Consequently, this work has developed an optimised hedging policy for the Ubonratana based on the existing rule curves for the multipurpose reservoir. The optimisation used Genetic Algorithms (GA) whose fitness function was the sum of squares of the water deficits.

METHODOLOGY

Rule curves and hedging for operation of single reservoir system

Figure 1(b) and (c) conceptualises single-stage and two-stage hedging, as developed in this study from the no-hedging policy in Fig. 1(a). The upper rule curve (URC) defines the maximum level for flood control purposes, the lower rule curve (LRC) defines the limit for conservation purposes, and the critical rule curve (CR) defines the trigger for rationing at the associated ratio. The distinguishing feature between the single-stage and the two-stage is that the former has one critical rule curve (and one associated rationing ratio), while the latter has two such critical curves and ratios. Thus, in comparison with the no-hedging rule curve illustrated in Fig. 1(a), normal operation in which the supply of full demand is attempted only occurs when the reservoir storage is outside the critical storage zones. Consequently, for the single-stage hedging policy (Fig. 1(b)), whenever the starting reservoir storage is below the critical rule curve, the water delivery is rationed by delivering only a fraction of the full demand, i.e. $D'_t = \alpha D_t$, where D'_t is the supply, D_t is the demand and α ($0 \le \alpha \le 1$) is the rationing ratio. For the two-stage hedging policy (Fig. 1(c)), the rationing is done in two levels of critical rule curves and two rationing factors to supply $\alpha_1 D_t$ and $\alpha_2 D_t$, respectively, where $0 \le \alpha_2 \le \alpha_1 \le 1$. The determination of the critical rule curves and the associated hedging factors α, α_1 and α_2 is achieved by GA optimisation. Although the hedging factors could also be time-dependent, this analysis has been restricted to constant factors for simplicity sake.

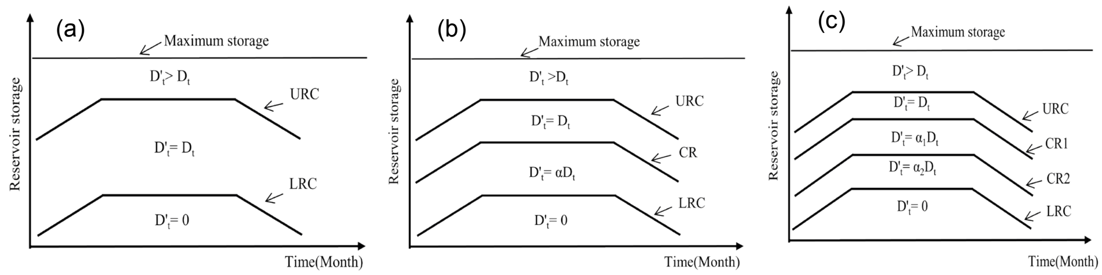

Fig. 1 Schematic illustration of hedging rules showing (a) no-hedging (b) single-stage hedging and (c) two-stage hedging.

Formulation of optimisation of hedging rules

The objective function and constraints are as follows.

The objective function is to minimise the sum of squares of the period shortages, i.e.:

$$Minimise\ \sum \left(D_t - D'_t\right)^2 \qquad \forall D'_t \le D_t \tag{1}$$

The constraints are as follows:

Single-stage hedging

$WA_t = S_t + Q_t$

$if\ WA_t \ge URC_t,\quad D'_t = S_t + Q_t - E_t - URC_t \ \&\ Y_t = D'_t - D_t$

$if\ URC_t \ge WA_t > CR_t,\quad D'_t = D_t \ \&\ Y_t = 0$

$if\ CR_t \ge WA_t > LRC_t,\quad D'_t = \alpha D_t$

$if\ WA_t \le LRC_t,\quad D'_t = 0$

$S_{t+1} = S_t + Q_t - D'_t - E_t$

$1 \ge \alpha \ge 0$

$URC_t \ge CR_t \ge LRC_t$

Two-stage hedging

$WA_t = S_t + Q_t$

$if\ WA_t \ge URC_t,\quad D'_t = S_t + Q_t - E_t - URC_t \ \&\ Y_t = D'_t - D_t$

$if\ URC_t \ge WA_t > CR1_t,\quad D'_t = D_t$

$if\ CR1_t \ge WA_t > CR2_t,\quad D'_t = \alpha_1 D_t$

$if\ CR2_t \ge WA_t > LRC_t,\quad D'_t = \alpha_2 D_t$

$if\ WA_t \le LRC_t,\quad D'_t = 0$

$S_{t+1} = S_t + Q_t - D'_t - E_t$

$1 \ge \alpha_1 \ge \alpha_2 \ge 0$

$URC_t \ge CR1_t \ge CR2_t \ge LRC_t$

where D_t is the water demand during period *t*; D'_t is the water delivery during period *t*; S_t is storage at beginning of time *t*; S_{t+1} is the storage at the end of time *t*; Q_t is the inflow to the reservoir during *t*; E_t is the evaporation loss during time *t*; Y_t is the excess water released during period *t*; WA_t is the water available at time *t*.

Genetic algorithm

GA optimisation was selected for the study because the technique has been widely applied for reservoir operational studies with great success; excellent reviews of some of the recent studies are provided by Hossain and El-shafie (2013) and Rani and Moreira (2010). In a GA, the solution set is represented by a population of chromosomes, with each chromosome being made up of the individual decision variables of the problem. These decision variables are also referred to as genes. Chromosomes are processed and combined according to their fitness, in order to generate new chromosomes that have the best features of two parents. Three fundamental operations are involved in manipulating the chromosomes and moving to a new generation: selection, crossover, and mutation (Michalewicz 1992). The current optimisation used a population size of 700 and the initial sampling of the real-coded decision variables was based on the uniform density function. After estimating the fitness values for each individual (chromosome), next generation individuals were selected based on fitness ranking (Wardlaw and Sheriff 1999) and the Roulette selection method. The selected individuals reproduce children for the next generation, which is based on the crossover (crossover fraction = 0.8) and mutation (mutation rate = 0.01). Two elite children were assumed. The genetic operations were repeated for 500 generations.

The decision variables for the hedging optimisation are the critical reservoir storage (CR) levels for each month of the year and the rationing factor (α). Thus, the numbers of decision variables are 13 and 26 for single-stage and two-stage hedging scenarios, respectively. In the single-stage hedging, decision variables 1 to 12 represent the monthly CR values and decision variable 13 represents the rationing ratio (α). Similarly, in the two-stage hedging, decision variables 1 to 12 and 13 to 24 represent CR1 and CR2, respectively; decision variables 25 and 26 represent α_1 and α_2, respectively.

Evaluated Performance Indices

To test the effectiveness of the hedging policies, reservoir simulations were carried out and relevant performance measures – reliability (time- and volume-based) and vulnerability (McMahon *et al*. 2006) – were evaluated as outlined below.

– Time-based Reliability (R_t) is the proportion of the total time period under consideration during which a reservoir can meet the full demand without any shortages:

$$R_t = N_s / N \tag{2}$$

where N_s is the total number of intervals out of N that the demand was met.

– Volume-based Reliability (R_v) is the total quantity of water actually supplied divided by the total quantity of water demanded during the entire operational period:

$$R_v = \sum_{t=1}^{N} D'_t \Big/ \sum_{t=1}^{N} D_t \, , \; \forall D'_t \le D_t \tag{3}$$

– Vulnerability is the average period shortfall as a ratio of the average period demand (Sandoval-Solis *et al*. 2011):

$$\eta = \frac{\sum_{t=1}^{f_d} [(D_t - D'_t)/D_t\,]}{f_d} ; t \in f_d \tag{5}$$

where η is vulnerability (dimensionless), f_d is the total duration of the failures, i.e. $f_d = N - N_s$ and all other terms are as defined previously.

Study area and input data

The Ubonratana Reservoir is the largest (capacity = 2431 Mm^3) reservoir in the upper Chi River basin in northeastern Thailand. The dam is located on the Pong River at Phong Neap, Ubonratana district in Khon Kaen province, between latitudes 16° and 17°30′N and longitudes 101°15″ and 102°45″ E. The single, multi-purpose reservoir has been operated for a long time using rule curves developed by the Electricity Generating Authority of Thailand (EGAT), the dam operators. The dam provides water for consumptive uses (domestic, industrial, irrigation), Pong River instream flow augmentation, hydropower generation (installed capacity = 25.2 MW) and flood control (EGAT, 2002). All the water deliveries first pass through the turbines for power generation before being allocated to the other uses. This study used the reservoir inflow data of 384 months (1980–2012). Gross water requirements (domestic, industrial, irrigation, instream flow) for the 384 months was 30 140 Mm^3, i.e. a monthly average of 78.49 Mm^3.

RESULTS AND DISCUSSION

The optimised values for the decision variables are shown in Table 1. For convenience, the no-hedging policy is denoted by H0, while the single-stage and two-stage integrated hedging rules curves are denoted by H1 and H2, respectively. Figure 2(a) and (b) are the graphical illustration of the optimised hedging policies. In general the optimised critical rule curves fulfil the specified constraints, since for example both critical rule curves are bounded by the upper and lower rule curves, and the second stage critical rule curve is everywhere below the first stage critical curve for the two-stage hedging policy. The optimised rationing ratios obtained and shown in Table 1 are also well behaved, with both of the met water demands for the two-stage rationing being greater than the single-stage rationing. While only 82% of the full demand is met during rationing for the single stage, the first and second stages of the rationing in the 2-stage policy met 92 and 84%, respectively of the full demands. Also for the 2-stage policy, the second stage rationing is more restricted (i.e. less water is supplied) than the first stage rationing, as expected.

Table 1 Ordinates(Mm^3) of tested rule curves and operating policies

Policy	Ration ratio	Rule Curve	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
H0	–	URC	1371	1127	946	797	906	1441	1902	1902	1902	1820	1740	1557
		LRC	843	748	661	582	621	661	869	869	869	797	772	748
H1	0.82	CR	1087	1014	946	615	865	975	1485	1486	1431	1332	1195	1132
H2	0.92	CR1	1071	906	775	748	832	1045	1765	1825	1721	1454	1643	1305
	0.84	CR2	960	820	754	586	806	984	1151	1746	1509	977	1361	1296

The results of the performance simulations for the different rule curves are summarised in Table 2. In terms of the total amount of water released over the 384 months of the simulation, H0 was marginally better than the other two; however, this may have masked incidences of large single period shortages with H0. The vulnerability (η) is a measure of the impact of large single period shortages and as shown in Table 2, the vulnerability for H0 is almost 2.4 times as high as that for H1. This situation highlights the benefit of water saving during normal reservoir operation because it can bring about a significant reduction in the impacts (or vulnerability) of water shortage.

A reduction in the number and amount of large single-period shortages often comes at the expense of larger number of periods of moderate and small water shortages, and this is no exception in the current study. For example as seen in Table 2, while the number of occasions in which demand was unmet was only 31 for H0, this has grown to 82 and 99 for H1 and H2, respectively. This has in turn affected the systems time-based reliability, R_t, which deteriorated from about 92% for H0 to 79% and 74% for H1 and H2, respectively. However, as noted by Adeloye (2012), this should not be a source of concern since in terms of water availability as characterised by the volumetric reliability, R_v, the systems performance is still largely acceptable.

Table 2 Summary of evaluated reservoir performance indices for the tested hedging policies.

Policy	Total period demand (Mm^3)	Total period release (Mm^3)	Total period deficit (Mm^3)	f_d	R_t, (%)	R_v (%)	η
H0	30140	28640	1500	31	91.93	95.02	0.70
H1	30140	28412	1728	82	78.65	94.27	0.29
H2	30140	28333	1807	99	74.22	94.00	0.26

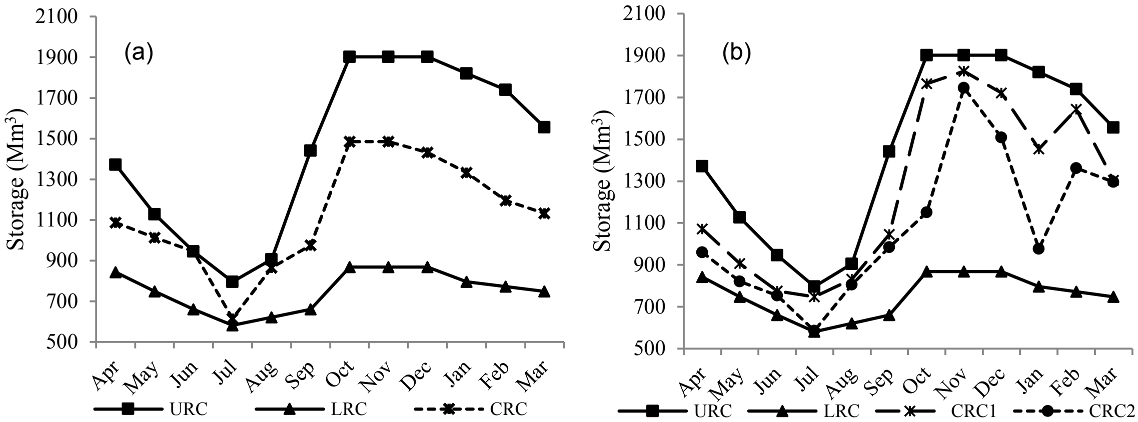

Fig. 2 Optimised hedging rules at Ubonratana for: (a) single-stage (H1) and (b) two-stage (H2).

CONCLUSION

This study has developed optimised hedging policies based on the existing rule curves at Ubonratana Reservoir in northeastern Thailand. The significant feature of the reported work is that single-stage and two-stage hedging policies were developed using GA to obtain the decision variables. Subsequent reservoir simulations to test the effectiveness of the hedging rules show that significant reduction in the number of large single-period water shortages can be achieved by rationing, resulting in manageable vulnerability for the Ubonratana. Reducing the number of large shortages caused the total number of failure periods to rise, leading to significant deterioration in the evaluated time-based reliability at Ubonratana. However, since the amount of water shortages for most of these additional shortage periods was low to moderate, the overall volumetric reliability of the reservoir was practically unaffected. This is re-assuring since what should matter most in reservoir operation is not the number of failure occasions but the deficit sustained during such failures. In terms of the vulnerability, the two-stage hedging outperformed both the single-stage and no-hedging policies. This might be an indication that further refinements of the hedging policy to include for example three stages or four stages might be warranted and this aspect is being taken up as the next stage of this study.

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