Assessing Performance of Multipurpose Reservoir System Using Two-Point Linear Hedging Rule

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Abstract. Reservoir operation is one of the important filed of water resource management. Innovative techniques in water resource management are focussed at optimizing the available water and in decreasing the environmental impact of water utilization on the natural environment. In the operation of multi reservoir system, efficient regulation of the release to satisfy the demand for various purpose like domestic, irrigation and hydropower can lead to increase the benefit from the reservoir as well as significantly reduces the damage due to floods. Hedging rule is one of the emerging techniques in reservoir operation, which reduce the severity of drought by accepting number of smaller shortages. The key objective of this paper is to maximize the minimum power production and improve the reliability of water supply for municipal and irrigation purpose by using hedging rule. In this paper, Type II two-point linear hedging rule is attempted to improve the operation of Bargi reservoir in the Narmada basin in India. The results obtained from simulation of hedging rule is compared with results from Standard Operating Policy, the result shows that the application of hedging rule significantly improved the reliability of water supply and reliability of irrigation release and firm power production.

Keywords: Type II two-point linear hedging rule, reservoir operation, Standard Operating Policy.

1. Introduction
Reservoir operation studies aim for reliable supply of water for various uses like municipal requirements, irrigation requirements, hydropower generation requirements, flood control, and recreation storage requirements in the reservoir. A planning model can help to make decisions like fixing the reservoir size, maximum demand, and changing the cropping pattern. Depending upon the situations, several operating policies are used. In planning model, Standard Operating Policy (SOP) is considered as the one of the simplest policy, which plans to release a amount of water equal to the water demand, if possible [1]. The reservoir operation using hedging rules has been established as one of the important advances in the field of reservoir operation during the past three decades. SOP increase the single period severe deficit but hedging rule minimize the impact of deficits by distributing the deficit over a longer duration. The literature concering reservoir operation extensively demonstrated and detailed literature reviews were provided by [2-5]. In the case of hydropower reservoir, the water demand is not constant, but the power demand is constant. Hence by considering nonlinearity of head (H) and flowrate (Q) in power equation \( P \propto QH \), new form of SOPp is introduced by [6]. Sasireka et al [7] demonstrated two point linear hedging rule and discrete phased
hedging rule for hydropower reservoir operation with a case study. In this paper, Type II two point linear hedging rule is applied for Bargi reservoir for hydropower generation.

1.1 Type II Two-point Linear hedging rule
Shiau [8] in his paper depicted about reserve-storage based two-point hedging rule, which is represented as ‘type II two-point hedging rule’ (Figure 1). When the available water is less than $P_1$, there is no reservoir release as per this rule and the available water is stored as reserve for the next period. Ramakrishnan [9] studied a multipurpose reservoir system in which a similar rule was adopted for irrigation supply. During severe drought water will be preserved for future drinking water supply, a higher priority water use, and will not be released for irrigation requirement in the current period. This hedging rule may suit such irrigation water releases that are controlled by drinking water reserves. In Figure 1, $(P_1, P_1)$ referred as Starting Available Storage, SAS and $(P_2, P_2)$ referred as Ending Available Storage, EAS. The $x$-axis is representing 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 “Available Storage (AS)” is the sum of the initial storage in the reservoir and the expected inflow during the period considered minus evaporation losses.

![Figure 1. Type II two-point linear hedging rule.](image)

The Type II two-point hedging rule can be mathematically represented as follows.

$$P_1 = aD_t; \quad P_2 = bD_t; \quad P_1 = 0; \quad P_2 = D_t; \quad 0 \leq a \leq 1; \quad 1 \leq b \leq \frac{K + D_t}{D_t}$$

(1a)

$$R_t = 0, \quad \text{if } AS_t \leq P_1$$

$$R_t = P_1 + \frac{D_t - P_1}{P_2 - P_1} \times (AS_t - P_1), \quad \text{if } P_1 \leq AS_t \leq P_2$$

$$R_t = D_t, \quad \text{if } AS_t \geq P_2$$

(1b)

$$\text{Spill}_t = \begin{cases} AS_t - K - D_t, & \text{if } AS_t \geq (K + D_t) \\ 0, & \text{otherwise} \end{cases}$$

(1c)

When the available Storage ($AS$) falls below $P_1$, the available water has been kept as storage to meet the future demand. To adopt this policy, the number of parameters for which the optimal values are to be identified per period is two, namely the points $P_1$ and $P_2$. 


1.2 Modified Type II Two-Point Linear Hedging Rule For Hydropower Reservoir Operation

In hydropower reservoir operation water release is not a fixed quantity, hence when the head available is more, a smaller quantity of release is sufficient compared to a release when the head is low. In water supply reservoir operation water demand is constant and it is considered as a control parameter for hedging rule. However in case of hydropower reservoir operation the power demand is constant but water demand is continuously varying due to change in head, hence, two quantities like release at maximum capacity of reservoir and minimum release to produce firm power were worked and used as a control parameter. In Model-1, the hedging control parameter $C_P$ is estimated such that if all the $C_P$ quantity of water available in the reservoir is released that should produce the firm power. In Model-2, the hedging control parameter $C_P$ is estimated such that it is quantity of water to be released to generate the firm power when the head available is assumed equal to the maximum possible head. Thus, the release as per the modified Type II two-point hedging rules can be written as follows.

\[ P_{1_x} = aC_P, \quad P_{2_x} = bC_P, \quad P_{x,y} = \text{Power max}; \quad 0 \leq a \leq 1; \quad 1 \leq b \leq \frac{K + C_P}{C_P} \quad (2a) \]

\[ R_t = 0, \quad \text{if } AS_t \leq P_{1_x} \]

\[ R_t = P_{1_x} + \frac{C_P - P_{1_x}}{P_{2_x} - P_{1_x}} \times (AS_t - P_{1_x}), \quad \text{if } P_{1_x} \leq AS_t \leq P_{2_x} \]

\[ R_t = C_P, \quad \text{if } AS_t \geq P_{2_x} \quad (2b) \]

2. Study Area

Bargi reservoir in India constructed across the river Narmada, Madhya Pradesh is selected as a study area for demonstrating simulation of modified Type II two-point linear hedging rule. The latitude and longitude of the dam is 22°56.5’N and 79°55.5’E respectively. This reservoir is a multipurpose reservoir, it serves water supply for domestic and industrial purposes, irrigation and the generation of hydropower. Presently, one left bank canal system which consists of two units of capacity of 45 MW each are operational.

| Month | Mean Inflow (10^6 m³) | Mean Evaporation rate (cm/month) | Irrigation Demand (10^6 m³) | Hydropower demand (M kWh) |
|-------|-----------------------|-------------------------------|-----------------------------|--------------------------|
| Jun.  | 146.7                 | 19.8                          | 55.9                        | 20                       |
| July  | 1568.8                | 11.4                          | 192.5                       | 40                       |
| Aug.  | 3038.1                | 10.0                          | 69.3                        | 60                       |
| Sep.  | 1500.7                | 10.8                          | 240.0                       | 60                       |
| Oct.  | 433.1                 | 7.8                           | 435.9                       | 60                       |
| Nov.  | 120.5                 | 6.0                           | 191.0                       | 30                       |
| Dec.  | 81.2                  | 7.8                           | 274.7                       | 30                       |
| Jan.  | 56.9                  | 6.8                           | 322.7                       | 20                       |
| Feb.  | 41.1                  | 6.9                           | 200.4                       | 20                       |
| Mar.  | 25.0                  | 12.6                          | 79.2                        | 20                       |
| Apr.  | 12.5                  | 17.7                          | 53.4                        | 20                       |
| May.  | 7.3                   | 23.9                          | 76.9                        | 20                       |
The monthly water demand from the reservoir through the left bank canal for domestic water supply is $4.5 \times 10^6$ m$^3$. The annual water demand from the reservoir for irrigation is $2.1601 \times 10^8$ m$^3$ and annual firm energy demand of the reservoir is 363 MkWh. Table 1 shows the mean inflow, evaporation rate and demand in the reservoir. Reservoir capacity and storage levels are given in Table 2. In this study, 475 numbers of monthly data from June 1951 to December 1990 was used for demonstration of hedging rule.

| Table 2. Storage capacity and reservoir level of Bargi reservoir |
|---------------------------------------------------------------|
| **Storage capacity (10$^6$ m$^3$)** | **Reservoir level (m)** |
| Gross | Live | Dead | Maximum | Full | Dead storage |
|-------|------|------|---------|------|--------------|
| 3920  | 3180 | 704  | 425.7   | 422.76| 403.55       |

3. Methodology

Simulation is a mathematical technique which is used in this study, to compare the performance of reservoir using hedging rule with standard operating policy. Bargi reservoir is a multipurpose reservoir hence water release is made as per the order of priority as follows: municipal water supply, irrigation and hydropower production. Water supply for municipal and irrigation purpose is done based on SOP, shown in figure 2. The continuity equation used for simulation model is given below

$S_{mon} = S_{max} + I_{mon} - I_{mon} - Spill_{mon} \forall_{mon}$

where, $R_{mon}$ is the release made for municipal and irrigation requirement and power generation, $I_{mon}$ is the reservoir inflow and $Evp_{mon}$ is monthly evaporation volume, which is calculated from the water spread area (WSA) multiplied by the rate of evaporation. The WSA equation is given below

$WSA = (-8 \times 10^{-6} \times S^2) + (0.113 \times S - 39.854)$

where $S$ = (Beginning storage + End storage)/2.

Hydropower release is made as per the Standard Operating Policy for power (SOP$_P$) [3]. In figure 3, $S$ represents the release corresponding to the firm power, $R_c$ represents release corresponding to maximum capacity of the reservoir. From $P_1$ to $P_2$ the curve is falling curve due to increasing of head, hence to calculate the varying flow rate between these points a equation is arrived with help of dam data using curve fit.

Table 1 shows that the minimum power required for all the month in Bargi reservoir are 20 MkWh. Hence in this study, simulation is attempted to maximize the minimum power of 20 MkWh. In
simulation of type II two-point hedging rule, the control parameter ($C_p$) corresponding to minimum release, in Model-I is $406.53 \times 10^6$ m$^3$ and for release corresponding to maximum capacity in Model-II is $255 \times 10^6$ m$^3$ which is obtained from the power equation $P=\eta \gamma QH$ (where $P$ - Power in MW, $\eta$ - Efficiency of the turbine (60%), $\gamma$ - unit weight of water Q – Flow rate in $10^6$ m$^3$ and H – Operating head). By varying the coefficients (‘a’ and ‘b’) in both the model, the best performance of the reservoir is identified. Both the Models the coefficient ‘a’ varies from 0.1 to 1. In Model-I ‘b’ varies from 1 to 10.65, and Model-II it varies from 1 to 16.39.

4. Results and Discussion

The performance of the reservoir has been identified by using different performance indices namely, average power production, average spill, reliability of release for various purposes and number of times zero power produced. The reliability of the system [11] given as follows.

$$\text{Reliability of the system} = \frac{\text{Number of target release achieved (success)}}{\text{Total No of Operating Period}}$$

(5)

Table 3 shows the comparison of simulation of SOP results with best results obtained from type II hedging rule by both the model. The coefficient (a,b) at which the best results are obtained are also given in table 3. For average power production and considering spill Model-I perform better compared to Model-II and SOP. Maximum average irrigation release is better in both the Model compared to simulation of SOP. For remaining all other performance Model-II showed better results compared to Model-I and SOP.

| Performance Indices                          | Model-I Values | Coefficients | Model-II Values | Coefficients | Simulation using SOP & SOP$_p$ |
|---------------------------------------------|----------------|--------------|-----------------|--------------|-------------------------------|
| Maximum average power production (MW)       | 25.51          | 0.1, 1       | 22.03           | 0.1, 1       | 22.94                         |
| Minimum average Spill ($10^6$m$^3$)         | 119.9          | 0.1, 1       | 160.88          | 0.1, 1       | 147.66                        |
| Maximum average irrigation release ($10^6$m$^3$) | 183.04        | 0.8 – 1, 10.65 | 183.04          | 0.1-1, 13-16.39 | 173.38                |
| Maximum Reliability of Firm power (%)       | 12.84          | 1, 10.65     | 15.16           | 0.5-1, 16.39 | 10.95                         |
| Maximum Reliability of target irrigation release(%) | 100           | 0.9 -1, 10.65 | 100             | 0.1-1, 16.39 | 90.53                         |
| Maximum Reliability of municipal water supply (%) | 100           | 0.5-1, 10.65 | 100             | 0.1-1, 16.39 | 97.05                         |
| Minimum No. of times zero power produced    | 8              | 0.2, 0.3, 10.65 | 0               | 0.1-0.6, 0.1-1, 15, 16.39 | 45.00                 |
There is a trade-off between average power production and reliability of water supply for municipal, irrigation and hydropower production. The average power production decreases with increasing of coefficient but it is reverse in the case of reliability water supply for the above mentioned purposes. The most important aim of the hedging rule is to reduce the severity of drought that is continuous drought by accepting number of smaller droughts. By applying hedging rule it is observed the there is no zero power production in the Model-II and only 8 numbers of zero power production in Model-I and it is more about 45 numbers of zero power production when the reservoir is operated with SOP.

| Results from Model-I                                      | Results from Model-II                                      |
|-----------------------------------------------------------|-----------------------------------------------------------|
| ![Average Power Production (10^6 m^3)]                   | ![Average Power Production (10^6 m^3)]                   |
| ![Average irrigation release (10^6 m^3)]                 | ![Average irrigation release (10^6 m^3)]                 |
| ![Average spill (10^6 m^3)]                              | ![Average spill (10^6 m^3)]                              |

| Coefficient 'b'  |
|------------------|
| 0.1              |
| 0.2              |
| 0.3              |
| 0.4              |
| 0.5              |
| 0.6              |
| 0.7              |
| 0.8              |
| 0.9              |
| 1                |

| Coefficient 'b'  |
|------------------|
| 0.1              |
| 0.2              |
| 0.3              |
| 0.4              |
| 0.5              |
| 0.6              |
| 0.7              |
| 0.8              |
| 0.9              |
| 1                |
Reliability of target power produced (%)

Reliability of target power produced (%)

Reliability of Target irrigation release (%)

Reliability of Target irrigation release (%)

Reliability of water supply (%)

Reliability of water supply (%)

Figure 4. Performance of reservoir using type II two-point linear hedging by Model-I and Model-II.

The performance of the reservoir operation using type II two-point linear hedging rule by varying the values of coefficient (a=0.1 to 1, b=1 to 10.65) for Model-I and (a= 0.1 to 1, b= 1 to 16.39) for Model-II are shown as a contour plot in Figure 4. Figure 4 is helpful for choosing the alternative reservoir operation rule to get maximum benefit from the reservoir.

5. Conclusion
Application of hedging rule for hydropower operation is considered as a new research area in the field of water resource management. Hence in this paper one of the simplest ‘type II two-point hedging rule’ is used for hydropower release of a multipurpose reservoir as case study to identify the performance of the reservoir. The results show that the water supply for municipal and irrigation is satisfied with 100% reliability using hedging rule but it is 97.05% and 90.53% respectively using SOP.
The overall performance shows that the type II two-point hedging rule perform well compared to Standard Operating Policy.

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