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Parameterizaion – Simulation – Optimization Approach for Reservoir Operation

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PARAMETERIZAION – SIMULATION – OPTIMIZATION APPROACH FOR RESERVOIR OPERATION

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Abstract: *During periods of significant water shortage or when drought is impending, it is customary to implement some kind of water supply reduction measures with a view to prevent the occurrence of severe shortages (vulnerability) in the near future. In other words, such rationing measures tend to distribute the total shortage over a significant number of periods thus minimizing the maximum single period shortage. In the case of operation of a water supply reservoir, this reduction of water supply is effected through hedging schemes or hedging policies. When a drought is expected to start within the next few periods, these policies aim to build up the reservoir storage proactively to guard against the possible future shortages. This may result in likely increase in total deficit. Thus, a reduction in the vulnerability (severity of shortage) might result in an increase in shortage ratio (complement of volume reliability). Therefore, compromising hedging policies are to be evolved for which we need to resort to a multiple objective optimization model. This research work aims to build up a multi-objective optimization framework that would enable the selection of the compromising hedging policies. Three of the popular hedging rules, (i) linear two-point hedging, (ii) non-linear two-point hedging, and (iii) modified two-point hedging are employed as options within the framework. The case example used for illustration is the Hemavathy reservoir in Karnataka. The multi-objective evolutionary search based technique (Non-dominated Sorting based Genetic Algorithm – II) is used to identify the pareto-optimal front of hedging policies that seek to obtain the trade-off between shortage ratio and vulnerability. A performance comparison between the three hedging rules is presented for the selected compromising policies from the respective pareto-optimal fronts. The modified hedging rule is seen to be more efficient when compared with the two-point linear hedging rule and the two-point non-linear hedging rule.*

Keywords: *Parameterization; Simulation; Optimization; Hedging policy; Shortage ratio; Vulnerability; NSGA-II.*

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INTRODUCTION

The rule or policy of any reservoir operation involves deciding the amount of releases to be made from the reservoir to meet the specified demands for different purposes based on the "current storage in the reservoir and the expected (likely) inflows to the reservoir" (available water). The standard operation policy is a simple operating rule for a reservoir, which aims to meet the demand in each period based on the available water in the current period. If the available water is higher than the demand, then the demand is completely satisfied. If available water is less than the demand, then the available water is released towards meeting the demand. This policy is likely to result in high volumes of deficits in the future periods of operation. In order to avoid severe water deficits during drought periods or when drought is impending, hedging is done, which reduces water supplies proactively and conserves more water for future use. Thus, hedging provides insurance for high-valued water uses, where reservoirs have low refill potentials or highly uncertain inflows (Draper and Lund, 2004).

The trigger for the initiation and the termination of hedging along with the amount of rationing to be done in each time step typically characterize a hedging rule. The parameters of a hedging rule can be expressed as a function of water available in the reservoir, which is the sum of the current storage and the expected inflows into the reservoir. Bayazit and Unal (1990) defined the two-point hedging rule in terms of starting water availability (volume of water availability above which the reservoir release is hedged, SWA) and ending water availability (the volume of water availability at which hedging is stopped and normal situation is restored, EWA). The effectiveness of hedging rules can be enhanced by having control over the amount of water to be released during hedging. Accordingly, Srinivasan and Philipose (1996, 1998) included the hedging factor as a third parameter along with the starting water availability (SWA) and the ending water availability (EWA) to define the modified two-point hedging rule. The hedging factor specifies the amount of hedging to be done in each time step. The modified two-point hedging rule essentially provides an offset to the SOP in the period where hedging is done. They evaluated the trade-off among the reservoir performance indicators based on large number of pre-defined hedging policies, using Monte-Carlo simulation technique. However, such simulation models do not yield optimal hedging rules.

Optimization models that make use of systems techniques have been employed in a number of research works to identify the hedging rules either with regard to the economic outcomes such as benefit/loss functions [Draper and Lund, 2004; You and Cai, 2008 a,b] or perfomance outcomes such as water supply reliability, vulnerability [Hashimoto et al., 1982; Shih and Revelle, 1994,1995; Neelakantan and Pundarikanthan, 1999; Shiau and Lee, 2005; Celeste and Billib (2009)]. The optimal appropriation of water can be done by analyzing the benefits of current release against the benefits of storing water for future use as carryover storage (Draper & Lund, 2004). Draper and Lund (2004) have provided an analytical view of hedging rules and operations by deriving optimal hedging policies, given a pair of benefit functions for current delivery and carry-over storage. You and Cai (2008a) have expanded the theoretical analysis of Draper and Lund (2004) to develop a conceptual two-period model for reservoir operation. Since it is difficult to derive the actual benefit/utility functions for current delivery as well as carry-over storage, the water supply characteristics of reservoirs are used as surrogates to evaluate their performance.

Shih and ReVelle (1994) used mixed-integer non-linear programming technique and polytope search procedure to find the optimal linear hedging rule with starting water availability as the only decision vector, by minimizing the maximum shortfall or vulnerability. Following this, they also proposed an explicit two-phase discrete hedging rule and implemented the same using mixed-integer programming model (Shih and ReVelle, 1995). This formulation was solved for only a single critical drought. Oliveira and Loucks (1997) proposed a piecewise linear hedging rule to derive the optimal hedged operating policy for multi-reservoir systems using genetic algorithm (GA). However, the performance of the hedging rule was evaluated based only on the single objective of minimizing the total deficit. Neelakantan and Pundarikanthan (1999, 2000) developed an artificial neural network based simulation-optimization model to obtain optimal trigger storage volumes for multi-reservoir water supply system, using discrete hedging rules.

Tu et al. (2008) have developed a mathematical model to simultaneously optimize the water allocation between the different purposes and search for the trigger (storage) volumes as well as the rationing factors. Recently, Celeste and Billib (2009) investigated the performance of seven stochastic models used to define optimal reservoir operating policies. They have introduced the two-point non-linear hedging, in which an exponent is employed to shape the hedging curve non-linearly between the starting water availability and the ending water availability. Shiau (2009) has shown the merits of the multi-period ahead hedging method when used in combination with the two-point hedging rule of Srinivasan and Philipose (1996, 1998) incorporating time-varying hedging parameters into the rule.

PRESENT STUDY

In the present research work, a parameterization-simulation-optimization framework is proposed for obtaining the pareto-optimal hedging policies for the operation of a reservoir that supplies water for irrigation purpose. These policies seek to obtain the trade-off between the two primary objectives adopted by a water manager while operating the reservoir during times of droughts, namely, i) shortage ratio and ii) vulnerability. The three hedging rules used for reservoir operation form the core of the model (simulation part) and a multi-objective reservoir performance optimization model is the driver of the framework. The decision variables of the optimization model are the parameters of the three hedging rules. Performance evaluation of the selected hedging policies from the pareto-optimal front is carried out by reservoir simulation using the following reservoir performance indicators, occurrence reliability, resilience, mean event deficit and event vulnerability. The case example used of illustration is the Hemavathy reservoir in Karnataka, Southern India. Derivation of the pareto-optimal hedging policies and the detailed evaluation of the same have been done using the observed monthly stream flows into the Hemavathy reservoir. The multi-objective evolutionary search based technique (Non-dominated Sorting based Genetic Algorith – II) is employed to obtain the trade-off solutions. A performance comparison between the three hedging rules is presented for the selected operating policies from the respective pareto-optimal fronts.

PARAMETERIZATION–SIMULATION–OPTIMIZATION (PSO) FRAMEWORK

The following parameterization-simulation-optimization (PSO) framework is developed in this study to obtain the optimal trade-off between the two surrogate objective functions mentioned below, for three of the common hedging rules namely, i)Two-point linear hedging (Bayazit and Unal, 1990), ii)Two-point non linear hedging (Celeste and Billib, 2009) and iii)Modified two-point hedging (Srinivasan and Philipose, 1996).

Objective Functions

i) Minimize Period Vulnerability: $Z1 = Minimize\{V_p\}$ … (1)
ii) Minimize Shortage Ratio: $Z2 = Minimize\ \{SR\}$ … (2)
D_t denotes the demand during period 't', R_t denotes the release made during period't'.

In equation (1), Period Vulnerability refers to the maximum single period deficit encountered over the operation horizon, i. e.

$$V_p = \max(D_t - R_t)$$

where D_t = demand at period t; R_t = release at period t; V_p = period vulnerability.
In equation (2), shortage ratio computed as the ratio of the sum of total deficits to the sum of total demands.

$$SR = \frac{\sum_{t=1}^{T}(D_t - R_t)}{\sum_{t=1}^{T}(D_t)}$$

where, T = total number of periods of operation in the horizon considered; SR = shortage ratio.

Constraints specifying the hedging rules

The constraints that define each of the three hedging rules considered in this study are presented below with a brief discussion. Any one of the three hedging rules can be invoked into the PSO framework.

Two-point linear Hedging rule

The definition sketch of the two-point linear hedging rule suggested by Bayazit and Unal (1990) is presented in Fig. 1 below. In case of the two-point hedging rule, when the water availability falls below the SWA, the available water in the reservoir is released towards meeting the demand. So, the storage of the reservoir at the end of this time period will become zero. In the next time period, water available becomes the same as the inflow into the reservoir. If the inflow into the reservoir also dwindles, then, the water availability becomes very less and so the vulnerability will be the same as in case of standard operating policy. Once the available water is more than ending water availability, hedging is stopped and normal operation is resumed.

$$AW_t = S_t + I_t \quad \dots (3)$$

$$R_t = AW_t \quad if \quad AW_t \leq SWA_t \qquad \ldots (4)$$

$$R_t = SWA_t + (AW_t - SWA_t) \times \left(\frac{D_t - SWA_t}{EWA_t - SWA_t} \right) \quad if \ SWA_t \leq AW_t \leq EWA_t \qquad \ldots (5)$$

$$R_t = D_t \quad if \quad EWA_t \leq AW_t \leq K + D_t \qquad \ldots (6)$$

$$R_t = D_t \quad if \quad K + D_t \leq AW_t \qquad \ldots (7)$$

$$Spill_t = \begin{cases} AW_t - K - D_t & if \ \ K + D_t \leq AW_t \\ 0 & else \end{cases} \qquad \ldots (8)$$

$$S_{t+1} = S_t + I_t - R_t \quad Spill_t \qquad \ldots (9)$$

$$SWA_t = \alpha * D_t \qquad \ldots (10)$$

$$EWA_t = D_t + (K * \beta) \qquad \ldots (11)$$

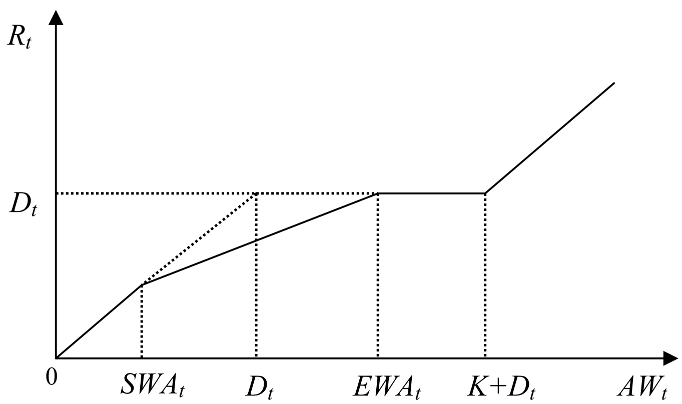

Fig. 1. Two-point Linear Hedging Rule

In equations (3)-(11), AW_t denotes the available water during time period 't', S_t denotes the initial storage, S_{t+1} the final storage, R_t the release and Q_t the inflows during time period 't' and K the capacity of the reservoir. In the optimization formulation of the two point hedging rule, the decision vector consists of two parameters namely α and β that indicate starting water availability (SWA_t) and ending water availability (EWA_t) respectively.

Two-point Non-linear Hedging rule

The definition sketch of the two-point non-linear hedging rule suggested by Celeste and Billib (2009) is presented in Fig. 2 unlike the two point linear hedging rule herein, the connect between the SWA_t and the EWA_t (marked in Fig. 2) is a non-linear curve.

Out of the equations (3) to (11), excepting equation (5), all the other equations remain the same as in the case of the two point linear hedging rule. Equation (12) replaces equation (5) of the two point linear hedging rule

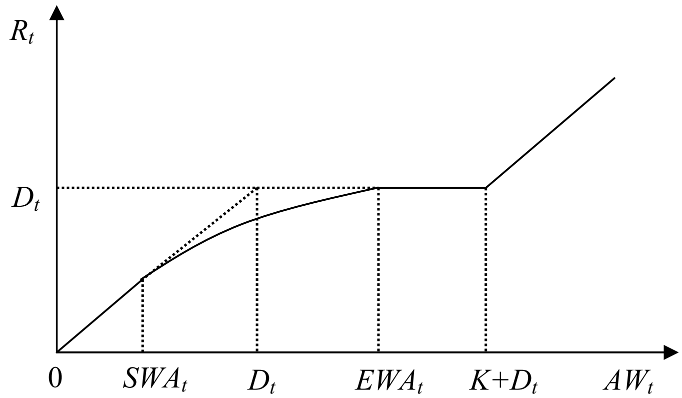

Fig. 2. Two-point Non - linear Hedging Rule

$$R_t = SWA_t + (D_t - SWA_t) \times \left(\frac{AW_t - SWA_t}{EWA_t - SWA_t} \right)^m \quad if \ SWA_t \le AW_t \le EWA_t \qquad \dots (12)$$

The exponent (index) 'm' denotes the non-linearity of the two point hedging curve. If m=1, it becomes linear two point hedging rule itself. In the optimization formulation that uses the two-point non-linear hedging rule, the decision vector consists of three parameters namely *α, β and m*.

Modified two-point hedging rule

The basic definition sketch of the modified two-point hedging rule suggested bySrinivasan and Philipose (1 996, 199 8) is presented in Fig. 3 b elow. In this rule, the hed ging factor (HF) specifies the amount of rationing to be done. Thisanswers the question "howmuch to hedge?" in addition to the starting and the ending periods of hedging.

$$AW_t = S_t + I_t \qquad \dots (13)$$
$$R_t = AW_t \quad if \quad AW_t \le SWA_t \qquad \dots (14)$$
$$R_t = AW_t (1 - HF) \quad if \quad SWA_t \le AW_t \le D_t \qquad \dots (15)$$
$$R_t = D_t (1 - HF) \quad if \quad D_t \le AW_t \le EWA_t \qquad \dots (16)$$
$$R_t = D_t \quad if \quad K + D_t \le AW_t \qquad \dots (17)$$
$$Spill_t = \begin{cases} AW_t - K - D_t & if \ K + D_t \le AW_t \\ 0 & else \end{cases} \qquad \dots (18)$$
$$S_{t+1} = S_t + I_t - R_t \quad Spill_t \qquad \dots (19)$$
$$SWA_t = \alpha * D_t \qquad \dots (20)$$
$$EWA_t = D_t + (K * \beta) \qquad \dots (21)$$
$$0 \le HF \le 1$$

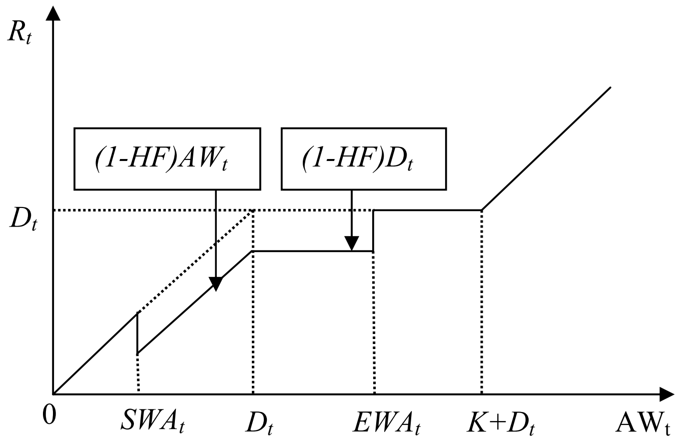

Fig. 3. Modified Two-point Hedging Rule

In equations (13)-(21), AW_t denotes the available water during time period 't', S_t denotes the initial storage, S_{t+1} the final storage, R_t the release and Q_t the inflows during time period 't' and K the capacity of the reservoir. In the optimization formulation of the modified two point hedging rule, the decision vector consists of three parameters namely α, β, and HF.

Performance Evaluation

The PSO framework will provide a number of pareto-optimal solutions corresponding to each of the three hedging rules that are invoked. These pareto-optimal solutions obtained from the framework need to be evaluated in detail for their operational performance over the time horizon considered using the reservoir simulation module. For the reservoir performance evaluation over the operation horizon the following performance indicators are computed.

i). Occurrence based reliability, the ratio of the number of times the demand is satisfied to the number of times the reservoir is operated (Hashimoto et al., 1982).

ii). Resilience, the ratio of the number of times the system moved from failure to success to the total number of periods the system was in failure state (Hashimoto et al., 1982).

iii). Mean event deficit, the ratio of the total deficit volume encountered during the operation horizon to the total number of failure events. Herein, 'event' denotes a sequence of failure periods. High magnitude of event deficit encountered during an irrigation season is detrimental to crop yield.

iv). Event vulnerability is the maximum event deficit encountered during the operatio horizon of the reservoir.

Solution Technique

The technique adopted in this research work to solve the multi-objective optimization problem is the Non-dominated Sorting Genetic Algorithm – II (NSGA-II) proposed by Deb et al. (2002). This technique is known to be better than the traditional multi-objective optimization methods such as ε-constraint method, weighted sum method in generating near-global pareto-optimal fronts. This technique is suited for handling complex objective functions involving discontinuities, disjoint feasible spaces and noisy function evaluations (Fonseca and Fleming, 1995). The multi-objective optimization model is the driver and the simulation model that is based on the hedging rules forms the engine of the framework. The decision variables of the optimization model are the hedging rule parameters. The strings generated from NSGA-II are evaluated for the two fitness functions using the simulation model. The near-(global) optimal search is based on the "survival of th e fitt est" principle of the evolution theory. The improvements in the quality of the solutions are basically achieved through the genetic operators, selection, cross-over and mutation. Elitist-based Non-dominated sorting, tournament selection and crowded comparison operator are a few of the special features implemented into NSGA-II to enhance its speed, quality and diversity of the non-dominated solutions. The MOGA input requirements are p opulation size, num ber of generations, cro ssover probability , mutation probability and random seed. The other inputs required for running the simulation module are inflows into the reservoir irrigation demands and physical characteristics of the reservoir and the choice of the hedging rule for the operation of thereservoir. After a detailed sensitivity analysis, the MOGA parameters were chosen to be: initial random seed = 0.25; mutation probability = 0.001; cross-over probability = 0.7; population size = 100; number of generations = 300.

CASE EXAMPLE - HEMAVATHY RESERVOIR

Hemavathy Reservoir is located on the River Hemavathy, a tributary of the River Cauvery in Karnataka, southern India. About 88% of the annual flow is experienced during the monsoon period June-October (Table 1). The peak inflows will be during August and July. Irrigation is practiced in the region during both the wet(June-October) and dry (November-March) seasons. In the summer months (April and May), there is no irrigation. The period-wise inflows and the target yields are given in Table 1. It may be observed from Table 1 that, normally, the filling of the reservoir takes place during the wet period and the emptying will be during the dry period. Thus, the within-year storages are predominant. The salient features of the Hemavathy reservoir are presented in Table 2. The unregulated monthly stream flows measured for a period of 58 years (1916-1974) at a downstream gauging station have been used as reservoir inflows in this study.

Table 1. Mean monthly inflows and monthly target yields

Month	Inflow (Mm^3)	Target Yield (Mm^3)
JUN 150		165
JUL 8	56	260
AUG 665		275
SEP 2	96	75
OCT 285		50
NOV 127		120
DEC 55		280
JAN 30		350
FEB 18		225
MAR 14		80
APR 14		20
MAY 36		10

Table 2. Salient features of the Hemavathy Reservoir project

Location	Upper reaches of the Cauvery River basin in southern India

Gross storage capacity	1048 Mm^3
Liver storage capacity	962.77 Mm^3
Water spread area	8502 hectares
Catchment area	5910 km^2
Types of soil	Red loamy soil and red sandy soil
Average monthly temperature	18^0 to 32^0 C
Crops Grown	
Kharif (wet) season (June-Oct)	Rice, Jowar, Ragi, Maize, Groundnut, Tobacco, Potato, Soyabeans
Rabi (dry) season (Nov-Mar)	Ragi, Jowar, Maize, Wheat, Groundnut, Potato, Coriander, Soyabeans, Safflower, Pulses

RESULTS AND DISCUSSION

After a sensitivity analysis, the NSGA-II parameters were determined as: cross-over probability = 0.7; mutation probability = 0.001; number of generations =300; population size = 100; initial random seed = 0.25;

The non-dominant solutions obtained at the end of 300 generations are plotted (Fig. 4) as pareto-optimal fronts for the three hedging policies compared. From Fig. 4 it is observed that there is no significant difference between the two-point linear hedging case and the two-point non-linear hedging case with regard to the non-dominant solutions obtained. This is also clear from the parameter values presented in Table 3 for the two hedging rules corresponding to three typical non-dominant solutions namely, the minimum shortage ratio solution, minimum vulnerability solution and the compromising solution. Also, the other performance indicators computed by reservoir simulation are found to match closely between the two hedging rules in case of all the three typical non-dominant solutions selected for investigation (Table 4).

From Fig. 4 and Table 4, it may be noted that the non-dominant solution corresponding to the minimum shortage ratio is formed to the identical for all the three hedging rules and that solution is the same as the standard operation policy (SOP). This is quite understandable since the SOP tends to minimize the overall shortages encountered over the operation horizon.

The compromise solution obtained from the pareto-optimal front (Fig. 4) of the modified hedging rule is found to be more efficient compared with the compromising solution obtained for the other two hedging rules. In fact, for the same vulnerability, a 1.6% reduction in shortage ratio is noted. Also a considerable increase is observed in occurrence based reliability and resilience and a significant drop is seen in the mean event deficit.

For the minimum vulnerability solution, a reduction of nearly 20% is seen in period vulnerability and event vulnerability, in case of the modified hedging rule when compared to the other two hedging rules for a decrease of 2% in the shortage ratio. Moreover, there is a notable increase in the occurrence reliability.

Table 3. Parameter values obtained from NSGA-II for the three cases of hedging

Hedging Type	**Non-dominant Solution**	**Hedging Parameters**				**Shortage ratio**	**Period Vul.(Mm³)**
		α	β	m	HF		
Two-point Linear	Min S/R	0.554	0	-	-	0.031	216.58
	Compromise	0.448	0.285	-	-	0.060	128.01
	Min Vul	0.672	0.989	-	-	0.119	82.62
Two-point Non-linear	min S/R	0.987	0	0.952	-	0.031	216.58
	Compromise	0.452	0.281	0.990	-	0.059	128.06
	Min Vul	0.618	0.982	0.767	-	0.115	82.99
Modified two-point	min S/R*	0.793	0.025	-	0	0.031	216.58
	Compromise	0.589	0.137	-	0.273	0.048	128.65
	Min Vul	0.808	0.896	-	0.185	0.134	65.04

i) α & β are the hedging parameters for Two-point linear hedging.
ii) α, β & m are the hedging parameters for Two-point non-linear hedging.
iii) α, β & HF are the hedging parameters for Modified two-point hedging.

Table 4. Simulation results for the non-dominant solutions selected

Policy	**Pareto-optimal Solution**	**Performance Indicators**			
		Occurrence Reliability	**Resilience**	**Event Vulnerability (Mm³)**	**Mean Event Deficit (Mm³)**
SOP	0	.929	0.510	596.36	135.19
Two-point Linear Hedging	Minimum S/R	0.929	0.510	596.36	135.19
	Compromise 0	.591	0.197	478.33	118.37
	Minimum Vul	0.258	0.108	870.91	233.20
Two-point Non-linear Hedging	Minimum S/R	0.926	0.490	596.36	135.19
	Compromise 0	.594	0.198	480.81	116.43
	Minimum Vul	0.261	0.108	865.84	226.45
Modified Two-point Hedging	Minimum S/R	0.929	0.510	596.36	135.19
	Compromise 0	.775	0.352	460.20	96.17
	Minimum Vul	0.330	0.118	695.77	268.13

SOP – Standard Operation Policy; S/R – Shortage Ratio; Vul.– Vulnerability;

SUMMARY AND CONCLUSIONS

A parameterization-simulation-optimization (PSO) framework is proposed for obtaining compromising hedging policies for the operation of a reservoir that supplies water for irrigation purpose. These hedging policies seek to obtain the trade-off between minimizing shortage ratio and minimizing vulnerability, the two primary objectives of a water manager for the operation of a reservoir during droughts. The performance of three commonly used hedging rules for reservoir operation is compared. The case example used for illustration is the operation of the Hemavathy

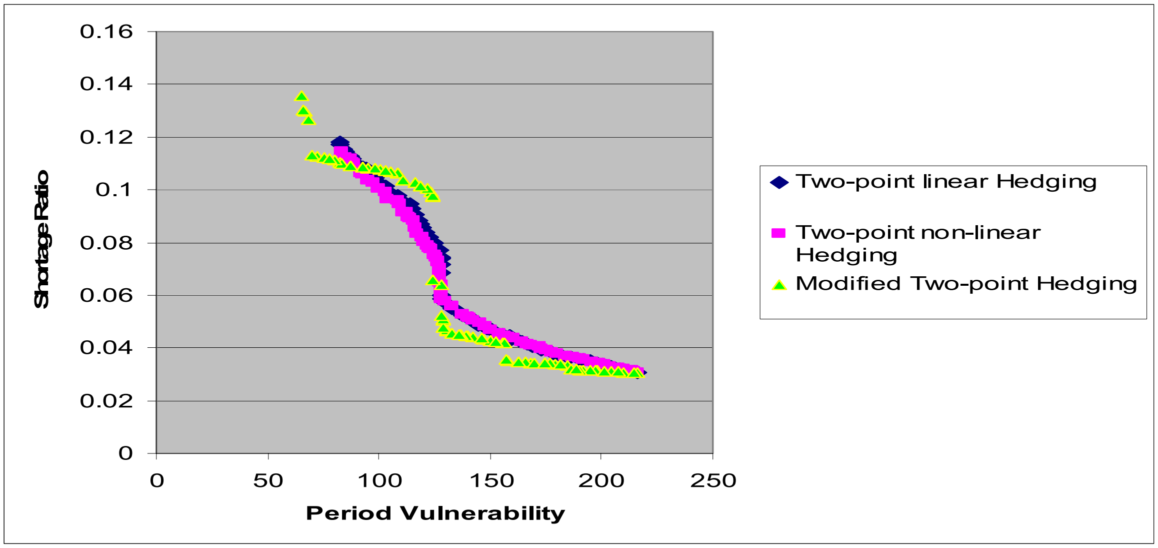

Fig. 4. Pareto-optimal fronts for the three hedging rules - case example : Hemavathy reservoir.

reservoir, Southern India. The results from th is case exam ple show that the operational performance of the modified hedging rule withthree hedging parameters proposed by Srinivasan and Philipose (1996, 1998) is better than that of the two-point linear hedging rule of Bayazit and Unal (1990) and the two-point non-linear hedging ru le of Celeste and Billib (2009). The generality of this conclusion requires further investigation.

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