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Research Article
Alternative Approach of Firefly Algorithm for Flood Control Rule Curves

[1]Anongrit Kangrang, [1]Nutthapong Srikamol, [1]Rattana Hormwichian, [2]Haris Prasanchum and [3]Ounla Sriwanpheng

[1]Faculty of Engineering, Mahasarakham University, 44150, Thailand
[2]Faculty of Engineering, Rajamangala University of Technology Isan KhonKaen Campus, Muang Khon Kaen, 40000, Thailand
[3]Faculty of Water Resources, National University of Laos, Laos

Abstract

Background and Objective: Rule curves of reservoirs are necessary guides to operate reservoir system in the long run for both flood and draught control. The main objective of each rule curve depended on the characteristics of each reservoir. This paper proposed an alternative approach of a Firefly Algorithm (FA) to connect with the simulation model for searching optimal reservoir rule curves as the flood control area. **Materials and Methods:** Minimum average excess water and minimum frequency excess water were used as the objective functions for the searching procedure. The historic inflow, synthetic inflow data of 1,000 events and future inflow were used to evaluate efficiency of the flood control rule curves in showing situations of water shortage and excess water in term of frequency, magnitude and duration. The proposed model was applied to determine the optimal flood rule curves of the Nam Oon reservoir in the northeast region of Thailand. **Results:** The results showed that the patterns of the obtained rule curves were similar to the current rule curves. The optimal flood control rule curves were used to simulate the Nam Oon reservoir system for evaluating the situation of flood in long term operation. The results indicated that situations of water shortage and of excess water using optimal flood control rule curves from the proposed model were smaller than with current rule curves both for the present and future situations. **Conclusion:** The new obtained rule curves from the proposed FA model are better than the existing rule curves in decreasing flood situation.

Key words: Rule curves, flood control rule curves, firefly algorithm, simulation model, reservoir system

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Corresponding Author: Anongrit Kangrang, Faculty of Engineering, Mahasarakham University, 44150, Thailand Tel: (66) 43-754316 Fax: (66) 43-754316

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Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Now a days many countries face serious problems in management of natural resources, especially water resources which are important for the development of quality of life and human well-being. The problem of water resources is still serious and significant. In addition the problem is complex and tends to be more hazardous because of the impact of climate and land use changes[1,2]. Essential components of good water management are having sufficient tools for water management and having suitable water organization. Tools for water management consist of water control structures as hardware and organization structure and non-construction as software[3,4].

Often, an improvement of reservoir operation is a popular tool because it can be performed quickly and is a non-construction method. Reservoir operation is a complex multi-objective optimization problem with many conflicting objectives and constraints[5], rule curves are necessary guidelines using in reservoir operation. The curves indicated either the interval of required water levels or desired storage volumes of each reservoir at any particular month. These rule curves consisted of upper rule curves and lower rule curves for controlling monthly stored water in long term operation. However, they needed to improve and to find optimal values when used for a long time or if any data are changed.

There are many optimization techniques that have been applied to search optimal rule curves, such as dynamic programming[6-8], genetic algorithm[9,10], particle swarm optimization[11-13], ant colony optimization[14,15] and cuckoo search[16] etc. However, these techniques are subjected to limitations in their work and are only appropriate for the specific areas of use. If available, alternative optimization technique is easy to use and suitable for the area and it is worth studying. Last decade an alternative approach of firefly algorithm (FA) is a swarm based metaheuristic algorithm inspired by the flashing behaviour of fireflies. It is an effective and easy to implement algorithm[17-23]. Therefore, it is possible to apply the FA with reservoir simulation model for searching optimal rule curves.

The rationale behind the study was to achieve controlling flood situation by an alternative optimization approach. Hence, the main objective of this work was to apply the firefly algorithm in order to find the optimal reservoir rule curves for decreasing the flood situation. The proposed model was applied to determine the optimal flood rule curves of the Nam Oon reservoir in the northeast region of Thailand.

MATERIALS AND METHODS

Study area: The Nam Oon reservoir is located in Sakolnakorn province, Thailand. This work was done during 2017-2018. Location of the study area was shown in Fig. 1. The Nam Oon

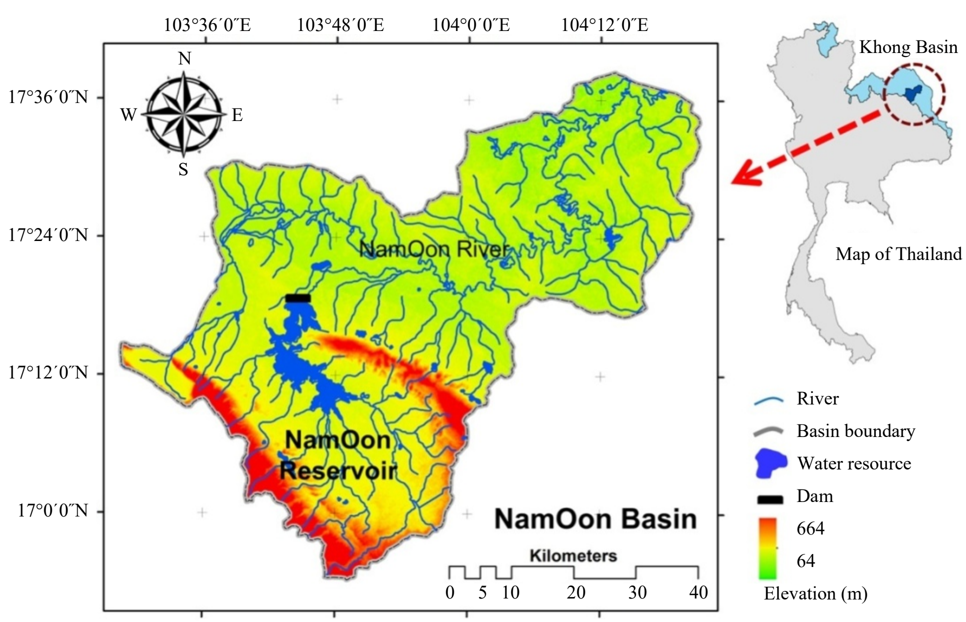

Fig. 1: Location of the Num Oon reservoir
Source: Land Development Department of Thailand, 2014

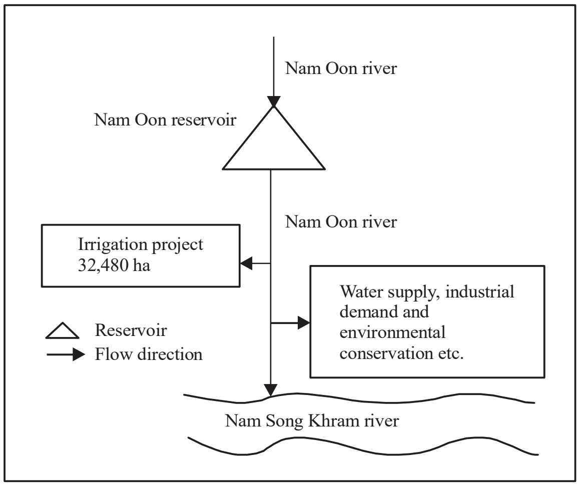

Fig. 2: Schematic diagram of the Num Oon reservoir system

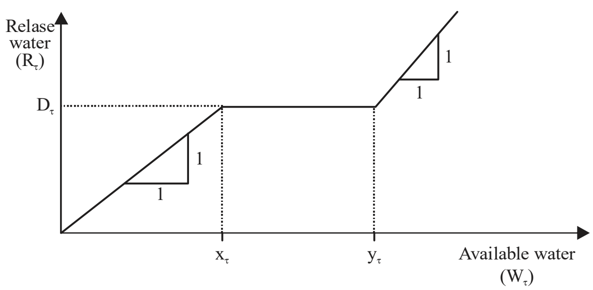

Fig. 3: Standard operating rule

reservoir is located in the Songkham Basin in the northeast region of Thailand with an irrigation area of 32,480 ha. The normal storage capacity and average annual inflow were 520 and 431.600 million m^3, respectively. The historic inflow data records were collected during 1992-2017 (26 years). The 19 years of future inflow data was created by the SWAT model considering land use change under scenario[24,25] B2 from 2018-2036.

The water requirements from Nam Oon reservoir were irrigation, industrial demand, domestic water supply and environmental conservation. Schematic diagrams of the Nam Oon system were presented in Fig. 2.

Reservoir simulation model: A reservoir simulation was created to operate reservoir system on the basis of the water balance concept. These physical reservoir data, hydrologic data, water requirement from the reservoir and related data were required in the operating system. First, available water was calculated by using the water balance concept as presented in Eq. 1. Next, monthly release of water was estimated by considering the available water with release criteria, standard operating rule and reservoir rule curves as showed in Fig. 3.

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

where, W_τ is the available water during month t, $S_{\tau-1}$ is the stored water at the end of month τ-1 from record data which set at full reservoir capacity for the start running, I_τ is the inflow to the reservoir during month t from record data, P_τ is the precipitation during month t from record data and E_τ is the average value of the evaporation loss during month t from record data.

Then the monthly release of water from the reservoir (R_τ) was used to calculate water shortage and excess water situations, which can be expressed as the average annual excess water per year (the first objective function for searching) and the frequency excess water per year (the second objective function for searching) as shown in Eq. 2 and 4, respectively. The x_τ is lower rule curves during month t and y_τ is upper rule curves during month t.

$$\text{Min Avr}_i = \left(\frac{1}{n}\sum_{v=1}^{n} Sp_v\right) \quad (2)$$

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

$$\text{Min Fre}_i = \left(\frac{1}{n}\sum_{v=1}^{n} Sf_v\right) \quad (4)$$

where, Avr_i is average excess water per year during iteration i, Sp_v is the excess water during year n (year in which releases are higher than the target demand), Fre_i is frequency excess water, Sf_n is the number of annual flood (year that releases higher than target demand), D_t is monthly target demand from the reservoir which calculated from all water demand in downstream area (this study used data from the previous study by Supakosol and Kangrang[25]) and i is the iteration number.

Application of firefly algorithm with reservoir simulation: The connection of the FA and reservoir simulation model started with initialized parameters covering all initial necessary data such as dead storage level, normal high water level, full capacity level and monthly water requirement. Then model became generated initial population of fireflies that each firefly represents the monthly rule curves of the reservoirs which were defined as the upper rule curves

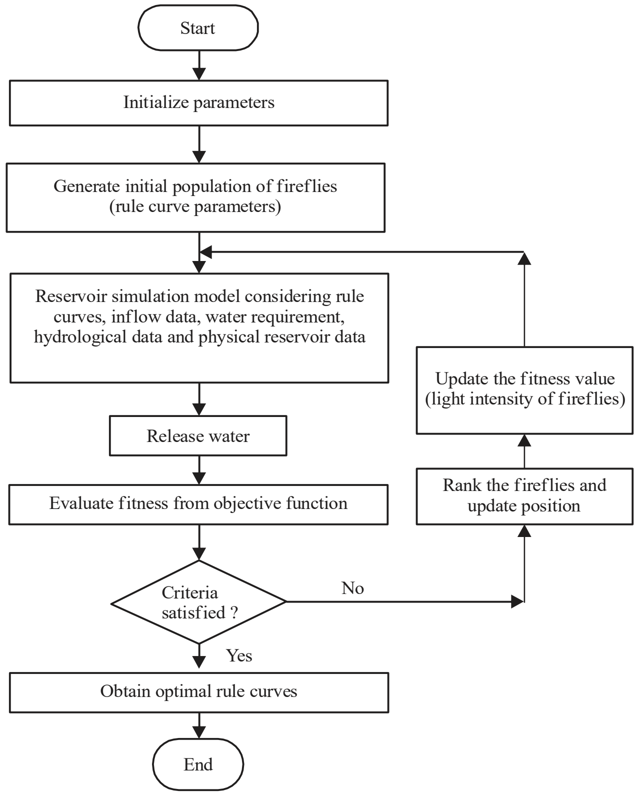

Fig. 4: Application of FA and reservoir simulation model for searching optimal rule curves

and the lower rule curves. Next, the first set of fireflies in the initial population (24 decision variables that consist of 12 values for upper rule curves and 12 values for lower rule curves) were sent to use in reservoir simulation model. Monthly release water was obtained from the reservoir simulation model considering those rule curves and standard operating rule. Next, the released water was used to determine the objective functions that were described in the previous section. Then, evaluations of the fitness from the objective function and update fitness values were done objective function. After that, the fireflies were ranked and their position updated. Next, the stopping criterion was checked. This procedure was repeated until criteria were met and the optimal rule curves were obtained. The FA and reservoir simulation model for searching the rule curves was described in Fig. 4.

Evaluation of the obtained rule curves: The obtained rule curves of the FA connecting with reservoir simulation model from reservoir were evaluated by using the obtained rule curves to simulate reservoir system considering each inflow case. Firstly, the 26 years of historic inflow were used in reservoir simulation model. Secondly, the 1,000 events of synthetic inflow from 26 years historic inflow were used to evaluate under the same conditions in reservoir simulation model. Finally, the 19 years of future inflow were used to evaluate again. The results of evaluation were shown by situations of water shortage and excess water in term of frequency, magnitude and duration.

Statistical analysis: The term of frequency was calculated from the number of annual flood or drought divide by the total considered years. The magnitude of excess water or shortage water was calculated from the total excess water or the total shortage water divide by the total considered years. Whereas, the maximum magnitude of excess water or shortage water was calculated from the yearly excess water or yearly shortage water for all considered years. The duration of excess water or shortage water was calculated from the number of adjacent annual flood or drought was divided by the total groups of adjacent annual flood or drought. Whereas, the maximum duration of excess water or shortage water was selected from the maximum number of adjacent annual flood or drought for all considered years. In addition, for the synthetic inflow case results were by mean $\pm$ standard deviation.

RESULTS

Optimal rule curves: The optimal rule curves producing the proposed FA model were shown in Fig. 5. These optimal rule curves were searched by using minimized excess water per year as the objective function of the search procedure considering both historic inflow and future inflow. The RC2-Avr spill-historic, the RC3-Avr spill-future and the current rule curves (RC1-current) were similar pattern. They also indicated that lower rule curves of using historic and future inflow were higher than current rule curves during March-July. Whereas, the upper rule curves of the new obtained rule curves during June-September were higher than current rule curves. However, the obtained upper rule curves (RC3-Avr spill-future) were lower than the current upper rule curves during October-November.

The optimal rule curves of the Nam Oon reservoir using minimized frequency excess water as the objective function of the search procedure considering historic inflow and future inflow were shown in Fig. 6. The pattern of RC4-Fre spill-historic, RC5-Fre spill-future and current rule curves were similar. They also indicated that lower rule curves of using historic and future inflow (RC4-Fre spill-historic and RC5-Fre spill-future) were higher than current rule curves during January-June. Whereas, the upper rule curves of the new obtained rule curves in July were lower than current rule curves.

Efficiency of the obtained rule curves: The efficiency of the newly obtained rule curves from all cases of searching were evaluated by the operating reservoir simulation considering each historic inflow data. About

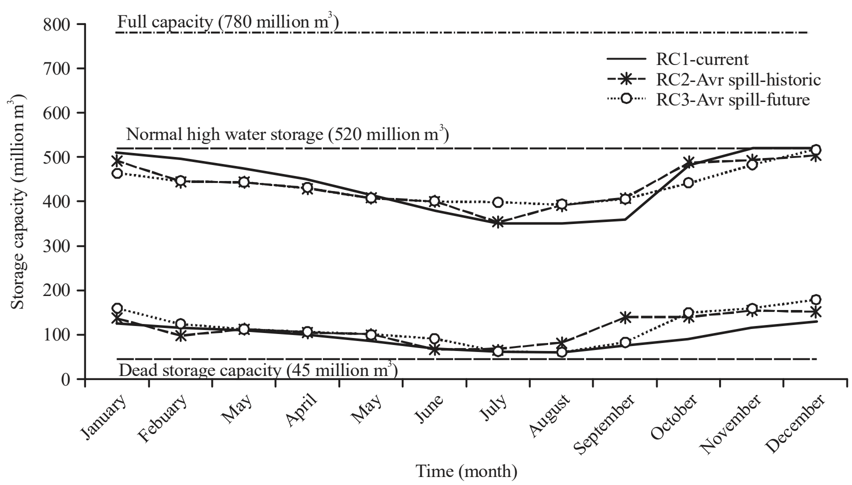

Fig. 5: Optimal rule curves of the Num Oon reservoir using minimum average excess spill water as the objective function of the search procedure

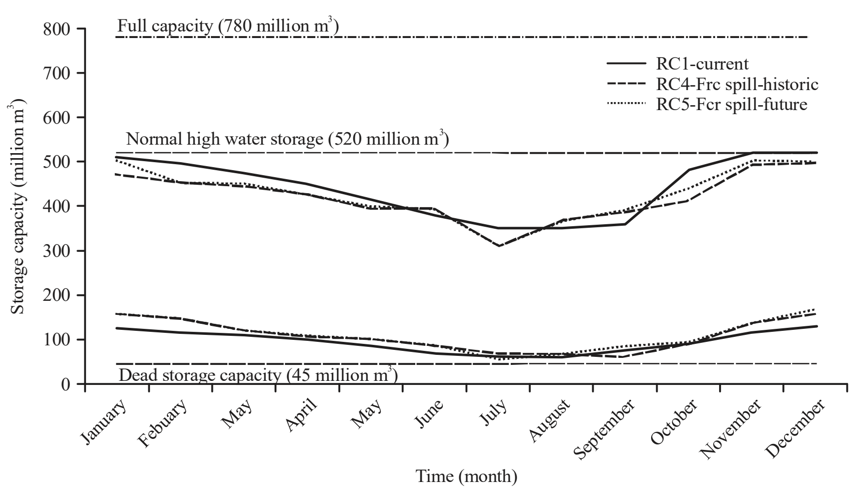

Fig. 6: Optimal rule curves of the Num Oon reservoir using minimum frequency excess water as the objective function of the search procedure

Table 1: Situations of water shortage and excess water of the Nam Oon reservoir considering historic inflow 26 years

			Volume (Million m^3)		Time period (year)	
Situations	Rule curves	Frequency (times/year)	Average	Maximum	Average	Maximum
Water deficit	RC1-current	0.962	44.923	152.000	12.500	15.000
	RC2-Avr historic	0.462	20.846	131.000	1.714	3.000
	RC3-Avr future	0.538	22.923	133.000	2.000	3.000
	RC4-Fre historic	0.769	37.846	141.000	5.000	9.000
	RC5-Fre future	0.962	38.462	141.000	12.500	13.000
Excess water	RC1-current	0.769	113.402	476.959	4.000	6.000
	RC2-Avr historic	0.692	88.723	457.760	3.000	5.000
	RC3-Avr future	0.692	92.428	511.201	3.000	5.000
	RC4-Fre historic	0.769	106.775	515.740	4.000	6.000
	RC5-Fre future	0.731	106.731	515.740	3.167	6.000

Table 2: Situations of water shortage and excess water of the Nam Oon reservoir considering synthetic inflow 1,000 samples

				Volume (Million m^3)		Time period (year)	
Situations	Rule curves		Frequency (times/year)	Average	Maximum	Average	Maximum
Water deficit	RC1-current	μ	0.971	41.586	130.189	18.238	21.056
		σ	0.032	6.258	36.162	6.990	4.693
	RC2-Avr historic	μ	0.482	18.080	109.518	2.418	4.823
		σ	0.108	7.848	28.958	0.865	2.039
	RC3-Avr future	μ	0.518	19.167	109.414	2.565	5.194
		σ	0.106	8.091	28.427	0.924	2.143
	RC4-Fre historic	μ	0.803	33.035	122.708	6.022	10.708
		σ	0.084	7.417	35.520	3.485	4.295
	RC5-Fre future	μ	0.951	34.541	120.663	16.361	19.769
		σ	0.043	6.953	33.835	7.381	5.136
Excess water	RC1-current	μ	0.676	90.509	356.605	3.376	7.017
		σ	0.100	19.573	74.965	1.402	2.960
	RC2-Avr historic	μ	0.551	67.278	327.006	2.575	5.216
		σ	0.113	18.270	81.102	0.897	2.179
	RC3-Avr future	μ	0.559	68.432	328.763	2.595	5.293
		σ	0.111	18.283	81.524	0.916	2.200
	RC4-Fre historic	μ	0.633	81.158	348.277	2.938	6.096
		σ	0.101	18.764	79.845	1.104	2.472
	RC5-Fre future	μ	0.635	81.780	346.294	3.016	6.259
		σ	0.102	19.108	78.410	1.142	2.572

μ: Mean, σ: Standard deviation

26 years of monthly inflow data for Nam Oon reservoir were considered in reservoir operation. Table 1 showed the situations of water shortage and excess water of the Nam Oon reservoir considering historic inflow 26 years in operating reservoir simulation. They indicated that the situations of water shortage (0.462 times/year, 20.846 million m^3/year and 1.714 years for frequency, magnitude and duration, respectively) and excess water (0.692 times/year, 88.723 million m^3/year and 3.00 years for frequency, magnitude and duration, respectively) using FA rule curves from considering the minimized average excess water as the objective function (RC2-Avr spill-historic) were the least as compared with other rule curves, because they were created from using historic inflow in searching process. They also showed that the newly obtained rule curves were better at decreasing the situation of water shortage and excess release than the current rule curves under historic scenario.

Furthermore, the 1,000 samples of synthetic inflow of each reservoir were generated from their historic inflow data. Table 2 showed the situations of water shortage and excess water of the Nam Oon reservoir considering synthetic inflow comprising 1,000 events in operating reservoir simulation. They indicated that the situations of water shortage (18.080 ± 7.848 million m^3/year) and excess water (67.278 ± 18.270 million m^3/year) using FA rule curves from considering minimize average excess water as the objective function (RC2-Avr spill-historic) were the least as compared with other rule curves. Whereas, the results of using current rule curves for evaluation gave the highest value.

Table 3: Situations of water shortage and excess water of the Nam Oon reservoir considering future inflow 19 years

			Volume (Million m^3)		Time period (year)	
Situations	Rule curves	Frequency (times/year)	Average	Maximum	Average	Maximum
Water deficit	RC1-current	0.632	20.316	57.000	3.000	5.000
	RC2-Avr historic	0.316	5.105	62.000	2.000	4.000
	RC3-Avr future	0.263	3.895	46.000	1.667	3.000
	RC4-Fre historic	0.526	15.737	77.000	3.333	5.000
	RC5-Fre future	0.789	16.632	75.000	5.000	9.000
Excess water	RC1-current	0.947	234.065	522.880	9.000	17.000
	RC2-Avr historic	0.947	218.067	492.614	9.000	17.000
	RC3-Avr future	0.947	217.089	480.715	9.000	17.000
	RC4-Fre historic	0.947	228.591	515.494	9.000	17.000
	RC5-Fre future	0.947	228.706	522.880	9.000	17.000

Moreover, the efficiency of the newly obtained rule curves of Nam Oon reservoir were evaluated by the operating reservoir simulation considering 19 years of future inflow under land use change and climate change of B2 scenario. Table 3 showed the situations of water shortage and excess water of the Num Oon reservoir considering future inflow 19 years (2018-2036). They indicated that the average magnitudes of the water shortage (3.865 million m^3/year) and excess water (217.089 million m^3/year) using the future rule curves (RC3-Avr spill-future) were the least as compared to the other rule curves. Furthermore, the frequencies and duration times of the water shortage and excess water of using the future rule curves (RC3-Avr spill-future) were the lowest too.

DISCUSSION

The patterns of obtained rule curves from all searching cases and the patterns current rule curves (Fig. 5, 6) were similar because of the seasonal inflow effect and the same conditional effect like the other studies in Thailand[7,10,13,14]. In addition, these effects of searching were important to control the shape of the optimal rule curves as described in many previous studies[3,6,9]. The new obtained lower rule curves were higher than current lower rule curves during dry season, these conditions can control among of release water by decreasing the water release in order to save more water during dry season like the previous studies by Hormwichian *et al.*[10], Kangrang *et al.*[13] and Kangrang and Lokham[14]. Whereas, the new obtained upper rule curves during June-September were higher than the current upper rule curves, these conditions can save more water by decreasing the excess water and keeping high water level. Moreover, the new obtained upper rule curves were lower than the current upper rule curves during October-November, hence these new obtained rule curves can alleviate flood situation better than the current rule curves due to the increasing water release can make more reserve volume in the reservoir.

The results of evaluation the efficiency of the new obtained rule curves (Table 1-3) indicated that the situations of water shortage excess water using FA rule curves from considering the historic in flow were the least as compared with other rule curves. Because the rule curves were created from using historic inflow in searching process can alleviate flood situation in historic scenarios better than the other rule curves like the other studies by Hormwichian *et al.*[10], Kangrang *et al.*[13] and Kangrang and Lokham[14]. Moreover, results of the evaluation also indicated that the situations of water shortage excess water using FA rule curves from considering the future inflow were the least as compared with other rule curves because they were created from using future inflow in searching process like the other studies by Chang *et al.*[9], Hormwichian *et al.*[10], Kangrang *et al.*[13] and Kangrang and Lokham[14]. Comparison the results of the proposed FA with their results of the other optimization techniques should be considered.

CONCLUSION

This study applied Firefly Algorithm (FA) with a reservoir simulation model for searching optimal rule curves. The results indicated that the proposed model with two objective functions provided the new rule curves. The patterns of these rule curves were similar due to seasonal inflow effect and the same searching conditions. However, there were some different points especially during the rainy season. Furthermore, the results also revealed that the rule curves from using minimum average excess water and considering historic inflow in searching process can alleviate excess water situation less than other rule curves in both historic inflow and synthetic inflow situations. In addition, the obtained rule curves from using minimum average excess water and considering future inflow in searching process can alleviate situations of flood more than the current rule curves in future inflow situation.

SIGNIFICANCE STATEMENT

This study discovered the Firefly Algorithm (FA) connecting with the simulation model for searching optimal flood control rule curves that can be beneficial for finding optimal rule curves. The new obtained rule curves from the proposed FA model were better than the existing rule curves in decreasing flood situation. This study will help the researchers to search the optimal flood control rule cures of the reservoir in flooding area.

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