12	20	28	36
MAR	3	9	15	21	27
APRIL	3	9	15	21	27
MAY	15	45	75	105	135

Table 10: Scenario 1 Operating policy for the month of August

INFLOW STATE/STORAGE STATE	i=1	i=2	i=3	i=4	i=5
k=1	2	4	6	7	7
k=2	3	5	7	7	7
k=3	4	6	8	7	7
k=4	5	7	8	7	7
k=5	6	8	8	7	7
k=6	7	8	8	7	7
k=7	8	8	8	7	7
k=8	9	8	8	7	7
k=9	9	8	8	7	7
k=10	9	8	8	7	7

Table 11: Scenario 2 Operating policy for the month of August

INFLOW STATE/STORAGE STATE	i=1	i=2	i=3	i=4	i=5
k=1	2	4	6	8	8
k=2	3	5	7	8	8
k=3	4	6	7	8	8
k=4	5	7	8	8	8
k=5	6	7	8	8	8
k=6	7	8	8	8	8
k=7	8	9	8	8	8
k=8	8	9	8	8	8
k=9	9	9	8	8	8
k=10	10	9	8	8	8

Target storage: Target storage for each month is set taking into account the flood water during the monsoon period. Therefore the reservoir is set to its lowest state in the month of June and July to account for flood water and filled to its capacity during the non-monsoon seasons.

RESULT AND DISCUSSION: Stochastic dynamic programming model described above is applied to single reservoir for determining optimal monthly operating rules under three scenarios.

Operation policies have been obtained under the three scenarios. The weight ages used in this study are only for illustrative purpose. The results for a typical month (August) are given for the scenarios 1 and 2 in above Tables 10. And 11respectively.

Results show that the SDP approach can be very useful in determining the optimal reservoir policies. Results are also very much encouraging.

CONCLUSION:

Limited results show that the developed model has the potential to solve real world reservoir problems, particularly relating to operating policies.

The model can also be solved as a stochastic multi-objective dynamic programming problem for determining the Pareto optimal fronts.

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