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Optimal Hedging Policies for Hydropower Generation at Ubolratana Reservoir

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ABSTRACT

Hydropower is regarded as an important source of electrical energy to enhance the efficiency of renewable energy use. However, the effects of the inflow uncertainty on a reservoir operation which cannot maintain the water level so that it is sufficient for generating power in some critical periods, makes reliable energy generation in certain periods unpredictable. Thus, this research developed different types of optimal hedging policies (one-point hedging, two-point hedging, three-point hedging, multiple hedging-non seasonal effects and multiple hedging-seasonal effects), which facilitate energy generation in association with basic operational concepts. The aim of the hedging policies was to reduce the water release in some periods even when there was enough water for serving all sectors of water demand. Consequently, the water level in the reservoir would be higher and this would be beneficial for energy generation. This research used the reservoir water balance concept to construct a reservoir operational model and applied the optimization approach with a genetic algorithm to find the optimal parameters of each policy. The Ubolratana Reservoir in Thailand was selected as the study area. The simulated results and their performance based on the reservoir operational model with the optimal hedging policies using daily long term data from 1970 to 2010 showed that using the various types of optimal hedging for the reservoir operation produced higher levels of firm energy. Moreover, the two types of multiple hedging gave better performance in terms of higher energy production compared to the existing rule curve. Additionally, using optimal multiple hedging with the seasonal parameters for operation increased energy production by controlling the reservoir water level so that it did not exceed the normal pool level and was not lower than the minimum pool level. In principle, when the optimal hedging policies were applied, the water storage in the reservoir was strictly limited and did not encroach the surcharge storage and inactive zones in some critical drawdown and fulfilled periods. Therefore, some water storage was kept in the active storage zone and was beneficial for energy generation together with other off-stream uses downstream.

Keywords: reservoir operation, hydropower, Ubolratana Reservoir

INTRODUCTION

Most large reservoirs in Thailand have been developed predominantly for hydropower purposes to enhance the efficiency of renewable energy sources and to reduce the cost of commercial energy which become more expensive nowadays. The scheme to develop new hydropower plants has

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also been extended to medium and small reservoirs to increase the potential of hydropower production to meet the rising demand for electricity in the future. In general, generating hydropower from a reservoir system is undertaken in co-operation with other off-stream uses like irrigation and municipal demand, among others, to meet the goal of multipurpose reservoir operation. However, the different reservoir purposes need different reservoir operation schemes and also result in the reservoir operation being complex. The coordinated operation of multipurpose and multi reservoir systems requires an effective decision-making process which involves many decision variables, multiple objectives, considerable risk and uncertainty (Oliveira and Loucks, 1997). Therefore, various reservoir operational policies have been created and used as guidance tools specifically to assist operators in decision making during normal and critical operational periods.

Hedging policies have been increasingly emphasized for the appropriate operation of reservoir systems since the early 2000s. It is actually the modified form of the Standard Operating Policy (SOP) which is the basic source of reservoir operational guidelines. In principle, a hedging policy is normally used for rationing the water supply during severe drought and bringing down the higher deficits by marginally reducing the normal supply in some periods (Neelakantan and Pundarikanthan, 1999; Rittima, 2009). The aim of hedging is to distribute the anticipated deficit uniformly, so that its severity is reduced (Jain and Singh, 2003). By doing this, the reservoir water storage would be preserved for future requirements and can supply at a higher level in the following periods which is beneficial for energy generation at the same time. There are various forms of hedging such as one-point hedging, two-point hedging, three-point hedging, continuous hedging and multiple hedging as shown in Figure 1 (Draper and Lund, 2004).

The release policy of one-point hedging begins at the origin and increases linearly until it intersects with the target level of release and the release determination is then conformed to the SOP. For two-point hedging, a linear hedging rule begins from a first point occurring somewhere up from the origin on the shortage portion of the standard operation policy to a second point occurring where the hedging slope intersects the target release. The three-point hedging is adapted from two-point hedging; consequently an intermediate point is specified to introduce two linear portions to the hedging portion of the overall release policy. For continuous hedging, the

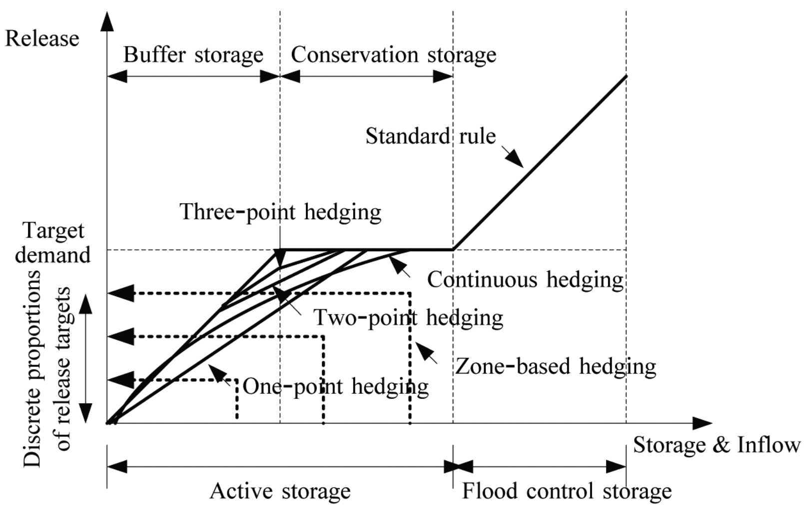

Figure 1 Types of hedging policies.

slope of the hedging portion is adjusted smoothly. Meanwhile, the release policy of multiple hedging is specified as the discrete proportions of release targets for different zonal levels of water availability. The parameters of multiple hedging comprise the threshold storage levels of $L_1, L_2, \ldots, L_n$ and hedging factors of $HF_1, HF_2, \ldots, HF_n$ which represent the release ratios at the storage levels of $L_1, L_2, \ldots, L_n$, respectively. These threshold storage levels are specified as the active reservoir capacity ratio (K) whereas the derivation of hedging factors refers to the target water demand.

It appears that the application of hedging policy for the appropriate reservoir operation has been mostly presented in terms of optimal hedging; consequently, the optimization-simulation technique has been used to develop the different types of optimal hedging. For instance, Shiau and Lee (2005) proposed compromise programming and combined simulation techniques to derive the optimal hedging policies for a water supply reservoir. Neelakantan and Pundarikanthan (1999) developed a methodology for reservoir operational planning in Chennai city with the application of optimal multiple hedging policies through the combined use of the simulation-optimization approach. In addition, to save time in finding the optimal parameter set of hedging, the genetic algorithm (GA) has been intensively used. The GA is actually based on the biological principles of evolution and provides an interesting alternative to classical gradient-based optimization methods. It is particularly useful for highly nonlinear problems and models. The GA approaches the entire design space randomly and then improves the found design points by applying genetics-based principles and probabilistic selection criteria (Schreyer, 2006). The GA has been widely applied for finding the optimal reservoir operation rules. For example, Oliveira and Loucks (1997) proposed an approach to identify the reservoir operating rules using genetic algorithms. Harmwichian *et al.* (2009) developed a conditional genetic algorithm model for searching the optimal reservoir rule curves of the reservoir system located in northeastern Thailand. Kim *et al.* (2008) also proposed a multiobjective genetic algorithm to develop single reservoir operating rules.

Following the basic principle of hedging policy in raising the water head in the reservoir in some periods, this study used the derived optimal hedging policies to benefit energy production improvement and selected the Ubolratana Reservoir in Thailand as a case study. The optimization approach with the genetic algorithm was applied in the derivation of the optimal parameters of each policy and to determine the maximum energy production generated over the operational periods.

METHODS

Data collection and water requirement estimation

The daily historical data associated with the mass balance of Ubolratana Reservoir and operational records were collected. The data comprised rainfall, inflow, evaporation and seepage, all sectors of water requirement, reservoir release and actual energy production from 1970 to 2010. The data were preliminarily checked and corrections made by time series plotting for missing and abnormal data. In addition, estimation of the water requirements in the Nong Wai irrigation project was carried out based on the actual diversion released through two main canals above the Nong Wai weir and the water allocation plan provided by the Royal Irrigation Department (RID). Hence, each sector of water requirement—both irrigation and downstream control—was generated and finally combined.

Development of reservoir operation model

The conventional mass balance principle was used to develop the operation model of Ubolratana Reservoir. This operation model was constructed on a daily basis and used the initial storage, inflow, precipitation and evaporation data as the major inputs. The developed operation model was calibrated to find the suitable parameters for a multi-objective reservoir system and also so that its performance could also resemble that of actual operation. The determination of modeled release at different times was done by considering the optimal hedging policies derived from the embedded optimization submodel. Therefore, a set of decision variables, the objective function and the constraints of the optimization submodel were formulated as one part of the reservoir operation model to help in solving the optimal parameters of the hedging policies.

Derivation of optimal hedging policies

(1) Problem formulation with optimization technique

The embedded optimization submodel was formulated to obtain the different forms of optimal hedging policies. This study proposed one-point hedging, two-point hedging, three-point hedging and multiple hedging with yearly and seasonal parameters to demonstrate their operational performances by comparison with the data received from the actual operation. The parameter a_1 of the one-point hedging that represents the changing point on the target demand line was specified as a decision variable—that is, the optimal parameter a_1 on the target demand line needs to be solved. Similarly, for the two-point and three-point hedging, where b_1, b_2 and c_1, c_2, c_3 are parameters set, respectively, the distinct points on the proportional line and also the target demand line are specified as the decision variables. For multiple hedging, only a set of the threshold storage levels, L_1, L_2, …, L_n is specified as the decision variable of the optimization submodel. This study used n = 3 to represent the different parameters of multiple hedging policies used for the different reservoir states covering the drawdown, normal and fulfilled operational periods, respectively—these parameters were solved to find the optimal discrete proportions of release targets for the optimal zonal levels of water availability as shown graphically in Figure 2.

The Ubolratana Reservoir has also been designed for the supply of hydropower. Therefore, to enhance the functional efficiency in hydropower production, the objective functions considered in the reservoir optimization submodel were defined by maximizing the energy production over the operational periods. The capability of reservoir operation to fulfil the irrigation requirement was still taken into account by measurements from the reservoir performance indicators. The constraint specifications covered the major parts of the reservoir's characteristics corresponding to release target, actual release, reservoir storage, power production and the restricted constraint of the non-linear optimization. The release target constraints of the various types of hedging policies were defined by referring to the target demand and the available reservoir storage in the different periods. The reservoir continuity equation was used to specify the actual release and reservoir storage constraints. The total release volume was considered from power and non-power outlets and the release at each period was limited to not more than the maximum permissible reservoir release. The reservoir storage constraint was set to range from dead storage to full storage over the time horizon. The constraint for power production was also defined by the maximum capacity to produce power and the minimum requirement for hydroelectricity. In addition, the optimization technique with the genetic algorithm was applied to solve the optimal parameters of the proposed hedging until reaching the maximum values of the objective function and satisfying these constraints as defined below.

(2) Objective function

Maximize $$G = \sum_{t=1}^{T} \bar{n}.\gamma.R_t^p.H_t.t$$

(3) Constraints

(3.1) Release target

■ One-Point hedging

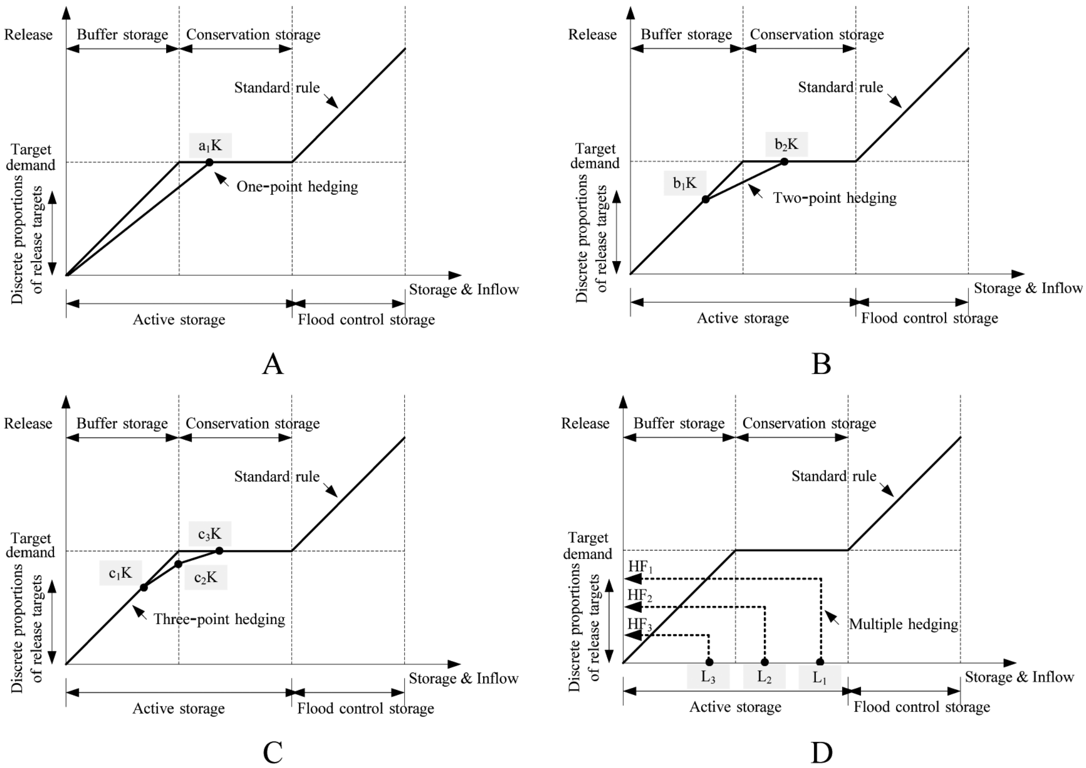

Figure 2 Various form of hedging policies and their parameters: (A) One-Point hedging; (B) Two-Point hedging; (C) Three-Point hedging; and (D) Multiple hedging. (a_1; b_1, b_2; c_1, c_2, c_3; and L_1, L_2, …, L_n represent the changing point on the target demand line specified as a decision variable for one-point, two-point, three-point and multiple hedging, respectively; HF_1, HF_2, HF_3 are the hedging factors; and K is the active reservoir capacity.)

$$T_t = S_{t-1} - S_{NPL} \ ; \ S_{t-1} \geq S_{NPL}$$

$$T_t = D_t \ ; \ [S_{MPL} + S_{a_1K}] \leq S_{t-1} < S_{NPL}$$

$$T_t = [\frac{S_{t-1} - S_{MPL}}{S_{a_1K}}] x D_t \ ; \ S_{MPL} \leq S_{t-1} < [S_{MPL} + S_{a_1K}]$$

$$T_t = 0 \ ; \ S_{t-1} < S_{MPL}$$

■ Two-Point hedging

$$T_t = S_{t-1} - S_{NPL} \ ; \ S_{t-1} \geq S_{NPL}$$

$$T_t = D_t \ ; \ [S_{MPL} + S_{b_2K}] \leq S_{t-1} < S_{NPL}$$

$$T_t = [\frac{S_{t-1} - S_{b_1K}}{S_{b_2K} - S_{b_1K}}] x D_t \ ; \ [S_{MPL} + S_{b_1K}] \leq S_{t-1} < [S_{MPL} + S_{b_2K}]$$

$$T_t = [\frac{S_{t-1} - S_{MPL}}{S_{b_1K}}] x D_t \ ; \ S_{MPL} \leq S_{t-1} < [S_{MPL} + S_{b_1K}]$$

$$T_t = 0 \ ; \ S_{t-1} < S_{MPL}$$

■ Three-Point hedging

$$T_t = S_{t-1} - S_{NPL} \ ; \ S_{t-1} \geq S_{NPL}$$

$$T_t = D_t \ ; \ [S_{MPL} + S_{c_3K}] \leq S_{t-1} < S_{NPL}$$

$$T_t = [\frac{S_{t-1} - S_{c_2K}}{S_{c_3K} - S_{c_2K}}] x D_t \ ; \ [S_{MPL} + S_{c_2K}] \leq S_{t-1} < [S_{MPL} + S_{c_3K}]$$

$$T_t = [\frac{S_{t-1} - S_{c_1K}}{S_{c_2K} - S_{c_1K}}] x D_t \ ; \ [S_{MPL} + S_{c_1K}] \leq S_{t-1} < [S_{MPL} + S_{c_2K}]$$

$$T_t = [\frac{S_{t-1} - S_{MPL}}{S_{c1}K}] x D_t \; ; \; S_{MPL} \le S_{t-1} < [S_{MPL} + S_{c1}K]$$

$$T_t = 0 \; ; \; S_{t-1} < S_{MPL}$$

■ Multiple hedging

$$T_t = D_t \; ; \; S_{t-1} \ge S_{L1}$$
$$T_t = HF_1 x D_t \; ; \; S_{L2} \le S_{t-1} < S_{L1}$$
$$T_t = HF_2 x D_t \; ; \; S_{L3} \le S_{t-1} < S_{L2}$$
$$T_t = HF_3 x D_t \; ; \; S_{t-1} < S_{L3}$$

(3.2) Actual release

$$R_t = S_{t-1} + I_t + P_t - E_t - K \; ; \; S_{t-1} + I_t + P_t - E_t - T_t > K$$
$$R_t = T_t \; ; \; 0 < S_{t-1} + I_t + P_t - E_t - T_t \le K$$
$$R_t = S_{t-1} + I_t + P_t - E_t \; ; \; S_{t-1} + I_t + P_t - E_t - T_t \le 0$$
$$R_t = R_t^p + R_t^s$$
$$0 \le R_t^p \le R_{max\,t}$$

(3.3) Reservoir storage

$$S_t = S_{t-1} + I_t + P_t - R_t - E_t \; ; \; S_t \le K$$
$$S_t = K \; ; \; S_t > K$$

(3.4) Power production

$$G_{min} \le G_t \le G_{max}$$

(3.5) Others

$$S_t, I_t, P_t, E_t, R_t, R_t^p, R_t^s \ge 0$$

where S_t and S_{t-1} are the reservoir storage in time t and t-1, respectively; I_t is the reservoir inflow in time t; P_t is the precipitation on the surface of the reservoir in time t; E_t is the evaporation losses in time t; T_t is the target release in time t; $L_1, L_2, \ldots, L_n$ are the threshold storage levels; $HF_1, HF_2, \ldots, HF_n$ are the hedging factors; R_t is the total reservoir release in time t; R_t^p is the reservoir release used for energy production in time t; R_t^s is the reservoir release from non-power outlets in time t; $R_{max\,t}$ is the maximum release in time t; S_{MPL} is the storage capacity at the minimum pool level; S_{NPL} is the storage capacity at the normal pool level; G_t is the energy production in time t; G_{min} and G_{max} are the minimum and maximum values of energy production; $\overline{n}$ is the efficiency coefficient of the hydropower plant; γ is the specific weight of water; H_t is the average net head level in time t; and K is the active reservoir capacity.

Evaluating the performances of reservoir operation

The long-term operation of the Ubolratana Reservoir was simulated by using the various types of optimal hedging policies for a release determination. The performance indicators of reservoir operation in terms of the modelled release, energy production and the reliability index were evaluated and finally compared with the actual operation.

Case study area

The Ubolratanra Reservoir is the major multipurpose reservoir upstream in the Chee River in northeast Thailand. This reservoir was completed in 1966 with an active storage capacity of 2,263.60 million cubic meters (mcm) mainly to provide irrigation in the Nong Wai irrigation project and for downstream river control as shown in Figure 3. The Ubolratana Reservoir was also designed for hydropower generation to accommodate the local needs in Khonkaen province and the neighboring area. The description of the general meteo-hydrological data and the reservoir system are illustrated in Table 1.

From the historical operational records collected from 1970 to 2010, it was found that the Ubolratana Reservoir used the developed rule curve as an operational guideline. However, high risk reservoir operation during the critical drawdown and fulfilled periods still occurred especially in 1978, 1982, 1986, 1994, 2002 and 2007 due to high fluctuations in reservoir inflow. Furthermore, the difficulty of controlling water storage in the Ubolratana Reservoir which has a height of 7 m above the minimum pool level made reservoir management even harder. For this reason,

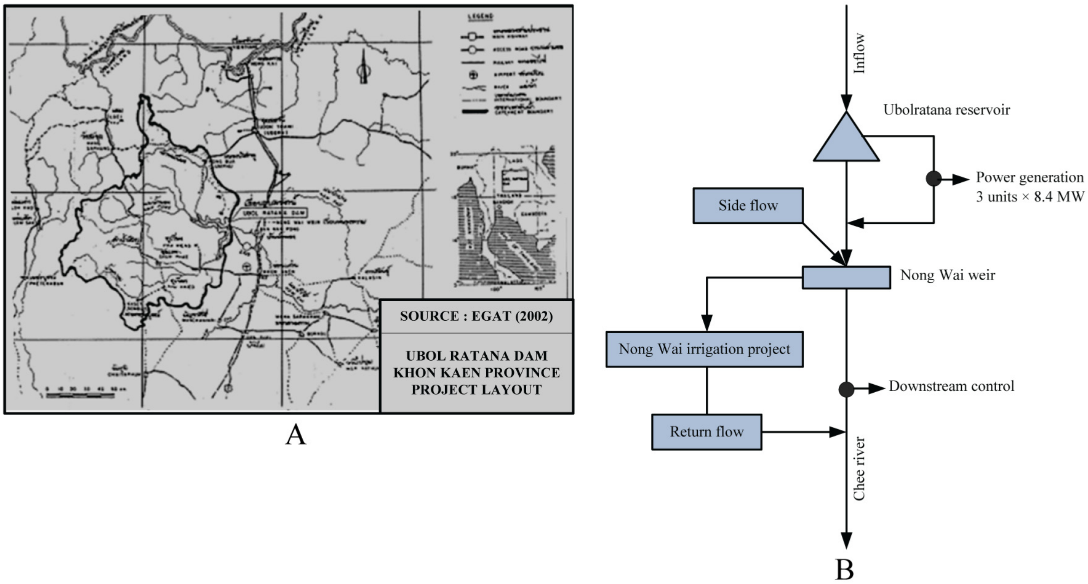

Figure 3 (A) Location of the study area at Ubolratana Reservior and (B) schematic diagram of the reservoir system.

Table 1 General meteo-hydrological data and description of Ubolratana Rreservoir.

Meteo-hydrological data		Reservoir data	
Drainage area (km^2)	12,104	Reservoir characteristics	
Annual rainfall (mm.yr^{-1})	1,200	Reservoir capacity (mcm)	2,263.60
Annual reservoir inflow (mcm.yr^{-1})	2,466	Max.PL (m msl)	186.60
Annual reservoir release (mcm.yr^{-1})	1,943	NPL (m msl)	182.00
Annual water requirement (mcm.yr^{-1})		MPL (m msl)	175.00
Irrigation	788	Hydropower plant characteristics	
Downstream control	128	Installed capacity (units × MW)	3 × 8.30
Annual energy production (GWHr.yr^{-1})	56	Total capacity (MW)	24.90

mcm = Million cubic meters, m msl = meters above mean sea level; Max.Pl = Maximum pool level; NPL = Normal pool level; MPL = Minimum pool level; MW = Megawatts.

the Ubolratana Reservoir was selected for the case study.

RESULTS AND DISCUSSION

Estimated water requirement

The Nong Wai irrigation project is situated on the downstream side of the Ubolratana Reservoir. From the recorded data in 2011, the irrigated area was 257,176 rai (1 rai = 0.16 ha) in the wet season and 167,989 rai in the dry season. It was estimated that the annual water requirement for irrigation is approximately 788 mcm based on the actual diversion release at the Nong Wai weir in the wet season and the water allocation plan of the RID in the dry season. Meanwhile, the annual water requirement for downstream river control was kept at a constant rate of 128 mcm to preserve the nature of the downstream environment. After combining these two water requirements, the generated annual water requirement on a daily basis is shown in Figure 4; there have been high fluctuations in September and October as shown by the dotted line. This was quite the opposite for the irrigated area where water supply was nearly constant even in the wet season. Hence, the average daily release (the dashed line in Figure 4) was used to adjust the generated water requirement of the reservoir system from September until the beginning of November. Finally, the adjusted water requirement (the bold line in Figure 4) was determined and used as the target release in the development of the reservoir operational model and the derivation of optimal hedging policies over the long term operational period.

Derived optimal parameters of hedging

The optimal parameters of various types of hedging were obtained by the genetic algorithm approach used in the embedded optimization submodel (Tables 2 and 3). In this searching process, a binary encoding scheme was used to transform the decision variables of each type of hedging into chromosomes. The genetic algorithm started with a finite population of randomly chosen chromosomes in the design space and its fitness value was then evaluated. All of the genetic operators—reproduction, cross-over and mutation processes—were also assigned a probability

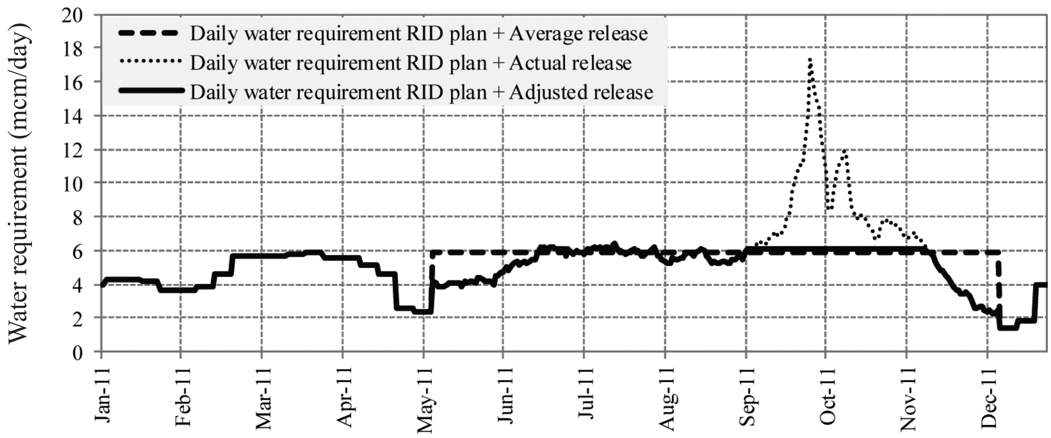

Figure 4 Annual generated water requirement of Nong Wai irrigation project. (RID = Royal Irrigation Department; mcm = Million cubic meters.)

Table 2 Optimal parameters of one-point hedging, two-point hedging and three-point hedging.

Parameter	Optimal parameter	Point	Reservoir storage (mcm)
One-Point hedging			
a_1	0.0000010	a_1K	502.30
Two-Point hedging			
b_1	0.0003524	b_1K	502.92
b_2	0.0004457	b_2K	503.08
Three-Point hedging			
c_1	0.0001691	c_1K	502.60
c_2	0.0009951	c_2K	504.05
c_3	0.0012146	c_3K	504.44

a_1; b_1, b_2; and c_1, c_2, c_3 represent the changing point on the target demand line specified as a decision variable for one-point, two-point and three-point hedging, respectively. K is the active reservoir capacity; mcm = Million cubic meters.

of occurrence. This study specified cross-over, mutation and random selection probability equal to 0.9, 0.1, and 0.1, respectively. Finally, the genetic algorithm proceeded to apply changes to the ranked individual design points which led to the best improvement of the population fitness.

It was found that the optimal parameter of one-point hedging to reach the maximum energy production was 0.0000010 which was equivalent to 502.30 mcm of reservoir capacity. This showed that the intersecting point on the target demand line of one-point hedging was very near the minimum pool level required to keep the water head in the reservoir at its highest. For two-point hedging, the distinct points on the proportional line and the target demand line were found at 502.92 and 503.08 mcm of the reservoir capacity where the optimal parameters were 0.0003524 and 0.0004457, respectively. It was noticeable that these two parameters were very close to each other and not far from the reservoir capacity at the minimum pool level. Similarly, the optimal parameter set for three-point hedging showed small differences in the distinct points on its hedging with the optimal parameters of 0.0001691, 0.0009951, and 0.0012146, respectively. The two changing slopes of this three-point hedging were between 502.60, 504.05, and 504.44 mcm of reservoir capacity.

For the multiple hedging policy with yearly parameters, it was shown that to meet the operational objectives for hydropower, the threshold storage levels of the Ubolratana Reservoir had to be maintained between 502.66 and 505.84 mcm of reservoir capacity or the optimal parameters were ranged from 0.0002030 to 0.0020090. Meanwhile, at least 80% of off-stream water uses were still served during the severe drought. It also showed similar results to the multiple hedging policies with seasonal parameters for which the threshold storage levels were between 502.82 and 505.86 mcm of reservoir capacity in the dry season and between 502.97 and 505.96 mcm of reservoir capacity in the wet season. Furthermore, each threshold storage level in the wet season was a little higher than in the dry season, which benefitted hydropower generation.

Regulating the water release from the reservoir with the optimal hedging policies was compared to the SOP. For optimal one-point hedging, it was noticeable that when the available storage was less than 502.30 mcm, the small current deficit allowed some water to remain in the reservoir. However, the release determination by optimal one-point hedging during the normal period was satisfied at the target demand level when the water storage in the reservoir ranged

Table 3 Optimal parameters of multiple hedging.

Optimal parameter	Non-seasonal effects		Seasonal-effects			
	Annual	Reservoir storage	Dry season	Reservoir storage	Wet season	Reservoir storage (mcm)
L_1	0.0020090	505.84	0.0020223	505.86	0.0020790	505.96
L_2	0.0004000	503.00	0.0016268	505.17	0.0016708	505.24
L_3	0.0002030	502.66	0.0002935	502.82	0.0003804	502.97
HF_1	0.90	-	0.90	-	0.90	-
HF_2	0.85	-	0.85	-	0.85	-
HF_3	0.80	-	0.80	-	0.80	-

L_1, L_2, …, L_n represent the changing point on the target demand line specified as a decision variable for multiple hedging; HF_1, HF_2, HF_3 are the hedging factors; mcm = Million cubic meters.

from a minimum of 502.30 mcm up to the storage capacity at the normal pool level. For the reservoir operation in the fulfilled period with optimal one-point hedging, the surplus water exceeding the storage capacity was released to avoid severe flood failure on the downstream side and to prevent dam stability problems. A small deficit still occurred with the different deficit portions after the optimal two-point and three-point hedging were employed, or the reservoir storage was less than 503.08 and 504.44 mcm, respectively. However, release determination during the normal and fulfilled periods still conformed to the SOP as it has with optimal one-point hedging. Meanwhile, water was released in different ratios from the reservoir during the drawdown period by optimal multiple hedging when the available water storage was less than 505.84 mcm for the first case, and 505.86 mcm in the dry season and 505.96 mcm in the wet season for the latter case. The release policy in the normal and fulfilled periods with the optimal multiple hedging was still the same as the SOP.

Reservoir operation results

The operation results simulated from the reservoir operation model from 1970 to 2010 showed differences in terms of release, energy production, water level, water storage and performance indicators after the various types of optimal hedging policies were performed. These results were compared with the actual operation which used the reservoir rule curve as an operating policy. The rule curve which is actually a famous guidance tool used by reservoir operators to regulate the water release was developed for Ubolratana Reservoir. However, the latest adjustment of the rule curve was carried out by the Electricity Generating Authority of Thailand for different ratios in 2002 using the HEC-3 simulation technique and has continued to be used up until the time of the study. The overall description of the simulated and calibrated operation results are shown in Table 4.

The annual release results revealed that the minimum annual release performed by the optimal one-point, two-point and three-point hedging methods ranged between 633.09 and 806.61 and between 1,517.98 and 1,519.56 mcm for optimal multiple hedging with yearly (non seasonal effects) and seasonal effects parameters, respectively. These were higher than the ones observed from the actual operational records in which the minimum annual release that could be served was merely 268.28 mcm. This indicated that the various types of optimal hedging helped in enhancing the quantity of water release especially during drawdown periods. It also confirmed that using optimal multiple hedging for reservoir operation gave better results in terms of the maximum annual release which varied by nearly 5,266 mcm. These results were slightly higher than those received from optimal one-point, two-point, and three-point hedging which were between 2.13 and 2.66% lower but these in turn were slightly higher than obtained from the actual operation by approximately 0.83%. These results also indicated that the water supply management in the reservoir with the optimal hedging especially during the fulfilled period gave results closer to the actual operation performed according to the rule curve. Moreover, there was good performance when controlling the reservoir water supply during high flow periods with optimal multiple hedging so that this method also helped in reducing any mismanagement effects on dam stability. In addition to the analyzed average annual release, it was found that all types of optimal hedging gave higher values when compared with those obtained from actual operation. The average annual releases performed by optimal one-point, two-point, and three-point hedging were not much different (around 2,000 mcm). Moreover, the average annual release received from the two types of optimal multiple hedging increased up to 2,208.06–2,209.02 mcm which were higher than obtained from the actual operation by nearly 12% as shown in Figure 5.

Table 4 Simulated reservoir operation results using various types of operating policies.

Result	Reservoir operation policy						
	Actual operation	Calibrated model	1PHG	2PHG	3PHG	MHG-NSE	MHG-SE
Modelled data							
1. Total release ($mcm.yr^{-1}$)							
Min. annual release	268.28	268.28	806.61	706.98	633.09	1,519.56	1,517.98
Max. annual release	5,222.18	5,222.18	5,153.74	5,144.76	5,125.51	5,265.82	5,265.43
Avg. annual release	1,929.93	1,929.93	2,008.13	1,986.95	1,969.07	2,209.02	2,208.06
2. Annual energy production ($MWhr.yr^{-1}$)							
Min. annual energy production	4,586.00	5,858.87	25,496.15	23,848.36	21,484.39	34,965.76	34,928.32
Max. annual energy production	122,214.30	122,262.92	112,706.75	112,706.75	112,706.75	112,706.75	197,726.74
Avg. annual energy production	61,537.56	61,581.41	61,439.85	60,783.98	60,237.98	67,699.36	80,400.94
3. Reservoir water level (m msl)							
Min. water level	173.26	172.80	175.08	175.08	175.08	175.08	175.08
Max. water level	183.70	185.17	179.77	179.77	179.77	179.77	179.77
Avg. water level	178.14	178.22	177.06	177.06	177.06	177.06	177.06
4. Reservoir storage (mcm)							
Min. reservoir storage	335.20	335.06	518.82	518.68	519.87	518.31	518.39
Max. reservoir storage	3,283.50	3,788.28	1,547.90	1,547.90	1,547.90	1,547.90	1,547.90
Avg. reservoir storage	1,231.61	1,232.20	943.90	944.02	944.42	943.18	943.24
Reservoir indices							
Reliability indices (%)	88.87	89.72	84.12	84.68	87.02	79.05	79.13
1. Shortage mode	90.66	93.81	84.12	84.68	87.02	79.05	79.13
2. Spillage mode	98.21	95.91	100.00	100.00	100.00	100.00	100.00

mcm = Million cubic meters; m msl = meters above mean sea level; Min. = Minimum, Max. = Maximum, Avg. = Average; MWhr = Megawatt hour.

1PHG = One-Point hedging; 2PHG = Two-Point hedging; 3PHG = Three-Point hedging; MHG-NSE = Multiple hedging–non seasonal effects; MHG-SE = Multiple hedging–seasonal effects.

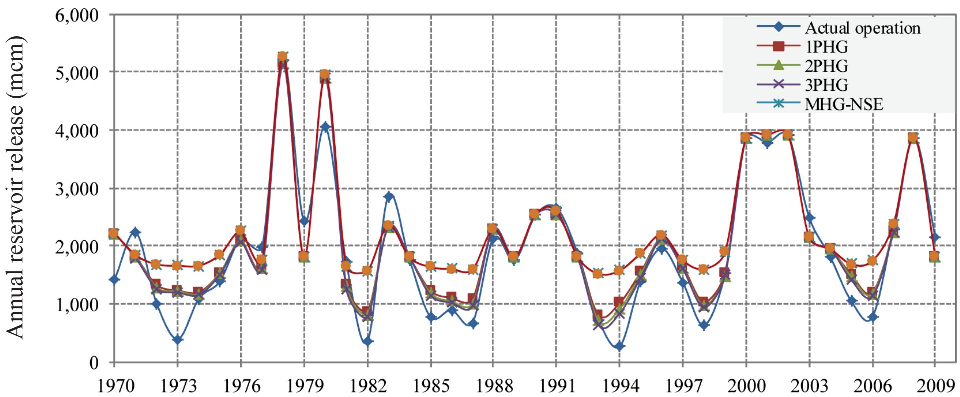

Figure 5 Annual release obtained from various types of hedging policies. (1PHG = One-Point hedging; 2PHG = Two-Point hedging; 3PHG = Three-Point hedging; MHG-NSE = Multiple hedging–non seasonal effects; MHG-SE = Multiple hedging–seasonal effects; mcm = Million cubic meters.)

The efficiency of energy production of the Ubolratana Reservoir was partially associated with the water release data performed by the various types of optimal hedging. Consequently, when the optimal one-point, two-point, and three-point hedging was applied, the minimum value of annual energy production (the firm energy) ranged between 21,484.38 and 25,496.15 Megawatt hours (MWhr) which was higher than the actual operation data. Moreover, the minimum energy production per year greatly increased to 34,923.32–34,965.76 MWhr when the optimal multiple hedging was used which equated to a 78.65–86.88% energy increase. Meanwhile, operating the reservoir under the existing rules generated the minimum annual energy production of 4,586 MWhr because of the difficulty in controlling the reservoir water level to be within the active storage zone in some periods and facilitating hydropower generation. These results confirmed that using various types of optimal hedging for the reservoir operation could produce higher amounts of firm energy. For the analyzed maximum energy production from water supply management during high flow periods, it could be said that an attempt to control water storage in the reservoir by not encroaching the surcharge storage zone by optimal hedging resulted in a decrease in the water level in the fulfilled period. Consequently, the maximum energy production achieved with the various types of optimal hedging was lower than from the actual operation excluding the optimal multiple hedging with the seasonal parameter under which the maximum energy production obtained from the long-term operation record reached 197,726.74 $MWhr.yr^{-1}$. The average energy production per year was also investigated as an indicator of the overall efficiency of energy production over the operational periods; it was expressed as the average values of the energy production resulting from the optimal one-point, two-point, and three-point hedging and ranged between 60,237.99 and 61,439.85 $MWhr.yr^{-1}$ which was very close to the actual operational data. However, the operational results showed higher values for average energy production of 67,699.36 and 80,400.94 $MWhr.yr^{-1}$ when optimal multiple hedging with yearly and seasonal parameters was applied, respectively (Figure 6).

The reservoir water level and water storage results showed that by using various types of optimal hedging as reservoir operating policies it was possible to maintain the water level in the reservoir to be within the active storage zone.

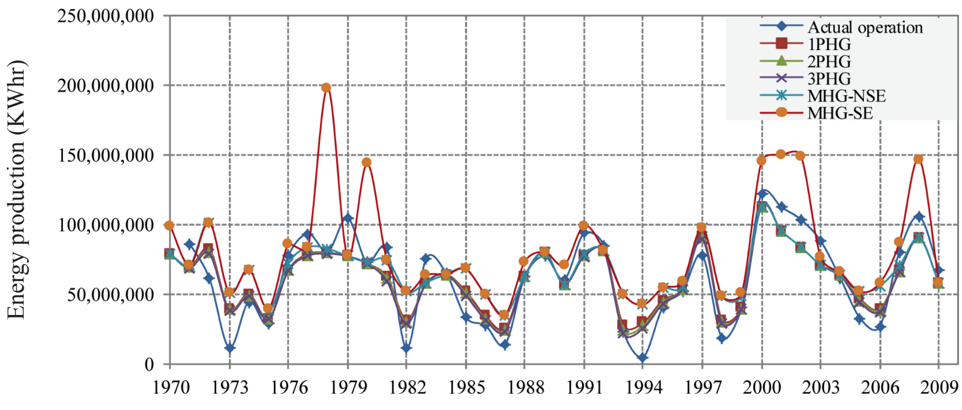

Figure 6 Annual energy production obtained from various types of hedging policies. (1PHG = One-Point hedging; 2PHG = Two-Point hedging; 3PHG = Three-Point hedging; MHG-NSE = Multiple hedging–non seasonal effects; MHG-SE = Multiple hedging–seasonal effects; KWhr = Kilowatt hours.)

Accordingly, the water level in the reservoir was kept between 175.08 and 179.77 meters above mean sea level (m msl) or the reservoir water storage ranged between 518.31 and 1,547.90 mcm. By comparing the actual operation data with data collected based on the existing rule, it was found that the range of water levels in the reservoir was greater and ranged between 173.26 and 183.70 m msl indicating that the water supply management in the reservoir during drawdown and fulfilled periods was not able to keep the water from being lower than the minimum pool level and higher than the normal pool level. In other words, the water supply management performed by the optimal hedging during the drawdown and fulfilled periods performed better not only for the irrigation and downstream control but also for hydropower generation. The results of the investigation into the performance indicator for off-stream water uses showed that the reliability indices for both the spillage and shortage modes performed by the various types of optimal hedging were at least nearly 80% which were acceptable for a real application.

In addition, it was found that the efficiency in hydropower production of the Ubolratana Reservoir by using the optimal one-point, two-point and three-point hedging was very close to the operational results obtained from the optimal linear release rules under which the reservoir release was set as a function of storage and inflow with simple parameters (Rittima *et al.,* 2011). Moreover, using the optimal multiple hedging with seasonal parameters gave higher values of average annual energy when compared to the results received from two types of the optimal linear rule ($R_t = aS_t$ and $R_t = cS_t+dI_t$). It also confirmed that optimal multiple hedging helped in improving the operational performance for two water supply reservoirs in Thailand—namely; the Mun Bon and Lam Chae Reservoirs by reducing the severity of water deficit and increasing the reservoir yield for future uses (Rittima, 2012).

CONCLUSIONS

The study applied the advantage of a hedging policy, which is principally a water demand management approach during severe drought, to benefit hydropower generation. The developed simulation-optimization model was constructed by maximizing the energy production of the Ubolratana Reservoir and various types of optimal hedging policies were consequently derived by a genetic algorithm. The reservoir operation results showed that using all types of optimal hedging for the reservoir operation could produce higher amounts of firm energy. Moreover, two types of multiple hedging gave better performances especially in terms of energy production which was higher than that generated under the existing rule curve. Additionally, using the optimal multiple hedging policies with seasonal parameters for operation also resulted in higher energy production by controlling the reservoir water level so that it did not exceed the normal pool level and was not lower than the minimum pool level. In principle, when the optimal hedging policies were applied, the water storage in the reservoir was strictly limited and did not encroach the surcharge storage and inactive zones during some critical drawdown and fulfilled periods. Therefore, some water storage was kept in the active storage zone and was beneficial for energy generation together with other off-stream uses downstream.

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