AN IMPROVEMENT OF RESERVOIR RULE CURVES FOR INCREASING STORAGE CAPACITY

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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 curves 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 swarm 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.
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).

\[ W_r = S_{r-1} + I_r + P_r - E_r \]  

Where

- \( W_r \) is the available water during month \( r \), \( S_{r-1} \) is the stored water at the end of month \( r-1 \), \( I_r \) is the monthly inflow to the reservoir, \( P_r \) is the precipitation during month \( r \), and \( E_r \) is the average value of the evaporation loss. \( LRC_r \) is lower rule curves during month \( r \) and \( URC_r \) is upper rule curves during month \( r \).

After operation for all months along the considered inflow period, all monthly releases of water from the reservoir (\( R_r \) 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-1.Standard operating rule.](image)

**Figure-1.** Standard operating rule.

\[ W_r = S_{r-1} + I_r + P_r - E_r \]  

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 months 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:

\[ \text{Min } H (X_i) = \left( \frac{1}{n} \sum_{v=1}^{n} S_h \right) \]  

if \( R_i < D_i \); Then \( S_h = \sum_{i=1}^{12} (D_i - R_i) \)  

Else \( S_h = 0 \)
Where

\( n \) is the total number of considered years, \( S_h \) is the water shortage during year \( v \) (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:

\[
\text{Min } U(X_i) = \left( \frac{1}{n} \sum_{v=1}^{n} S_{p_v} \right) \quad \text{--------------------------------- (4)}
\]

If \( R_v > D_v \), Then \( S_{p_v} = \sum_{i=1}^{12} (R_i - D_i) \) \quad \text{---------------- (5)}

Else \( S_{p_v} = 0 \)

where \( n \) is the total number of considered years, \( S_{p_v} \) is the excess spill water during year \( v \) (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:

\[
\text{Max } N(X_i) = \left( \frac{1}{n} \sum_{v=1}^{n} S_{N_v} \right) \quad \text{--------------------------------- (6)}
\]

where \( n \) is the total number of considered years, \( S_{N_v} \) is the stored water at the end of the month of November during year \( v \) (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 km² (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 km². 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 km² (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.](image-url)
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.

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 curve.

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 curve.

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 curve.
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
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.
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.
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 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 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.
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 situation under considering 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 the 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 rule curves. In addition, the other terms such as frequency, maximum magnitude and duration are better too.
Table 1. Situations of water shortage and excess water of Ubolrat reservoir considering 1,000 samples of synthetic inflow for each using obtained rule curves.

<table>
<thead>
<tr>
<th>Situations</th>
<th>Rule curves</th>
<th>Frequency (times/year)</th>
<th>Magnitude (MCM/year)</th>
<th>Duration (year)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Average</td>
<td>Maximum</td>
</tr>
<tr>
<td>Water</td>
<td>RC1-current</td>
<td>µ 0.887</td>
<td>532.161</td>
<td>1,481.370</td>
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<td></td>
<td></td>
<td>σ 0.036</td>
<td>25.132</td>
<td>144.276</td>
</tr>
<tr>
<td>shortage</td>
<td>RC2-min short-historic</td>
<td>µ 0.873</td>
<td>382.219</td>
<td>1,425.750</td>
</tr>
<tr>
<td></td>
<td></td>
<td>σ 0.029</td>
<td>29.178</td>
<td>170.698</td>
</tr>
<tr>
<td></td>
<td>RC3-max store-historic</td>
<td>µ 0.908</td>
<td>427.853</td>
<td>1,411.100</td>
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<td></td>
<td></td>
<td>σ 0.032</td>
<td>27.612</td>
<td>180.318</td>
</tr>
<tr>
<td></td>
<td>RC4-min short-future</td>
<td>µ 0.728</td>
<td>391.611</td>
<td>1,451.790</td>
</tr>
<tr>
<td></td>
<td></td>
<td>σ 0.051</td>
<td>28.749</td>
<td>177.481</td>
</tr>
<tr>
<td></td>
<td>RC5-max store-future</td>
<td>µ 0.668</td>
<td>553.036</td>
<td>3,511.172</td>
</tr>
<tr>
<td></td>
<td></td>
<td>σ 0.045</td>
<td>33.939</td>
<td>825.291</td>
</tr>
<tr>
<td>Excess</td>
<td>RC1-current</td>
<td>µ 0.668</td>
<td>553.036</td>
<td>3,511.172</td>
</tr>
<tr>
<td>water</td>
<td></td>
<td>σ 0.045</td>
<td>33.939</td>
<td>825.291</td>
</tr>
<tr>
<td></td>
<td>RC2-min short-historic</td>
<td>µ 0.462</td>
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<td></td>
<td></td>
<td>σ 0.051</td>
<td>38.386</td>
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<td></td>
<td>RC3-max store-historic</td>
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<td>434.704</td>
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<td></td>
<td></td>
<td>σ 0.050</td>
<td>36.919</td>
<td>781.299</td>
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<td></td>
<td>RC4-min short-future</td>
<td>µ 0.472</td>
<td>400.127</td>
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<td></td>
<td></td>
<td>σ 0.050</td>
<td>36.579</td>
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<td></td>
<td>RC5-max store-future</td>
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<td>410.739</td>
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<td></td>
<td></td>
<td>σ 0.051</td>
<td>35.803</td>
<td>801.723</td>
</tr>
</tbody>
</table>

Note: µ = average, σ = standard deviation
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.

<table>
<thead>
<tr>
<th>Situations</th>
<th>Rule curves</th>
<th>Frequency (times/year)</th>
<th>Magnitude (MCM/year)</th>
<th>Duration (year)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Average</td>
<td>Maximum</td>
</tr>
<tr>
<td>Water shortage</td>
<td>RC1-current</td>
<td>µ 0.896</td>
<td>269.447</td>
<td>757.691</td>
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<tr>
<td></td>
<td></td>
<td>σ 0.038</td>
<td>16.004</td>
<td>152.021</td>
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<tr>
<td></td>
<td>RC2-min short-histor</td>
<td>µ 0.813</td>
<td>250.013</td>
<td>763.371</td>
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<tr>
<td></td>
<td></td>
<td>σ 0.041</td>
<td>16.311</td>
<td>151.119</td>
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<td></td>
<td>RC3-max store-histor</td>
<td>µ 0.807</td>
<td>253.242</td>
<td>750.824</td>
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<td></td>
<td></td>
<td>σ 0.034</td>
<td>16.291</td>
<td>152.057</td>
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<tr>
<td></td>
<td>RC4-min short-future</td>
<td>µ 0.819</td>
<td>254.257</td>
<td>747.261</td>
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<td></td>
<td></td>
<td>σ 0.035</td>
<td>16.317</td>
<td>150.126</td>
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<tr>
<td></td>
<td>RC5-max store-future</td>
<td>µ 0.827</td>
<td>252.196</td>
<td>752.351</td>
</tr>
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<td></td>
<td></td>
<td>σ 0.033</td>
<td>15.219</td>
<td>151.571</td>
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<td>Excess water</td>
<td>RC1-current</td>
<td>µ 0.689</td>
<td>464.752</td>
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<td></td>
<td></td>
<td>σ 0.051</td>
<td>16.812</td>
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<td></td>
<td></td>
<td>σ 0.055</td>
<td>17.213</td>
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<tr>
<td></td>
<td>RC3-max store-histor</td>
<td>µ 0.651</td>
<td>446.241</td>
<td>2,344.044</td>
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<td></td>
<td></td>
<td>σ 0.058</td>
<td>17.174</td>
<td>491.473</td>
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<td>RC4-min short-future</td>
<td>µ 0.642</td>
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<td></td>
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<td>σ 0.051</td>
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<td>RC5-max store-future</td>
<td>µ 0.653</td>
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<tr>
<td></td>
<td></td>
<td>σ 0.056</td>
<td>17.181</td>
<td>491.331</td>
</tr>
</tbody>
</table>

Note: µ = average, σ = standard deviation
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.

<table>
<thead>
<tr>
<th>Situations</th>
<th>Rule curves</th>
<th>Frequency (times/year)</th>
<th>Magnitude (MCM/year)</th>
<th>Duration (year)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Average</td>
<td>Maximum</td>
</tr>
<tr>
<td>Water shortage</td>
<td>RC1-current</td>
<td>µ</td>
<td>0.982</td>
<td>42.586</td>
</tr>
<tr>
<td></td>
<td></td>
<td>σ</td>
<td>0.031</td>
<td>6.258</td>
</tr>
<tr>
<td></td>
<td>RC2-min spill-historic</td>
<td>µ</td>
<td>0.642</td>
<td>27.208</td>
</tr>
<tr>
<td></td>
<td></td>
<td>σ</td>
<td>0.103</td>
<td>8.126</td>
</tr>
<tr>
<td></td>
<td>RC3-max store-historic</td>
<td>µ</td>
<td>0.679</td>
<td>28.288</td>
</tr>
<tr>
<td></td>
<td></td>
<td>σ</td>
<td>0.067</td>
<td>3.774</td>
</tr>
<tr>
<td></td>
<td>RC4-min spill-future</td>
<td>µ</td>
<td>0.693</td>
<td>18.821</td>
</tr>
<tr>
<td></td>
<td></td>
<td>σ</td>
<td>0.108</td>
<td>8.149</td>
</tr>
<tr>
<td></td>
<td>RC5-max store-future</td>
<td>µ</td>
<td>0.704</td>
<td>33.801</td>
</tr>
<tr>
<td></td>
<td></td>
<td>σ</td>
<td>0.085</td>
<td>1.206</td>
</tr>
<tr>
<td>Excess water</td>
<td>RC1-current</td>
<td>µ</td>
<td>0.876</td>
<td>90.523</td>
</tr>
<tr>
<td></td>
<td></td>
<td>σ</td>
<td>0.107</td>
<td>19.571</td>
</tr>
<tr>
<td></td>
<td>RC2-min spill-historic</td>
<td>µ</td>
<td>0.547</td>
<td>66.475</td>
</tr>
<tr>
<td></td>
<td></td>
<td>σ</td>
<td>0.118</td>
<td>18.249</td>
</tr>
<tr>
<td></td>
<td>RC3-max store-historic</td>
<td>µ</td>
<td>0.835</td>
<td>170.384</td>
</tr>
<tr>
<td></td>
<td></td>
<td>σ</td>
<td>0.052</td>
<td>21.719</td>
</tr>
<tr>
<td></td>
<td>RC4-min spill-future</td>
<td>µ</td>
<td>0.455</td>
<td>68.654</td>
</tr>
<tr>
<td></td>
<td></td>
<td>σ</td>
<td>0.112</td>
<td>18.225</td>
</tr>
<tr>
<td></td>
<td>RC5-max store-future</td>
<td>µ</td>
<td>0.780</td>
<td>155.301</td>
</tr>
<tr>
<td></td>
<td></td>
<td>σ</td>
<td>0.071</td>
<td>22.881</td>
</tr>
</tbody>
</table>

Note: \( \mu \) = average, \( \sigma \) = 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 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.
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.

<table>
<thead>
<tr>
<th>Rule curves</th>
<th>Stored water at the end of November (MCM)</th>
<th>(\mu)</th>
<th>(\sigma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RC1-current</td>
<td></td>
<td>1,586.051</td>
<td>44.682</td>
</tr>
<tr>
<td>RC2-min short-histor</td>
<td></td>
<td>1,792.157</td>
<td>26.241</td>
</tr>
<tr>
<td>RC3-max store-histor</td>
<td></td>
<td>1,849.263</td>
<td>24.191</td>
</tr>
<tr>
<td>RC4-min short-future</td>
<td></td>
<td>1,675.483</td>
<td>39.941</td>
</tr>
<tr>
<td>RC5-max store-future</td>
<td></td>
<td>1,824.774</td>
<td>38.821</td>
</tr>
</tbody>
</table>

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.

<table>
<thead>
<tr>
<th>Rule curves</th>
<th>Stored water at the end of November (MCM)</th>
<th>(\mu)</th>
<th>(\sigma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RC1-current</td>
<td></td>
<td>1,356.476</td>
<td>30.324</td>
</tr>
<tr>
<td>RC2-min spill-histor</td>
<td></td>
<td>1,428.935</td>
<td>32.178</td>
</tr>
<tr>
<td>RC3-max store-histor</td>
<td></td>
<td>1,761.193</td>
<td>30.219</td>
</tr>
<tr>
<td>RC4-min spill-future</td>
<td></td>
<td>1,625.921</td>
<td>31.914</td>
</tr>
<tr>
<td>RC5-max store-future</td>
<td></td>
<td>1,712.713</td>
<td>32.291</td>
</tr>
</tbody>
</table>

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.

<table>
<thead>
<tr>
<th>Rule curves</th>
<th>Stored water at the end of November (MCM)</th>
<th>(\mu)</th>
<th>(\sigma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RC1-current</td>
<td></td>
<td>326.347</td>
<td>13.361</td>
</tr>
<tr>
<td>RC2-min spill-histor</td>
<td></td>
<td>327.307</td>
<td>16.384</td>
</tr>
<tr>
<td>RC3-max store-histor</td>
<td></td>
<td>431.128</td>
<td>7.258</td>
</tr>
<tr>
<td>RC4-min spill-future</td>
<td></td>
<td>365.141</td>
<td>17.278</td>
</tr>
<tr>
<td>RC5-max store-future</td>
<td></td>
<td>412.612</td>
<td>9.826</td>
</tr>
</tbody>
</table>

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 (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 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
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.

<table>
<thead>
<tr>
<th>Situations</th>
<th>Rule curves</th>
<th>Frequency (times/year)</th>
<th>Magnitude (MCM/year)</th>
<th>Duration (year)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Average</td>
<td>Maximum</td>
</tr>
<tr>
<td>Water shortage</td>
<td>RC1-current</td>
<td>0.341</td>
<td>25.273</td>
<td>660.021</td>
</tr>
<tr>
<td></td>
<td>RC2-min short-historic</td>
<td>0.242</td>
<td>24.340</td>
<td>412.214</td>
</tr>
<tr>
<td></td>
<td>RC3-max store-historic</td>
<td>0.340</td>
<td>22.860</td>
<td>418.932</td>
</tr>
<tr>
<td></td>
<td>RC4-min short-future</td>
<td>0.021</td>
<td>21.801</td>
<td>290.431</td>
</tr>
<tr>
<td></td>
<td>RC5-max store-future</td>
<td>0.331</td>
<td>23.861</td>
<td>418.089</td>
</tr>
<tr>
<td>Excess water</td>
<td>RC1-current</td>
<td>0.982</td>
<td>2,086.461</td>
<td>4,711.864</td>
</tr>
<tr>
<td></td>
<td>RC2-min short-historic</td>
<td>0.982</td>
<td>2,055.181</td>
<td>4,697.881</td>
</tr>
<tr>
<td></td>
<td>RC3-max store-historic</td>
<td>0.982</td>
<td>2,084.963</td>
<td>4,702.331</td>
</tr>
<tr>
<td></td>
<td>RC4-min short-future</td>
<td>0.982</td>
<td>2,047.095</td>
<td>4,689.417</td>
</tr>
<tr>
<td></td>
<td>RC5-max store-future</td>
<td>0.982</td>
<td>2,083.969</td>
<td>4,702.331</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Situations</th>
<th>Rule curves</th>
<th>Frequency (times/year)</th>
<th>Magnitude (MCM/year)</th>
<th>Duration (year)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Average</td>
<td>Maximum</td>
</tr>
<tr>
<td>Water shortage</td>
<td>RC1-current</td>
<td>0.849</td>
<td>249.724</td>
<td>695.024</td>
</tr>
<tr>
<td></td>
<td>RC2-min short-historic</td>
<td>0.756</td>
<td>241.485</td>
<td>694.001</td>
</tr>
<tr>
<td></td>
<td>RC3-max store-historic</td>
<td>0.746</td>
<td>242.081</td>
<td>670.033</td>
</tr>
<tr>
<td></td>
<td>RC4-min short-future</td>
<td>0.727</td>
<td>240.574</td>
<td>651.765</td>
</tr>
<tr>
<td></td>
<td>RC5-max store-future</td>
<td>0.759</td>
<td>246.211</td>
<td>693.217</td>
</tr>
<tr>
<td>Excess water</td>
<td>RC1-current</td>
<td>0.691</td>
<td>445.797</td>
<td>2,728.844</td>
</tr>
<tr>
<td></td>
<td>RC2-min short-historic</td>
<td>0.682</td>
<td>442.141</td>
<td>2,727.537</td>
</tr>
<tr>
<td></td>
<td>RC3-max store-historic</td>
<td>0.683</td>
<td>437.327</td>
<td>2,727.635</td>
</tr>
<tr>
<td></td>
<td>RC4-min short-future</td>
<td>0.638</td>
<td>445.133</td>
<td>2,728.352</td>
</tr>
<tr>
<td></td>
<td>RC5-max store-future</td>
<td>0.662</td>
<td>441.982</td>
<td>2,727.591</td>
</tr>
</tbody>
</table>
Table-9. Situations of water shortage and excess water of the Nam Oon reservoir using future inflow for each obtained rule curves.

<table>
<thead>
<tr>
<th>Situations</th>
<th>Rule curves</th>
<th>Frequency (times/year)</th>
<th>Magnitude (MCM/year)</th>
<th>Duration (year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water shortage</td>
<td>RC1-current</td>
<td>0.381</td>
<td>24.602</td>
<td>3.778</td>
</tr>
<tr>
<td></td>
<td>RC2-min spill-historic</td>
<td>0.381</td>
<td>16.605</td>
<td>4.501</td>
</tr>
<tr>
<td></td>
<td>RC3-max store-historic</td>
<td>0.381</td>
<td>11.924</td>
<td>4.503</td>
</tr>
<tr>
<td></td>
<td>RC4-min spill-future</td>
<td>0.381</td>
<td>11.032</td>
<td>4.533</td>
</tr>
<tr>
<td></td>
<td>RC5-max store-future</td>
<td>0.342</td>
<td>18.021</td>
<td>2.421</td>
</tr>
<tr>
<td>Excess water</td>
<td>RC1-current</td>
<td>0.982</td>
<td>199.661</td>
<td>11.520</td>
</tr>
<tr>
<td></td>
<td>RC2-min spill-historic</td>
<td>0.981</td>
<td>197.581</td>
<td>14.510</td>
</tr>
<tr>
<td></td>
<td>RC3-max store-historic</td>
<td>0.961</td>
<td>196.358</td>
<td>16.012</td>
</tr>
<tr>
<td></td>
<td>RC4-min spill-future</td>
<td>0.922</td>
<td>177.504</td>
<td>11.520</td>
</tr>
<tr>
<td></td>
<td>RC5-max store-future</td>
<td>0.962</td>
<td>182.551</td>
<td>10.143</td>
</tr>
</tbody>
</table>

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).
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 conclusion 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.

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REFERENCES


