Review of Hedging Rules Applied to Reservoir Operation

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Abstract - The application of hedging rules in reservoir operation is one of the important advances in the field of reservoir operation studies during the past three decades. The objectives of this paper are (a) to provide a comprehensive review of the different type of hedging models, and (b) to provide some directions for future research. The models are compared from a general perspective and suitability for practical applications. This review paper is expected to provide a quick and improved understanding with criticism of the different hedging rules and their implications in decision support.

Keywords: Reservoir operation, hedging rule, reservoir performance, drought management

I. INTRODUCTION

Reservoir operation study is an important field of water resources management as this has a direct bearing on the economy of a region. Hence, it is important to operate the reservoirs efficiently not only during normal operating conditions but also during extreme situations like droughts. The reservoir operation requires certain operating policy or operating rules in order to achieve the stated objectives. However, arriving at the best set of operation rules or the optimal operation policy that would satisfy the specified objectives has been a challenging task. Significant amount of research has been conducted on this subject of obtaining the optimal operating policy for single and multi-reservoirs serving single or multiple purposes, over the last four decades and detailed literature reviews have been provided by Yeh [1], Wurbs [2] and Labadie [3] in which various mathematical programming formulations and solution techniques have been discussed in detail. Standard Operation Policy (SOP) is the most simple policy which aims to release the entire water demand, if available; if not, release whatever quantity is available. This means that this policy does not consider preserving water for future requirements. This policy is represented in the graphical form in Fig. 1. The SOP is the optimal operating policy if the objective is to minimize the total deficit over the operation horizon considered. However, this policy lacks flexibility and is not suited for reservoir operation during drought periods or when the drought is impending, since it is likely to increase the maximum single period deficit (vulnerability). On the other hand, the hedging rule is suitable for drought conditions, as this rule considers the preservation of some water to meet the future demands in addition to the current release requirements. Hedging increases water stored in the reservoir by accepting small current deficits to guard against unacceptable large deficits that are likely to occur in future. Hedging rule distributes the deficits in water supply across time to minimize the impact of drought.

During a drought, a hedging rule is to be implemented by the operator of the reservoir. Hence, a set of hedging rules is to be developed and given to the operator and the rules should be simple such that the operator should feel comfortable. In the case of drinking or irrigation water supply during drought, the rationing needs to be publicized to the end-users of water and hence, it is desirable that the hedging rules be essentially simple in form. The research works reported in the last few decades on hedging operations primarily focus on formulating different forms of hedging rules. A few research works in the last decade have focused on obtaining the optimal hedging rule to be adopted during droughts that identifies “when to hedge” and “how much to hedge”. Considerable interest has developed in the analytical exploration of the optimal hedging concept, based on a simple economic interpretation given by Draper and Lund [4]. Further, the importance of improving the reliability of the inflow forecasts is being sensed. Better hedging decisions and water management during droughts can be achieved by integrating hedging triggers such as drought indices and economic information into hedging rules and through the application of the improvised long-lead streamflow forecasts.

An attempt is made in this paper to review the various research works carried out on water supply reservoir hedging during the last few decades and suggest the directions for future research. The emphasis of the review will be on discussion of the various reservoir hedging rules proposed in the water resources management literature, examine the implications, advantages and limitations of each hedging rule; reviewing a few recent analytical studies as well as optimal hedging operation based studies that deal with reservoir hedging; and providing future research directions.

II. HEDGING RULES

The hedging concept in water resources was drawn from the natural resource economics and finance sector where it is used often. In 1982, Hashimoto et al. [5] showed that the hedging rules were more appropriate when the loss function was non-linear. Since it is difficult to arrive at estimates of the economic and social benefits in many cases of reservoir operation, surrogate reliability measures were used to evaluate the operation. It is known that a single period severe shortage effects more damage than a few smaller shortages spread in time which amounts to the same shortage when added [6]. Effects of hedging with an explicit demand-management policy based operation of reservoir using the hedging rule were first studied by Bayazit and Unal [7] through stochastic simulation analysis and were further extended by Srinivasan and Philipose [8],[9]. Optimization of a hedging rule for a water supply reservoir was demonstrated by Shih and ReVelle [10],[11]. After 1995, a number of researchers worked on hedging based reservoir operation, which indicates the general acceptance of hedging rule in drought-prone reservoir operation. In the past three decades, many different forms of hedging rules were developed. Hence, depending on the requirement, options are available to choose a hedging rule of sufficient complexity. Understanding the implications of these rules is essential for the efficient operation of the reservoirs, especially during droughts. This section provides the details of the following forms of the hedging rules.

Two-point linear hedging rule was introduced for reservoir management by Bayazit and Unal [7] and investigated in detail. The scheme is shown in Fig. 2. 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 as Starting Water Availability, SWA, and *P2* 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 available water (sum of the initial storage in the reservoir and the expected inflow during the period) 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. 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 demand, the values of these two values are obvious. Further, the inflow of the current period is assumed known. In real-time management problems, a forecast model is also required, using which the inflow for the current period or periods ahead are to be forecasted and used in hedging. It is a known fact that no forecast model can be 100% efficient. That is, during the derivation of optimal hedging parameters ($P1_x$ and $P2_x$), using the historical data, the inflows are assumed known (otherwise, known as perfect forecast). Hence, when the above rule is adopted for real-time operation of the reservoir, a good forecast model is required to forecast the likely inflows during the current period/ or a few subsequent periods accurately.

One point hedging rule (Fig. 3) was highlighted by Shih and ReVelle [10]. This is a special case of two-point hedging rule. When the starting point P1 of two-point hedging rule is the origin, the two-point linear hedging rule reduces to the one-point hedging. In the SOP, for the segment $AW_t \leq D_t$, the release is represented by a 45-degree line (slope equal to 1.0) in the rule graph. However, in the one-point hedging rule, the line is having a slope of less than 1.0 until $AW_t = P1_x$.

Reserve-storage based two-point hedging rule was reported by Shiau [12] as another special type of two-point hedging rule, which he named as 'type II two-point hedging rule' (Fig. 4). When the water availability is less than $P1_x$, no release is made by this rule and that availability is stored as reserve for the next period. Ramakrishnan [13] 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.

Srinivasan and Philipose [9] modified the two-point hedging rule and presented the three-point linear hedging rule (Fig. 5a), which was slightly modified later by Shiau [14] later (Fig. 5b). The portion to the left of P_3 (from P_1 to P_3 in Fig. 5a) represents the supply based hedging where the hedged release (R_t) is proportional to the available water (AW_t) in that period, while in the portion to the right of the curve (from P_3 to P_2), the release is proportional to the demand in that period. This hedging rule essentially provides an offset to the SOP in the period where the hedging has begun. A third parameter was introduced by Srinivasan and Philipose [9], namely, hedging factor (HF) that specified the amount of hedging to be done. The general form of 3-point hedging rule has been described by Draper and Lund [4] as consisting of two linear segments with different slopes. The first segment has a slope of 1.0 and represents "no carry-over storage" and the slope of the second segment is less than 1.0 (milder) and has a carry-over storage value. Beyond P_2, no hedging is done (Fig. 5b).

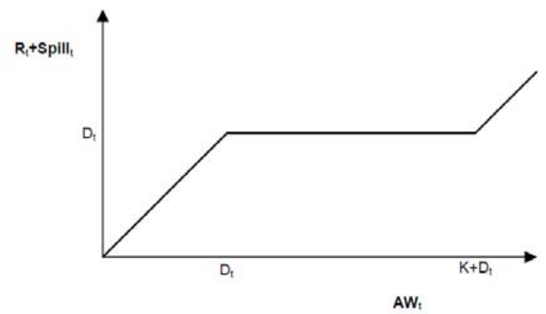

Fig. 1. Standard Operating Policy

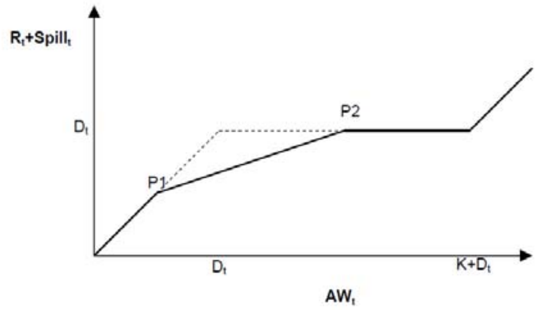

Fig. 2. Two-point linear hedging rule

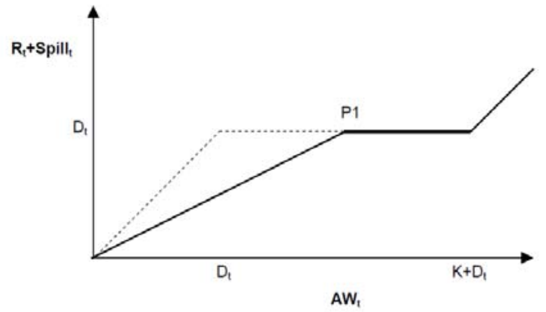

Fig. 3. One-point linear hedging rule

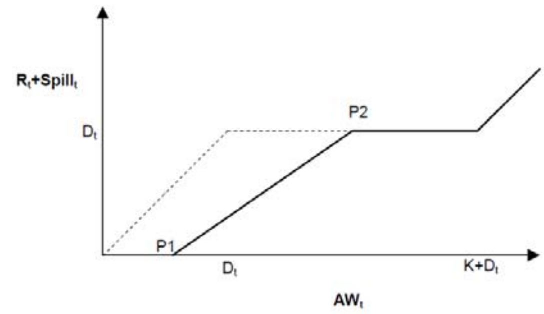

Fig. 4. Reserve-storage based two-point hedging rule

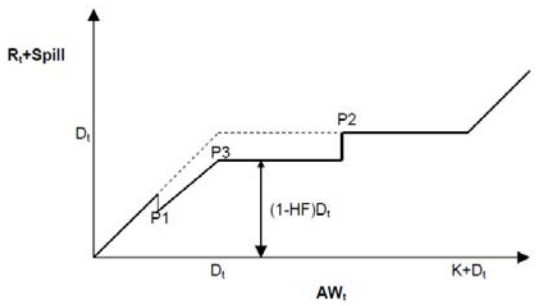

Fig. 5a. Three-point linear hedging rule as proposed by Srinivasan and Philipose [9]

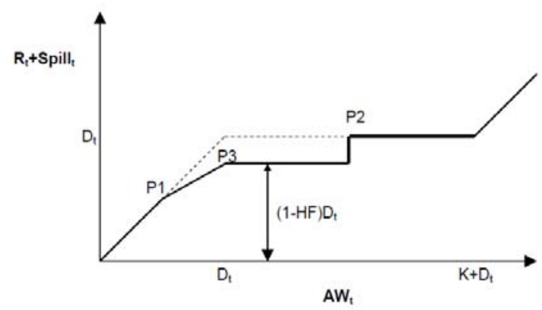

Fig. 5b. Three-point linear hedging rule as proposed by Shiau [14]

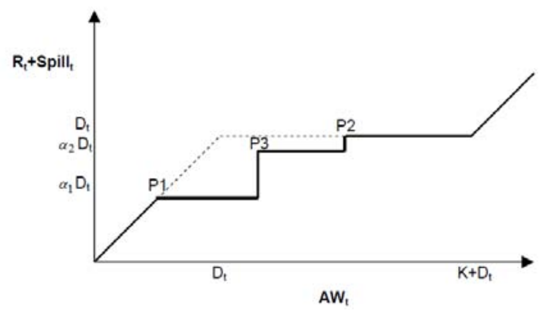

Fig. 6. Discrete phased hedging rule

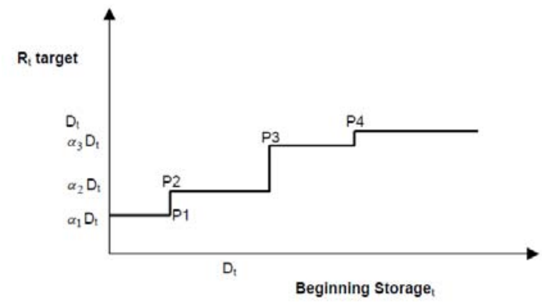

Fig. 7. Discrete phased hedging rule controlled by beginning storage

The discrete phased hedging rule (Fig. 6) was introduced by Shih and ReVelle [10],[11] which is closer to the practical operation during drought periods or when drought is impending. This rule is more realistic as the water managers do not usually have the option of a continuous gradation [15], as they need to declare the rationing to the public in a simple manner.

In many cities, especially in developing countries, during droughts, rationing is being performed by supplying water on alternate days, or twice in three days [16],[17]. Such demand management strategies may be treated as 50% or 66.67% respectively of the supply required to meet the full demand. Accordingly, Neelakantan and Pundarikanthan [16],[17] introduced a different discrete phased hedging rule (Fig. 7) from that of Shih and ReVelle [10],[11] scheme. In this, instead of available water, they considered only the beginning storage *(BS_t)* in period *t* to trigger the hedging. Hence, there is no need to predict or forecast the current-period inflow before making a release decision. However, instead of 'release' in the y-axis, they considered 'release target' (Fig. 7). Thus, the release may not be always equal to the target while attempted to release the target quantity utilizing the current period inflow also.

This rule has also been considered in the study of Celeste and Bilib [18]. A major limitation of not considering the likely inflows in the current period of operation, may result in unnecessary hedging in some periods in case surplus inflows are received. In most of the hedging rules, usually when $0 \le AW_t \le P1_x$, no additional hedging is implemented as the available water itself is very small. In this, when $0 \le BS_t \le P1_x$, the corresponding rule segment shows a horizontal line where as in other hedging rules, when $0 \le AW_t \le P1_x$, this segment is represented by a 45 degree inclined line. The rule provides ‘Release Target’, which means the release will be aimed to match with this value. When BS_t is smaller than the release target, if the inflow in the current period is sufficient the target will be met; otherwise, whatever maximum possible (but less than the ‘release target’) will be released. Similarly, the rule curve depicting the spill component also does not arise. Tu et al [19] used discrete phased hedging rule to a multi reservoir system in which the beginning storage was used to trigger the hedging.

The definition sketch of the two-point non-linear hedging rule suggested by Celeste and Billib [18] is presented in Fig. 8. Unlike the two-point linear hedging rule, herein, the connection between the points P_1 and P_2 is a non-linear curve. The mathematical representation of release for the case $P1_x \le AW_t \le P2_x$, is given below.

$$R_t = P1_y + (D_t - P1_y) \times \left(\frac{AW_t - P1_x}{P2_x - P1_x} \right)^m , \quad if \ P1_x \le AW_t \le P2_x \tag{1a}$$

wherein the exponent *m* denotes the non-linearity of the two point hedging curve between P_1 and P_2. When $m = 1$, it becomes two-point linear hedging rule itself. The value of m between 0 and 1 provides a curve above the linear connection between *P1* and *P2*; while $m > 1$ provides a curve below the linear connection. For the two-point non-linear hedging rule, the decision vector consists of three parameters namely *a*, *b* and *m*.

Though Celeste and Billib [18] limited *m* between 0 and 1, the lower limit should be more than 0. When *m* is less than 1.0 and small, there are chances for the release value as per the above equation to be greater than the availability, which is not feasible. For example, when $m=0$, the term $\left(\frac{AW_t - P1_x}{P2_x - P1_x} \right)^m = 1$, and hence $R_t = D_t$. However, if the $AW_t < D_t$ (for example if $AW_t = P1_x$), a release equal to the demand is not possible. Hence there is a lower limit higher than zero for *m*.

The SOP does not allow water to be released more than the availability. The release due to SOP can be written as

$$R_t = P1_y + (D_t - P1_y) \times \left(\frac{AW_t - P1_x}{D_t - P1_x} \right), \quad if \ P1_x \le AW_t \le D_t \tag{1b}$$

Comparing the above equations, the release to be realistic the value for *m* should be such that $\left(\frac{AW_t - P1_x}{P2_x - P1_x} \right)^m \le \left(\frac{AW_t - P1_x}{D_t - P1_x} \right)$. This also means that

$$m \ge \frac{\log\left(\frac{AW_t - P1_x}{D_t - P1_x} \right)}{\log\left(\frac{AW_t - P1_x}{P2_x - P1_x} \right)}. \tag{1c}$$

A modification is proposed in this paper to overcome the above problem. Basically the range $P1_x \le AW_t \le P2_x$ is split into two and the release equation is given for each range as:

$$R_t = P1_y + (AW_t - P1_y) \times \left(\frac{D_t - P1_x}{P2_x - P1_x} \right)^m , \quad if \ P1_x \le AW_t \le D_t \tag{1d}$$

and

$$R_t = P1_y + (D_t - P1_y) \times \left(\frac{AW_t - P1_x}{P2_x - P1_x} \right)^m, \quad if\ \mathrm{D_t} \le AW_t \le P2_x \tag{1e}$$

When AW_t=D_t, both the equations provide the same release. In the modified equations, $m=0$ provides SOP and $m=1$ provides two-point linear hedging rule. The value of m between 0 and 1 provides a curve above the linear connection between *P1* and *P2*; while $m > 1$ provides a curve below the linear connection. There is no upper limit and when $m \to \infty$, the rule curve behaves like a discrete phased hedging rule.

The one-period ahead hedging was extended to construct multi-period ahead hedging schemes (Fig. 9) by Shiau [14]. It is well known fact that hedging conserves water for later use during deficit periods. However, hedging too early may sacrifice the reliability of long-term water supplies and increase the number of deficit periods. Hence, deciding on the 'number of periods ahead of which rationing to be started' is vital in any drought management scheme. However, a reliable river flow prediction/forecast model is essential for this. The *k*-period water availability at period *t*, denoted by AW_k, is defined as the initial (beginning) storage at period *t*, plus the total inflow, and minus total evaporation losses during the periods from period *t* to $t+k-1$. That is

$$AW_{t,k} = BS_t + \sum_{i=1}^{k} (I_{t+i-1} - loss_{t+i-1}) \tag{2}$$

where $AW_{t,k}$ is the k-period water availability at period *t*, BS_t is the beginning storage in period t, I_t is the inflow during period *t* and $loss_t$ is the evaporation loss during period *t*.

This is similar to the available water when the k-periods are grouped together as a single period. The hedging trigger is based on the comparison of $AW_{t,k}$ with the total sum of demands during the same k periods, i.e., $\sum_{i=1}^{k} D_{t+i-1}$. However, as specified by Shiau [14], the rationing is to be implemented only at time *t* rather than the entire *k*-periods together. Likewise, the hedging trigger at time $t+1$ is to be determined by the *k*-period accumulated water availability at time $t+1$. A typical multi-period ahead three-point linear hedging rule is presented in Fig. 9. It is to be noted that when k=1, this will become the simple three-point linear hedging rule.

One of the moot questions for research in hedging based reservoir operation is "how long to hedge?" given the forecast of uncertain inflows that are stochastic in nature. Although it is desirable to consider a long forecast horizon in decision making, longer forecasts are less reliable due to the limitations of the existing forecast models. This means that there exists a trade-off between the gain in information due to long lead time forecasts and the error that can be expected in such forecasts. Recently, You and Cai [20] have introduced the concept of decision horizon and forecast horizon with regard to the stochastic reservoir operation under hedging. When the decisions in the initial few periods (decision horizon) are not affected by future data beyond a particular period, then, the latter period is known as "forecast horizon". You and Cai [20] have derived a local necessary condition for finding forecast horizon for a given decision horizon. Their research seems to give a good lead to the finding the answer for the moot question referred earlier.

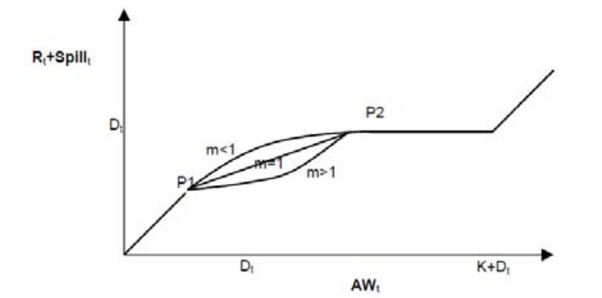

Fig. 8. Two-point non-linear hedging rule

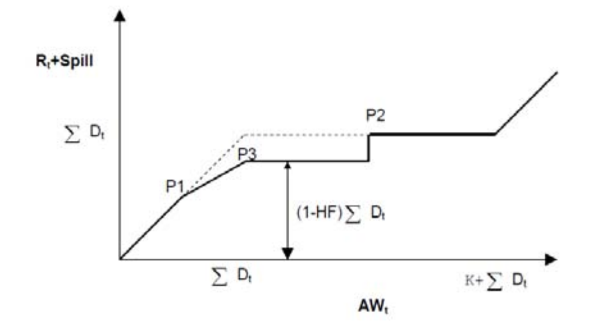

Fig. 9. Multi-period ahead hedging rule

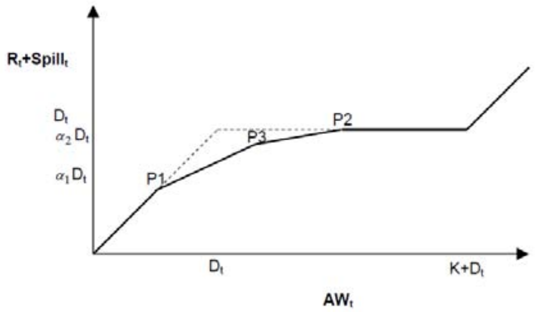

Fig. 10. Piece-wise linear hedging rule

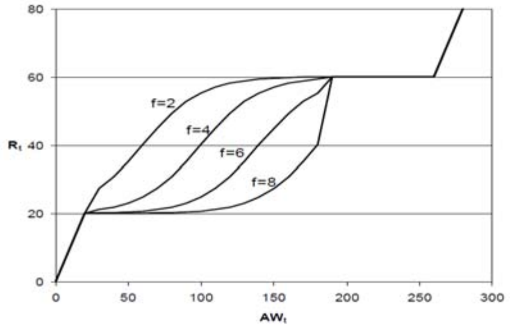

Fig. 11. Typical sigmoid based non-linear hedging rule with different values of f

III. SCOPE FOR NEW HEDGING RULES

The piecewise linear hedging rule is presented in Fig. 10. This rule resembles a piece-wise linearization of a curve and hence given the name. Sigmoid type functions may be good alternatives to the 2-point non-linear hedging rule proposed by Celeste and Billib [18], as they can smoothly connect the hedging trigger points P1 and P2. Sigmoid functions, which produce s-type curves, may be suitable for this and some of the plausible functions are listed in Table I.

TABLE I. Typical Sigmoid Type Functions and Their Characteristics

Function name	Functional relationship	Range of y	Value of x corresponding to		
			y=-0.95	Y=0.05	y=0.95
Logistic sigmoid function	$y=\frac{1}{1+e^{-x}}$	0 to 1	NA	-2.93	+2.93
Tanh function	$y=\frac{e^{x}-e^{-x}}{e^{x}+e^{-x}}$	-1 to +1	-1.83	0.05	+1.83
Sigmoid type 1	$y=\frac{x}{\sqrt{1+x^2}}$	-1 to +1	-3.04	0.05	+3.04
Sigmoid type 2	$y=\frac{x}{1+\lvert x\rvert}$	-1 to +1	-19.00	0.05	+19.00

For example, the Logistic sigmoid function can be used in the non-linear two-point hedging rule as follows.

$$P1_x = aD_t;\ P2_x = bD_t;\ P1_x = P1_y;\ 0 \le a \le 1;\ 1 \le b \le \frac{K+D_t}{D_t} \tag{3a}$$

$$R_t = AW_t, \quad if\ AW_t \le P1_x$$
$$When\ \ if\ \mathrm{P1_x} \le AW_t \le P2_x$$
$$x = \left(\frac{AW_t - P1_x}{P2_x - P1_x}\times 8\right) - f$$
$$y = \frac{1}{1+e^{-x}} \tag{3b}$$
$$R_t = \min\left(P1_x + (y \times (1-a)\times D_t), AW_t\right)$$
$$R_t = D_t, \quad if\ AW_t \ge P2_x$$

$$Spill = \begin{cases} AW_t - K - D_t, & if\ AW_t \ge (K+D_t) \\ 0, & otherwise \end{cases} \tag{3c}$$

Theoretically, the value of x can be varied between $-\infty$ and $+\infty$; however in the above equations the range is limited between -4 and +4 and correspondingly the value of f may be varied between 0 and 8 to get different forms of the hedging curve that connects the triggers. The effects of different values of f are shown in Fig. 11.

While $P1_X \le AW_t \le P2_X$, the release can be written as $R_t = P1_X + (y \times (1-a) \times D_t)$, however, as in the two-point non-linear hedging rule, very close to $P1_x$, the release can be slightly more than the availability for small values of *f*. Hence, the release can be taken as: $R_t = \min(P1_X + (y \times (1-a) \times D_t), AW_t)$. This adjustment will not affect the monotonically increasing nature of the curve. The parameters of the above sigmoid function based two-point non-linear hedging rule are *a, b* and *f*. Similar equations can be framed for 'beginning storage' based rules also. Moreover, similar rules can be proposed using other sigmoid type functions as well. The hedging rules based on these functions may be suitable, when the economics based benefit functions are used in finding the optimal hedging policy.

IV. Analytical Studies On Reservoir Hedging

A two-period (periods t and t+1) reservoir operation model analytically with the objective of maximization of the sum of the benefit due to current water delivery and carryover storage value was studied by Draper and Lund [4]. They found that the following condition for optimal hedging for a water supply reservoir.

$$\frac{\partial B(R)}{\partial R} = \frac{\partial C(S)}{\partial S} \tag{4}$$

where $B(\ )$ is the benefit function due to water release, *R* is the current water release, $C(\ )$ is the benefit function due to carryover storage, and *S* is the current carryover storage. This explains that at optimality the marginal benefit of carryover storage is equal to the marginal benefit that can be obtained if that carryover storage is released instead of storing. They analyzed benefit functions of quadratic, cubic, or power equation forms. When $B(\ )$ is linear that results in SOP as the optimal rule. They also proved that the quadratic benefit functions (of the form $Benefit = a + bx + cx^2$ in which a, b and c are constants) for both release and carryover storage, results in two-point or one-point hedging rules as optimal hedging rule. Power functions (of the form $Benefit = qx^p$ in which p and q are constants and p is less than 1) for benefits on both release and carryover storage results in non-linear hedging rule passing through the origin as the optimal hedging rule. This study initiated a separate branch of research and further developed by the following researches.

You and Cai [21],[22] extended the Draper and Lund [4] study addressing the start and end of hedging, the extent of hedging with respect to the demand, inflow uncertainty, and evaporation loss. They proved some intuitive knowledge on reservoir operation like (a) if the water availability is either too low or too high, the role of hedging is trivial; (b) hedging can be implemented by a simple way with a constant delivery ratio when the second order of the utility function in the current period is linearly proportional to that in the future period. This study was further extended by Zhao et al [23] to study the optimality conditions for SOP and hedging rule. They analyzed the effects of mass balance, nonnegative release, and storage constraints under both certain and uncertain conditions. They concluded that a higher uncertainty level in the future implies water to be reserved as insurance for future use and thus makes hedging rule more favorable.

Shiau [9] used the following objective function $Min\ z = B(R_t) + C(S_{t+1})$ where $B(R_t) = w\left(\frac{D_t - R_t}{D_t}\right)^m$, $C(S_{t+1}) = (1-w)\left(\frac{S_{t+1}^T - S_{t+1}}{S_{t+1}^T}\right)^m$, w is the weighing factor assigned to the loss function of reservoir release target, m is a constant and S_{t+1}^T is the target for carryover storage from period t to t+1. In the above expressions, the following ranges of values are considered: $0 < w < 1$; $m > 1$, to have a convex function and $0 \le S_{t+1}^T \le K$. Further, they defined a factor called the inverse-weighted target ratio $\eta_t = \left(\frac{1-w}{w}\right)\left(\frac{D_t}{S_{t+1}^T}\right)$ for convenience. They found that $\eta_t \le 1$, results in two-point linear hedging rule (Fig. 2), $\eta_t = 1$ results in one-point linear hedging rule (Fig. 3) and $\eta_t \ge 1$ results in the reserve storage based two-point hedging rule or the two-point type II hedging rule (Fig. 4).

The analytical studies provide more insight into the behavior of the hedging based operations. The analytical concepts are to be explored further and can be implemented into the optimal reservoir operation models and applied to practical case studies to achieve effective water management during drought periods and when drought is impending.

V. FUTURE DIRECTIONS OF RESEARCH

Some studies [24],[25],[26],[27] employed drought indices based on meteorological and hydrological conditions in reservoir operation. Using such drought indicators may represent the reality closer than the triggers based on "beginning storage" or "water availability". In this regard, recognizing the plausible relationships (lag times) between the meteorological droughts and the hydrological droughts, may enable obtaining an early forecast of expected streamflows and reservoir storages, in turn, leading to timely and improved hedging decisions.

The economic values of shortages should be assessed for obtaining good optimal reservoir operation rules. The difficulties in estimating the economic values are to be listed and analyzed. The procedures for judging the economic values of both direct and indirect costs and benefits with reasonable accuracy are to be researched. The water resources management field has been using the water supply based surrogate performance indicators for long time and it is time that efforts are made to obtain real economic data. In the recent past, quadratic equations for benefit functions which were approximated based on historical data were used for Zayandeh-rud reservoir system in Iran [28]; and Moghaddasi et al. [29] suggested operating rules for the long-term operation of the same reservoir for irrigation supply by coupling a regional water allocation model with a hedging based reservoir operation model. In their study, they have identified the optimal values of the hedging triggers of a two-point water supply hedging rule using the economic criterion of given in reference [4]. Cubic equations for benefit functions were used for water supply of Beijing city in China [23]. Refining such approximations may lead the research to the next level of using realistic economic value based hedging.

In the case of multi-purpose reservoir operation, the release rules may be developed by integrating the different rule curves developed for the various purposes with the appropriate hedging strategies and prioritization of the different objectives. Some limited attempts in this direction have been made in the references [19],[30],[31]. Improvements in this direction are desirable.

It is obvious that the long-term performance measures such as reliability, shortage ratio and resilience of a hedging rule-based operation are likely to be poorer than the performances obtained by the SOP based operation. Precise performance indicators such as reliability and resilience are defined with regard to the performance states defined as either 'success' or 'failure'. Instead, if fuzzy measures of performance are developed and used, they may be capable of judging the hedging rules in a more complete fashion. Future research may focus in developing appropriate performance indicators in this direction.

The SOP is useful in water resources planning and design (to estimate the capacity of the reservoir) and not as a real-time operation rule or policy and this policy utilizes the value of storage plus projected inflow as the signal for release decisions. The SOP can use such a signal, as it does not need to declare a rationing until after the period is over, which is a rather unrealistic mode of operation [10]. When hedging is triggered based on "storage plus inflow" (water availability), it should have the support (backing) of a good forecast/prediction model. Shiau and Lee [32] suggested the monthly decile inflows as a surrogate for the forecast of future inflows in the use of hedging rules for real-time reservoir operations and such dependability-based surrogates can be explored further. The triggers for hedging could be decided based on forecasts obtained from drought indices as well as climate indices. Research is also to focus on attempts to find the forecast horizon needed to derive the appropriate hedging policies for reservoir operation [20], [18]. The authors feel that the sigmoid type functions may be good alternatives, as they can smoothly connect the points P1 and P2, the starting and the ending points of hedging in terms of water availability.

VI. HEDGING RULES FOR HYDROPOWER RESERVOIR OPERATION

Hedging rules are popular in drinking and irrigation water supply. Application of hedging is now gaining focus for hydropower reservoir operation. In the case of hydropower generation, the benefit is a function of product of head of water and flow-rate, while for other cases benefit is a function of flow-rate only. Hence, the hedging rules used for other purposes cannot be directly used for hydropower reservoir operation. The power generation (P) from hydropower reservoir is directly proportional to both flowrate (Q) and available head (H) at the turbine ($P \propto QH$). The relationship between head and available storage (*AS*) in the reservoir is non-linear. In the case of hydropower reservoir, the water demand is not constant; but the power demand is constant. The operation rules may be presented in the graphical form with 'power generation possible' (based on releasing all the *AS*) on x-axis and 'power generation' (suggested as per the rule) on y-axis.

However, providing the rule with *AS* on x-axis and 'release of water' on y-axis is more readable. In 2014, Zeng et al [33] used 'energy available' on x-axis and 'current generation' on the y-axis.

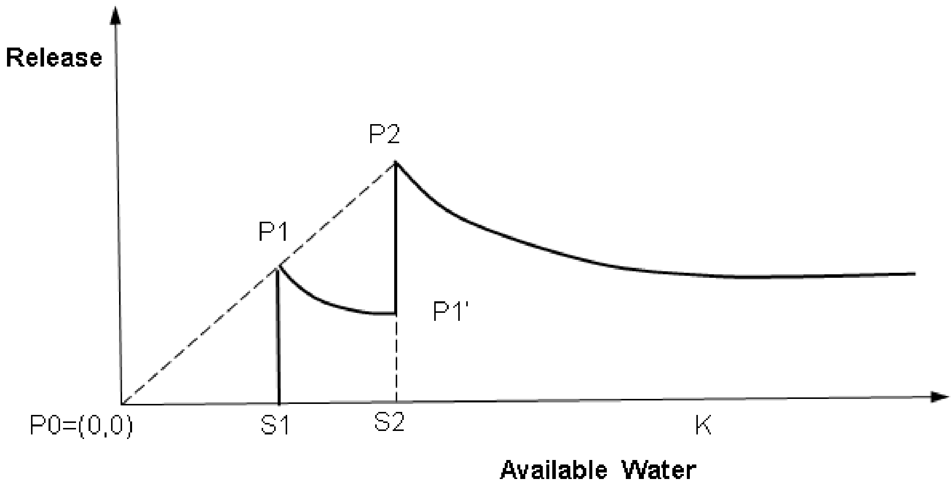

Fig. 12. Standard hedging rule proposed by Neelakantan and Sasireka [34]

A different form of hedging rule for hydropower reservoir operation was proposed by Neelakantan and Sasireka [34] which is shown in Fig. 12. As per the proposal, if a reservoir system has two turbines of equal power generation capacity. S1 is the quantity of available-water at which releasing all the S1 will produce the 50% of the maximum power generation potential. S2 is the quantity of available-water at which releasing all the S2 will produce the 100% of power generation potential. The straight line connecting P0, P1 and P2 is a 45° line. As it is, it is called standard rule and if the S1 and S2 values are to be shifted the right such that some amount of water could be saved for future use for the hedging case.

VII. Summary

An attempt has been made in this paper to review the different hedging rules in the context of water supply reservoir operations and provide directions for future research in this area. Emphasis of the review has been placed on: i) discussion of the various reservoir hedging rules proposed in the water resources management literature, their implications, advantages and limitations; ii) describing the objective functions and performance indicators used in obtaining the optimal hedging formulations; iii) reviewing a few recent analytical studies as well as optimal hedging operation based studies that deal with reservoir hedging. It is hoped that this paper will enable the researchers in this area to develop a wider as well as deeper understanding of the hedging rules/policies and implement them in optimal reservoir operation studies. Developing realistic economics based benefit/loss functions, fuzzy logic based performance indicators, non-linear hedging rules, devising improvised forecast methods provide interesting topics for future research. The bigger challenge lies in integrating the economic objective functions, fuzzy performance constraints, drought indices and climate indices based forecasts as triggers for the hedging rules, within the optimal reservoir operation framework.

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