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Hedging Policy for Reservoir System Operation: A Case Study of Mun Bon and Lam Chae Reservoirs

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ABSTRACT

A reservoir operation model of Mun Bon and Lam Chae reservoirs was developed to simulate reservoir operation using a hedging policy. A variety of common hedging forms was specified, including one-point hedging, two-point hedging and zone-based hedging. The simulated results were compared with the standard operating policy and probability based rule curve. The percentage of failure frequency, average annual shortage and end water availability were explored. Additionally, three reservoir performance indices, in terms of time-based reliability, vulnerability and resiliency were evaluated. The results indicated that two-point and three-point hedging performed well for all components of reservoir behavior compared with the standard operating policy and other hedging policies. The main outcome was that the risk of a water shortage during the simulation period could be reduced and some water could be retained for use in later periods.

Key words: hedging policy, reservoir system operation, Mun Bon and Lam Chae reservoirs

INTRODUCTION

The complexity of a reservoir system, taking into account the uncertainties of inflow and increasing water demand means that reservoir operators face a tough task. Consequently, various reservoir strategies have been formulated to serve the needs of decision makers for proper reservoir management. Reservoir operation policy is one of the strategies generated to guide the release decisions especially by reservoir planners and operators. It appears that the development of reservoir operating rules in the past decade has been more intensive. Large numbers of simulation and optimization models have been developed to obtain optimal operating rules. Meanwhile, new techniques, including the use of a genetic algorithm, heuristic algorithm, fuzzy approach or rough set approach have been employed to derive operating rules. An optimal reservoir operation policy is needed for successful reservoir planning and management.

Reservoir operation policy

A reservoir operation policy is a decision support tool that provides guidance for reservoir operations to meet the requirements of various users. In general, it is widely known in the following forms:

Standard operating policy

A standard operating policy (SOP) is the simplest and most often-used reservoir policy that releases, if possible, only the demand required in each period, and does not preserve water for future

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requirements. If sufficient water is not available to meet demand, the reservoir is emptied. If there is excess water, the reservoir will fill and then spill the excess water as shown in Figure 1. Thus, standard operating policy is the optimal operating policy with the objective to minimize the total deficit over the time horizon (Neelakantan and Pundarikanthan, 1999).

Hedging policy

The concept of a hedging policy has been formulated since the 1980s and has been further emphasized in water resources planning and management up to the present. A hedging policy attempts to retain existing water storage for use in later periods. In principle, some water is stored, even when there is enough water for target demand in the present period. The common forms of hedging are described in the following manners (Draper and Lund, 2004):

(1) One-point hedging; release begins at the origin in Figure 2 and increases linearly until it intersects with the target level of release.

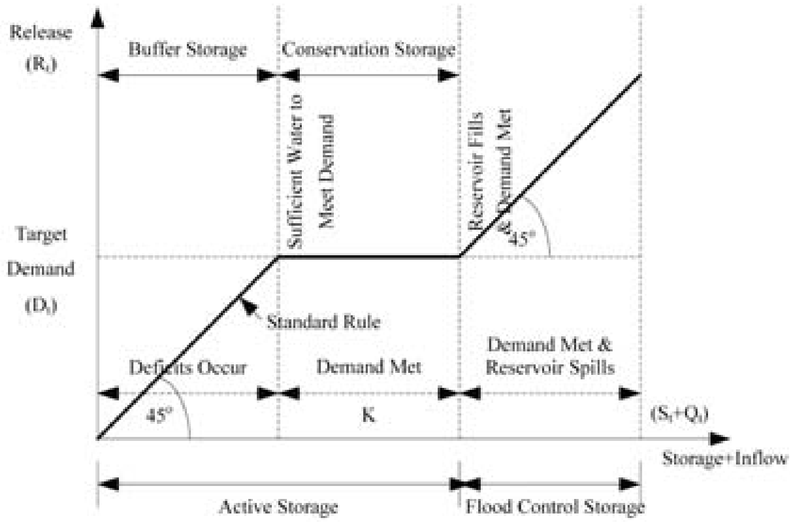

Figure 1 Standard operating policy.

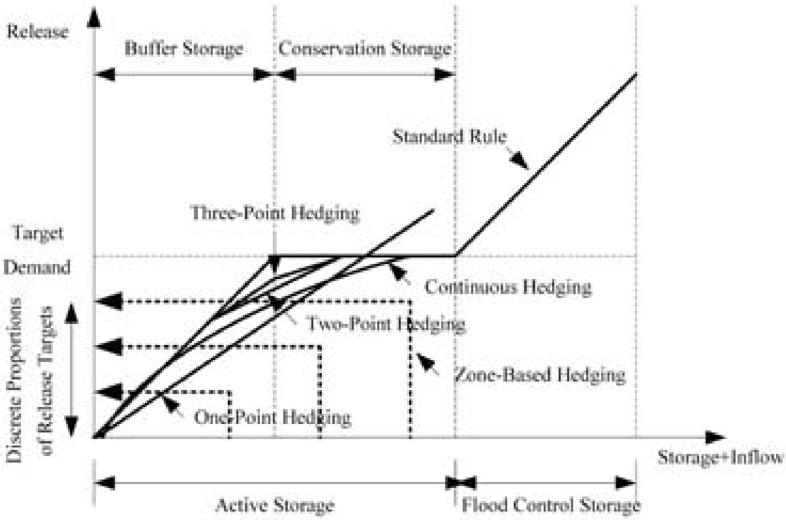

Figure 2 Types of hedging rules.

(2) Two-point hedging; a linear hedging rule begins from a first point occurring somewhere up from the origin in the shortage portion of the standard operation policy, to a second point occurring where the hedging slope intersects the target release.

(3) Three-point hedging; an intermediate point is specified in the above rule, introducing two linear portions to the hedging portion of the overall release rule.

(4) Continuous hedging; the slope of the hedging portion of the rule can vary continuously.

(5) Zone-based hedging; hedging quantities are discrete proportions of release targets for different zonal levels of water availability.

This study aimed to examine the performance of reservoir operation when various types of hedging policy were used to determine the release rules. The simulated results were compared with the standard operating policy and probability based rule curve. The Mun Bon and Lam Chae reservoirs were selected for a case study.

MATERIALS AND METHODS

Required data

(1) The monthly hydrological data was gathered and preliminarily examined for the period 1952 to 2004 from the Mun Bon and Lam Chae reservoirs to determine the reservoir water balance. The data was composed mainly of inflow, rainfall and evaporation figures for each reservoir. Because the Mun Bon and Lam Chae dams became operational as reservoirs in 1995, the monthly inflow data prior to 1995 was measured from streamflow gauging stations and some missing data was reconstituted using HEC-4. The reservoir inflow data after construction had been completed was calculated using the concept of reservoir water balance based on evaporation and losses that had been observed previously.

(2) The monthly historical data for the two reservoirs was collected covering the water stage, water storage and water release data.

(3) The existing water demand for agricultural uses and non-agricultural uses in 2004 was estimated.

(4) Physical reservoir data such as reservoir storage zones, elevation-area-storage curves and irrigable area amongst other data was used.

(5) The probability-based rule curve with 5% allowable risk was used as the release decision rule for each reservoir (Table 1).

Table 1 Probability based rule curve with 5% allowable risk of Mun Bon and Lam Chae reservoirs (all figures are millions of cubic meters).

Month	Mun Bon reservoir		Lam Chae reservoir	
	URC	LRC	URC	LRC
Jan	140.87	71.81	267.89	134.31
Feb	140.65	70.12	274.09	122.94
Mar	141.00	56.29	273.55	101.16
Apr	141.00	46.69	273.26	74.09
May	140.39	40.14	262.46	56.72
Jun	135.64	37.19	253.04	50.70
Jul	127.60	34.23	254.99	38.81
Aug	117.92	22.36	247.88	37.91
Sep	79.81	24.57	191.43	20.83
Oct	95.17	20.77	158.21	52.43
Nov	130.77	20.77	270.05	37.48
Dec	141.00	75.66	274.88	154.92

Source : (Rittima, 2002)

Methods

(1) Construct the reservoir operation model for the Mun Bon and Lam Chae reservoirs as a simulation model using the Simulink Toolbox in Matlab. The various forms of hedging policy such as one-point, two-point, three-point, and zone-based hedging were used to formulate the reservoir operation rules. The simulation results in terms of failures frequency, average annual shortage and end-water availability were explored by a comparison with the standard operating policy.

(2) Evaluate the reservoir performance indices for each reservoir policy.

The study area

The Mun Bon and Lam Chae reservoirs are located in Nakhon Ratchasima province covering a total drainage area of 1055 km^2 in the Upper Mun river basin. The location and a river schematic diagram are shown in Figure 3. Water stored by these reservoirs is used for agriculture, domestic-municipal and industrial water supply and for downstream control of the Mun Bon Irrigation Project.

The reservoir capacity of the Mun Bon and Lam Chae reservoirs is approximately 141 and 275 × 10^6 m^3, respectively. The long-term average annual rainfall is rather high over this study area, ranging between 1070 and 1200 mm/yr. The average annual inflow is 93.89 and 207.43 × 10^6 m^3/yr for the Mun Bon and Lam Chae reservoirs, respectively. The annual reservoir losses from evaporation and seepage are 19.58 and 33.33 × 10^6 m^3/yr for the Mun Bon reservoir and Lam Chae reservoirs, respectively. The general characteristics of the Mun Bon and Lam Chae reservoirs are summarized in Table 2.

The total irrigated area served by the Mun Bon reservoir is 45,136 rai in the wet season and 17,933 rai in the dry season, which equals the total water availability. On the other hand, the irrigated area served by the Lam Chae reservoir is only partly cultivated, since it is newly developed. In addition, the Mun Bon reservoir must allocate 0.03 × 10^6 m^3/yr for the Charakae Hin subdistrict municipality, Khon Buri district and 4.80 × 10^6 m^3/yr for downstream control. The Lam Chae reservoir must allocate 61.56 × 10^6 m^3,/yr for downstream control.

RESULTS AND DISCUSSION

Formulation of reservoir operation model

The reservoir operation model of the Mun Bon and Lam Chae reservoirs was

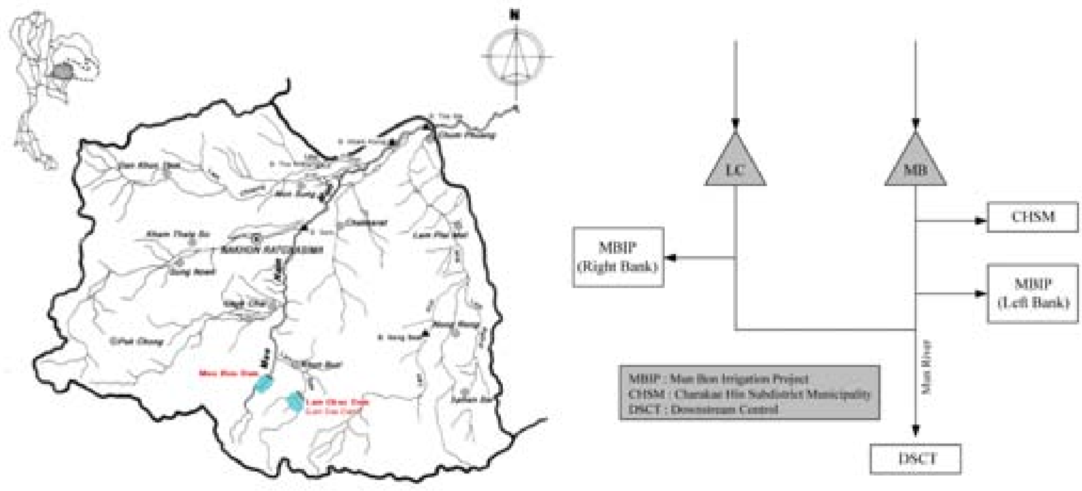

Figure 3 Location of the study area-Upper Mun river basin and river schematic diagram.

constructed using the Simulink Toolbox in Matlab. Model formulation proposed optional guidelines for reservoir release instead of using the usual traditional policy. Therefore, various types of hedging policy were utilized and the simplified water balance approach was applied for tracking reservoir operation.

The model was designed to be displayed graphically, with five main components: input data, reservoir data, reservoir operation system and reservoir performance indicators. In the designed model, the reservoir data required for water balance modeling was used as input data and included inflow data, rainfall data, losses data, water demand data, and physical reservoir data. In addition, the model also contained several types of hedging policy in parts of the reservoir operation system in order to specify the release rules. The reservoir performance indicators were measured by considering aspects of the available water supply, with the input and output datasets being presented as a time-series plot. The model configuration is shown in Figure 4.

Table 2 The general characteristics of the Mun Bon and Lam Chae reservoirs.

Characteristics	Mun Bon reservoir	Lam Chae reservoir
1. Location	Khonburi, Nakhon Ratchasima province	
2. Drainage area (km^2)	454	601
3. Minimum pool level (10^6 m^3)	7	7
4. Maximum pool level (10^6 m^3)	141	275
5. Average annual rainfall (mm/yr)	1,200	1,070
6. Average annual inflow (10^6 m^3/yr)	93.89	207.43
7. Average annual losses (10^6 m^3/yr)	19.58	33.33
8. Irrigated area (rai)		
-Wet season	41,400	113,750
-Dry season	16,330	64,260

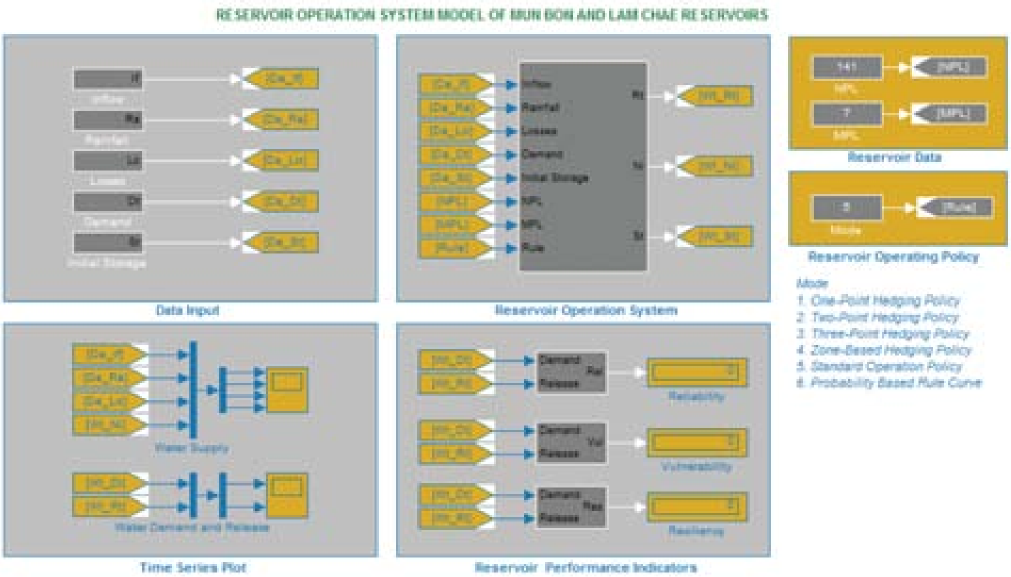

Figure 4 Reservoir operation model of the Mun Bon and Lam Chae reservoirs.

Determination of hedging policy

The determination of various hedging policies referred to the possible different situations of reservoir behavior that could occur. The patterns of each hedging policy were specified as follows:

(1) One-point hedging; the starting point of the target release level was set at 5%, 10% and 20% of the total capacity of the Mun Bon reservoir and was adjusted to 1%, 2% and 3% of the total capacity for Lam Chae reservoir.

(2) Two-point hedging; the first point was specified at 70%, 80% and 90% of the release target, which was in the shortage portion of the standard operating policy for both reservoirs. The second point was only specified at 10% and 2% of total reservoir capacity for the Mun Bon and Lam Chae reservoirs, respectively, on the release target line.

(3) Three-point hedging; two linear portions of the release rule had to be specified in this policy, so therefore, the middle point was added, while the determination of the first point and last point remained the same as for two-point hedging. For the Mun Bon reservoir, the middle point was determined at 8.5%, 9% and 9.5% of the total capacity, while the middle point was set at 0.5%, 1% and 1.5% of the total capacity for the Lam Chae reservoir.

(4) Zone-based hedging; for the Mun Bon reservoir, two rules of zone-based hedging were set using the discrete proportions of the release targets for different zonal levels of water availability. When the reservoir filled from zero storage to 10% of the total capacity, only 80% of the target release was satisfied for both rules. If the reservoir storage increased up to 20% of the total capacity for rule 1 and 25% of the total capacity for rule 2, only 90% of the target release was met. When the reservoir storage increased up to the full storage capacity, the full target release was completely satisfied for both rules. Likewise, two rules of zone-based hedging were specified for the Lam Chae reservoir. Only 80% of the target release was met when the reservoir storage varied between 0 to 1% of the total capacity for rule 1 and between 0 to 1.5% of the total capacity for rule 2. When the reservoir storage increased up to 2% and 3% of the total capacity for rules 1 and 2, respectively, 90% of the target release was allowed. Finally, the full target release was satisfied for the remaining zonal level of water availability.

However, continuous hedging was omitted in this study because of the difficulty of finding the proper formulas to represent the existing reservoir operation in the selected study area.

As mentioned above, it was noticeable that two important factors; the percent of water storage and the allowable water release, were used to specify the parameters for each hedging policy under the real-life conditions for the reservoir. For example, the parameter of one-point hedging and the second point of two-point hedging, the second and third points of three-point hedging, as well as the first point of zone-based hedging were set up by reference to the probability-based lower rule line. Additionally, the traditional reservoir release condition was taken into account, so that the level was not allowed to be lower than 70 to 80% of total water demand, otherwise it produced a high deficit for all water users. Consequently, some hedging policies used in this study were specified as ranging between 70 and 90% of total water demand. However, it seemed like there were no precise criteria to specify the parameters of the hedging policy transparently because all of these values must actually be prescribed by the reservoir operators in order to address the allowable risk by learning from experience and expertise in the reservoir operation.

The results of reservoir operation simulation

Table 3 presents the simulated results from the reservoir operation model of the Mun Bon and Lam Chae reservoirs, which were produced in this study. The three main characteristics including the failure frequency, average shortage and end-water availability were investigated and compared. The description of the simulated results is explained in the following section.

Mun Bon reservoir

The simulated results for the Mun Bon reservoir, showed that the frequency of failure resulting from one-point hedging ranged between 24.92 and 28.86%, which was greater than that resulting from using the standard operating policy for reservoir operation. However, when two-point hedging was applied, the failure frequency tended to be lower, ranging from 8.99 to 14.67%. For three-point hedging, the failure frequency varied between 12.62 and 14.98%, which was much lower than that resulting from using the standard operating policy and one-point hedging. However, it was more frequently in the range from 48.26 to 55.21% when different types of zone-based hedging were employed. By contrast, the failure frequency from the probability based rule curve with 5% of allowable risk was almost zero, being only 0.95%.

The study results also considered a part of the average annual shortage of each reservoir operating policy. It appeared that the annual shortage was between 14.82 and 16.58 × 10^6 m^3/hr for one-point hedging, which was the same as for the standard operating policy. Moreover, the annual shortage became much lower ranging between 0.55 and 0.77 × 10^6 m^3/yr for two-point hedging and between 0.75 and 2.48 × 10^6 m^3/yr for three-point hedging. However, the zone-based hedging gave the highest annual shortage of 26.43 to 27.09 × 10^6 m^3/yr. It also appeared that the shortage hardly ever occurred when the probability based rule curve was used.

In addition, the end-water availability was investigated in order to compare the available reservoir storage of each operating policy at the end of the simulation period. The results showed that the final reservoir storage resulting from two-point and zone-based hedging was nearly the same as the standard operation policy, which ranged from 12.50 to 15.58% of total reservoir capacity. The end-water availability seemed to be lower

Table 3 Reservoir simulation results (mcm = million cubic meters).

Reservoir operating policy	Mun Bon reservoir			Reservoir operating policy	Lam Chae reservoir		
	Failure frequency (%)	Average shortage (mcm/yr)	End-water availability (%K)		Failure frequency (%)	Average shortage (mcm/yr)	End-water availability (%K)
SOP	24.13	14.42	12.50	SOP	25.39	36.38	6.48
0.05-PBRC	0.95	0.06	29.55	0.05-PBRC	1.23	0.98	6.48
1-point hedging				1-point hedging			
0.05K 24.92	14.82	17.25	0.01K	25.87	37.00	7.45	
0.10K 25.55	15.31	22.00	0.02K	27.69	38.68	6.75	
0.20K 28.86	16.58	31.50	0.03K	28.23	40.16	9.40	
2-point hedging				2-point hedging			
0.70D-0.10K	8.99	0.77	13.81	0.70D-0.02K	6.62	2.79	6.48
0.80D-0.10K	9.31	0.54	13.37	0.80D-0.02K	6.62	2.12	6.48
0.90D-0.10K	14.67	0.55	13.18	0.90D-0.02K	6.62	1.45	6.48
3-point hedging				3-point hedging			
0.70D-0.085K-0.10K	14.98	2.48	7.42	0.70D-0.005K-0.02K	6.47	1.49	6.48
0.80D-0.090K-0.10K	14.04	1.59	7.30	0.80D-0.010K-0.02K	6.47	0.99	6.48
0.90D-0.095K-0.10K	12.62	0.75	6.91	0.90D-0.015K-0.02K	6.47	0.50	6.48
Zone-based hedging				Zone-based hedging			
0.10K:0.80D/0.20K:0.90D/K:D	48.26	26.43	15.58	0.010K:0.80D/0.02K:0.90D/K:D	31.86	61.25	6.48
0.10K:0.80D/0.25K:0.90D/K:D	55.21	27.09	15.58	0.015K:0.80D/0.03K:0.90D/K:D	34.07	62.20	6.48

between 6.91 and 7.42% of total reservoir capacity for three-point hedging. On the other hand, one-point hedging gave a wide range of water availability that varied between 17.25 and 31.50% of the total reservoir capacity, which was the highest final storage when compared with the other rules and was very close to the probability based rule curve.

Lam Chae reservoir

For Lam Chae reservoir, it was apparent that the three components of the simulated results (failure frequency, average shortage and end-water availability) that resulted from two-point and three-point hedging were almost the same and also gave the better results when compared with the other hedging rules or the standard operation policy. In addition, all types of two-point and three-point hedging gave the same values in terms of the percentage of failure frequency and end-water availability. Only 6.6 and 6.47% failure frequency occurred with two-point hedging and three-point hedging, respectively, whereas the final storage of these two policies was 6.48% of total reservoir capacity. Additionally, the average shortage was slightly different among the different types of two-point and three-point hedging, which merely varied between 0.50 and 2.79 × 10^6 m^3/yr. All components of the simulated results of one-point hedging were very close to the standard operating policy. The percentage of failure frequency for one-point hedging ranged between 25.87 and 28.23%, which was higher than for either two-point or three-point hedging. The average shortage seemed to be the highest ranging from 37.00 to 40.16 x 10^6 m/yr. In contrast with the 5% allowable risk probability based rule curve, all types of zone-based hedging gave poor results, especially in failure frequency and average shortage terms, even though the end-water availability remained the same as for the other rules.

In summary, two-point and three-point hedging gave similar results regarding failure frequency, average annual shortage and end-water availability. Moreover, their results were better than those that resulted from using other hedging rules, as well as for the standard operation policy. However, it was apparent that the results were quite different from using the 5% allowable risk of probability based rule curve. The reason was that the selected rule curve was actually constructed based on the probability of reservoir inflow corresponding to the allowable failure risk as specified. Consequently, it gave the best, simulated results in comparison with other rules.

Evaluation of reservoir performance indices

To explore the performance of reservoir operation using the various operating policies, the three major performance indicators of reliability, vulnerability and resiliency were estimated. Reliability actually represents the probability of non-failure performance during the entire operation period. The severity of failure during a failure period is measured by vulnerability. Resiliency explains the rapidity of recovery time from failure (McMahon *et al*., 2005). The simulations produced the following results.

Mun Bon reservoir

The performance indicators for the Mun Bon reservoir are shown in Figure 5. The reliability resulting from one-point hedging was very close to that obtained by using the standard operation policy, which ranged between 71.14 and 75.08%. Moreover, it tended to be higher between 85.33 and 91.01% for two-point hedging and slightly less between 85.02 and 87.38% for three-point hedging. However, very poor results were obtained when zone-based hedging was used. Almost half of the entire operation was in the non-satisfactory period. Meanwhile, the 5% allowable risk of probability based rule curve gave the highest reliability of 99.05% because it had the upper limit and lower limit lines at an acceptable level of performance to guide how much water should be released during that period. The small shortages resulting from two-point and three-point hedging were very close to the probability based rule curve ranging between 0.51 and 1.90 × 10^6 m^3/yr.

Meanwhile, the severity of water shortage resulting from one-point and zone-based hedging, as well as from the standard operation policy were in the same range of 10.40 to 12.35 × 10^6 m^3/yr or 12.75 to 15.14% of the annual water requirement for the Mun Bon reservoir. In addition, the highest value of resiliency that was obtained from two-point hedging implied that the recovery times from unsatisfactory situations were faster than under the other operating policies.

Lam Chae reservoir

There were many similarities in the simulated results between the Lam Chae and Mun Bon reservoirs as presented in Figure 6. All types

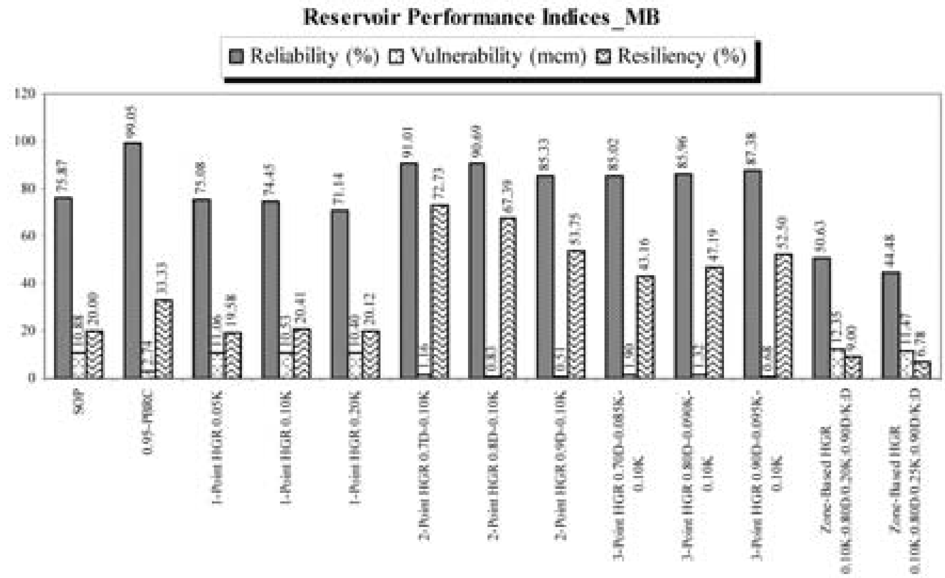

Figure 5 Reservoir performance indices for the Mun Bon reservoir (mcm = millions of cubic meters).

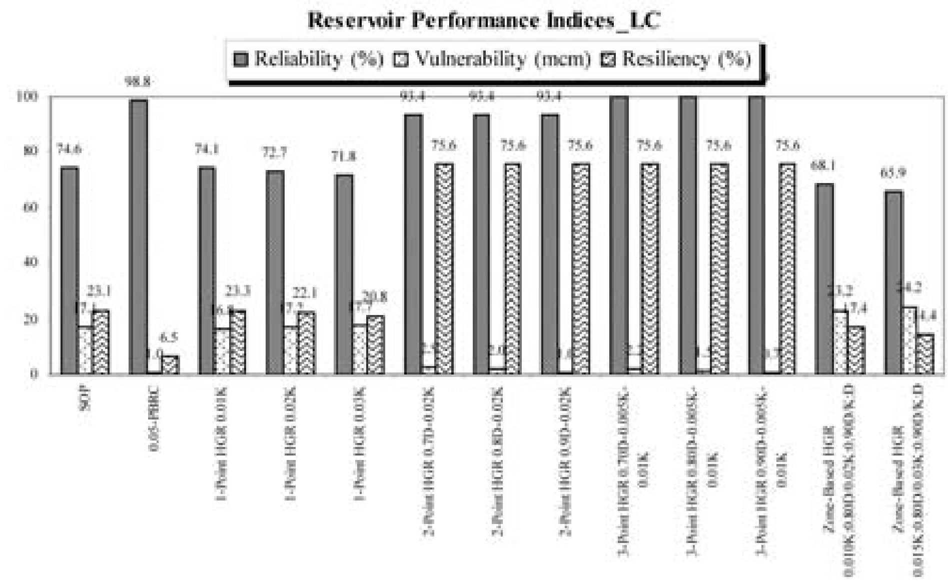

Figure 6 Reservoir performance indices for Lam Chae reservoir (mcm = millions of cubic meters).

of two-point and three-point hedging performed well in terms of the reliability, vulnerability and resiliency indices. Reliability was very high at 93.38% and 99.93% for two-point and three-point hedging, respectively. These figures meant that the possibility that the reservoir could deliver sufficient water to meet target demand was very high. Furthermore, only a very small shortage of 0.73 to 2.94 × 10^6 m^3/yr occurred during the simulation period. However, there was a very quick recovery from that situation because the value of the resiliency term was very high (75.61%) in comparison with the other reservoir operating rules. In a similar manner to the Mun Bon reservoir, the performance indicators for one-point hedging were very close to the standard operation policy, whereas the zone-based hedging gave the opposite results for every component of reservoir behavior.

CONCLUSIONS

This study examined different types of hedging policy: one-point, two-point, three-point, and zone-based hedging to formulate the release decision rules for the Mun Bon and Lam Chae reservoirs. Results considered in the study were: the failure frequency, average annual shortage, end-water availability and performance indicators, which were compared with the standard operation policy together with the probability based rule curve. The following conclusions were drawn from the study:

(1) The simulated results confirmed that two-point and three point hedging gave similar results for all components of reservoir behavior investigated. The results also showed that all reservoir performance indicators under these policies were better than under the standard operation policy or one-point or zone-based hedging.

(2) Two-point and three-point hedging could reduce the risk of water shortage during the simulation period, which was indicated by the values of the failure frequency and average annual shortage. In addition, the water availability at the end of the simulation period also confirmed that the simple-release concept of the hedging policy could retain some water for use in later periods.

(3) Setting the pattern of hedging policy had an impact on the outcomes of the study. Consequently, an optimization technique should be used in order to determine the most adequate hedging pattern for a real-life reservoir system situation and also to enhance the usefulness of a hedging policy for reservoir operation.

ABBREVIATIONS

MB = Mun Bon reservoir
LC = Lam Chae reservoir
km^2 = Square kilometer
mm/yr = Millimeter per year
SOP = Standard operation policy
PBRC = Probability based rule curve
URC = Upper rule curve
LRC = Lower rule curve
K = Reservoir capacity
D = Water demand

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