Jordan Journal of Civil Engineering, Volume **10**, No. **3**, **2016**

Application of Hedging Rules in the Operation of Hydro-Power Reservoirs

Sasireka, K. $^{1)}$ ***and Neelakantan, T.R.*** $^{2)}$

$^{1)}$ Assistant Professor, School of Civil Engineering, Sastra University, Thanjavur 613401, India.
E-Mail: sasireka@civil.sastra.edu
$^{2)}$ Associate Dean (Research) and L&T ECC, Chair Professor, Center for Advanced Research in Environment, School of Civil Engineering, Sastra University, Thanjavur 613401, India.
E-Mail: trneelakantan@civil.sastra.edu

ABSTRACT

The application of hedging rules in reservoir operation has been established as one of the important advances in the field of reservoir operation studies during the past three decades. Hedging rules distribute the deficits over a longer duration to minimize the impact of deficits. Thus, hedging provides the insurance of high-valued water uses, where reservoirs experience uncertain inflows. Formulating different forms of hedging rules and proposing appropriate objective functions that adequately describe the trade-off among the operational performance indicators have been attempted for water supply and irrigation release from reservoirs. Research on hedging rule-based operation of reservoirs for hydro-power generation has not yet gained sufficient attention, probably due to its complexity due to non-linearity. In this study, hedging rules are formulated for Indira Sagar reservoir for hydro-power generation. Discrete phased hedging rule and two-point linear hedging rule are developed and demonstrated in this research. While the two-point linear hedging rule is one of the simple hedging rules, the discrete phased hedging rule is a more realistic rule as it will facilitate better planning of alternative sources of power generation or rationing. The results indicate the advantages of applying the hedging rules over the standard operating policy.

KEYWORDS: Reservoir operation, Hedging rules, Hydro-power generation, Simulation.

INTRODUCTION

Water resources management through reservoir operation plays a key role in economy. Reservoir operation requires operating rules, and hence significant research has been conducted on obtaining the optimal reservoir operating policy (Loucks et al., 1981; Yeh, 1985; Simonovic, 1992; Wurbs, 1993; Labadie, 2004). Standard Operation Policy (SOP) is a simple policy which aims at releasing the entire water demand, if available; if not, release of whatever quantity of water available is carried out and SOP does not consider preserving water for future requirements (Stedinger, 1984). Hedging rules consider the preservation of some water to meet future demands. Hedging increases water stored in a reservoir by accepting some deficit in the current period in order to protect the reservoir against large future deficits. Thus, hedging rules distribute the deficits across time to minimize their impact. The recent research works on hedging policies focused on formulating different forms of hedging rules and proposing appropriate objective functions that adequately describe the trade-off among the operational performance indicators.

Almost all the reported works which used hedging

Received on 23/1/2015.
Accepted for Publication on 7/2/2015.

rules for reservoir operation considered either drinking water demand, irrigation water demand or both together. However, it seems hedging rules were not applied to hydro-power generation reservoirs. Operation of hydro-power generation reservoirs is unique as the power generation is a function of both the head available and quantity of release. In hydro-power operation of reservoirs, instead of fixing the water demand, power demand is fixed and hence water demand is a function of head available. Hence, to suit this situation, the operation policies should be defined in a different manner for hydro-power reservoir operation.

TWO-POINT LINEAR HEDGING RULE

This rule was introduced for reservoir management by Bayazit and Unal (1990) and investigated in detail. The scheme of this rule is shown in Fig. 1. The points *P1* and *P2* in the graph are given by the coordinates ($P1_x$, $P1_y$) and ($P2_x$, $P2_y$), respectively. The point *P1* is referred to as Starting Water Availability, SWA, while *P2* is referred to as Ending Water Availability, EWA. The two-point hedging rule replaces the SOP between these points *P1* and *P2*; and outside this range SOP operates. The x-axis is representing the available water and the y-axis is representing the sum of release towards the demand and spill. D_t is the demand in time-period *t* and *K* is the capacity of the reservoir. The "water availability" is the sum of the initial storage in the reservoir and the expected inflow during the period considered. Srinivasan and Philipose (1996, 1998) and Shiau (2009) defined water availability (available water) as the sum of the initial storage in the reservoir and the inflow during the period minus the evaporation loss during the period. The two-point hedging rule can be mathematically represented as follows:

$$P1_x = aD_t;\ P2_x = bD_t;\ P1_x = P1_y;\ P_{2y} = D_t;$$

$$0 \le a \le 1;\ 1 \le b \le \frac{K + D_t}{D_t} \quad (1a)$$

$$R_t = AW_t\,,\quad if\ AW_t \le P1_x$$

$$R_t = P1_y + \frac{D_t - P1_y}{P2_x - P1_x} \times \left(AW_t - P1_x\right),$$

$$if\ P1_x \le AW_t \le P2_x$$

$$R_t = D_t\,,\quad if\ AW_t \ge P2_x \quad (1b)$$

$$Spill_t = \begin{cases} AW_t - K - D_t\,, & if\ AW_t \ge (K + D_t) \\ 0, & otherwise \end{cases} \quad (1c)$$

When the available water (*AW_t*) falls below *$P1_x$*, the available water in the reservoir is released towards meeting the demand. Hence, the storage of the reservoir at the end of the period will become zero. To adopt this policy, the number of parameters for which the optimal values are to be identified per period is two; namely the points *$P1_x$* and *$P2_x$*. Since *$P1_y$* is equal to *$P1_x$* and *$P2_y$* is equal to the demand, these two values are obvious.

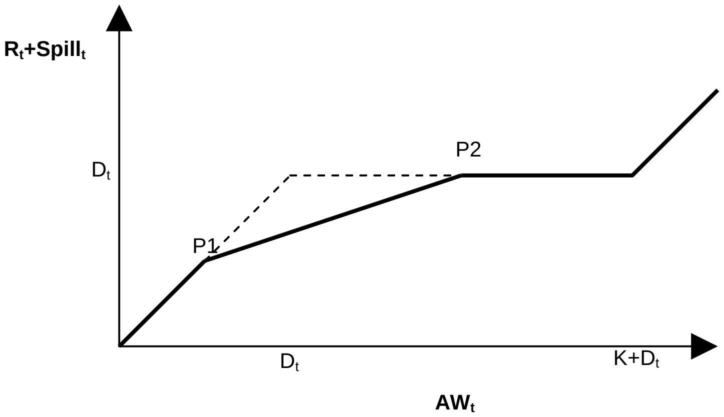

Figure (1): Two-point linear hedging rule for water supply reservoir operation

TWO-POINT LINEAR HEDGING RULE FOR HYDRO-POWER RESERVOIR OPERATION

A quantity of water which is on release produces a situation in which the expected full capacity power is not a fixed quantity, as the head also plays a role. When the head available increases, a smaller quantity of release is sufficient compared to a release when the head is low. Hence, two quantities were worked out and used to control the release through the two different hedging rules used. In type 1, the hedging control parameter *F* is estimated such that if all the *F* quantity of water available in the reservoir is released, maximum power (installed capacity) should be produced. In type 2, the hedging control parameter *F* is estimated such that the quantity of water to be released leads to generate the maximum power (installed capacity) when the head available is assumed equal to the maximum possible head. Thus, the release as per the newly proposed hedging rules can be written as follows.

$$P1_x = aF;\ P2_x = bF;\ P_{2y} = Power\,max;$$
$$0 \le a \le 1;\ 1 \le b \le \frac{K+F}{F} \qquad \text{(2a)}$$

$$R_t = AW_t,\quad if\ AW_t \le P1_x$$
$$R_t = P1_x + \frac{F - P1_x}{P2_x - P1_x} \times \left(AW_t - P1_x\right),$$
$$if\ P1_x \le AW_t \le P2_x$$
$$R_t = F,\quad if\ AW_t \ge P2_x \qquad \text{(2b)}$$

DISCRETE PHASED HEDGING RULE

Neelakantan and Pundarikanthan (1999, 2000) proposed a discrete phased hedging rule (Fig. 2) for drinking water supply reservoir operation. The point *P1* in the graph is given by the coordinates ($P1_x$, $P1_y$). Considered is only the beginning storage *(BS_t)* in period *t* to trigger the hedging. On the y-axis, considered is the 'release target' *(RT_t)*. Thus, the release may not be always equal to the target while attempting to release the target quantity utilizing the current period inflow. The mathematical form of the discrete phased hedging rule is given below. D_t is the demand in time-period *t*.

$$0 \le \alpha_1 \le \alpha_2 \le \alpha_3 \le 1; \qquad \text{(3a)}$$

$$RT_t = \alpha_1 D_t,\quad if\ BS_t \le P1_x$$
$$RT_t = \alpha_2 D_t,\quad if\ P2_x \le BS_t \le P3_x$$
$$RT_t = \alpha_3 D_t,\quad if\ P3_x \le BS_t \le P4_x$$
$$RT_t = D_t,\quad if\ BS_t \ge P4_x \qquad \text{(3b)}$$

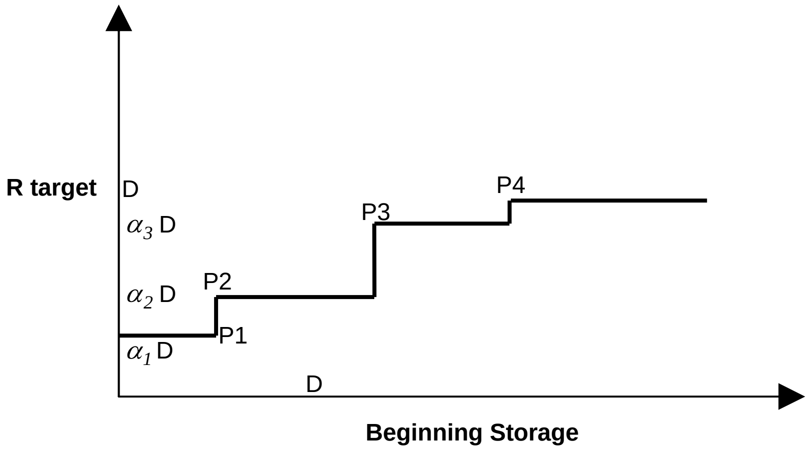

Figure (2): Discrete phased hedging rule of Neelakantan and Pundarikanthan (1999, 2000)

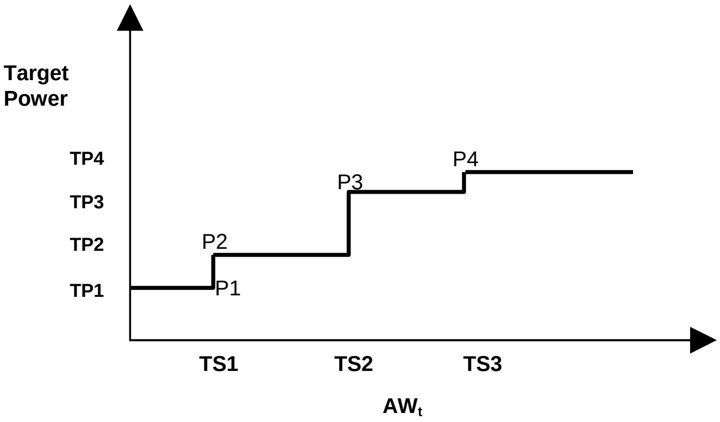

Figure (3): Discrete phased hedging rule for hydro-power reservoir operation

DISCRETE PHASED HEDGING RULE FOR HYDRO-POWER RESERVOIR OPERATION

In the present work, the above hedging rule was modified for hydro-power reservoir operation as follows (see Fig. 3). As the water release is expected to be more or less uniform in drinking water supply reservoir operation, power generation is to be uniform in hydro-power generation operation. Hydro-power generation plants usually have a number of turbines. When the quantity of water release is not sufficient to operate all the turbines at their maximum efficiency, it is logical to operate few of them at their maximum efficiency. For example, if there are 8 turbines, and the quantity released is small, an option of operating 3 turbines at their maximum efficiency is preferred rather than operating all the 8 turbines at low efficiencies. This practical operational preference is brought in the modified policy.

On the x-axis, available storage is the sum of the initial storage in the reservoir and the expected inflow during the period considered. Instead of fixing the water release quantity as target, power to be generated is fixed as target as TP1, TP2, TP3 and TP4 are based on the available storage values.

$$\begin{aligned} TP_t &= TP1, \quad if\ \mathrm{AW}_t \le P1_x \\ TP_t &= TP2, \quad if\ \mathrm{P2}_\mathrm{x} \le AW_t \le P3_x \\ TP_t &= TP3, \quad if\ P3_x \le AW_t \le P4_x \\ TP_t &= TP4, \quad if\ AW_t \ge P4_x \end{aligned} \tag{4}$$

Once the target power is known, the target for water release can be estimated from the equation $P = \gamma QH$, where P is power, γ is the unit weight of water and H is the head available. If sufficient water is available, the target has to be met; if not, the available quantity is to be released.

INDIRA SAGAR RESERVOIR

The newly formulated hedging rules for hydro-power reservoir operation were used for the simulation of the operation of Indira Sagar reservoir in India and analyzed. River Narmada has its origin near Amarkantak village in Madhya Pradesh at an elevation of 1065 m above mean sea level in Maikala hills of central India. It is the fifth longest river and the biggest west-flowing river in India. Indira Sagar reservoir is constructed across the river Narmada and is located at 22º17’00” N and 76º 28’00” E. The capacity of the reservoir at its full capacity level of 262.13 m is 12,212 million m^3, whereas at its minimum drawdown level of 237.70 m the storage capacity is 1357 million m^3. The tail water level at the power house is at 196.6 meters. The major purpose of the reservoir is hydro-power generation. The capacity of the power plant is 1000 MW. It consists of eight power generating turbines, each with a capacity of 125 MW.

SIMULATION MODEL

Monthly historical inflows into the Indira Sagar reservoir were collected for 32 years from the period 1948 to 1980. A monthly simulation that uses the mass balance principle was developed. The evaporation from the reservoir was estimated using the storage-water spread area relationship. The hydro-power generation was estimated using the equation $P = \gamma QH$. In a monthly step, both the head corresponding to the beginning storage and the head corresponding to the final storage were worked out and the average was used in the equation for power generation. For a given power target, the head was initially arbitrarily assumed and Q is estimated. When the quantity of water Q was released resulting in a final storage, the corresponding head was estimated. Thus, the estimated average head may not match the assumed value. Hence, the head was adjusted iteratively till convergence. The efficiency of the turbines was taken as 0.85. The objective of the study is applying hedging rules to minimize severe shortages in power production for the hydro-power reservoir. A monthly time step was used in the simulation of the reservoir operation.

RESULTS AND DISCUSSION

The results of different hedging rules were compared using simple performance indicators, such as average power produced, average spill experienced, standard deviation of power production and number of months in which the power production has gone below 125 MW. In the reservoir operation using two-point linear hedging rule, for type 1 policy, *F* was estimated as 6750.92 million m^3 and for type 2 policy, *F* was estimated as 5225.8 million m^3.The parameters *a* and *b* (refer to Equation 2a) were varied and the results obtained for each set of *a* and *b* values were analyzed. Values used for *a* were 0 to 1 in steps of 0.1 and values used for *b* were 1.0, 1.5, 2.0, 2.5 and 2.81 (for type 1) and 1.0, 1.5, 2.0, 2.5, 3.0 and 3.34 (for type 2).

For type 1 policy, for a value of (a, b) = (0.0, 2.81), the average power production is maximum (396.79 MW). The minimum standard deviation (295.90 MW) of power production occurred at (a, b) = (0.1, 2.81). Average spill was minimum (88.29 million m^3 per month) at a = 1 and was not varying with respect to b. For type 2 policy, for (a, b) = (0.0,3.34), the average power production is maximum (399.7 MW). The minimum standard deviation (267.39 MW) of power production occurred at (a, b) = (0.1, 3.34). Average spill was minimum (130.4 million m^3) at a = 1 and was not varying with respect to b. The average power production values obtained for different values of a and b for type 1 policy and type 2 policy are presented in Tables 1 and 2, respectively.

The reliability of the system (Srinivasan et al., 1999) is defined by an indicator as follows:

$$v = 1 - \frac{m}{n}; \qquad (5)$$

where *v* is the reliability, m is the number of months in which the power production is less than 125 MW (power production from one turbine) and n is the total number of months of operation. In the present case, n is the 32x12 = 384. The reliability values obtained for different values of a and b for type 1 policy and type 2 policy are presented in Tables 3 and 4, respectively.

Tables 3 and 4 indicate that the performance was good at highest ‘b’ value and lowest ‘a’ value. This indicates that the rationing of water should begin at the lowest level of storage and that rationing should continue even during the high storage conditions in order to increase the performance.

In the analysis with discrete phased hedging rule, two cases were considered. In case 1, the target power values TP1, TP2, TP3 and TP4 (refer to Eqn. 4 and Fig. 3) were taken as 125, 250, 500 and 1000 MW, respectively. In case 2, the target power values TP1, TP2, TP3 and TP4 were taken as 125, 375, 625 and 1000 MW, respectively. For various TS1, TS2 and TS3 values, the performance of the system was evaluated and the results are tabulated in Tables 5 and 6. These two tables show that lower average power production reduces the risk of low reliability and that there exists a trade-off between power production and reliability.

Comparison between two-point hedging and phased discrete hedging rules for hydro-power reservoirs indicates that two-point hedging rule is slightly better in terms of average power production; however, phased discrete hedging rule outperforms two-point heding rule in terms of reliability.

Table 1. Average power production (MW) for various a and b values using type 1 policy

a b	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
1.00	354.64	354.64	354.641	354.64	354.64	354.64	354.64	354.64	354.641	354.64	354.64
1.50	374.94	371.49	368.514	366.11	364.08	362.39	360.79	359.11	357.532	356.19	354.64
2.00	386.78	381.28	376.596	373.01	369.92	367.15	364.7	361.98	359.467	357.2	354.64
2.50	393.96	387.56	381.352	376.68	372.85	369.49	366.54	363.3	360.377	357.66	354.64
2.81	396.79	390.36	383.506	378.35	374.15	370.45	367.22	363.78	360.693	357.79	354.64

Table 2. Average power production (MW) for various a and b values using type 2 policy

a b	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
1.0	362.55	362.55	362.55	362.55	362.55	362.55	362.55	362.55	362.55	362.55	362.55
1.5	377.22	375.03	372.80	370.32	368.95	367.79	366.79	365.86	364.87	363.71	362.55
2.0	386.74	382.92	379.09	376.06	373.06	371.16	369.37	367.53	365.99	364.27	362.55
2.5	393.40	389.16	384.08	380.33	376.79	374.23	371.88	369.57	367.04	364.83	362.55
3.0	398.26	393.81	388.02	383.49	379.86	376.51	373.83	371.22	368.16	365.34	362.55
3.34	399.69	395.86	390.12	384.98	381.00	377.44	374.55	371.87	368.55	365.52	362.55

Table 3. Reliability for various a and b values using type 1 policy

a b	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
1.00	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53
1.50	0.65	0.65	0.63	0.58	0.56	0.56	0.55	0.55	0.54	0.54	0.53
2.00	0.73	0.72	0.68	0.62	0.59	0.56	0.56	0.55	0.55	0.54	0.53
2.50	0.80	0.79	0.74	0.66	0.60	0.57	0.56	0.55	0.55	0.54	0.53
2.81	0.84	0.83	0.77	0.68	0.61	0.58	0.56	0.55	0.55	0.54	0.53

Table 4. Reliability for various a and b values using type 2 policy

a b	0.00	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00
1.00	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56
1.50	0.65	0.66	0.66	0.62	0.59	0.58	0.57	0.56	0.56	0.56	0.56
2.00	0.73	0.73	0.73	0.68	0.63	0.60	0.59	0.57	0.56	0.56	0.56
2.50	0.80	0.79	0.80	0.72	0.67	0.61	0.59	0.58	0.56	0.56	0.56
3.00	0.85	0.86	0.86	0.76	0.69	0.65	0.60	0.59	0.57	0.56	0.56
3.34	0.89	0.89	0.89	0.80	0.71	0.66	0.61	0.59	0.57	0.56	0.56

Table 5. Performance of reservoir operation for case 1 of discrete phased hedging rule

TS1	TS2	TS3	Average Power Production (MW)	Standard Deviation of Power Production	Average Spill (million m^3)	Reliability
1000	3000	5000	384.55	371.34	659.83	0.35
2000	4000	6000	381.91	368.72	717.45	0.26
3000	5000	7000	382.69	356.63	741.66	0.09
5000	7000	9000	369.47	324.36	865.41	0.01

Table 6. Performance of reservoir operation for case 2 of discrete phased hedging rule

TS1	TS2	TS3	Average Power Production (MW)	Standard Deviation of Power Production	Average Spill (million m^3)	Reliability
1000	3000	5000	384.48	365.05	616.18	0.38
2000	4000	6000	383.91	372.3	690.10	0.31
3000	5000	7000	383.12	360.39	727.08	0.16
5000	7000	9000	375.19	334.62	828.45	0.02

CONCLUSION

Hedging rules have been in use for water supply reservoir operation for the past few decades. Hedging rules for hydro-power reservoir operation were attempted in this study. Two-point linear hedging and discrete phased hedging rules were modified to suit the hydro-power reservoir operation and were applied to the operation of Indira Sagar reservoir. The present study indicates that hedging-based operation of hydro-power reservoirs is possible. In this parametric study, only limited discrete values for the parameters were considered and a limited number of performance indicators were used. Further research is required to explore the selection of performance indicators.

REFERENCES

Bayazit, M., and Unal, E. (1990). “Effects of hedging on reservoir performance”. Water Resour. Res., 26 (4), 713-719.

Labadie, J.W. (2004). “Optimal operation of multi-reservoir systems: state-of-the-art review”. J. Water Resour. Plan. Manag., 130 (2), 93-111.

Loucks, D.P., Stedinger, J.R., and Haith, D.A. (1981). Water resources system planning and analysis". Prentice-Hall, Englewood Cliffs, NJ, USA.

Neelakantan, T.R., and Pundarikanthan, N.V. (1999). "Hedging rule optimization for water supply reservoir systems". Water Resour. Manag., 13 (6), 409-426.

Neelakantan, T.R., and Pundarikanthan, N.V. (2000). "Neural network-based simulation-optimization model for reservoir operation”. J. Water. Resour. Plan. Manag., 126 (2), 57-64.

Shiau, J.T. (2009). “Optimization of reservoir hedging rules using multi-objective genetic algorithm”. J. Water Resour. Plan. Manag., 135 (5), 355-363.

Simonovic, S.P. (1992). “Reservoir system analysis: closing gap between theory and practice”. J. Water Resour. Plan. Manag., 118 (3), 262-280.

Srinivasan, K., Neelakantan, T.R., Narayan, P.S., and Nagarajukumar, C. (1999) "Mixed-integer programming model for reservoir performance optimization". J. Water Resour. Plan. Manag., 125 (5), 298-301.

Srinivasan, K., and Philipose, M.C. (1996). “Evaluation and selection of hedging policies using stochastic reservoir simulation”. Water Resour. Manag., 10 (3), 163-188.

Srinivasan, K., and Philipose, M.C. (1998) “Effect of hedging on over-year reservoir performance”. Water Resour. Manag., 12 (2), 95-120.

Stedinger, J.R. (1984). “Performance of LDR models for preliminary design and reservoir operation”. Water Resour. Res., 20 (2), 215-224.

Wurbs, R. (1993). “Reservoir-system simulation and optimization models”. J. Water Resour. Plan. Manag., 119 (4), 455-472.

Yeh, W.W.G. (1985). “Reservoir management and operation models: a state-of-the-art review”. Water Resour. Res., 21 (12), 1797-1818.