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Multi-objective future rule curves using conditional tabu search algorithm and conditional genetic algorithm for reservoir operation

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ABSTRACT

Multi-objective future rule curves are imperative recommendations for operating multipurpose reservoirs throughout long term periods. This research utilized the conditional tabu search algorithm (CTSA) and conditional genetic algorithm (CGA) combining to the reservoir simulation model through contemplating the multiple-purpose functionals when exploring processes for finding adaptable rule curves of a single reservoir. The historic inflow data during 1966–2016 (51 years) including the future inflow during 2017–2041 (25 years) in case of the B2 scenario of IPCC for the Ubolrat Reservoir in Thailand were applying to create the searching conditions. The 500 synthetic events of historical inflow and 25 years of future inflow were used to calculate the reservoir operation process for assessing the obtained rule curves. As a result, the predicament of water scarcity and spill water were illustrated in terms of frequency scale and duration along with the maintained water at the edge of the rainy period. The operation outcomes suggest that the multi-objective rule curves developed by the CGA can alleviate the frequency of flooding and drought situations appropriately than the CTSA during the future period. However, the rule curves obtained from both optimization techniques indicate better performance correlated to the actual rule curves along with having more maintained water at the end of the rainy period (November), which has continued benefits betwixt the dry period because the reservoir can discharge water in sufficient quantities to the downstream area.

1. Introduction

Currently, many areas are facing more severe flood and drought situations due to the impacts of climate variation, land use and land cover changes, including population increase, economic expansion, and highly demand of natural resources for human consumption (Awotwi et al., 2017). An improvement in water resource management is needed to prevent the mentioned situation. The demand management and supply sites of water resource management are considered to solve these serious problems. Often a non-construction method is required first to save time and budget, for example, to increase irrigation efficiency, to involve public participation and to improve reservoir operation. Finding the adaptable rule curve under the reservoir operation rules is absolutely necessary for improving water management in the reservoir. The upper line and lower line of reservoir rule curves are imperative guidelines in order to release and storage of water over long term operation. In general, for the reservoir operation including water storage and release, it is considered monthly within one year, taking into account the main factors such as inflow into reservoir, hydrological processes (such as infiltration and evaporation) and water demand in downstream areas and because the reservoir operation requires results to manage the water management system which is a non-linear and highly complex problem (Jain et al., 1998; Chang et al., 2005; Jothiprakash and Arunkumar, 2014). The adaptive reservoir rule curves have been solved for use in reservoir operation during long term consideration.

Over the past decade, the optimization techniques, especially in the meta-heuristic search group, which include: genetic algorithm (GA), bat algorithm (BA), ant colony optimization (ACO), simulated annealing algorithm (SA), particle swam optimization (PSO), weed optimization (WO) and cuckoo search (CS) have been applied to develop the optimal rule curves (Kangrang et al., 2011, 2017; Ming et al., 2015; Afshar, 2013; Afshar et al., 2015; Akbari-Alashti et al., 2015; Ashofteh et al., 2015; Bozorg-Haddad et al., 2015; Ji et al., 2015; Azizipour et al., 2016). The reservoir rule curves developed from the use of optimization techniques are necessary to go through effective improvements and integrations which must be carried out along with important physical parameters

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such as historic inflow into the reservoir, quantity of water requirement from the downstream area. Moreover, searching conditions with various objective functions and smoothing functions were applied to improve the efficiency of modified model. However, rule curves are needed for use with the future situation under multipurpose demand. Hence, the multi-objective rule curves of the reservoir are important information for future operation. In addition, there many effective optimization techniques that have not been adopted to combine with reservoir operation in order to developing optimal rule curves, like the tabu search technique.

Tabu search is a meta-heuristic procedure designed for finding suitable answer from complicated optimization problems. This method is different from other meta-heuristics, which do not rely on randomness or selection based on probability. It is a deterministic method, which searches for answers from the immediate best answer. This technique is forbidden to look for an answer to the same set of existing answers, also known as a tabu-list (in order to prohibit the search for old or lost answers in cyclic, which will result in the inability to find new answer that is more suitable than the previous answer). It has been effectively adapted to solve many problems in the engineering fields, such as industrial, electrical and transportation as well as water resources management (Cunha and Ribeiro, 2004; Zhang, 2011). The tabu search is recognized as being able to avoid giving the final answer that is the local optimum value and can continue to search until the answer is near to the global optimum point. Its capability relies on the fine-tuning of a few criterions (Glover and Laguna, 1997; Faigle and Kern, 1992; Sa-ngiamvibool et al., 2011; Kangrang et al., 2018).

The main goal of this research was to implement a conditional tabu search algorithm (CTSA) to intergrade with the reservoir simulation system by regarding the multi-objective functions for finding the optimal multi-objective rule curves. In order to reach this goal, the recommended model was illustrated to the Ubolrat Reservoir in Thailand examining the recorded reservoir inflow data during 1966–2016 (51 years) and simulated future inflow data during 2017–2041 (25 years) under the B2 scenario of IPCC. In addition, to confirm the adaptive rule curve performance developed from CTSA. Comparison of reservoir management results in the minimize water shortage, minimize excess spill water, and maximize collected water at the edge of wet period situations compared to the existing rule curve and the optimal rule curve developed from the conditional genetic algorithm CGA technique under the synthesis of 51 years historic inflow and the 25 years in future period has been expanded to indicate the effectiveness of the CTSA optimal rule curve obtained from this study.

2. Methodology

2.1. The model of reservoir operation system

The reservoir operation system consists of the available water that is determined from the water balance theory and water demands downstream from the site. The estimation of water from the reservoirs allocated to the downstream areas is considered in two main areas, consisting of: 1) monthly water demand for various activities, including water supply production, electricity production, irrigation, industry, ecological conservation, 2) available water in reservoirs, which are considered from important parameters such as inflow flowing into the reservoir, including hydrological phenomenon changes such as evaporation and infiltration. The reservoir operation model is operated under the standard operating policy as expressed in Fig. 1 and Eq. (1).

$$R_{\nu,\tau} = \begin{cases} N_\tau + W_{\nu,\tau} - y_\tau, \ \ for \ \ W_{\nu,\tau} \geq y_\tau + N_\tau \\ N_\tau, \ \ for \ \ x_\tau \leq W_{\nu,\tau} < y_\tau + N_\tau \\ N_\tau + W_{\nu,\tau} - x_\tau, \ \ for \ \ x_\tau - N_\tau \leq W_{\nu,\tau} < x_\tau \\ 0, \ \ otherwise \end{cases} \tag{1}$$

where $R_{\nu,\tau}$ is the release of water during year ν and month τ (τ = representatives of the months 1 (January) to 12 (December)), N_τ is the net water requirement during months τ; x_τ is the lower point of rule curve in months τ; y_τ is the upper rule curve point in months τ and $W_{\nu,\tau}$ is the usable water by determining the water balance concept during year ν and months τ, as defined in Eq. (2):

$$W_{\nu,\tau} = S_{\nu,\tau} + Q_{\nu,\tau} - R_{\nu,\tau} - E_\tau - MS \tag{2}$$

where $S_{\nu,\tau}$ is the quantity of water stored at the end of the months τ; $Q_{\nu,\tau}$ is the quantity of inflow flowing into the reservoir, E_τ is the quantity of average monthly evaporation, and MS is the minimum reservoir storage quantity (at the dead storage level). The reservoir operating rule usually reserves the usable water quantity ($W_{\nu,\tau}$) for alleviating the risk of water insufficient in the future, when $0 \leq W_{\nu,\tau} < x_\tau$ - N_τ during long term period service.

In the process of finding the optimal capacity for releasing water from the reservoir each month, the multi-objective functions that were considered include average water shortage, frequency excess, frequency of water shortage or spill together with the maximum of stored water at the rim of the wet period, etc., in which all above -mentioned multi-objective functions are connected to find answers of the optimal rule curves with CTSA and CGA techniques. The details of the multi-objective functions that have been implemented in this study are shown in the next section.

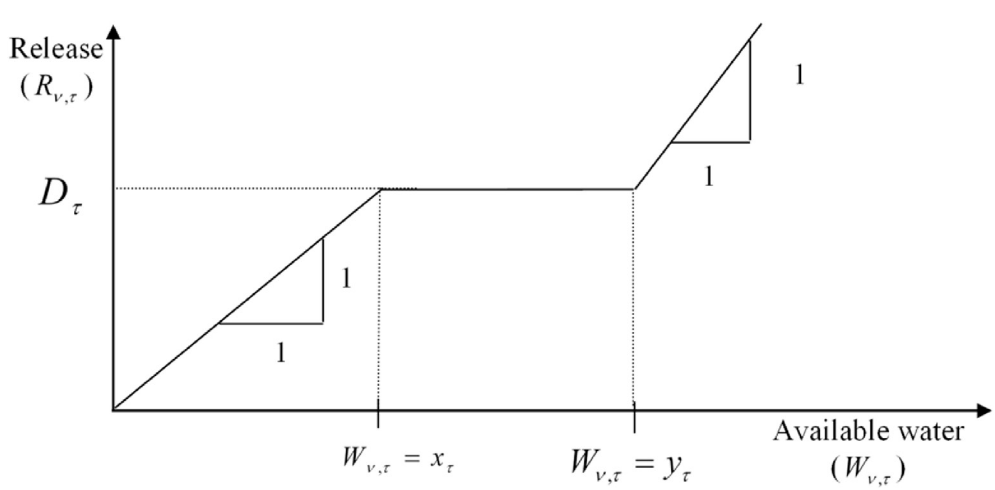

Fig. 1. Standard operating rule.

2.2. Multi-objective optimization

Many difficulties of water resources management, for example, demand-supply, flood protection, drought protection and power supply are related to the optimization of large scale problems. Classical optimization searching techniques such as linear programing (LP) including dynamic programing (DP) are generally not effective in solving large problems, especially with non-linear objective functions. Similarly, because reservoir management based on the operating rule curves involving relations among, downstream demand, inflow, and storage capacity is highly nonlinear and complex. The traditional optimization techniques are difficult to solve such a problem (Reddy and Kumar, 2006). Therefore, in order to overcome these complications, it is necessary to develop more robust optimization techniques and research to find effective optimization techniques. Simulation of certain natural processes, such as persistence or evolution of species, etc., has been modeled to develop optimization tools for problem solving. A large history is applicable on evolutionary optimization tools. These methods include genetic algorithms and tabu search (Li and Qui, 2015). These algorithms are applied to many water resource engineering optimization problems and proved efficient in solving problems. Evolutionary algorithms have been favored in single-objective optimization and, more recently, have also become ordinary in multi-objective optimization.

Since the main purpose of most reservoirs in Thailand consists of two parts: the delivery of sufficient water between the dry period and flood protection between the rainy period. Hence, research on the optimal rule curves generally focuses on a single purpose function such as preventing water shortages or flood protection. However, at present, the climate change situation has affected the hydrological system and the inflow flowing into the reservoir is inversely different from the past. For example, in Thailand during the year 2011, the Great Flood occurred, but in the year 2012–2015, there was a severe drought. Determining the optimization of rule curve with a single objective function may result in risk or inappropriate for future reservoir management. In order to comply with the main objectives of the reservoir and the future change situation, finding a quantitative relationship between these two purposes (protection of water shortages and flood) with different conditions or constrains must be considered in the non-linear multi-objective optimization problems, which must be met by limitations such as general reservoir operations rule, drought-flood protection, irrigation, water supply and ecological preservation. In this study, multi-objective functions include: 1) the minimum water shortage, 2) the minimum excess spill water and 3) the maximum of average maintained water at the last month of the wet period (November), has been taken into account for optimizing the reservoir rule curves. The operation of multi-objective optimization, which consists of 3 sequences as follows: In the first place, the minimum average quantity of insufficient water per year (Z) is set as the objective function of the finding process subject to the constraints on the simulation model as detailed in Eqs. (3) and (4):

$$\text{Min} \quad Z(Xi) = \left(\frac{1}{n} \sum_{\nu=1}^{n} Sh_\nu \right) \tag{3}$$

$$\text{if} \quad R_\tau < D_\tau; \text{Then} \quad Sh_\nu = \sum_{\tau=1}^{12} (D_\tau - R_\tau) \tag{4}$$

$$\text{Else} \quad Sh_\nu = 0$$

where n is the whole number of considered years, Sh_ν is the number of water shortage between years ν (year in which spills do not meet 100% of the objective requirement) and i is the iteration rounds. Then, the searching system is continued on condition that the termination criterion is accepted. This termination criterion is the optimum objective function with a slight change (less than 0.10 MCM).

Secondly, the minimum average quantity of release excess water per year (U) is address as the second objective function of the examining process subject to the limitations in the simulation model as defined in Eqs. (5) and (6):

$$\text{Min } U(Xi) = \left(\frac{1}{n} \sum_{\nu=1}^{n} Sp_\nu \right) \tag{5}$$

$$\text{if} \quad R_\tau > D_\tau; \text{Then} \quad Sp_\nu = \sum_{\tau=1}^{12} (R_\tau - D_\tau) \tag{6}$$

$$\text{Else} \quad Sp_\nu = 0$$

where n is the whole number of considered years, Sp_ν is the quantity of release excess water during years ν (year in which releases excess water are higher than the objective requirement) and i is the iteration rounds.

Thirdly, the maximum of the average maintained water quantity at the last month of the wet period (N) is set as the objective function of the finding process subject to the limitations in the simulation model as illustrated in Eq. (7):

$$\text{Max} \quad N(Xi) \quad = \left(\frac{1}{n} \sum_{\nu=1}^{n} SN_\nu \right) \tag{7}$$

where n is the whole number of considered years, SN_ν is the maintained water quantity at the last month of wet period (November is the last month of the wet season in Thailand) during years ν, and i is the iteration rounds.

2.3. Conditional tabu search algorithm connecting reservoir simulation for finding rule curves

The CTSA connecting with the reservoir simulation model is present as follows: Firstly, the CTSA begins with a set preliminary population $\{X_1, X_2, ..., X_n\}$ that is created randomly inside the possible space. The possible space is the value between the dead storage capacity and the normal highly water level of the considered reservoir. For single reservoir, rule curve comprised of 24 decision factors (for both 12 upper points and 12 lower points). The possible result of the repetition i^{th} is expressed as $X_i = [x_{i1}, x_{i2}, ..., x_{i24}]^T$. Then, the answer set of rule curve points will be brought into the reservoir simulation for executing the procedure. Finally, the monthly of water release is computed from the reservoir simulation model by regarding the answer set of rule curve points. The unification of the CTSA and reservoir simulation model is illustrated in Fig. 2.

2.4. Conditional genetic algorithm connecting reservoir simulation for finding rule curves

The operation of the connection between the CGA and the reservoir simulation model consists of 4 steps. The first is the creation of chromosomes by encoding patterns to change the decision variables, which include selection, crossover, and mutation processes. Each decision variable refers to the upper level and lower level lines of rule curve of the reservoir. Second, when calculating the results of the first chromosome in the primary population, the outcome is a 24 decision variable consisting of 12 values from the upper rule curve rule and 12 values from the lower rule curve, respectively. Third, the monthly water spilled from the reservoir will be reconsidered with regard to the new rule curves (with 24 values) yielded from the procedure of the reservoir simulation model. Then, the spilled water is used to determine the multi-objective functions that were explained in the previous section. Finally, the reproduction system will develop the novel rule curve value in the next age, which in this process is repeated until the answer is the optimal rule curve, both 12 points of the upper rule curve and 12 points of the lower rule curve (Prasanchum and Kangrang, 2018). The schematic of CGA connect with

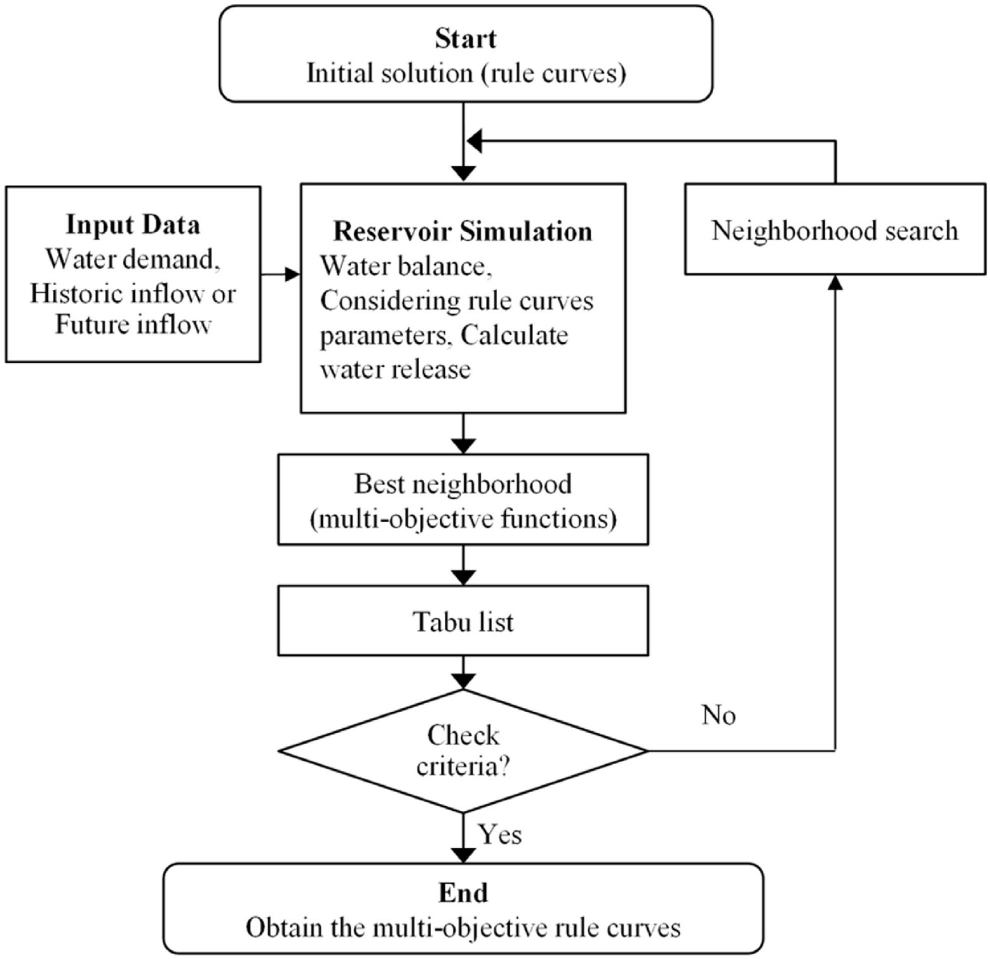

Fig. 2. Conditional tabu search algorithm connecting reservoir simulation for searching rule curves.

the reservoir simulation system for developing the optimal reservoir rule curves is illustrated in Fig. 3.

2.5. SWAT model and input data

The semi-distributed hydrological model, soil and water assessment tool (SWAT) (Arnold et al., 1998) was develop to projection the impact on water resource management practices on hydrological process, water quantity and quality caused by land use, land cover change and climate change, operates on a daily time step (Meaurio et al., 2015). SWAT also performs effectively in the event that the input data is insufficient, which is suitable for study areas with limited data. The model simulates a basin by separating the area into the sub-basins based on DEM, which are forward divided into the hydrologic response units (HRUs). The HRUs of each sub-basin comprise of the spatial physical data such as soil types, land use and land cover classification and topography. In addition, SWAT has a requirement to import daily climate data, which is the major variable for the operation of the model, namely, maximum-minimum temperatures, precipitation (rainfall), solar radiation, relative humidity and wind speed. These physical processes are concerned with the water movement required for the inflow assessment. The spatial data for importing to SWAT consist of; 1) Digital Elevation Model (DEM) in resolution of 30 × 30 m, 2) Land use map in 1:50,000 resolution, 3) Soil types map in 1:50,000 resolution, 4) Future climate data under the B2 scenario during the years 2017–2041 (generated from the PRECIS model).

In term of future climate data, PRECIS (Masud et al., 2016) is a regional climate model (RCM) created by the Hadley Center for Climate Prediction and Research, which purposes to anatomize the future climate phenomenon, delineating basis data from global dataset ECHAM4. The model has a spatial resolution of 0.22 °C in the grid and downscaled to 0.2 °C or about 22 × 22 km^2 (Lacombe et al., 2012). In this work, the daily climate data in the future for input to SWAT was used between years 2017–2041 in case of B2 IPCC SRES scenario, including precipitation, maximum and minimum temperatures, solar radiation, relative humidity and wind speed. The IPCC SRES scenario B2 was used as the model of the sustainable social, economic, and environmental problem solving including the economic development at average level and the environment conservation and social equality at local and regional levels. However, future climate data from PRECIS requires methods to reduce data bias before being used (Islam et al., 2008). In this work, the correction of data bias from PRECIS uses the Change Factor (CF) technique (Milville et al., 2010). The CF technique is a method for creating variables obtained from the ratio of monthly averages (for precipitation) and monthly differences (for temperature) between data from PRECIS and the observed stations (as shown in the position of the station in Fig. 4) at the same time period during the years 1992–2016 (25 years). The monthly variable value received from the CF method will be used to reduce the deviation of future climate data during the years 2017–2041 (25 years). In order to provide climate data (which has been downscaled) imported into SWAT and makes the calculation of the future inflow most reliable (Zhang et al., 2014). Therefore, this study has determined the number of years to predict the appropriate future inflow is 25 years in order to be consistent with the baseline year climate data obtained from the observed stations in the study area (for the use as the baseline data of the CF method) which has the most integrity and continuity of data.

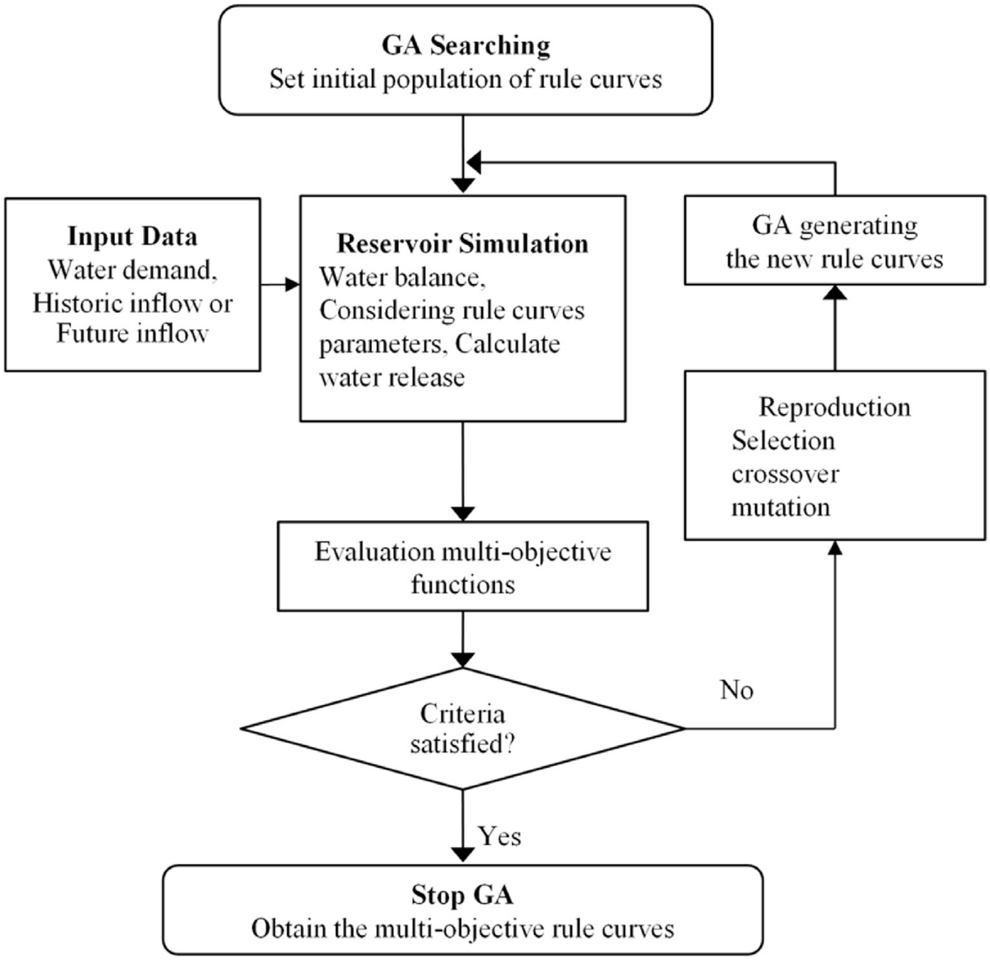

Fig. 3. Conditional genetic algorithm connecting reservoir simulation for searching rule curves.

2.6. Demonstrative research area

This research applied the presented models to the Ubolrat Reservoir, which has the third biggest dam in Thailand. The Ubolrat Reservoir is located in the Chi Basin in the northeastern region with an upstream watershed area of 3,282 km^2 (see Fig. 4). The mean annual temperature is 27 °C and the average annual precipitation is 1,411 mm. The Ubolrat Reservoir is a large multi-purpose reservoir, developed for a variety of purposes, including electricity generation, agriculture irrigation, flood protection, water supply production, fishing, industry, intercity transportation and ecosystems conservation. The reservoir has a normal storage volume of 2,431 MCM. The average inflow flows into the reservoir is 2,451.741 MCM per year. The schematic management diagram of the Ubolrat Reservoir is illustrated in Fig. 5.

In this study, the connection between the CTSA and the reservoir simulation model to develop the multi-objective rule curves is calculated with the MATLAB model. The three objective functions including; 1) minimize average water maintained per year, 2) minimize average excess release water per year, and 3) maximize average maintained water at the last month of the wet period (November). The recorded inflow data of the Ubolrat Reservoir during 1966–2016 (51 years) and simulated future inflow data during 2017–2041 (25 years) under the B2 scenario of IPCC (obtained from PRECIS, IPCC, 2000) is calculated using SWAT (see Fig. 6), which data from both periods will be used to determine each objective function. In the evaluation process of the optimal rule curves performance, the HEC-4 model was considered to create 500 synthetic monthly inflow events to test the new rule curves obtained from this CTSA technique, as well as to compare with the existing rule curves. Moreover, the future water demand and future inflow were also used to assess the obtained rule curves. Then, applying the CGA connecting with the reservoir simulation model for searching the multi-objective rule curves was done the same as when applying the CTSA for all cases. The 25 years of future inflows to the reservoir were created by the SWAT model under both climate and land use changes (Alansi et al., 2009; Lin et al., 2015; Vu et al., 2015; Ismail et al., 2017).

3. Results and discussion

3.1. Development of historic rule curves with multi-objective functions

In order to achieve the new historic rule curves developed from the reservoir simulation model integrating with CTSA and CGA while considering diverse objective functions, various data imported into the new rule curves development process includes; the 51 years of monthly historic inflow, evaporation, precipitation, irrigation demand, water supply production, industrial demand and ecological conservation (in each month). After the data has been processed by MATLAB, the result is the new historic rule curves that responds to the multi-objective functions. Then the shape of the new historic rule curves in every case will be plotted compared to the existing, which is presented in Figs. 7, 8, 9, and 10. The results demonstrated that the shape of new historic rule curve in every cases were homologous to the existing. The characteristics of these new historic rule curves are similar to the optimal rule curves of the reservoirs in Thailand that were previously studied (Ashofteh et al., 2015; Kangrang et al., 2017), mainly due to the effects of seasonal inflow changes.

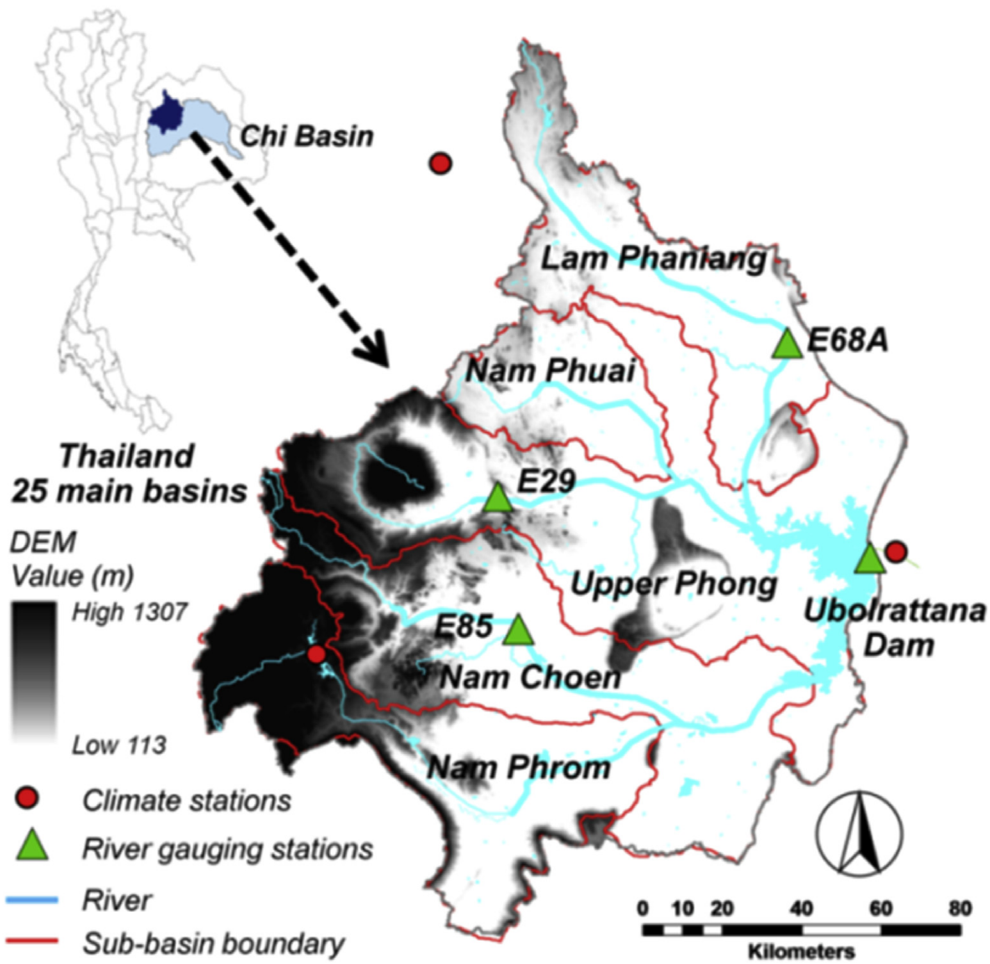

Fig. 4. Location of Ubolrat Reservoir.

In details, Figs. 7 and 9 illustrate the patterns of the optimal historic rule curves of the Ubolrat Reservoir that has been synthesized by CTSA and CGA models, by defining two objective functions: minimize water shortage (RC2-CTSA-min shortage, RC6-CGA-min shortage) and minimize excess spill water (RC3-CTSA-min spill, RC7-CGA-min spill), respectively, as well as compare to the currently rule curves. Considering the upper level line of the new historic rule curves yielded from CTSA and CGA for both function objectives, it has a higher position than the existing rule curves. For the lower level line, there is only a slight difference. Therefore, the reservoirs can increase storage capacity for use at November and into the next dry season, which is beneficial in reducing the risk of water shortage, as in the other studies (Ashofteh et al., 2015; Chiamsathit et al., 2015).

Figs. 8 and 10 also show the new historic rule curves using the maximize maintained water at November with the minimize water shortage (RC4-CTSA-max storage min shortage, RC8-GGA-max storage min shortage) and maximize maintained water at the end of the wet period with the minimize excess spill water (RC5-CTSA-max storage min spill, RC9-CGA-max storage min spill) by the CTSA and the CGA models, respectively, same as when compared with the existing rule curves. The new adaptive rule curves also demonstrated that the upper level lines of the CTSA for both described previously are higher positioning than the upper level line of the existing, especially during the wet season (August–October); whereas, the lower levels of them are lightly contrast. Therefore, this rule curves can increase the colleted water at the beginning of dry season, which the results are similar to the other studies (Guo et al., 2013; Chiamsathit et al., 2015).

3.2. *Development of future rule curves with multi-objective functions*

The future rule curve development procedure is an application of future inflow data between the years 2017–2041 (25 years) that is generated from the PRECIS (under the forecast of B2 scenario of IPCC) and the SWAT respectively. Including other monthly data needed for importing into reservoir simulation model by connecting with the CTSA and CGA techniques, which consider the conditions of the multi-objective functions as well as the creation of the optimal historic rule curves that has been detailed earlier. Figs. 11, 12, 13, and 14 implies the optimal future rule curves derived from CTSA and CGA techniques, which the patterns are analogous to the existing rule curves.

In term of the future upper rule curve lines, the storage capacity level of the CTSA (RC2-CTSA-future-min shortage, RC3-CTSA-future-min spill, RC4-CTSA-future-max storage-min shortage and RC5-CTSA-future-max storage-min spill) and CGA (RC6-CGA-future-min shortage, RC7-CGA-future-min spill, RC8-CGA-future-max storage-min shortage and RC9-CGA-future-max storage-min spill) indicated that the higher positioning than the currently upper rule curve in order to decrease the discharge and to retain the water volume to the full capacity of the reservoir at the last month of rainy period (November). These results will help the reservoirs have sufficient water volume and prevent water shortage situation in the next year. On the other hand, during the February–June (in drought season) the storage capacities (as illustrated in the lower rule curves) of the CTSA, CGA and exist are slightly different to mitigate the water shortage event during the drought season as well.

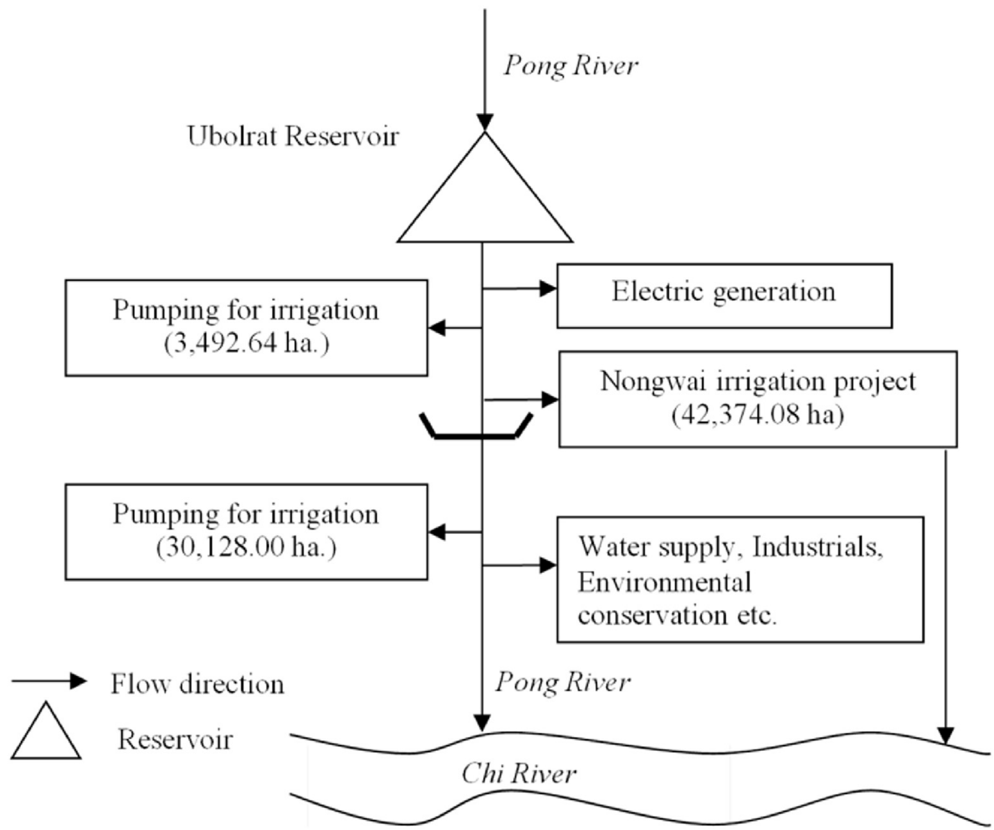

Fig. 5. Schematic diagram of Ubolrat basin.

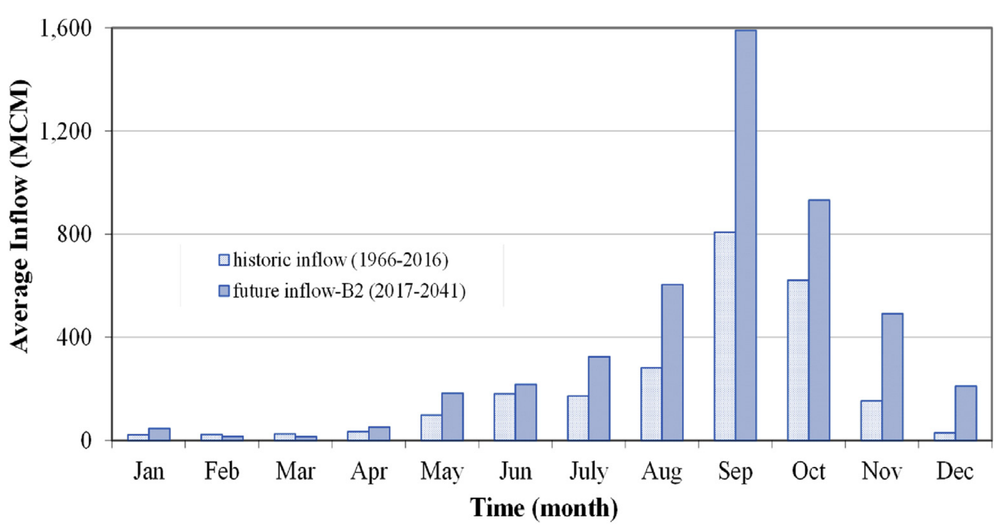

Fig. 6. Historic inflow and future inflow of Ubolrat Reservoir.

3.3. Performance of optimal rule curves in synthetic historic inflow conditions

The evaluation of historic optimal rule curves performance developed from CTSA and CGA techniques that have considered all of the multi-objective functions that have been conducted under reservoir simulation model. The synthetic data set of 500 situations of inflow were achieved from the reservoir recorded inflow during 1966–2016 (over 51 years). As the result, the historic monthly inflow are 306,000 situations (one situation representative event of 51 years, hence, 51 years × 12 months × 500 situations are 306,000 synthetic data of inflows). The situations of the water shortage when considering all cases of the multi-objective historic rule curves, which compared with the existing rule curves were illustrated in Table 1. The results implied that the average volumes of the water shortages of the optimal historic rule curves developing from CTSA and CGA models are less than the magnitudes when using the existing rule curves (352.099–440.822 and 194.532–242.528 MCM/year for average water shortage volumes of CTSA and CGA, respectively, compared to water shortages of existing rule curves result are 573.731 ± 16.630 MCM/year). Likewise, in term of the water shortages frequencies and duration times, the CTSA and CGA resulted are less than the currently rule curves.

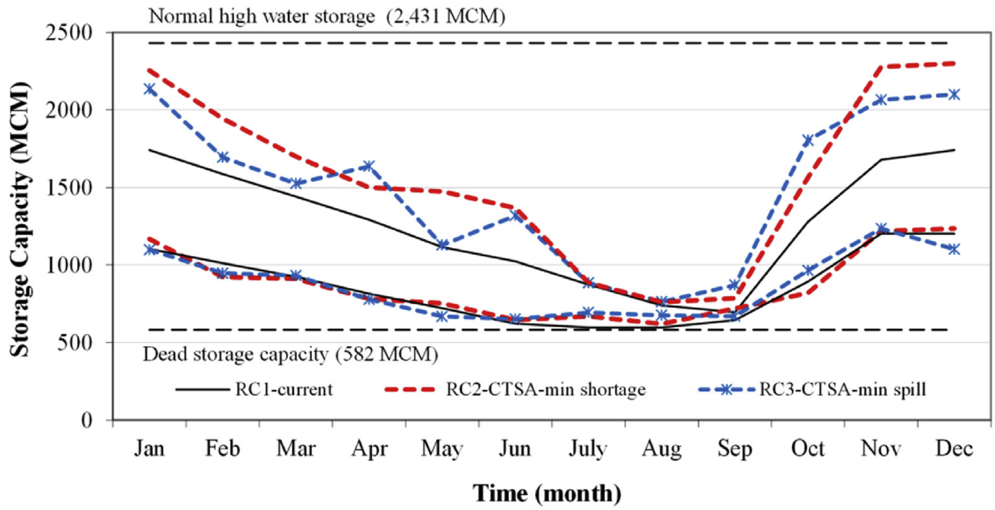

Fig. 7. Optimal historic rule curves of Ubolrat Reservoir using minimize water shortage and minimize excess spill water with CTSA model.

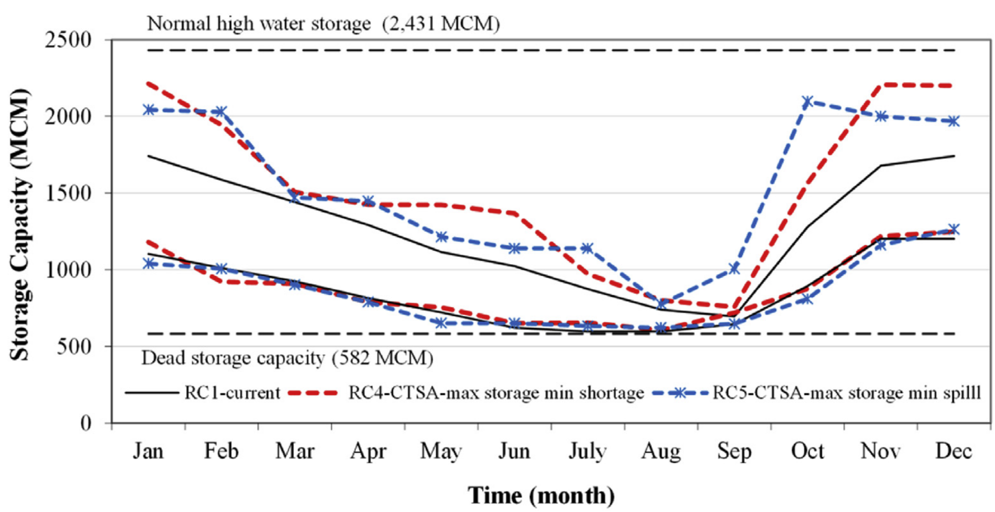

Fig. 8. Optimal historic rule curves of Ubolrat Reservoir using maximize stored water at end of wet season with CTSA model.

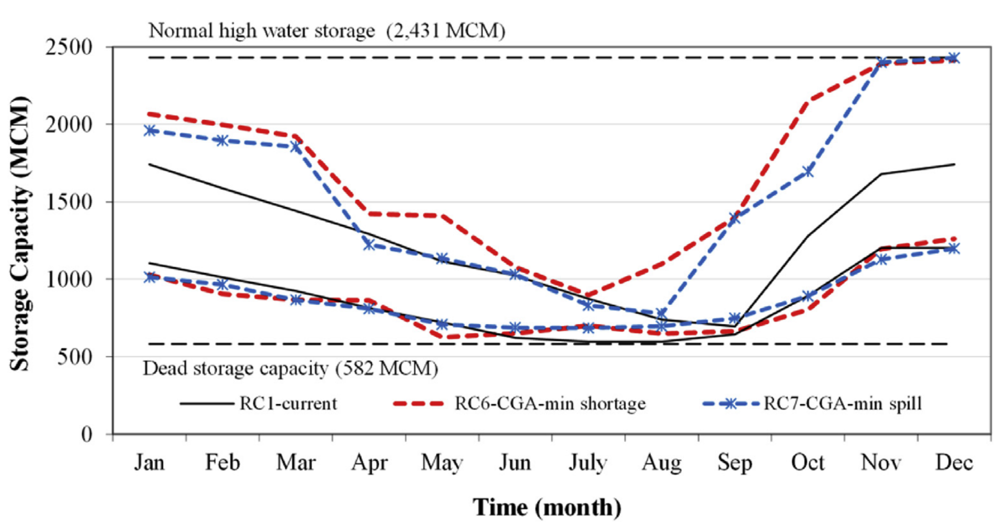

Fig. 9. Optimal historic rule curves of Ubolrat Reservoir using minimize water shortage and minimize excess spill water with CGA model.

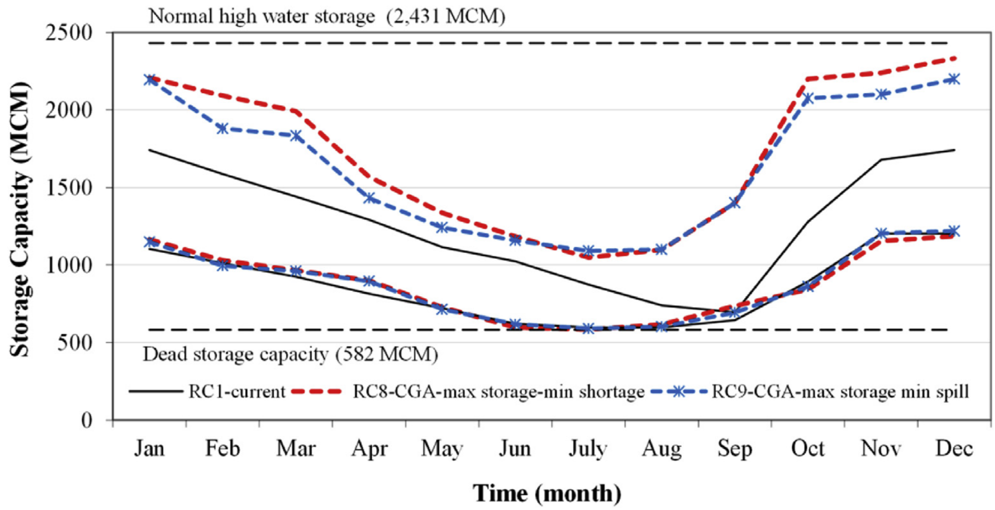

Fig. 10. Optimal historic rule curves of Ubolrat Reservoir using maximize stored water at end of wet season with CGA model.

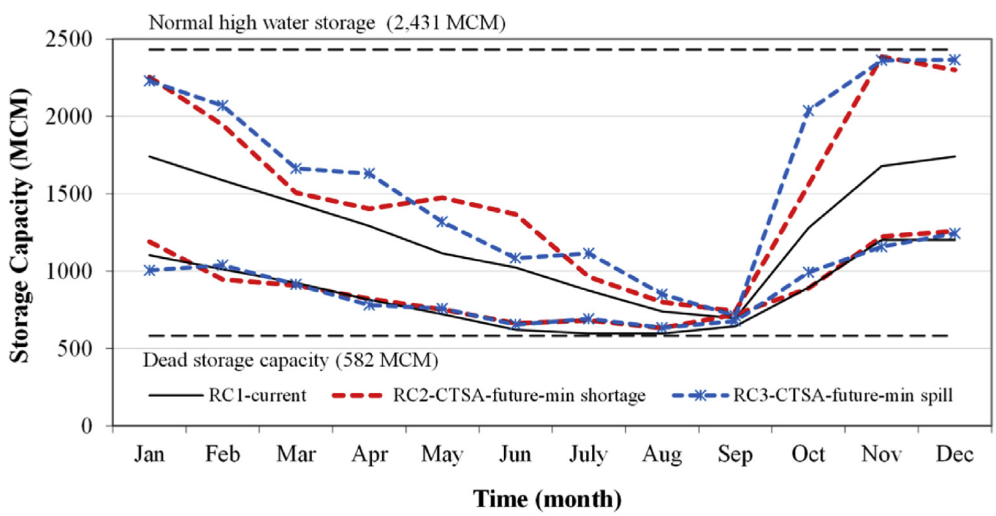

Fig. 11. Optimal future rule curves of Ubolrat Reservoir using minimize water shortage and minimize excess spill water with CTSA model.

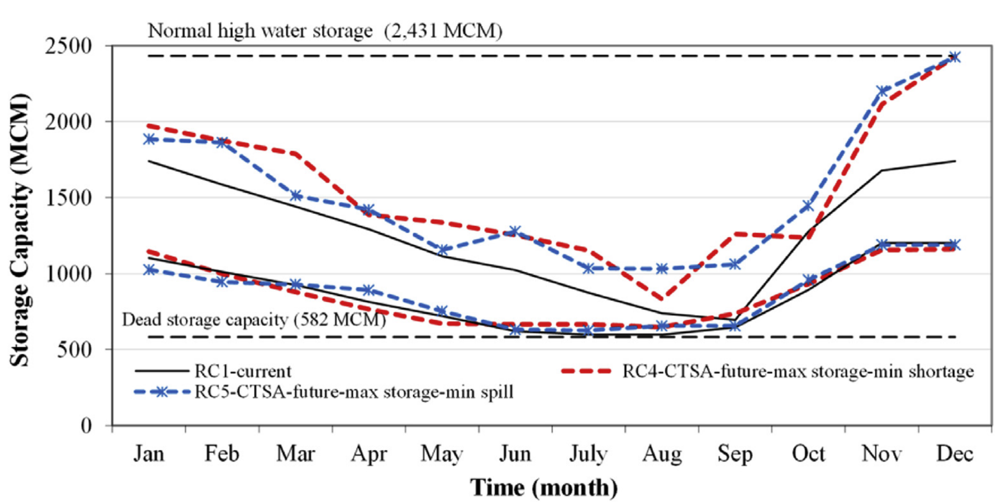

Fig. 12. Optimal future rule curves of Ubolrat Reservoir using maximize stored water at end of wet season with CTSA model.

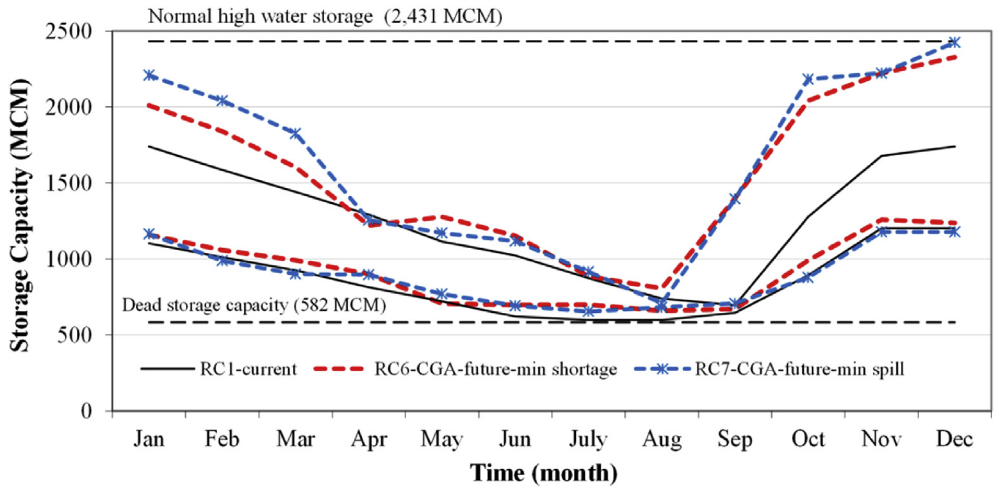

Fig. 13. Optimal future rule curves of Ubolrat Reservoir using minimize water shortage and minimize excess spill water with CGA model.

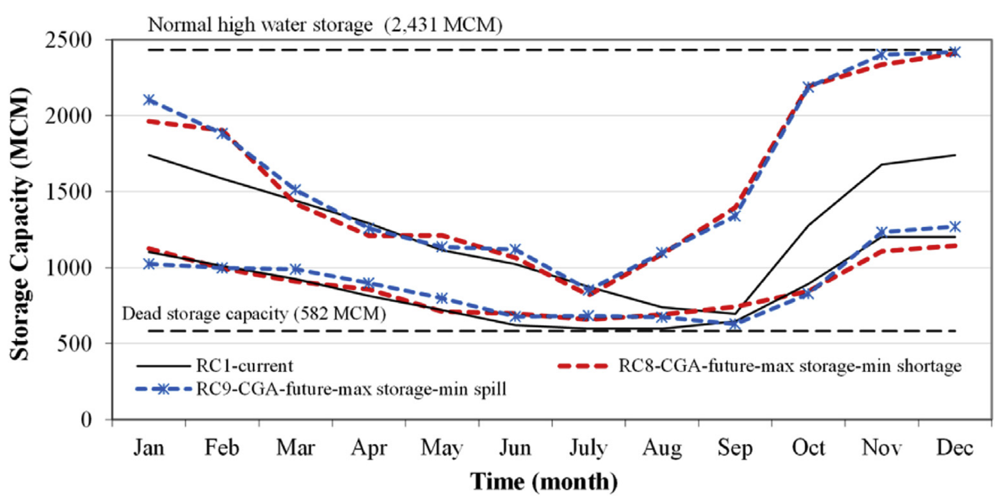

Fig. 14. Optimal future rule curves of Ubolrat Reservoir using maximize stored water at end of wet season with CGA model.

Table 1
Situations of water shortage of systems considering synthetic inflow for each multi-objective rule curve.

Rule curves		Frequency (times/year)	Magnitude (MCM/year)		Duration (year)	
			Average	Maximum	Average	Maximum
RC1 (existing)	μ	0.998	573.731	1,143.752	49.620	50.130
	σ	0.007	16.630	74.593	5.756	3.965
RC2-CTSA (min shortage)	μ	0.989	403.051	950.780	24.445	24.584
	σ	0.019	50.288	101.426	2.031	1.250
RC3-CTSA (min spill)	μ	1.000	368.945	868.384	24.974	24.994
	σ	0.002	48.778	100.453	0.581	0.134
RC4-CTSA (max store min shortage)	μ	0.971	440.822	983.536	22.571	23.422
	σ	0.025	54.208	90.159	4.594	2.791
RC5-CTSA (max store min spill)	μ	0.970	352.099	846.614	23.740	24.018
	σ	0.021	44.862	118.445	2.648	1.551
RC6-CGA (min shortage)	μ	0.918	194.532	799.054	13.686	24.926
	σ	0.028	16.197	134.716	6.910	8.704
RC7-CGA (min spill)	μ	0.861	221.518	757.486	8.429	13.280
	σ	0.057	42.056	136.632	4.822	4.765
RC8-CGA (max store min shortage)	μ	0.809	242.528	854.660	5.592	14.062
	σ	0.040	15.953	115.540	1.637	4.832
RC9-CGA (max store min spill)	μ	0.754	229.477	785.930	4.550	8.822
	σ	0.077	44.213	127.846	2.206	3.496

Note: μ = average, σ = standard deviation.

Table 2
Situations of excess spill water of systems considering synthetic inflow for each multi-objective rule curve.

Rule curves		Frequency (times/year)	Magnitude (MCM/year)		Duration (year)	
			Average	Maximum	Average	Maximum
RC1 (existing)	μ	0.991	1,329.556	4,373.919	40.776	44.836
	σ	0.013	25.662	703.638	13.596	9.212
RC2-CTSA (min shortage)	μ	0.964	1,161.846	3,719.305	16.416	19.608
	σ	0.036	149.563	826.108	7.373	5.343
RC3-CTSA (min spill)	μ	0.946	1,116.773	3,618.524	13.435	17.578
	σ	0.043	152.662	832.883	7.007	5.482
RC4-CTSA (max store min shortage)	μ	0.972	1,198.703	3,550.075	18.011	20.668
	σ	0.032	146.019	791.123	7.229	5.115
RC5-CTSA (max store min spill)	μ	0.929	1,090.938	3,675.750	11.709	16.218
	σ	0.050	154.351	843.222	6.662	5.495
RC6-CGA (min shortage)	μ	0.821	896.279	4,061.904	5.921	14.504
	σ	0.043	26.498	822.937	1.528	4.534
RC7-CGA (min spill)	μ	0.854	946.143	3,472.174	6.785	11.670
	σ	0.067	155.233	824.730	4.175	4.606
RC8-CGA (max store min shortage)	μ	0.850	949.593	4,180.262	6.495	15.696
	σ	0.037	25.931	759.958	1.779	4.855
RC9-CGA (max store min spill)	μ	0.859	939.422	3,565.385	6.783	11.960
	σ	0.064	153.825	857.181	3.476	4.431

Note: μ = average, σ = standard deviation.

The comparison results of each multi-objective rule curves with the existing in the situations of excess spill water were suggested in Table 2. The volume of the average magnitudes of excess spill adopting the CTSA and CGA are less than the results of the existing (1,090.938–1,198.703 and 896.279–946.143 MCM/year for average excess water of CTSA and CGA, respectively, compared to the excess releases of the existing of 1,329.556 ± 25.662 MCM/year). Similarly, the CTSA and CGA were shows the situations of the frequencies and duration times of the excess spill less than the frequencies and duration times when using the existing rule curves.

In the situation of the stored water at the end of wet period (November) as illustrated in Table 3. The CTSA and CGA rule curves demonstrated that the volume of water was higher than the storage level when resulting with the existing rule curves. The retained water level when using the RC9-CGA (max store min spill, considering Fig. 14) is the highest with 1,824.724 ± 77.820 MCM. This result has occurred because of being affected by the search of the objective function. However, the high storage capacity of the reservoir at the end of the wet season absolutely warranty keeping in great water quantity for the next dry season.

Table 3
Maximum stored water at end of wet season considering synthetic inflow for each multi-objective rule curve.

Rule curves		Stored water at end of November (MCM)
RC1 (existing)	μ	1,186.050
	σ	24.689
RC2-CTSA (min shortage)	μ	1,344.452
	σ	81.650
RC3-CTSA (min spill)	μ	1,395.906
	σ	77.908
RC4-CTSA (max store min shortage)	μ	1,291.003
	σ	76.889
RC5-CTSA (max store min spill)	μ	1,523.400
	σ	84.027
RC6-CGA (min shortage)	μ	1,772.150
	σ	25.241
RC7-CGA (min spill)	μ	1,575.413
	σ	69.945
RC8-CGA (max store min shortage)	μ	1,799.241
	σ	24.191
RC9-CGA (max store min spill)	μ	1,824.724
	σ	77.820

Note: μ = average, σ = standard deviation.

3.4. Performance of optimal future rule curves in future inflow conditions

The optimal future rule curves archived from the CTSA and CGA model connect with all of the multi-objective functions were adopted to manage the reservoir operation process for assessing the performance by considering 25 years of future inflow under B2 scenario during 2017–2041. Table 4 illustrates the performance of the future rule curves are more applicable than the actual rule curves in term of situations of water shortage. The yield in the table expressed that the average magnitudes using the CTSA and CGA future rule curves are less than the actual rule curves (151.360–192.440 and 20.320–64.120 MCM/year for the average water shortages of CTSA and CGA, respectively, compared to the water insufficient volume with the existing of 239.560 MCM/year). In the same manner, the CTSA and CGA provides in volume less than the actual rule curves in term of the frequencies and duration times of the water shortages. In addition, considering the RC9-CGA (for the future-max store min spill situation), when the test result to compare with the existing rule curves, the adaptive rule curves has shown the least volume of water discharge, which represents that the reservoir can maintain more water to its maximum level at the last month of the rainy period following the finding objective function.

Assessment results for excess water discharge situations are presented in Table 5. The performance of the Ubolrat Reservoir future rule curves in the part of the average magnitudes of the excess water discharge are less than the existing (2,716.586–2,791.694 and 2,554.879–2,606.556 MCM/year for CTSA and CGA, respectively, compared to the excess water discharge of the existing that are 2,847.486 MCM/year). Table 6 shows the stored water volume of the reservoir at the last month of the wet period (November) when using CTSA and CGA rule curves. The reservoir storage capacity is more than the retained level when using the existing. The maintained level when using RC8-CGA (future max store min shortage) had the maximum storage level of 2,268.305 MCM. Similarly, these performances of the optimal future rule curves are related to the outcomes when using the optimal rule curves generated from the historical record inflow that examine the same multi-objective functions.

It can be concluded that the proposed CTSA model is another search suitable technique, so the outcomes are close to optimal goal of the CGA model depend on the identical condition. Nevertheless, the ability of each method was determined by many researches (Bozorg-Haddad et al., 2015; Ming et al., 2015; Kangrang et al., 2017). Include connecting to the multi-condition allowing the reservoir to be managed properly and with the highest efficiency regardless of any situation. Clearly confirmed for

Table 4
Situations of water shortage of systems using future inflow for each multi-objective future rule curve.

Rule curves	Frequency (times/year)	Magnitude (MCM/year)		Duration (year)	
		Average	Maximum	Average	Maximum
RC1- existing	0.960	239.560	752.000	24.000	24.000
RC2-CTSA (future-min shortage)	0.800	137.240	575.000	6.667	10.000
RC3-CTSA (future-min spill)	0.920	180.040	673.000	11.500	12.000
RC4-CTSA (future-max store min shortage)	0.840	192.440	473.000	5.250	9.000
RC5-CTSA (future-max store min spill)	0.960	151.360	551.000	24.000	24.000
RC6-CGA (future-min shortage)	0.760	36.600	205.000	3.800	8.000
RC7-CGA (future-min spill)	0.640	64.120	209.000	2.667	8.000
RC8-CGA (future-max store min shortage)	0.240	24.000	205.000	1.000	1.000
RC9-CGA (future-max store min spill)	0.160	20.320	274.000	1.000	1.000

Table 5
Situations of excess spill water of systems using future inflow for each multi-objective future rule curve.

Rule curves	Frequency (times/year)	Magnitude (MCM/year)		Duration (year)	
		Average	Maximum	Average	Maximum
RC1- existing	1.000	2,847.486	5,092.670	25.000	25.000
RC2-CTSA (future-min shortage)	1.000	2,716.586	4,912.280	25.000	25.000
RC3-CTSA (future-min spill)	1.000	2,729.111	5,242.492	25.000	25.000
RC4-CTSA (future-max store min shortage)	1.000	2,791.694	4,927.072	25.000	25.000
RC5-CTSA (future-max store min spill)	1.000	2,732.714	4,902.676	25.000	25.000
RC6-CGA (future-min shortage)	1.000	2,582.710	5,108.716	25.000	25.000
RC7-CGA (future-min spill)	1.000	2,606.556	5,156.568	25.000	25.000
RC8-CGA (future-max store min shortage)	1.000	2,564.337	5,068.219	25.000	25.000
RC9-CGA (future-max store min spill)	1.000	2,554.879	5,079.817	25.000	25.000

this study is that the results of the evaluation of rule curves performance generated from the CTSA technique are analogous to the optimal rule curves developed from the CGA technique (GA is a technique that has been widely accepted around the world for a long time in the research and development about reservoir rule curves, consequently, in this study, it is used to compare with the TSA in the same conditions). Moreover, the results of the research can be used to support, suggest and reference for how to improve the reservoir rule curves in higher efficiency for the fluctuating of situations, particularly issues related to climate change. However, since the CTSA is one of many techniques for search the optimal answer in the heuristic group, the methodology demonstrated in this article is expected to be a guideline for the other optimum search techniques for application to solve engineering issues, especially in the water resources management, which are highly complicated.

3.5. Limitation in the application of CTSA and CGA

As the answer from the CTSA and CGA results in the global optimal point and the quality of the solution still deteriorates when the intensity of the issue enlarges. Hence, the limitation of searching the answer for the optimal reservoir rule curves in this research is indicated that in the answer interval between the upper and lower rule curves that have large fluctuations. For example, in case of the optimal historic rule curve as illustrated in Fig. 7 (for the CTSA model). At the upper rule curve under the conditions of the optimal answer to the minimum water spill situation (RC3-CTSA min spill), during the dry season between March and July, the capacity positions in April and June are higher than March and May, respectively. In this case, the actual reservoir operation in the field using this upper rule curve lines will not be able to operate because the water capacity in the reservoir will continue to decrease (during the dry season) until July–August (at this time, the reservoir must have the lowest capacity to provide for the precipitation and inflow volumes at the end of rainy period). Likewise, the upper rule curve using constrain of maximum maintained water at November with the CTSA model (RC3-CTSA-max storage min spill) as shown in Fig. 8, the position of October shows higher results than November, which is inconsistent with the management due to the last month of the wet period and the reservoir capacity still needs to maintain the maximum amount of water until December and January of the next year. In addition, in the case of finding a control curve in the future situation for the CTSA model (see Fig. 11), it was found that there was a fluctuation of the answer interval in the upper rule curve for similar reasons to discuss the results of Fig. 7, both in the case of minimum storage and minimum spill. For all of the cases as described previous, the variations of seasonal inflow flowing into the reservoir, especially in the Northeastern region of Thailand, are important variables affecting the results of the rule curves in this pattern. However, in summary, when comparing the optimal rule curves results between the CTSA and CGA, the CGA showed less fluctuation than the results from the CTSA. Consequently, creating the conditions of the solution to reduce the fluctuation of the answers from both methods, it is absolutely necessary to increase the performance of the answers received from optimization techniques.

Table 6
Maximum stored water at end of wet season using future inflow for each multi-objective future rule curve.

Rule curves	Stored water at the end of November (MCM)
RC1- existing	1,615.067
RC2-CTSA (future-min shortage)	1,773.258
RC3-CTSA (future-min spill)	2,027.189
RC4-CTSA (future-max store min shortage)	1,681.478
RC5-CTSA (future-max store min spill)	1,840.312
RC6-CGA (future-min shortage)	2,141.277
RC7-CGA (future-min spill)	2,181.027
RC8-CGA (future-max store min shortage)	2,268.305
RC9-CGA (future-max store min spill)	2,264.062

4. Conclusion

This study proposed multi-objective reservoir rule curves by applying optimization techniques connecting with the reservoir simulation system for the finding procedure. The monthly historic and the future inflows (under the B2 scenario) were considered for each searching case. These optimization techniques were conditional tabu search algorithm (CTSA) and conditional genetic algorithm (CGA) that were applied to search the multi-objective rule curves for the Ubolrat Reservoir in the Northeast of Thailand. The 25 years future inflow and 500 sample synthetic inflow data for the reservoir were used to simulate the reservoir operating system for assessing the capability of the obtained rule curves. The results presented that the newly developed reservoir rule curves from CTSA are more appropriate for operation than the existing rule curves in both the historic and the future situations. The frequency and magnitude of water shortages and excess spill when considering the newly obtained rule curves are lower than with the existing. When comparing the newly developed rule curves from CTSA with the CGA rule curves as well as the current simulation process, it was found that these rule curves are homologous. The proposed CTSA model is a forceful method to find the optimal reservoir rule curves. This reveals that the CTSA and CGA methods considering future inflows are useful for finding multi-objective rule curves that are suitable for use in future predicaments. The maximum maintained water at the last month of the wet period (November) is an efficacy objective function for generating rule curves that keeps the storage capacity for the next dry period after November.

The results in this study indicate that the new rule curves developed from the CTSA and CGA techniques show more appropriate performance than the existing operation under the multi-objective functions and the efficiency comparison between two periods using historic inflow (1966–2016) and future inflow (2017–2041) as control variables. When considering the advantages of the optimal rule curves, it was found that the upper rule curve shows the position that is above the existing upper rule curve in all cases. The reason is due to the relationship between the multi-objective functions including; 1) minimize excess water spill for preventing flooding (early rainy season between August–September), the reservoirs need to increase capacity more than usual to support water streaming into the reservoir during this period, 2) the reservoirs can increase capacity and storage level more than usual at the last time of the wet period (between October to December), and 3) corresponds to the previous objective function, when the storage capacity increased, the reservoir will be releasing water to downstream areas adequately without causing the water shortage. For these reasons, the new upper rule curve illustrates higher positioning than the existing upper rule curve. However, the lower rule curves yielded from the CTSA and CGA techniques display the characteristics that are analogous to the existing lower curves due to the reasons described earlier. Nonetheless, the reservoir operation policy of the responsible agency has been primarily targeted to prevent flooding (as the "Great Flood" incident in 2011 which caused tremendous damage to life and property) which makes the existing rule curves, especially the upper rule curve, has a low level of water storage. While climate change is a major factor influencing the inflow flowing into the reservoir, there is a huge variation, with the trend or forecast of the inflow indicated in this study is higher than the normal average. Consequently, if applying the newly rule curves developed from the CTSA and CGA techniques for reservoir management, it is expected that the downstream area will reduce the risk to both events: minimum water shortage and excess spill, including the management in other situations efficiently and appropriately in the future.

In the process of creating the optimal rule curves, it is imperative to consider other variables that impact the inflow and water allocation in the reservoir system. The combination of various future change scenarios may help increase efficiency for rule curve to adapt and encounter the impacts of climate change in the future, which can be analyzed by forecasting scenarios for new greenhouse gas emissions (such as RCP2.6, RCP4.5 and RCP8.5) from the climate model that appeared widely in the present. In addition, studies on land use change issues that vary according to population growth, the needs of the agro-industry, new technology, or government policies are all important factors that must be considered because it affects the hydrologic processes, such as surface flow, infiltration, interception and evapotranspiration. In the analysis processes, applying data from aerial or satellite imagery, leading to the mathematical and GIS models, which can predict future land use change patterns in the future. The results obtained from the analysis with these techniques are expected to help create the optimal rule curves that can be adapted and more resistant to various situations. However, the development of techniques for searching optimal answers with the heuristic methods has increased, which each method has a unique or distinctive feature of finding different answers. Similarly, adopting these new techniques to develop rule curves and bringing comparative results is something that should be done to increase the choice of rule curves development to be the most effective for future reservoir management.

Declarations

Author contribution statement

Teerawat Thongwan: Conceived and designed the analysis; Analyzed and interpreted the data; Contributed analysis tools or data; Wrote the paper.

Anongrit Kangrang: Conceived and designed the analysis; Wrote the paper.

Haris Prasanchum: Contributed analysis tools or data.

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The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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