VOL. 14, NO. 18, SEPTEMBER 2019 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

AN IMPROVEMENT OF RESERVOIR RULE CURVES FOR INCREASING STORAGE CAPACITY

Anongrit Kangrang[1] Rattana Hormwichian[2] Pairot Pramual[3] and Komgrit Wongpakam[4]
[1]Faculty of Engineering, Mahasarakham University, Mahasarakham, Thailand
[2]Faculty of Engineering, Mahasarakham University, Mahasarakham, Thailand
[3]Faculty of Science, Mahasarakham University, Mahasarakham, Thailand
[4]Walai Rukhavej Botanical Research Institute, Mahasarakham University, Mahasarakham, Thailand
E-Mail: anongrit.k@msu.ac.th

ABSTRACT

Reservoir rule curves are necessary guidelines for both flood and drought control in operating multipurpose reservoirs. As sure storage enough water for next dry season controlling by rule curves with the maximum storage at the end of rainy season. This study applied the conditional genetic algorithm and reservoir simulation model to improve reservoir rule cures for storing the highest capacity at the end of rainy season. Historic inflow data and future inflow data under a climate change scenario were used in searching procedure. Three large reservoirs in the northeast region of Thailand were considered for this study-Ubolrat reservoir, Lampao reservoir and Nam Oon reservoir. The future inflow and the synthetic inflow were used to evaluate the efficiency of the newly obtained rule curves. The situations of water shortage and excess water as well as the stored water at the end of the wet season were used for describing the performance. The results showed that the optimal rule curves with objective function of maximum storage at the end of wet season can provide more stored water at the end of wet season than when other rule curves are used.The obtained rule curves can control the maximum storage at the end of rainy season and mitigate situations of water shortage and water excess better than the current rule curves.

Keywords: reservoir rule curves; optimization techniques; reservoir operation; genetic algorithm.

INTRODUCTION

Nowadays, flood and drought situations are serious problems in many regions because of high population growth, economic expansion, land use change and climate change, as well as conflict in water user etc. Water resource management is required to include all index issues in order to achieve high solving efficiency. The improvement of reservoir operation is an interesting method because it is a non-construction method that performs rapidly without investment cost. In addition the method can save time and money as well as enhance environmental conservation. The optimal rule curves are necessary guidelines for considering reservoir operation in non-construction methods.

Generally, monthly reservoir rule curves have been used to decide between releasing and storing water for each month during a considered inflow period. The historic inflow period of the reservoir is often used to simulate the reservoir system and is suitable for historic situations only. However, the future situation of a reservoir system requires optimal future rule curves that are suitable for operating reservoir effectively for both flood and drought control. Further, a reservoir operating system is a large and complex system [2, 11].

Many optimization techniques have been applied to find the optimal rule curves; for example, dynamic programming (DP), genetic algorithm (GA), differential evolution (DE), ant colony optimization (ACO), simulated annealing algorithm (SA), shuffled frog leaping algorithm (SFLA), particle swam optimization (PSO) and cuckoo search (CS), etc. [3, 4, 8, 12-15, 18]. The obtained rule curves are effectively applied for searching conditions, such as inflow data, water demand downstream, standard operating, smoothing function rule as well as objective functions of searching procedure. The GA was often applied to solve complex problems in many fields because of its easy application with many objective functions [9, 19, 21].

The objective functions of searching and the considered inflow data have a strong influence on the obtained rule curves. Therefore, suitable objective functions of the reservoir and considered inflow period are required for a multipurpose reservoir. Generally, the purposes of a multipurpose reservoir are to maximum stored water at the end of wet season in order to supply demands for the next dry season and to maximum empty reserve volume for mitigating flood events during the wet season. The conflict of interest for a multipurpose reservoir requires the optimal rule curves for each purpose and for each considered period.

This study proposes a conditional genetic algorithm (CGA) connected with the reservoir simulation model by considering both maximum storage at the end of rainy season and minimum situation of water shortage and excess water as the objective functions of searching procedures. The proposed model was applied to the Ubolrat reservoir, Lampao reservoir and Nam Oon reservoir in the northeast region of Thailand. The historic monthly inflow data and synthetic inflow data of each reservoir were considered in this study. Comparisons between rule curves of the proposed model and the current rule curves under synthetic inflow and future inflow scenarios were shown to demonstrate the effectiveness of each rule curve.

ARPN Journal of Engineering and Applied Sciences

MATERIALS AND METHODS

Reservoir operation model

The main items that are considered in the reservoir operating system were available water (calculated from the water balance concept) and downstream water demands from the reservoir. For each month, monthly release was estimated by considering the monthly available water under release criteria, operating policies and reservoir rule curves. For this study, the reservoir operation model was created following the concept of the water balance and using the standard operating rule. The reservoir operation model is operated under physical reservoir data, inflow data, water demand, hydrological data, standard operating rule and the water balance equation as presented in Figure 1 and Equation (1).

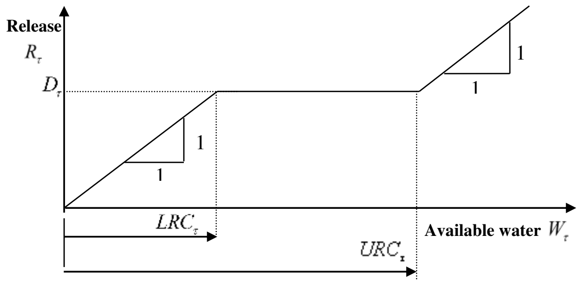

Figure-1. Standard operating rule.

$$W_\tau = S_{\tau-1} + I_\tau + P_\tau - E_\tau \quad (1)$$

Where

W_τ is the available water during month τ, $S_{\tau\text{-}1}$ is the stored water at the end of month τ-1; I_τ is the monthly inflow to the reservoir, P_τ is the precipitation during month τ, and E_τ is the average value of the evaporation loss. LRC_τ is lower rule curves during month τ and URC_τ is upper rule curves during month τ.

After operation for all months along the considered inflow period, all monthly releases of water from the reservoir (R_τ for all months) were used to calculate the objective function in the searching procedure. Results of each objective function were recorded and used in the CGA model until met the stop criteria and the optimal rule curves were obtained as described in Figure 2. The details of each objective function will be described in the next section.

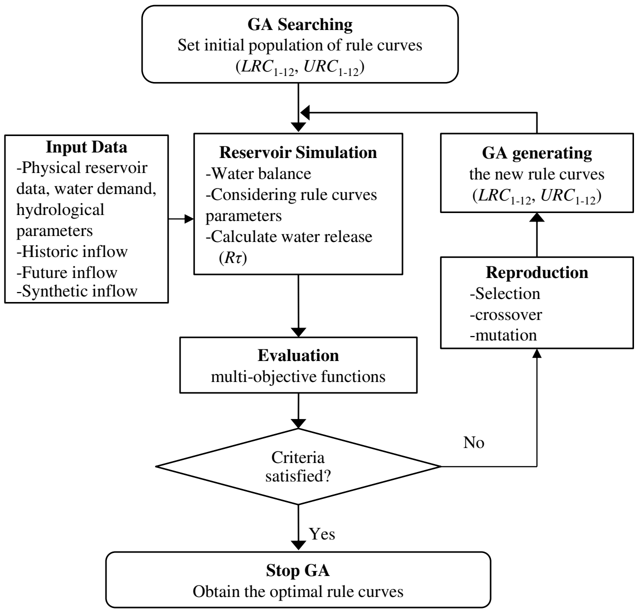

Figure-2. Conditional genetic algorithm with reservoir simulation for searching rule curves.

Conditional genetic algorithm connected with reservoir simulation

Firstly, the conditional genetic algorithm was created with the reservoir simulation model. The procedure starts from creating an initial population of rule curves, boundary search, probable crossover and mutation, objective function and stopping criteria. Then the population initial rule curves were sent to reservoir simulation model for operating reservoir by considering input data and physical information of the reservoir. The monthly release was calculated using initial rule curves for all moths along the inflow period. Then all monthly releases were used to calculate objective function and to evaluate the set of initial rule curves for accepting of first generation. Next, the new accepted rule curves (the selected populations for the first generation after cross over and mutation processes) were used to replace the initial population. This procedure was repeated until the new accepted rule curves were appropriate and the search was stopped [7]. The integrating conditional genetic algorithm and reservoir simulation model for searching optimal rule curves is described in Figure-2.

Three objective functions were considered. Firstly, the minimum average water shortage per year (H) was used as the objective function of the searching procedure subject to the constraints on the simulation model as in the following:

$$\text{Min } H\,(Xi) = \left(\frac{1}{n}\sum_{v=1}^{n} Sh_v\right) \quad (2)$$

$$\text{if } R_\tau < D_\tau;\text{Then } Sh_v = \sum_{\tau=1}^{12}\left(D_\tau - R_\tau\right) \quad (3)$$

$$\text{Else } Sh_v = 0$$

Where
n is the total number of considered years, Sh_v is the water shortage during year ν(a year in which releases are less than the target demand) and i is the iteration number.

Secondly, the minimum average excess water per year (U) was used as the objective function of the searching procedure subject to the constraints on the simulation model as in the following:

$$\text{Min } U \text{ (Xi)} = \left(\frac{1}{n}\sum_{v=1}^{n} Sp_v\right) \text{--------------------------------- (4)}$$

$$\text{if } R_\tau > D_\tau\text{; Then } Sp_v = \sum_{\tau=1}^{12}\left(R_\tau - D_\tau\right) \text{---------------- (5)}$$

$$\text{Else } Sp_v = 0$$

where n is the total number of considered years, Sp_v is the excess spill water during year ν(a year in which releases are higher than the target demand) and i is the iteration number.

Thirdly, the maximum of the average stored water at the end of the wet season (N) was used as the objective function of the searching procedure subject to the constraints on the simulation model as in the following:

$$\text{Max } N\ (Xi) = \left(\frac{1}{n}\sum_{v=1}^{n} SN_v\right) \text{--------------------------------- (6)}$$

where n is the total number of considered years, SN_v is the stored water at the end of the month of November during year ν(November is the last month of the wet season in Thailand) and i is the iteration number.

Illustrative application of proposed model

This study applied the proposed models to the 3 large reservoirs in the northeast region of Thailand. Firstly, the Ubolrat reservoir, in Khon Kaen province, is located in the Chi Basin with an upstream watershed area of 12,000 km^2 (see Figure-3). The average annual rainfall is 1,247 mm and the mean annual temperature is 26.9°C. The normal storage capacity and average annual inflow are 2,263 MCM and 2,478.591 MCM/year, respectively.

The Lampao reservoir, in Kalasin province, is located in the Upper-Lampao Basin, a branch of the Chi Basin (see Figure-3). It has an area of about 3,282 km^2. The average annual rainfall is 1,411 mm and the mean annual temperature is 27 °C. The normal storage capacity and average annual inflow are 1,980 MCM and 1,900 MCM/year, respectively.

The third reservoir is the Nam Oon reservoir in Sakon Nakhon province, is located in the Songkham Basin with an upstream watershed area of 1,100 km^2 (see Figure-3). The average annual rainfall is 1,411 mm and the mean annual temperature is 26.6°C. The normal storage capacity and average annual inflow are 520 MCM and 431.600 MCM/year, respectively.

The schematic diagrams of above reservoirs are presented in Figures 4-6 respectively. They indicate that the water demands from reservoirs are electricity generation, irrigation, flood control, industrial demand, domestic water supply and environmental conservation.

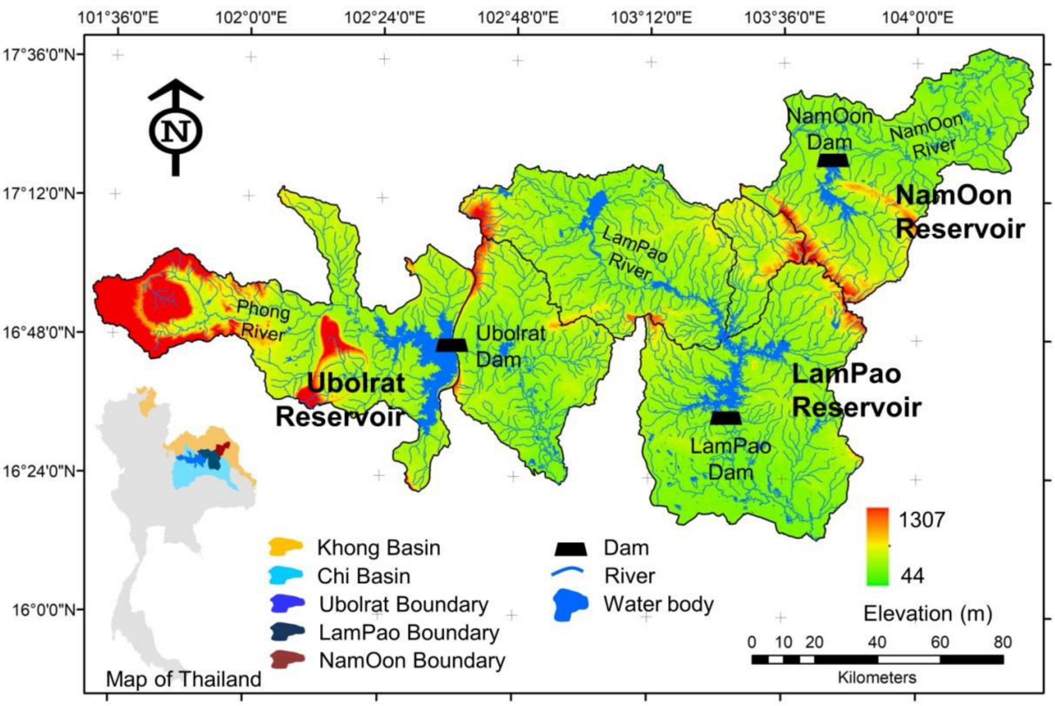

Figure-3. Location of the Ubolrat, the Lampao and the Nam Oon reservoirs.

ARPN Journal of Engineering and Applied Sciences

The CGA connecting the reservoir simulation model for finding the optimal rule curves is constructed through the MATLAB toolbox. There are 3 cases considering objective functions of the searching procedure; (1) minimum average water shortage per year (2) minimum average excess spill water per year and (3) maximum average stored water at the end of the wet season. For each considered objective, the functions that were used were both historic inflow data and future inflow data.

The 49 years of historic inflow data for Ubolrat reservoir was recorded from 1966 - 2014, whereas the 50 years of future inflow data was created by the SWAT model under scenario B2 from 2015 - 2064 [10, 17] (see Figure-7). The HEC-4 model was used to create the synthetic inflow data into the monthly inflows as a synthetic data set of 1,000 events for evaluating the efficiency of each obtained rule curve.

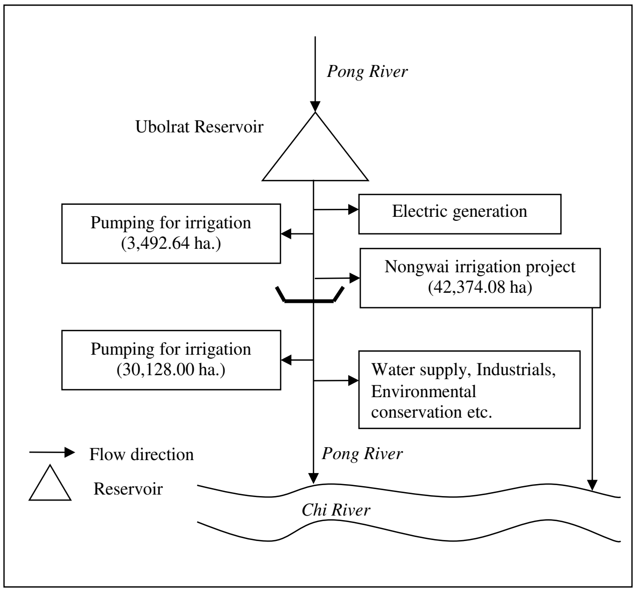

Figure-4. Schematic diagram of the Ubolrat basin.

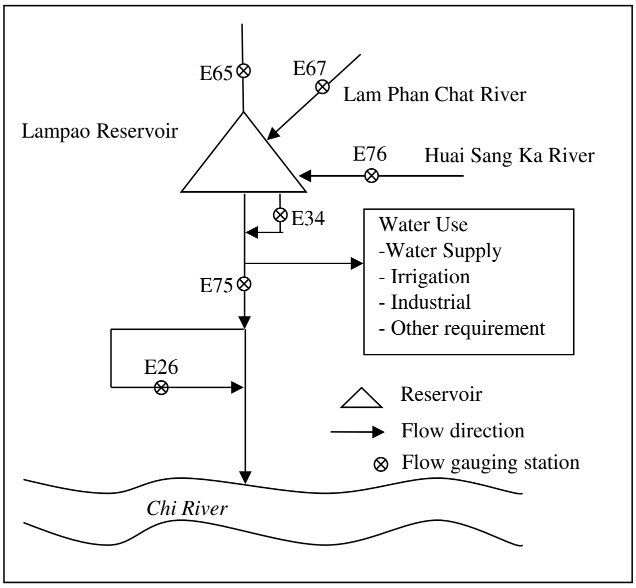

Figure-5. Schematic diagram of the Lampao basin.

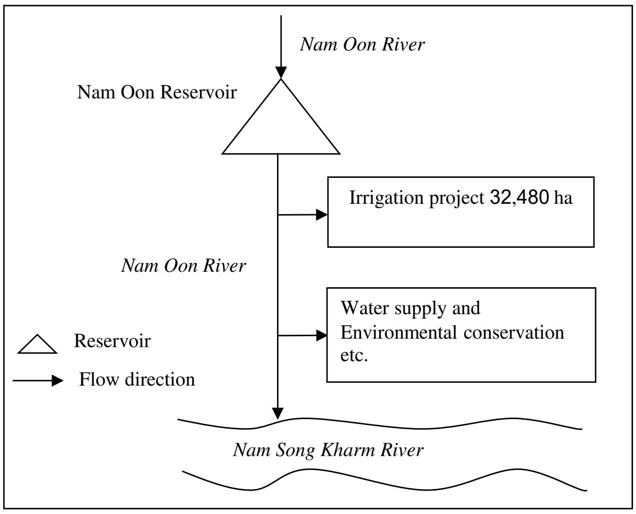

Figure-6. Schematic diagram of the Nam Oon basin.

The 46 years of historic inflow data for Lampao reservoir were recorded from 1968 - 2013, whereas the 50 years of future inflow data were created by the SWAT model under scenario B2 from 2014 - 2063 [10, 20] (see Figure-8). The HEC-4 model was used to create the synthetic inflow data into the monthly inflows as a synthetic data set of 1,000 events for evaluating the efficiency of each obtained rule curves.

For the Nam Oon reservoir, 25 years of historic inflow data were recorded from 1992 - 2016, whereas the 20 years of future inflow data were created by the SWAT model under scenario B2 from 2017 - 2036 [10, 20, 22] (see Figure-9). The HEC-4 model was used to create the synthetic inflow data into the monthly inflows as a synthetic data set of 1,000 events for evaluating the efficiency of each obtained rule curves.

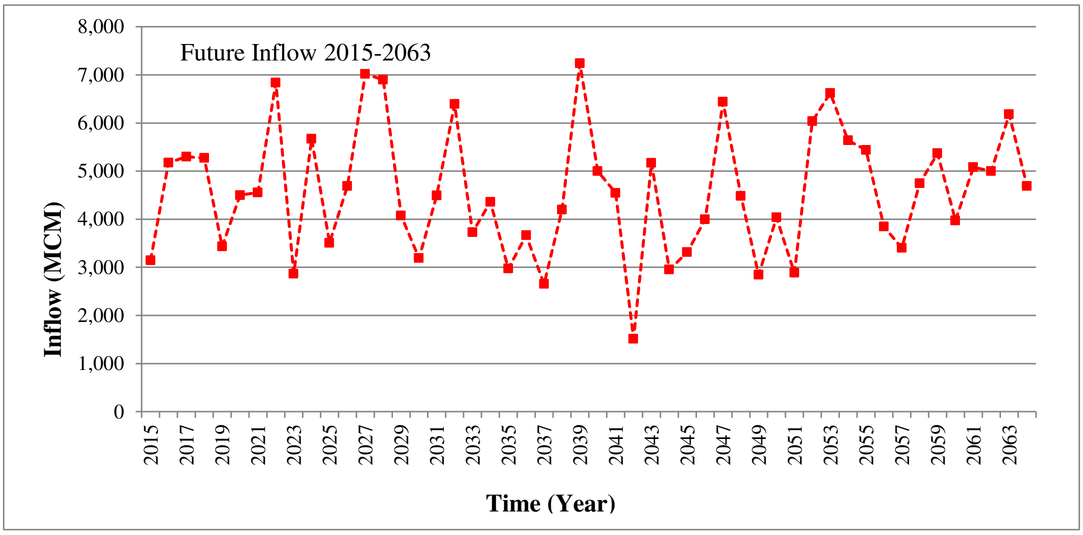

Figure-7. Future inflow of Ubolrat reservoir.

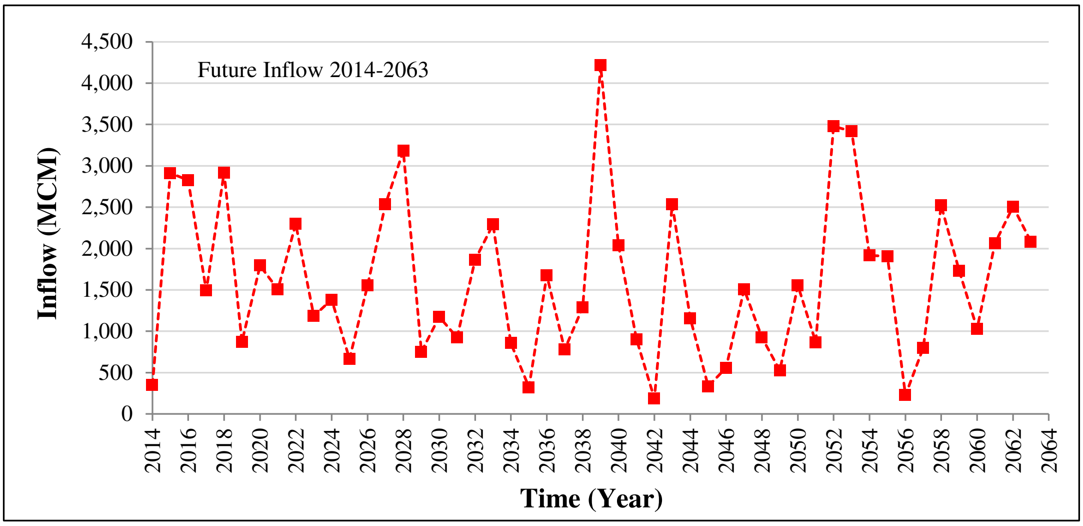

Figure-8. Future inflow of Lampao reservoir.

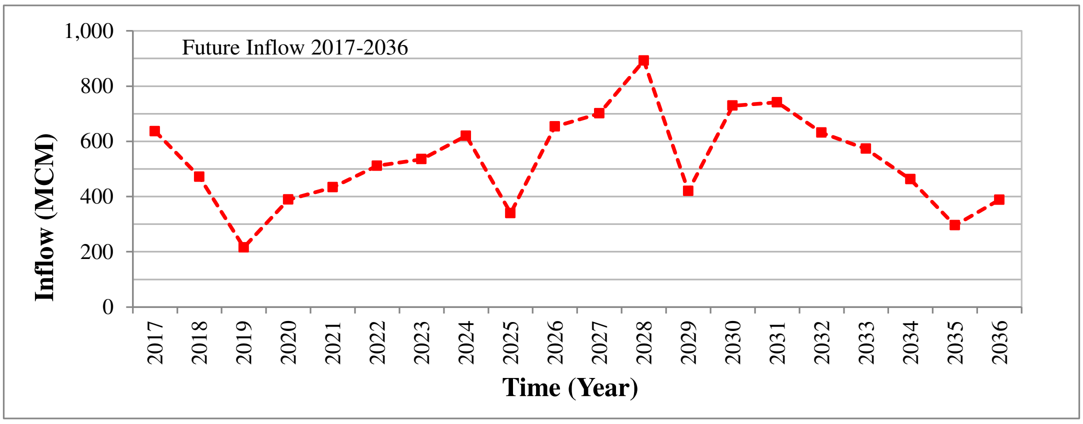

Figure-9. Future inflow of Nam Oon reservoir.

RESULTS AND DISCUSSIONS

Historic rule curves

The 49 years of monthly historic inflow data, monthly data of evaporation, rainfall, irrigation, domestic and industrial water requirements and monthly environmental conservation of the Ubolrat reservoir were used in the reservoir simulation model connecting with CGA while considering different objective functions. Then the optimal historic rule curves of each case were

ARPN Journal of Engineering and Applied Sciences

obtained. These obtained rule curves of all the cases were plotted to compare them with the current rule curves as shown in Figure-10. The rule curve patterns in all cases were similar to the current rule curves. The patterns of the obtained curves were similar to the patterns of other reservoirs in Thailand from other studies [1, 13, 15, 16] because of the seasonal inflow effect.

Figure-10 also presents the optimal historic rule curves of the Ubolrat reservoir using minimum average water shortage (RC2-min short-historic), using maximum average store water at the end of wet season (RC3-max store-historic) and the current rule curves (RC1-current). The obtained rule curves also indicated that the upper levels of CGA models for both objective functions are higher than the upper levels of the current rule curves, whereas the lower levels of them are lower than the lower levels of the current rule curves. Hence, they can increase the storage water during the end of wet season for the next dry season and they can release it to meet the demand during the dry season. This will help alleviate water shortages better than current rule curves like the other studies [5, 6].

The 46 years of monthly historic inflow data, monthly data of evaporation, rainfall, irrigation, domestic and industrial water requirements and monthly environmental conservation of the Lampao reservoir were used in the reservoir simulation model connecting with CGA while considering different objective functions. The obtained rule curves of all the cases were plotted to compare them with the current rule curves as shown in Figure-11.

Figure-11 also presents the optimal historic rule curves of the Lampao reservoir using minimum average water shortage per year (RC2-min spill-historic), using maximum average store water at the end of wet season (RC3-max store-historic) and the current rule curves (RC1-current). They indicated that the rule curve patterns in all cases were similar to the current rule curves. The patterns of the obtained curves were similar to the patterns of other reservoirs in Thailand reported in other studies [13, 15] because of the seasonal inflow effect. However, the upper levels of the newly obtained rule curves are higher than the current rule curves during the end of wet season. These can enhance performance to store more water than the using current rule curves.

The 25 years of monthly historic inflow data, monthly data of evaporation, rainfall, irrigation, domestic and industrial water requirements and monthly environmental conservation of the Nam Oon reservoir were used in the reservoir simulation model connecting with CGA while considering different objective functions. The obtained rule curves of all the cases were plotted to compare them with the current rule curves as shown in Figure-12.

Figure-12 also presents the optimal historic rule curves of the Nam Oon reservoir using minimum average excess water per year (RC2-min spill-historic), using maximum average store water at the end of wet season (RC3-max store-historic) and the current rule curves (RC1-current). The obtained rule curves also indicated that the upper levels of CGA models for both objective functions were higher than the upper level of the current rule curves during July to September, whereas the lower level of them were slightly different. Hence, they can increase the storage water during wet season. This will help alleviate water shortages in the next dry season. However, they will have less reserve volume for flood control than using the current rule curves.

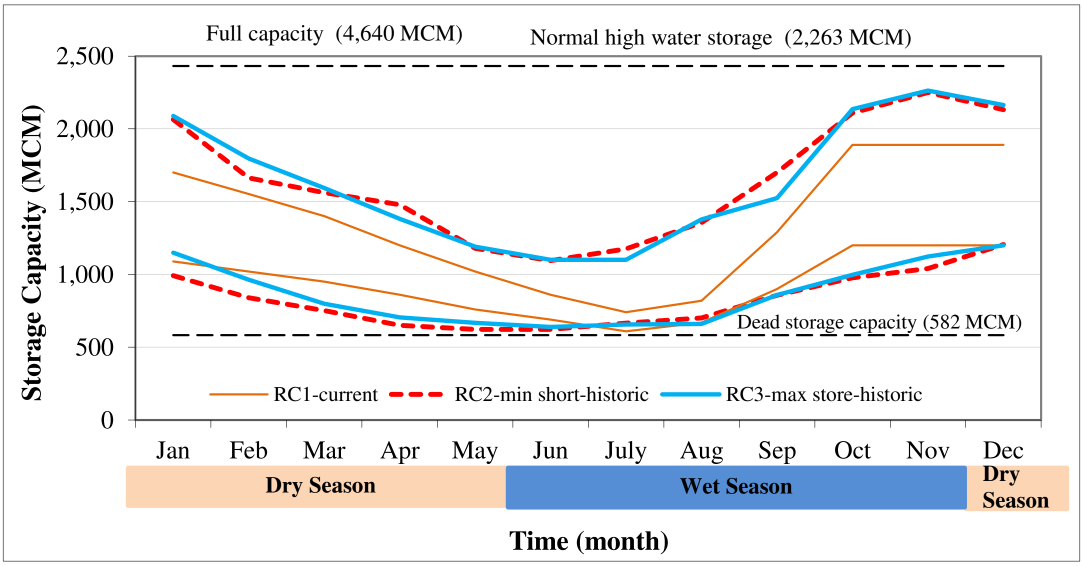

Figure-10. Optimal historic rule curves of Ubolrat reservoir.

ARPN Journal of Engineering and Applied Sciences

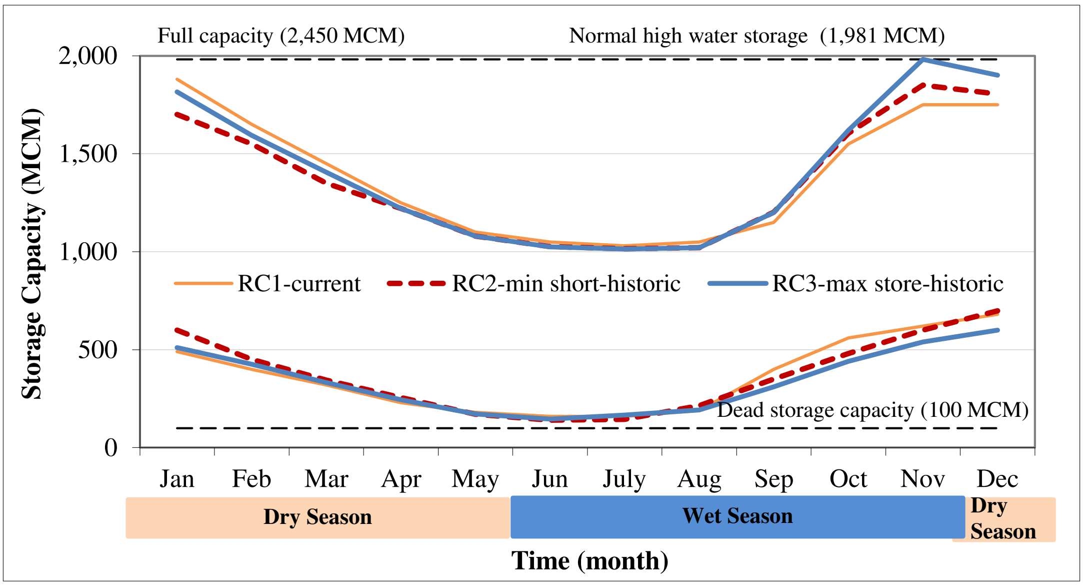

Figure-11. Optimal historic rule curves of Lampao reservoir.

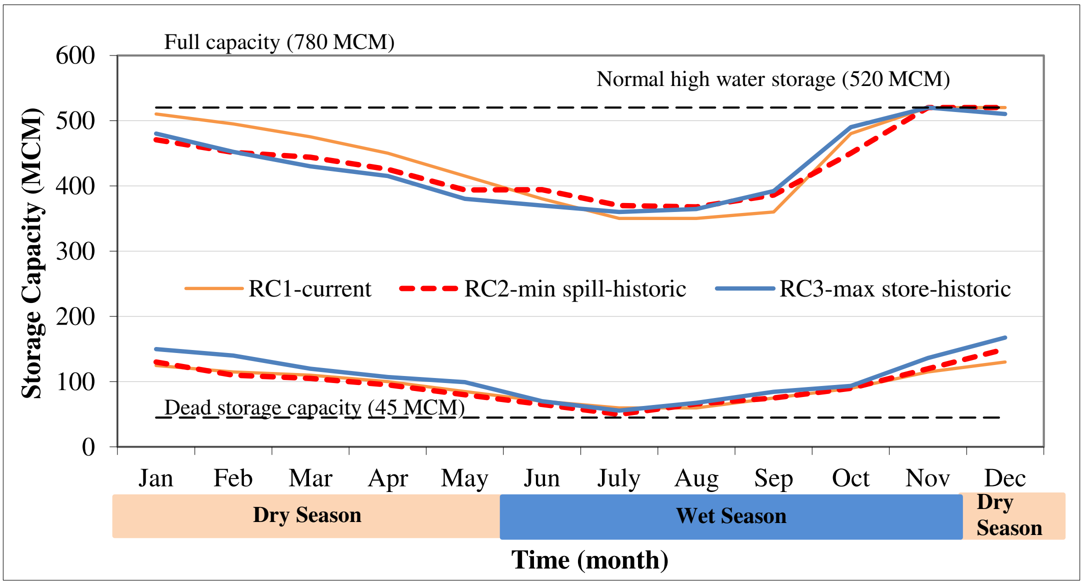

Figure-12. Optimal historic rule curves of Nam Oon reservoir.

Future rule curves

The 50 years future inflow period 2015-2064 under the B2 scenario and the other monthly information of the Ubolrat reservoir, as in the former section, were used in the reservoir simulation model connecting with CGA considering two different objective functions. The optimal future rule curves of each case were obtained. All the obtained future rule curves were plotted with the current rule curves as shown in Figure-13. They indicated that the rule curve patterns of all cases were similar when compared to the current rule curves.

Figure-13 also shows the optimal future rule curves of the Ubolrat reservoir using minimum average water shortage per year (RC4-min short-future), using maximum average store water at the end of wet season (RC5-max store-future) and the current rule curves (RC1-current). The obtained rule curves also indicated that the storage capacity of upper rule curves of CGA models for both objective functions was higher than the upper rule curves of the current rule curves, whereas the their lower levels were lower than the lower rule curves of current. Hence, they can reduce the spill water and keep the storage capacity full at the end of the rainy season. In addition they can release water to meet the demand during the dry season better than current rule curves.

The 46 years future inflow period 2014-2063 under the B2 scenario and the other monthly information of the Lampao reservoir, as in the former section, were used in the reservoir simulation model connecting with CGA considering two different objective functions. All the obtained future rule curves were plotted with the current rule curves as shown in Figure-14. They indicated that the rule curve patterns of all cases were similar when compared to the current rule curves.

ARPN Journal of Engineering and Applied Sciences

Figure-14 also shows the optimal future rule curves of the Lampao reservoir using minimum average water shortage per year (RC4-min short-future), using maximum average store water at the end of wet season (RC5-max store-future) and the current rule curves (RC1-current). The obtained rule curves also indicated that the storage capacity of upper rule curves of CGA models for both objective functions were higher than the upper rule curves of the current rule curves, whereas the their lower levels were slightly different. Hence, they can reduce the spill water and keep the storage capacity full at the end of the rainy season. This will help alleviate water shortages in the next year.

The 20 years future inflow period 2017-2036 under the B2 scenario and the other monthly information of the Nam Oon reservoir, as in the former section, were used in the reservoir simulation model connecting with CGA considering two different objective functions. The obtained future rule curves were plotted with the current rule curves as shown in Figure 15. They indicated that the rule curve patterns of all cases were similar when compared to the current rule curves too.

Figure-15 also shows the optimal future rule curves of the Nam Oon reservoir using minimum excess spill water (RC4-min spill-future), using maximum average store water at the end of wet season (RC5-max store-future) and the current rule curves (RC1-current). The obtained rule curves also indicated that the storage capacity of upper rule curves of CGA models for both objective functions were higher than the upper rule curves of the current rule curves during July to September, whereas the their lower levels were higher than the current rule curves during August to December. Hence, they can reduce the spill water and keep the storage capacity full at the end of the rainy season.

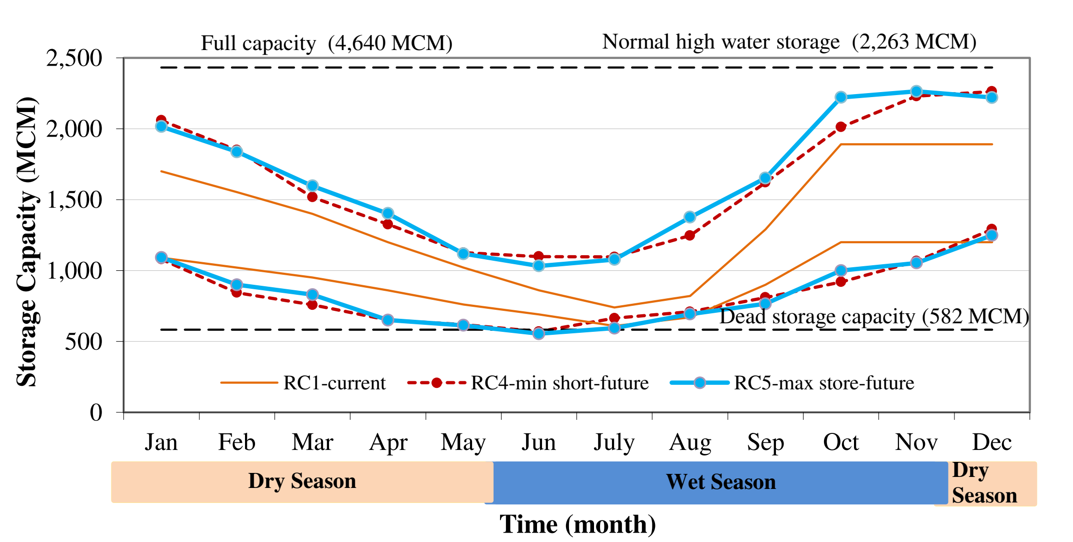

Figure-13. Optimal future rule curves of Ubolrat reservoir.

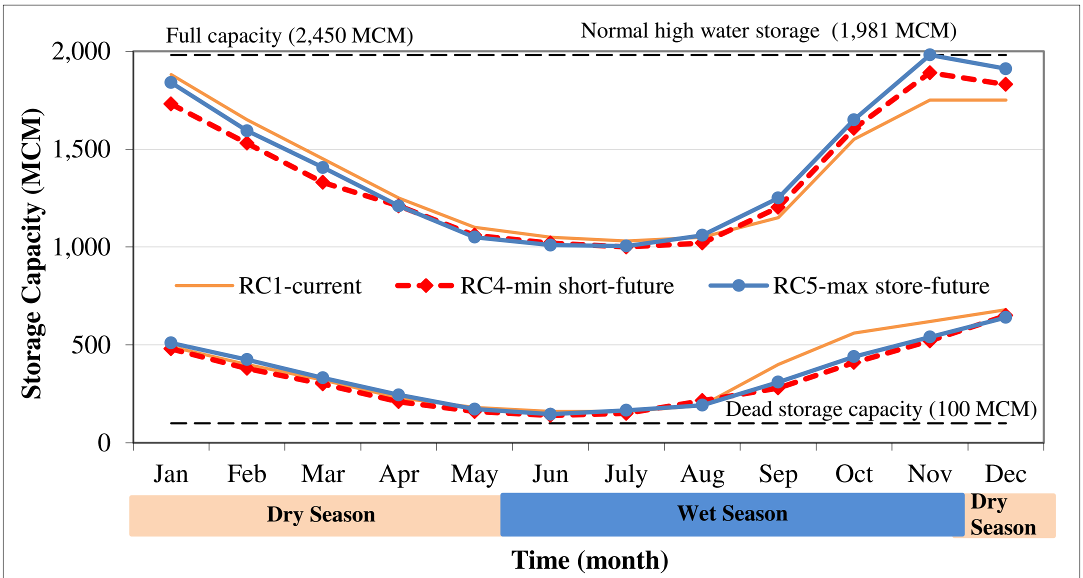

Figure-14. Optimal future rule curves of Lampao reservoir.

VOL. 14, NO. 18, SEPTEMBER 2019 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

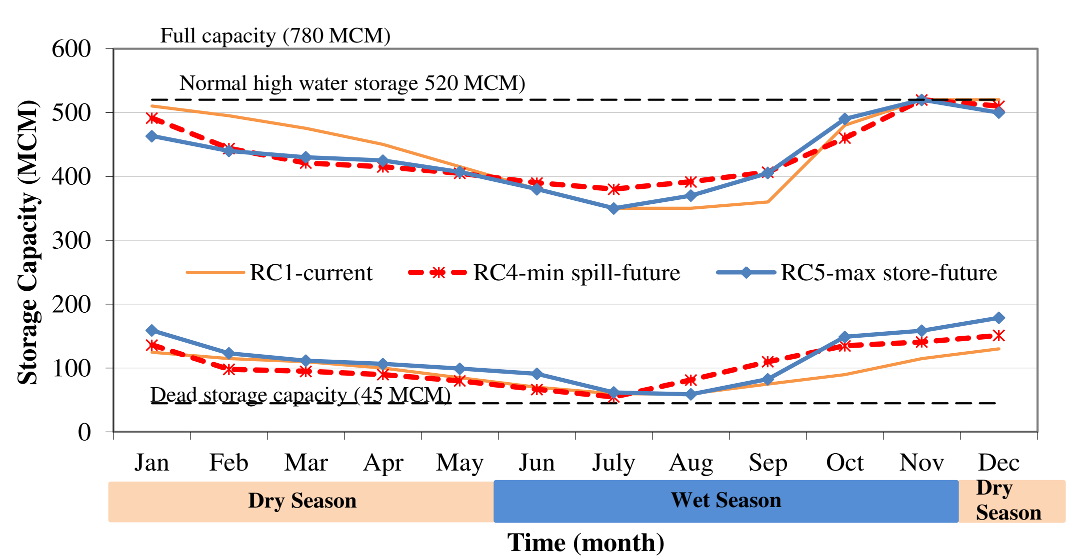

Figure-15. Optimal future rule curves of Nam Oon reservoir.

Efficiency of rule curves under synthetic inflow conditions

The efficiency of the obtained rule curves from all cases of searching was evaluated by the operating reservoir simulation considering the synthetic inflow data. The 1,000 samples of synthetic inflow were generated from the historic inflow over 49 years. Table-1 shows situations of water shortage and excess water when using each obtained rule curve and the current rule curves of the Ubolrat reservoir. They indicated that the average magnitudes of the water shortage and excess water using CGA rule curves (RC2, RC3, RC4 and RC5) were less than the magnitudes of using the current rule curves. The average water shortage of using RC2-min short-historic (312.289±29.178 MCM/year) is the least as compared with the other rule curves, because of the objective function effect. The obtained rule curves from using historic inflow in searching process (RC2-min short-historic) will alleviate water shortage situations by considering the synthetic inflow situation better than the other rule curves. Furthermore, the other terms of water shortage situation are better too, such as frequency and average magnitude.

Table-2 shows the situations of the water shortage and excess water when using each obtained rule curve and the current rule curves of the Lampao reservoir. They indicated that the average magnitudes of water shortage and excess water using CGA rule curves (RC2, RC3, RC4 and RC5) were less than the magnitudes obtained using the current rule curves. The average water shortage of using RC2-min short-historic (250.013±16.311 MCM/year) was the least compared with the other rule curves, because of the objective function effect. The obtained rule curves from using historic inflow in searching process (RC2-min short-historic) will alleviate the water shortage situation under considering synthetic inflow situation better than the other rule curves.

Table-3 shows the situations of the water shortage and excess water when using each obtained rule curve and the current rule curves of the Nam Oon reservoir. They indicated that the average magnitudes of the water shortage and excess water of using CGA rule curves (RC2, RC3, RC4 and RC5) were less than the magnitudes of using the current rule curves. The average excess water per year of using RC2-min spill-historic (66.475±18.249 MCM/year) was the least as compared with the other rule curves, because of the objective function effect. The obtained rule curves from using historic inflow in searching process (RC2-min spill-historic) will alleviate excess water situation under considering synthetic inflow situation better than the other rue curves. In addition, the other terms such as frequency, maximum magnitude and duration are better too.

VOL. 14, NO. 18, SEPTEMBER 2019 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

Table-1. Situations of water shortage and excess water of Ubolrat reservoir considering 1,000 samples of syntheticinflow for each using obtained rule curves.

Situations	Rule curves		Frequency (times/year)	Magnitude (MCM/year)		Duration (year)	
				Average	Maximum	Average	Maximum
Water shortage	RC1-current	μ	0.887	532.161	1,481.370	9.571	19.781
		σ	0.036	25.132	144.276	3.411	6.531
	RC2-min short-historic	μ	0.873	382.219	1,425.750	9.244	19.190
		σ	0.029	29.178	170.698	3.421	7.595
	RC3-max store-historic	μ	0.908	427.853	1,411.100	8.541	22.320
		σ	0.032	27.612	180.318	5.251	8.507
	RC4-min short-future	μ	0.728	391.611	1,451.790	4.774	11.000
		σ	0.051	28.749	177.481	1.342	4.306
	RC5-max store-future	μ	0.921	402.437	1,441.930	9.111	21.690
		σ	0.034	28.146	179.912	5.261	8.304
Excess water	RC1-current	μ	0.668	553.036	3,511.172	2.819	7.143
		σ	0.045	33.939	825.291	0.531	1.934
	RC2-min short-historic	μ	0.462	380.421	3,247.222	2.301	5.591
		σ	0.051	38.386	808.861	0.462	1.849
	RC3-max store-historic	μ	0.495	434.704	3,311.449	2.161	5.331
		σ	0.050	36.919	781.299	0.411	1.597
	RC4-min short-future	μ	0.472	400.127	3,187.957	2.294	5.382
		σ	0.050	36.579	814.751	0.472	1.601
	RC5-max store-future	μ	0.514	410.739	3,225.341	2.451	5.854
		σ	0.051	35.803	801.723	0.521	1.876

Note: μ = average ,σ = standard deviation

VOL. 14, NO. 18, SEPTEMBER 2019 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

Table-2. Situations of water shortage and excess water of Lampao reservoir considering 1,000 samples of synthetic inflow for each using obtained rule curves.

Situations	Rule curves		Frequency (times/year)	Magnitude (MCM/year)		Duration (year)	
				Average	Maximum	Average	Maximum
Water shortage	RC1-current	μ	0.896	269.447	757.691	7.13	16.81
		σ	0.038	16.004	152.021	2.18	5.35
	RC2-min short-historic	μ	0.813	250.013	763.371	5.41	13.11
		σ	0.041	16.311	151.119	1.54	4.21
	RC3-max store-historic	μ	0.807	253.242	750.824	5.49	13.11
		σ	0.034	16.291	152.057	1.54	4.28
	RC4-min short-future	μ	0.819	254.257	747.261	6.64	15.21
		σ	0.035	16.317	150.126	2.01	5.11
	RC5-max store-future	μ	0.827	252.196	752.351	6.15	14.36
		σ	0.033	15.219	151.571	1.97	4.84
Excess water	RC1-current	μ	0.689	464.752	2,357.582	3.38	9.52
		σ	0.051	16.812	485.517	0.75	2.71
	RC2-min short-historic	μ	0.653	448.332	2,336.563	3.24	8.32
		σ	0.055	17.213	491.082	0.75	2.78
	RC3-max store-historic	μ	0.651	446.241	2,344.044	3.23	8.31
		σ	0.058	17.174	491.473	0.75	2.62
	RC4-min short-future	μ	0.642	448.627	2,359.213	3.22	8.18
		σ	0.051	17.312	492.821	0.71	2.61
	RC5-max store-future	μ	0.653	447.163	2,348.024	3.21	8.23
		σ	0.056	17.181	491.331	0.76	2.67

Note: μ = average ,σ = standard deviation

ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

Table-3. Situations of water shortage and excess water of Nam Oon reservoir considering 1,000 samples of synthetic inflow for each using obtained rule curves.

Situations	Rule curves		Frequency (times/year)	Magnitude(MCM/year)		Duration (year)	
				Average	Maximum	Average	Maximum
Water shortage	RC1-current	μ	0.982	42.586	130.182	18.238	21.056
		σ	0.031	6.258	36.162	6.990	4.693
	RC2-min spill-historic	μ	0.642	27.208	116.851	1.818	2.968
		σ	0.103	8.126	29.725	0.684	1.405
	RC3-max store-historic	μ	0.679	28.288	144.549	25.000	25.000
		σ	0.067	3.774	3.681	0.000	0.000
	RC4-min spill-future	μ	0.693	18.821	114.814	2.445	4.918
		σ	0.108	8.149	28.601	0.866	2.054
	RC5-max store-future	μ	0.704	33.801	106.023	25.000	25.000
		σ	0.085	1.206	4.961	0.000	0.000
Excess water	RC1-current	μ	0.876	90.523	356.635	4.376	7.017
		σ	0.107	19.571	74.955	1.402	2.961
	RC2-min spill-historic	μ	0.547	66.475	318.839	2.537	5.161
		σ	0.118	18.249	80.273	0.846	2.160
	RC3-max store-historic	μ	0.835	170.384	344.268	7.543	7.018
		σ	0.052	21.719	66.248	6.713	3.454
	RC4-min spill-future	μ	0.455	68.654	325.539	2.581	5.238
		σ	0.112	18.225	81.325	0.906	2.183
	RC5-max store-future	μ	0.780	155.301	373.173	7.034	8.091
		σ	0.071	22.881	70.757	2.022	3.081

Note: μ = average ,σ= standard deviation

Table-4 shows the average maximum stored water at the end of the wet season (November) when using each obtained rule curve of the Ubolrat reservoir. The results indicated that the average maximum stored water at the end of the wet season when using the obtained rule curves from the proposed model were higher than the average maximum stored level when using the current rule curves. They found that the average maximum stored level when using RC3-max store-historic was the highest with 1,849.263±24.191 MCM, because of the searching objective function effect. The high capacity at the end of the wet season surely guarantees storing a lot of water for the next dry season.

Table-5 shows the average maximum stored water at the end of the wet season (November) when using each obtained rule curves of the Lampao reservoir. The results indicated that the average maximum stored water at the end of the wet season when using the obtained rule curves from the proposed technique was higher than the average maximum stored level when using the current rule curves. We found that the average maximum stored level when using RC3-max store-historic was the highest with 1,761.193±30.219 MCM, because of the searching objective function effect.

Table-6 shows the average maximum stored water at the end of the wet season (November) when using each obtained rule curve of the Nam Oon reservoir. The results indicated that the stored water at the end of the wet season when using obtained rule curves from the proposed model were higher than the average maximum stored level when using the current rule curves. They found that the stored level when using RC3-max store-historic was the highest with 431.128±7.258 MCM, because of the searching objective function effect.

VOL. 14, NO. 18, SEPTEMBER 2019 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

Table-4. Average maximum stored water at end of wet season using 1,000 samples of synthetic inflow for each obtained of the Ubolrat reservoir.

Rule curves	Stored water at the end of November (MCM)	
RC1-current	μ	1,586.051
	σ	44.682
RC2-min short-historic	μ	1,792.157
	σ	26.241
RC3-max store-historic	μ	1,849.263
	σ	24.191
RC4-min short-future	μ	1,675.483
	σ	39.941
RC5-max store-future	μ	1,824.774
	σ	38.821

Table-5. Average maximum stored water at end of wet season using 1,000 samples of synthetic inflow for each obtained of the Lampao reservoir.

Rule curves	Stored water at the end of November (MCM)	
RC1-current	μ	1,356.476
	σ	30.324
RC2-min short-historic	μ	1,428.935
	σ	32.178
RC3-max store-historic	μ	1,761.193
	σ	30.219
RC4-min short-future	μ	1,625.921
	σ	31.914
RC5-max store-future	μ	1,712.713
	σ	32.291

Table-6. Average maximum stored water at end of wet season using 1,000 samples of synthetic inflow for each obtained of the Nam Oon reservoir.

Rule curves	*Stored water at the end of November (MCM)*	
RC1-current	μ	326.347
	σ	13.361
RC2-min spill-historic	μ	327.307
	σ	16.384
RC3-max store-historic	μ	431.128
	σ	7.258
RC4-min spill-future	μ	365.141
	σ	17.278
RC5-max store-future	μ	412.612
	σ	9.826

Efficiency of rule curves under future inflow conditions

For the future situation, the obtained rule curves of all case searches were used to operate the reservoir system for evaluating the efficiency by considering future inflow scenario. Table-7 shows the situations of water shortage and excess water when using each obtained rule curves and the current rule curves of the Ubolrat reservoir. They indicated that the average magnitudes of the water shortages using the future obtained rule curves were less than the average magnitudes when using the current rule curves. The frequencies and duration of water shortages using the obtained rule curves from the proposed model were less than with the current rule curves too. In addition, the results also indicate that situations of water shortage when using the obtained of RC4-min short-future (21.801 MCM/year) are least because of the objective function effect. Furthermore, the other terms of water shortage situation are better than the other rule curves too, such as frequency, maximum magnitude and duration.

Table-8 shows the situations of water shortage and excess water when using each obtained rule curve and the current rule curves of the Lampao reservoir. The results indicated that the average magnitudes of the water shortages using the obtained future rule curves were less than the magnitudes when using the current rule curves. The results also indicate that situations of water shortage when using the obtained future rule curves of RC4-min short-future (240.574 MCM/year) were the least because of objective function effect. Furthermore, the other terms of water shortage situation were better than the other rule curves too, such as frequency, maximum magnitude and duration.

Table-9 shows the situations of water shortage and excess water when using each obtained rule curve and the current rule curves of the Nam Oon reservoir. They indicated that the average magnitudes of the excess water using the obtained future rule curves were less than the magnitudes when using the current rule curves. The results also indicate that situations of excess water when using the

ARPN Journal of Engineering and Applied Sciences

future rule curves of RC4-min spill-future (177.504 MCM/year) were least because of objective function effect. The frequency and duration time of the excess spill water using the obtained future rule curves were less than the frequency and duration when using the current rule curves. Furthermore, the results indicated that the average magnitudes of water shortage using the obtained rule curves from the proposed model are less than the magnitudes when using the current rule curves.

Table-7. Situations of water shortage and excess water of the Ubolrat reservoir using future inflow for each obtained rule curves.

Situations	Rule curves	Frequency (times/year)	Magnitude (MCM/year)		Duration (year)	
			Average	Maximum	Average	Maximum
Water shortage	RC1-current	0.341	25.273	660.021	1.167	3.000
	RC2-min short-historic	0.242	24.340	412.214	1.241	2.000
	RC3-max store-historic	0.340	22.860	418.932	1.417	4.000
	RC4-min short-future	0.021	21.801	290.431	1.011	2.000
	RC5-max store-future	0.331	23.861	418.089	1.419	4.000
Excess water	RC1-current	0.982	2,086.461	4,711.864	24.503	27.000
	RC2-min short-historic	0.982	2,055.181	4,697.881	24.503	27.000
	RC3-max store-historic	0.982	2,084.963	4,702.331	24.503	27.000
	RC4-min short-future	0.982	2,047.095	4,689.417	24.503	27.000
	RC5-max store-future	0.982	2,083.969	4,702.331	24.503	27.000

Table-8. Situations of water shortage and excess water of the Lampao reservoir using future inflow for each obtained rule curves.

Situations	Rule curves	Frequency (times/year)	Magnitude (MCM/year)		Duration (year)	
			Average	Maximum	Average	Maximum
Water shortage	RC1-current	0.849	249.724	695.024	5.42	8.00
	RC2-min short-historic	0.756	241.485	694.001	4.03	7.00
	RC3-max store-historic	0.746	242.081	670.033	4.09	7.00
	RC4-min short-future	0.727	240.574	651.765	4.25	6.00
	RC5-max store-future	0.759	246.211	693.217	4.61	8.00
Excess water	RC1-current	0.691	445.797	2,728.844	3.14	13.00
	RC2-min short-historic	0.682	442.141	2,727.537	3.21	14.00
	RC3-max store-historic	0.683	437.327	2,727.635	3.23	14.00
	RC4-min short-future	0.638	445.133	2,728.352	3.03	13.00
	RC5-max store-future	0.662	441.982	2,727.591	3.11	13.00

ARPN Journal of Engineering and Applied Sciences

Table-9. Situations of water shortage and excess water of the Nam Oon reservoir using future inflow for each obtained rule curves.

Situations	Rule curves	Frequency (times/year)	Magnitude (MCM/year)		Duration (year)	
			Average	Maximum	Average	Maximum
Water shortage	RC1-current	0.381	24.602	129.000	3.778	9.000
	RC2-min spill-historic	0.381	16.605	127.000	4.501	9.000
	RC3-max store-historic	0.381	11.924	106.000	4.503	9.000
	RC4-min spill-future	0.381	11.032	103.000	4.533	9.000
	RC5-max store-future	0.342	18.021	124.000	2.421	8.000
Excess water	RC1-current	0.982	199.661	925.360	11.520	20.000
	RC2-min spill-historic	0.981	197.581	925.360	14.510	20.000
	RC3-max store-historic	0.961	196.358	925.360	16.012	20.000
	RC4-min spill-future	0.922	177.504	925.360	11.520	20.000
	RC5-max store-future	0.962	182.551	925.360	10.143	20.000

Table-10 shows the average maximum stored water at the end of the wet season (November) when using each obtained rule curve of the Ubolrat reservoir. The results indicated that the stored water at the end of the wet season when using the new obtained rule curves was higher than the stored level when using the current rule curves. They also found that the stored level when using RC5-max store-future had the highest level of 2,260.231 MCM because of the searching objective function effect. In addition, these results are similar to the results when using the historic inflow rule curves (RC3-max store-historic).

Table-11 shows the average maximum stored water at the end of the wet season (November) when using each obtained rule curves of the Lampao reservoir. The results indicated that the stored water at the end of the wet season when using the new obtained rule curves was higher than the stored level when using the current rule curves. They also found that the stored level when using RC5-max store-future had the highest level of 1,897.928 MCM because of the searching objective function effect. In addition, these results are similar to the results when using the historic inflow rule curves (RC3-max store-historic).

Table-12 shows the average maximum stored water at the end of the wet season (November) when using each obtained rule curves of the Nam Oon reservoir. The results indicated that the stored water at the end of the wet season when using the new obtained rule curves was higher than the stored level when using the current rule curves. They also found that the stored level when using RC5-max store-future had the highest level of 495.432 MCM because of the searching objective function effect. In addition, these results were similar to the results when using the historic inflow rule curves (RC3-max store-historic) too.

Table-10. Average maximum stored water at end of wet season of the Ubolrat reservoir using future inflow for each obtained rule curves.

Rule curves	Stored water at the end of November (MCM)
RC1-current	1,915.067
RC2-min short-historic	1,973.251
RC3-max store-historic	2,177.181
RC4-min short-future	2,149.287
RC5-max store-future	2,260.231

Table-11. Average maximum stored water at end of wet season of the Lampao reservoir using future inflow for each obtained rule curves.

Rule curves	Stored water at the end of November (MCM)
RC1-current	1,495.548
RC2-min short-historic	1,556.971
RC3-max store-historic	1,872.218
RC4-min short-future	1,744.451
RC5-max store-future	1,897.928

Table-12. Average maximum stored water at end of wet season of the Nam Oon reservoir using future inflow for each obtained rule curves.

Rule curves	Stored water at the end of November (MCM)
RC1-current	435.632
RC2-min spill-historic	449.875
RC3-max store-historic	485.113
RC4-min spill-future	428.371
RC5-max store-future	495.432

CONCLUSIONS

This study applied a conditional genetic algorithm (CGA) with reservoir simulation model to search the optimal rule curves. There were 3 objective functions which applied to search optimal rule curves; (1) minimum average water shortage per year, (2) minimum average excess water spill per year and (3) maximum average store water at the end of wet season. The historic inflow and future in flow from the SWAT model were used in searching procedure. The future inflow and 1,000 samples of synthetic inflow were used to simulate the reservoir system for evaluating the performance of the obtained rule curves.

The results showed that the obtained rule curves from CGA with objective function of minimum average water shortage per year are more suitable for reservoir operation of the Ubolrat and Lampao than the current rule curves in both the synthetic inflow case and the future inflow case. Whereas, the obtained rule curves from CGA with objective function of minimum average excess water spill per year are more suitable for reservoir operation of the Nam Oon than the current rule curves in both the synthetic inflow case and the future inflow case.

Furthermore, the obtained rule curves from CGA with objective function of maximum store water at the end of wet season are more suitable for all reservoirs operation than the current rule curves in both the synthetic inflow case and the future inflow case too. These conclude that the CGA models considering future inflows are effective for searching optimal rule curves for future situations. Whereas the maximum average stored water at the end of the wet season is an effective objective function for searching optimal rule curves for storing water for the next dry season.

ACKNOWLEDGEMENTS

This research was financially supported by Mahasarakham University Grant 2019; the authors would like to acknowledge Mahasarakham University.

REFERENCES

[1] Ashofteh PS, Haddad OB and Loáiciga AH. 2015. Evaluation of climatic-change impacts on multiobjective reservoir operation with multiobjective genetic programming. Journal of Water Resources Planning. 141(11): 04015030.

[2] Azizipour M, Ghalenoei V, Afshar MH and Solis SS. 2016. Optimal operation of hydropower reservoir systems using weed optimization algorithm. Water Resources Management. 30(11): 3995-4009.

[3] Chaleeraktrakoon C and Kangrang A. 2007. Dynamic programming with the principle of progressive optimality for searching rule curves. Canadian Journal of Civil Engineering. 34(1): 170-176.

[4] Chang FJ, Chen L and Chang LC. 2005. Optimizing the reservoir operating rule curves by genetic algorithms. Hydrological Processes. 19: 2277-2289.

[5] Chiamsathit C, Adeloye AJ and Soundharajan BS. 2015. Assessing competing policies at Ubonratana reservoir, Thailand. Proceeding of the Institution of Civil Engineering - Water Management. 167(10): 551-560.

[6] Guo X, Hu T, Wu C, Zhang T and Lv Y. 2013. Multi-objective optimization of the proposed multi-reservoir operating policy using improved NSPSO. Water Resources Management. 27(7): 2137-2153.

[7] Hormwichian R, Kangrang A and Lamom A. 2009. A conditional genetic algorithm model for searching optimal reservoir rule curves. Journal of Applied Sciences. 9(19): 3575-3580.

[8] Hormwichian R, Kangrang A, Lamom A, Chaleeraktrakoon C and Patamatamkul P. 2012. Coupled-operations model and a conditional differential evolution algorithm for improving reservoir management. International Journal of Physical Sciences. 7(42): 5701-5710.

[9] Ilavarasan E and Thambidurai P. 2015. Genetic algorithm for task scheduling on distributed heterogeneous computing system. International Journal on Engineering Applications (IREA). 3(4): 108-117.

[10] IPCC. 2000. Summary of policymakers: Emission scenarios: A special report of IPCC workgroup III of the Intergovernmental Panel on Climate Change.

[11] Jain SK, Goel MK and Agarwal PK. 1998. Reservoir operation study of sabamati system, India. Journal of Water Resources Planning and Management. 124(1): 31-38.

ARPN Journal of Engineering and Applied Sciences

[12] Kangrang A, Compliew S and Hormwichian R. 2011. Optimal reservoir rule curves using simulated annealing. Proceedings of the Institution of Civil Engineers - Water Management. 164(WM1): 27-34.

[13] Kangrang A and Homwichian R, 2013. Optimal reservoir rule curves using conditional shuffled frog leaping algorithm and simulation. International Journal of Earth Sciences and Engineering. 6(6): 1392-1399.

[14] Kangrang A and Lokham C. 2013. Optimal reservoir rule curves considering conditional ant colony optimization with simulation model. Journal of Applied Sciences. 13(1): 154-160.

[15] Kangrang A, Pakoktom W, Nualnukul W and Chaleeraktrakoon C. 2017. Adaptive Reservoir Rule Curves by Optimization and Simulation. Proceedings of the Institution of Civil Engineers - Water Managemen. 170(WM5): 219-230.

[16] Kangrang A, Prasanchum H and Hormwichian R. 2017. Future runoff under land use and climate changes in the Nam Oon Basin, Thailand. International Journal of Ecology & Development. 32(3): 53-66.

[17] Kangrang A, Prasanchum H and Hormwichian R. 2018. Development of Future Rule Curves for Multipurpose Reservoir Operation Using Conditional Genetic and Tabu Search Algorithms. Advances in Civil Engineering. vol. 2018, Article ID 6474870, 10 pages.

[18] Ming B, Chang JX, Huang O, Wang YM and Huang SZ. 2015. Optimal operation of multi-reservoir system based on cuckoo search algorithm. Water Resources Management. 29(15): 5671-5687.

[19] Omar HA, Zaky EM, Ibrahim G, Elsawy A. 2013. An algorithm based levenberg marquardt method with genetic algorithm for solving continuation problems. International Journal on Numerical and Analytical Methods in Engineering (IRENA). 1(1): 20-30.

[20] Prasanchum H and Kangrang A. 2018. Optimal reservoir rule curves under climatic and land use changes for Lampao Dam using genetic algorithm. KSCE Journal of Civil Engineering. 22(1): 351-364.

[21] Soepangkat BOP, Norcahyo R, Pamuji DR and Lusi N. 2018. Multi-objective optimization in end milling process of ASSAB XW-42 tool steel with cryogenic coolant using grey fuzzy logic and backpropagation neural network-genetic algorithm (BPNN-GA) Approaches. International Review of Mechanical Engineering (IREME). 12(1): 42-54.

[22] Supakosol J and Kangrang A. 2017. Assessment of soil loss and nutrient depletion due to climate change impact in the SongKhram Basin, Thailand. International Journal of Ecology & Development. 32(2): 53-66.