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Research Article

Applying of Marine Predators Algorithm Linked with Reservoir Simulation Model considering Sedimentation for Reservoir Operation

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This paper proposes the Marine Predators algorithm (MPA) linked with the reservoir simulation model and considering sedimentation, in order to improve reservoir rule curves. The release criteria of the hedging rule (HR) and standard operating policy (SOP) were investigated in this study. The results showed that the patterns of the new optimal rule curves from the MPA technique considering sedimentation and using HR were practically useful in this study, as were the patterns of the new optimal rule curves using SOP and those of the existing rule curves. Furthermore, the new optimal rule curves using HR criteria were able to alleviate both water scarcity and excess water situations better than both existing rule curves and optimal rule curves using SOP in terms of minimal average water shortage. The new curves reduced minimal average water shortage by 53% and excess release water deficit by 19%, whereas the frequency of water shortage term was increased by 3%. The results of rule curves efficiency from MPA were higher than GA and FPA techniques in terms of providing solutions. There was a significant difference in the efficiency of water problem alleviation between considering and not considering sedimentation. It can be concluded that the MPA linked with reservoir simulation using HR criteria and considering sedimentation can be used to find optimal rule curve solutions effectively.

1. Introduction

Water is an essential resource for life on Earth from past to present. Nowadays, there are problems of water quantity and quality and conflicts of water use. The cause of these issues is due to economic and social expansion and due to the inefficient management of water resources [1–3]. These causes lead to a crisis in water supply. In addition, agriculture and industry, which provide the basis for national security, also have effect. For these reasons, suitable water resource management is an essential issue for all areas.

Water resource management involves planning, implementing, monitoring, analyzing, and correcting water to achieve consistency with the current situation which focuses on sustainable development on economics, society, and environment to maximize benefits consistently with available water. Generally, water resource management can be divided into construction and nonconstruction types. Nowadays, nonconstruction sites are popular as they are relatively more effective and take a short time and are recognized.

Reservoir management is one of the most effective measures for the development and management of integrated water resources in nonconstruction sites. The reservoir is responsible for storing, allocating, and mitigating floods and drought, which are managed under the reservoir operation process. The mission of reservoir operation is to decide how to store and deliver water for various purposes, planning how much water should be collected and delivered from the reservoir at different intervals through an essential and fundamental tool called reservoir rule curves [4–6].

Reservoir rule curves, also known as rule curves, are composed of two curves; the upper rule curve (URC) and the lower rule curve (LRC). There are daily, monthly, and yearly curves. It can be seen that the water level control in the reservoir is most feasible between the upper and lower levels. However, the use of rule curves is long-term management and this may impair the efficiency of reservoir operations [7, 8]. Therefore, a wide variety of rule curves have been developed. As an alternative or decision-making tool, the rule curves used in reservoir management have release criteria for determining water discharge as an integral part of reservoir management.

Often, the critical situation occurs in reservoir operation, when the inflow to reservoir is greater than the remaining reservoir capacity during the rainy season, but the water shortage downstream still occurs in next dry season. Therefore, the optimal reservoir operation is required for solving this critical problem. There are many reservoirs facing this problem [9, 10]. For this reason, suitable release criteria and completed physical reservoir information are required in simulating reservoir operation.

A release criterion is a condition for controlling the release or storage of water for reservoir operation. Standard operating rule (SOP) is to release as much water as the reservoir can provide to meet the target delivery [11–13]. Linear decision-making and hedging rules (HR) are applied to address the risks and damages caused by severe water shortages in the future [14, 15]. The water release criteria of the SOP have attracted attention and have been developed and implemented in a wide range of applications. However, such SOP can cause a single high range of water shortages. This is because the amount of water flowing into the reservoir has changed. Therefore, to mitigate current and future impacts, the HR policy was developed for the operation of reservoirs during the dry season under different conditions, which use the principle of high discharge [16–20]. In order to distribute predehydration, the HR water discharge threshold was found as a way to effectively resolve the single-period water shortage and reduce the water shortage. It can alleviate drought as well. Also, annual HR release criteria in reservoirs used to allocate agricultural water needs under the effects of climate change can very well mitigate current and future drought. Moreover, HR release criteria are suitable to be used in conjunction with a reservoir level control curve for managing reservoirs with runoff volumes greater than the crisis reservoir for managing both flood and drought situations.

Reservoir sedimentation is a major issue in many parts of the world which may be exacerbated by changes in catchment land use. The reservoir is designed to have enough capacity for the required amount of water. In addition, the reservoir function is determined by considering the correlation curve in capacity-area-elevation of the reservoir. However, sedimentation in the reservoir decreases the storage capacity of the reservoir over time [21–25].

In the past, finding the reservoir rule curves early was a trial and error method. This is suitable for less complex reservoir systems and is based on the experience of calculators. It is, therefore, uncertain whether it is the optimal rule curve if the reservoir system is more complex [26, 27]. Later, optimization methods were applied and developed to find rule curves, e.g., using simulation, dynamic programming [28, 29], genetic algorithms [30–33], genetic programming [34], Tabu search [35, 36], Harris hawks optimization [37], wind driven optimization [38], firefly algorithm [39], flower pollination algorithm [40, 41], grey wolf optimizer [42], and fast orthogonal search (FOS) [43]. Optimization techniques have been developed and applied in a wide variety of applications in solving numerical and engineering problems. Because optimization can find quite global best optimal using many techniques, they are smart and can find different answers. Regardless, these optimization techniques are the ultimate optimization techniques and are inspired by evolution, certain behaviors, and randomness mimicking natural phenomena. However, there is a constant need to adopt new techniques to solve both complexity and application problems quickly and easily.

A compelling new algorithm in the metaheuristic group is the MPA inspired by the foraging of the great and intelligent sea predators [44]. The MPA has been applied to solve engineering problems [45–49] such as designing a spring for compression tension, welded beam, and pressure vessel. However, it is not commonly used to find the optimal rule curves. Hence, it is an interesting technique that can be applied to the reservoir simulation model for solving rule curves problem.

According to the literature study above, the MPA approach is very successful when compared to other procedures under the same conditions and it is quite valuable when applied to other issues. Therefore, this research aimed to find optimal reservoir rule curves using the MPA linked with the HR release criteria considering sedimentation of the Ubolratana reservoir, Khon Kaen province in the northeast area of Thailand. The results of the study were divided into three main parts: (1) the efficiency of MPA rule curves considering HR and SOP in terms of maximum water shortage, (2) the efficiency of MPA rule curves considering sedimentation using HR and SOP, and (3) the comparison of optimal rule curves of MPA, GA, and FPA algorithms and their performances in terms of water shortage situations.

2. Materials and Methods

2.1. Study Area. The Ubolratana reservoir is located at longitude 102°37′06.0“E and latitude 16°46′31.4”N in Khon Kaen province in the northeast of Thailand as shown in Figure 1. The normal storage capacity and dead storage capacity are 2,431 MCM (10^6 m) and 581.67 MCM, respectively. The water surface area at normal storage is 137.90 km^2. A schematic diagram of the reservoir is presented in Figure 2 which indicates that the downstream water demands from the reservoir are electricity generation, irrigation, flood control, industrial demand, domestic water supply, and environmental conservation. The monthly water demands from the reservoir are shown in Table 1 indicating that the largest requirement is for irrigation and the least is industrial demand.

2.2. Inflow Data. The upper watershed area of the Ubolratana reservoir is 11,960 km^2 covering three provinces of

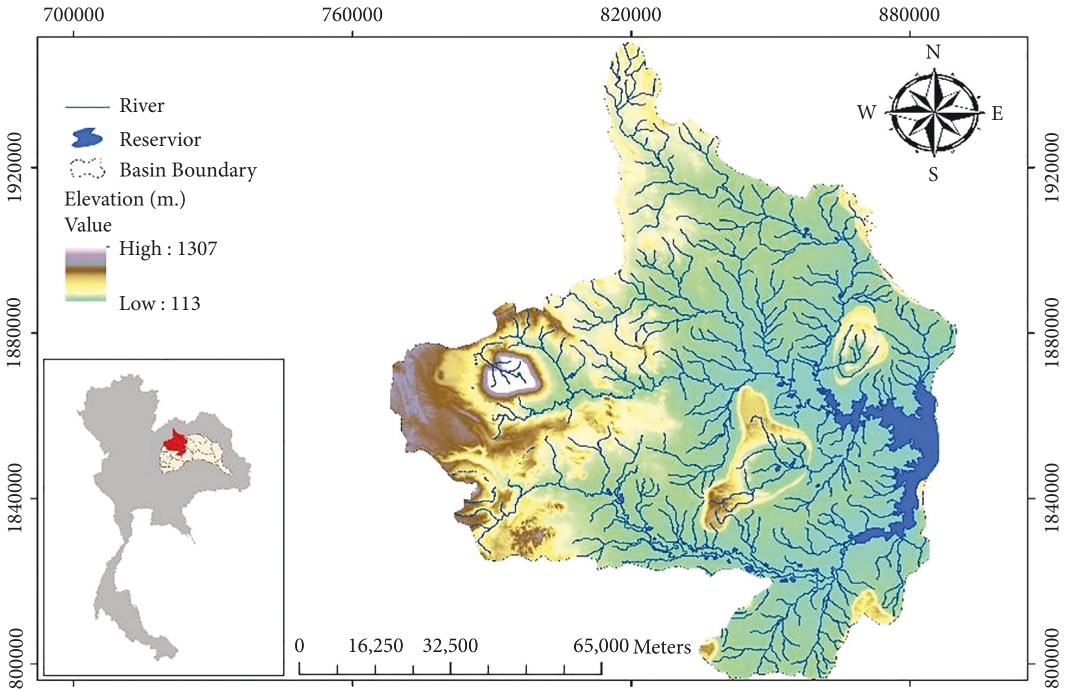


Figure 1: The location of Ubolratana reservoir.

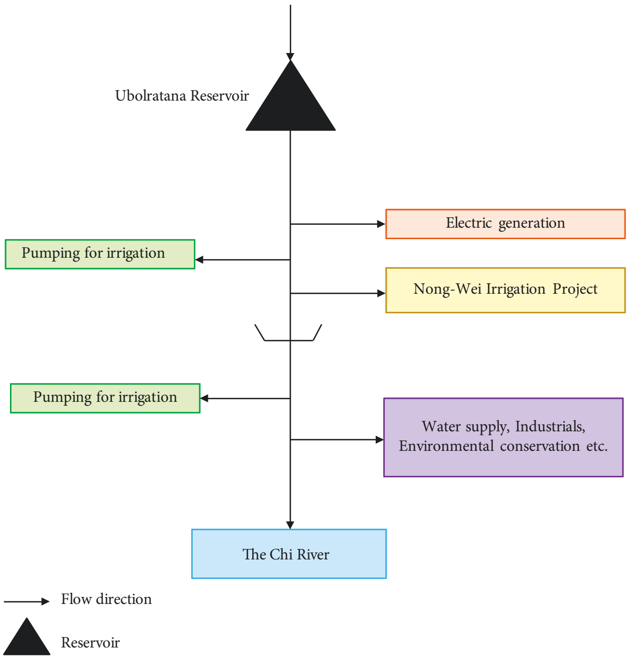


Figure 2: Schematic diagram of the Ubolratana reservoir.

Nong Bua Lamphu, Chaiyaphum, and Khon Kaen. Historic inflow data into the Ubolratana reservoir has been recorded for 52 years from 1971 to 2020; it was average when annual inflow was 2,465 MCM as shown in Figure 3. The data indicated that the maximum yearly inflow was 5,884 MCM in 1978 whereas the minimal yearly inflow was 387 MCM in 2019.

2.3. Reservoir Simulation Model. The reservoir operation performs under the reservoir simulation model using water balance equation considering reservoir rule curves and release criteria. The operation starts from calculation of the available water using the water balance concept considering monthly inflow and water demands of downstream sites. The monthly release of water is estimated by considering the monthly available water using release criteria and reservoir rule curves. For this study, the reservoir operation model was created following the concept of the water balance. The release criteria were considered in this study to consist of the HR and the SOP which evaluated their performance. The one-point hedging rule and standard operating policy are expressed in Figure 4. The one-point hedging rule and the standard operating policy are presented in the following equations, respectively.

The HR constraints are as follows: when $0 \le (1-DDIt)\cdot Dt \le SWAt$,

$$R_{\nu,\tau}=\begin{cases} WA_\tau, & \text{if } WA_\tau<SWA_\tau,\\ D_\tau+(SWA_\tau-D_\tau)\dfrac{WA_\tau-EWA_\tau}{SWAt_\tau-EWA_\tau}, & \text{if } SWA_\tau\le WA_\tau\le EWA_\tau,\\ D_\tau, & \text{if } EWA_\tau\le WA_\tau<D_\tau+C,\\ WA_\tau-C, & \text{if } WA_\tau\ge D_\tau+C,\\ 0, & \text{otherwise.} \end{cases} \quad (1)$$

Table 1: Downstream water demands from Ubolratana reservoirs.

Month/demands (MCM)	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Irrigation	114.320	103.260	143.720	94.830	16.220	31.620	114.320	130.660	116.950	130.660	0.000	16.330
Water supply	3.417	3.417	3.417	3.417	3.417	3.417	3.417	3.417	3.417	3.417	3.417	3.417
Industrial	1.583	1.583	1.583	1.583	1.583	1.583	1.583	1.583	1.583	1.583	1.583	1.583
Environmental	4.583	4.583	4.583	4.583	4.583	4.583	4.583	4.583	4.583	4.583	4.583	4.583
Total	123.903	112.843	153.303	104.413	25.803	41.203	123.903	140.243	126.533	140.243	9.583	25.913

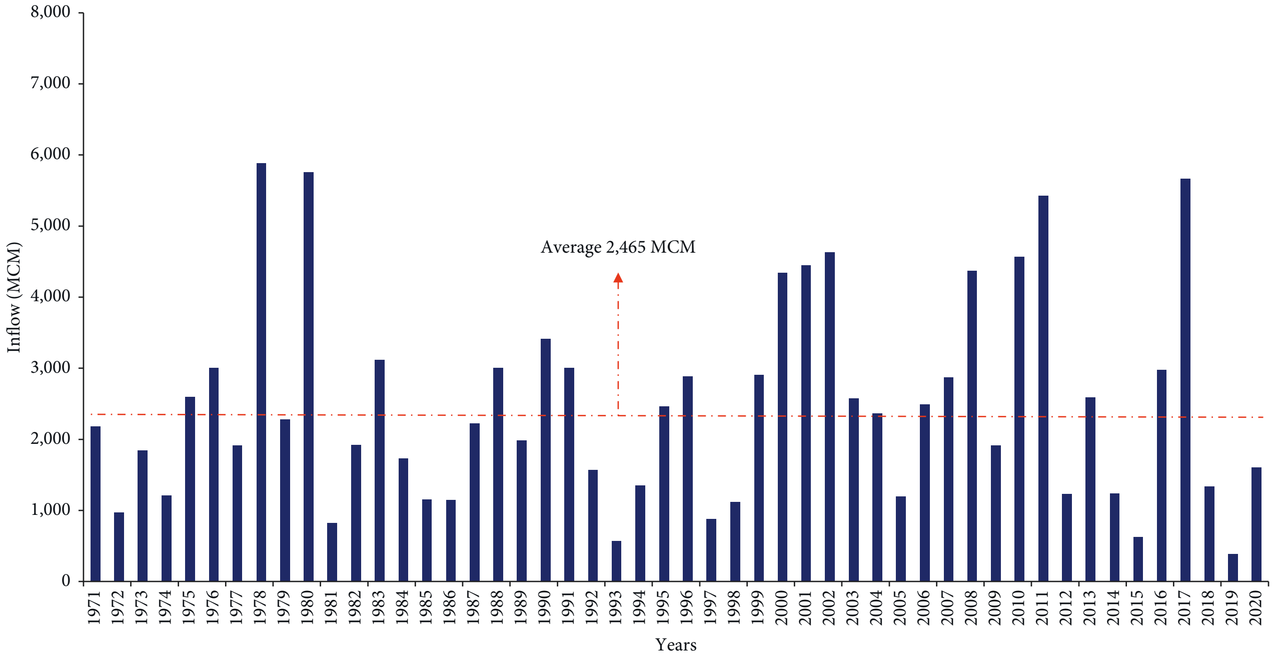


Figure 3: The yearly historic inflow into the Ubolratana reservoir.

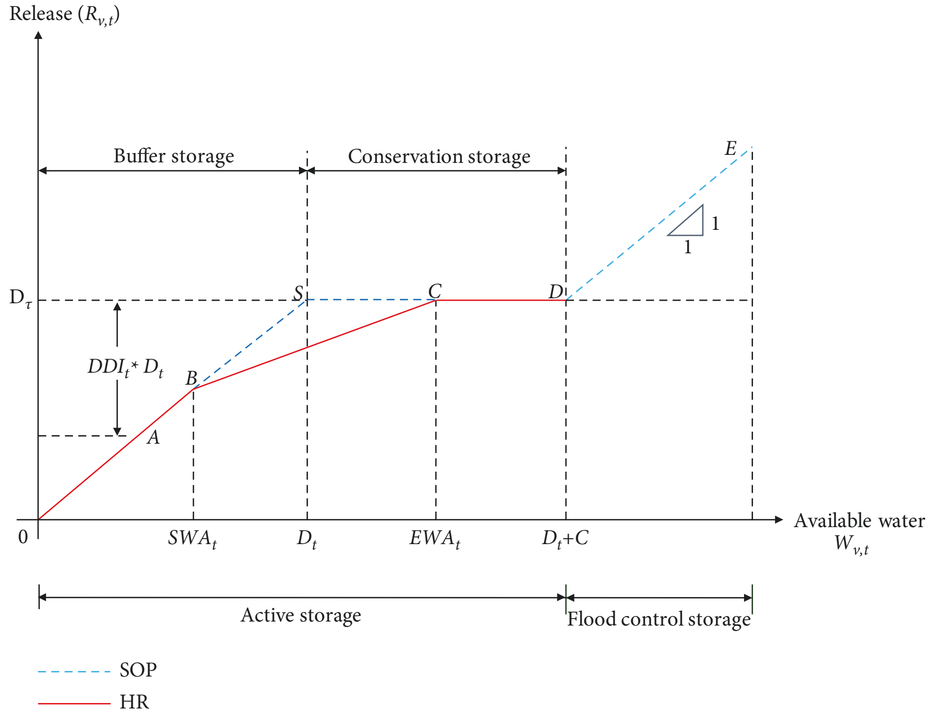


Figure 4: The HR and standard operating policy.

Here, $R_{v,\tau}$ is the total release of the aggregated reservoir at time τ; SWA_τ and EWA_τ are the starting and ending water availability of the aggregated reservoir at time τ; and D_τ is the water demand for the water-supply system at time τ.

The SOP constraints are as follows:

$$R_{v,\tau} = \begin{cases} D_\tau + W_{v,\tau} - D_\tau + C, & \text{for } W_{v,\tau} \geq D_\tau + C + D_\tau, \\ D\tau, & \text{for } D_\tau \leq W_{v,\tau} < D_\tau + C + D_\tau, \\ D_\tau + W_{v,\tau} - D_v, & \text{for } D_\tau - D_\tau \leq W_{v,\tau} < D_\tau, \\ 0, & \text{otherwise.} \end{cases} \tag{2}$$

Here, $R_{v,\tau}$ is the release of water during year v and month τ ($\tau = 1$ to 12 representing January to December); D_τ is the net water demand during month τ; D_t is the lower rule curve of month τ; Here, $D_t + C$ is the upper rule curve of month τ and $W_{v,\tau}$ is the available water by calculating the water balance concept during year v and month τ, as described in

$$W_{v,\tau} = S_{v,\tau} + Q_{v,\tau} - R_{v,\tau} - E_\tau, \tag{3}$$

where $S_{v,\tau}$ is the stored water at the end of month τ; $Q_{v,\tau}$ is the monthly inflow to the reservoir; $E\tau$ is the average value of the evaporation loss. The operating policy usually reserves the available water ($W_{v,\tau}$) for mitigating the risk of water shortage in the future, when $0 \leq W_{v,\tau} < D - D_\tau$ under long-term operation.

2.4. The Objective Functions for Searching Optimal Rule Curves. The objective functions of search procedure in this study were the minimal average water shortage as described in the first following equation, the minimal frequency of water shortage is shown in the second following equation, the minimal average excess water per year is shown in the third following equation, and the minimal frequency of excess water is revealed in the final following equation. These objective functions were used for calculations in the MPA.

The minimal average water shortage per year is

$$\text{Min}\, H_{(avr)} = \frac{1}{n} \sum_{v=1}^{n} Sh_V. \tag{4}$$

The minimal frequency of water shortage is

$$\text{Min Fre}_{(i)} = \frac{1}{n} \sum_{v=1}^{n} Sh_V. \tag{5}$$

The minimal average excess water per year is

$$\text{Min}\, P_{(avr)} = \frac{1}{n} \sum_{v=1}^{n} Sp_V. \tag{6}$$

The minimal frequency of excess water is

$$\text{Min Fre}_{(i)} = \frac{1}{n} \sum_{v=1}^{n} Sp_V, \tag{7}$$

where $H_{(avr)}$ is average water shortage per year, $Fre_{(i)}$ is frequency of water shortage, n is the whole magnitude of examined years, and Sh_V is minimization average water shortage in year v (year in which releases are less than the target demand) and Spv is the excess release water during year v (year in which releases are more than the target demand).

2.5. Application of MPA and Reservoir Simulation Model for Searching Optimal Rule Curves. MPA is a novel meta-heuristic algorithm developed to emulate the foraging strategies of the ocean predators and their interactions with the prey. MPA uses the widespread foraging strategy called the Brownian and Lévy [44]. If the concentration of prey in the hunting area is high, predators use the Brownian method and when the prey is low, they use the Lévy method. The MPA search process is divided into three phases based on different speed ratios: (1) a high-speed phase, where the prey speed is faster than the predator speed; (2) a unit speed ratio phase, where the prey speed and the predator speed are similar; and (3) a low-speed phase, where the prey speed is slower than the predator speed. In each stage, the movement of the predator and prey in nature is imitated separately [48, 49].

Connect the MPA with the reservoir simulation model:

1. Start with input data and set the MPA parameters such as number of populations (*N*), boundaries (*Xu*, *Xl*), and total number of iterations (*T*). The total number of populations will take part to optimize the formulated objective functions in the search space.
2. For this study, each decision variable represents the monthly rule curves of the reservoirs, which are defined as the upper rule curves and the lower rule curves. After the first set of fitness values of Prey Matrix in the initial population have been calculated (24 decision variables that consist of 12 values from the upper rule curves and 12 values from lower rule curves), the monthly release of water will be calculated in a reservoir simulation model using the HR and SOP considering those rule curves.
3. Next, the released water is used to evaluate the objective functions that were described in (4)–(7) of the previous section. After that, the objective functions will be used to determine the fitness value of Prey Matrix and then construct the Elite Matrix.
4. These rule curve parameters are evaluated under three phases of MPA [44]. The process will create new rule curve values in the next iteration. This procedure is repeated until the stop criteria condition is met and the optimal 24 values of the rule curves have been obtained. The diagram flowchart of the proposed method is shown in Figure 5.

2.6. Assessment of Sediment Load in Ubolratana Reservoir. The Ubolratana reservoir was built in 1966, with creating water surface area and capacity curves. The water surface area and storage capacity curve have been used to calculate storage and sedimentation. This curve was updated for estimation of storage capacity and sedimentation

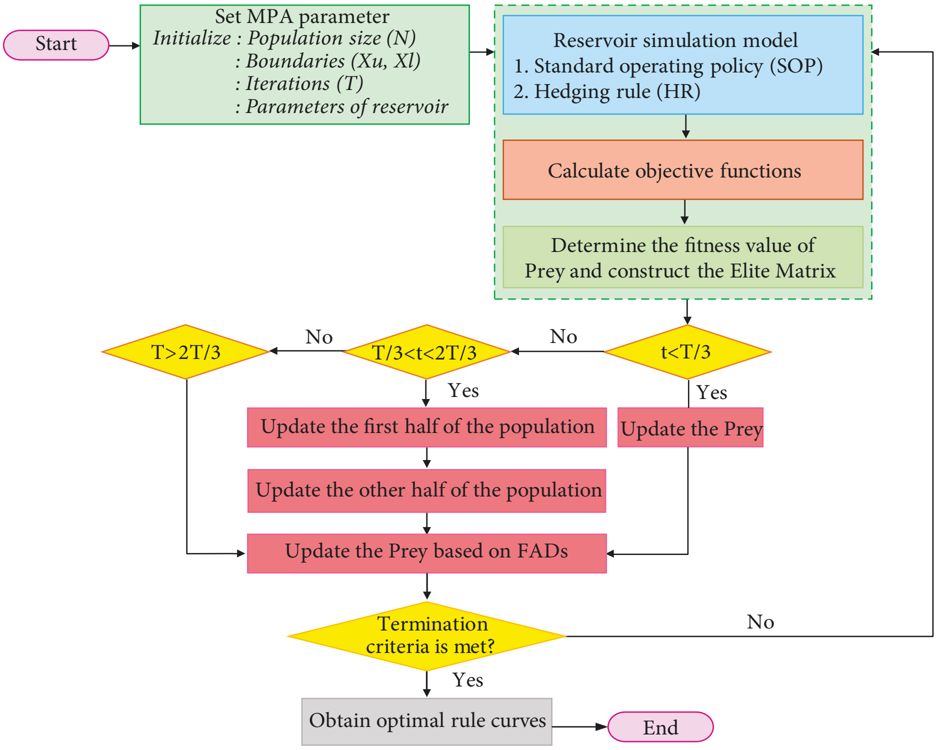


Figure 5: Application of MPA and reservoir simulation model for searching optimal rule curves.

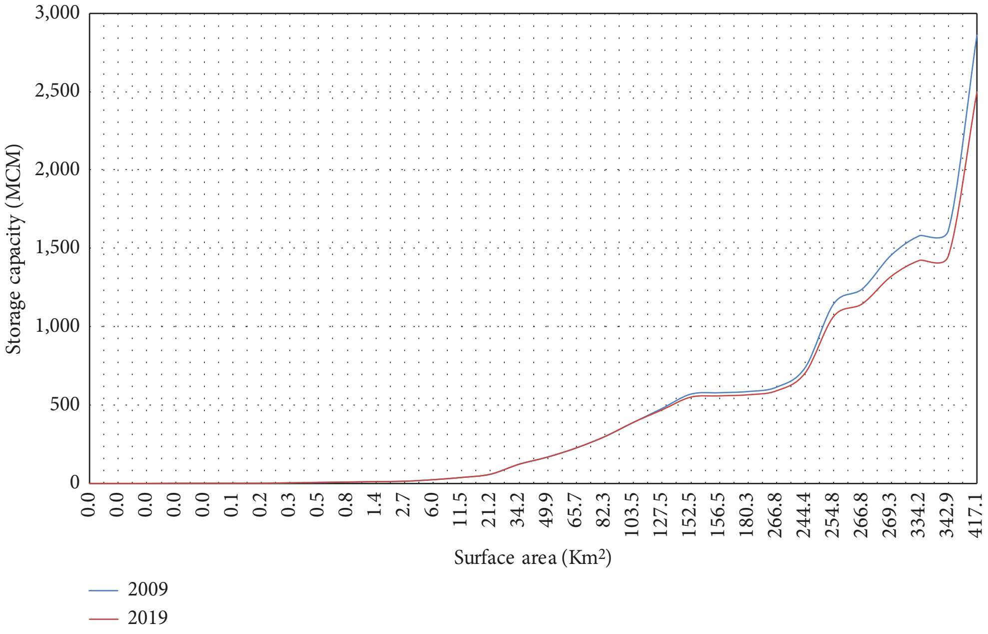
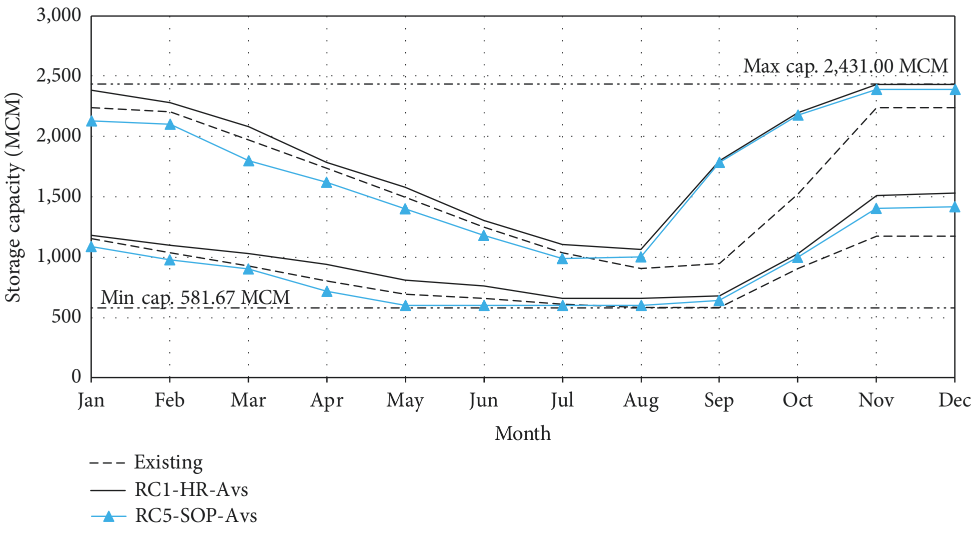


Figure 6: The storage capacity-surface area relationship of the Ubolratana reservoir in 2009 and in 2019.

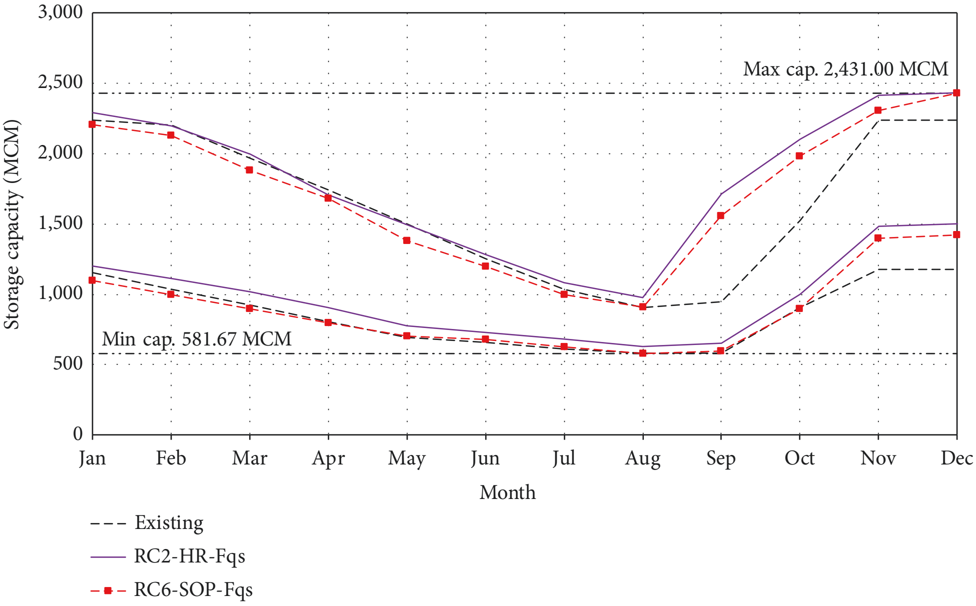
accumulation using remote sensing data in 2019 and an actual survey in 2009, which calculated the decrease in capacity at each water elevation. After 10 years, the capacity of the Ubolratana reservoir had decreased [50]. This study used their data for the cases that considered sedimentation in the reservoir, as shown in Figure 6.

3. Results and Discussion

3.1. The Efficiency of MPA Rule Curves considering HR and SOP. The optimal rule curves using MPA linked with the reservoir simulation model considering HR and SOP are shown in Figures 7 and 8. The patterns of optimal rule curves



(a)



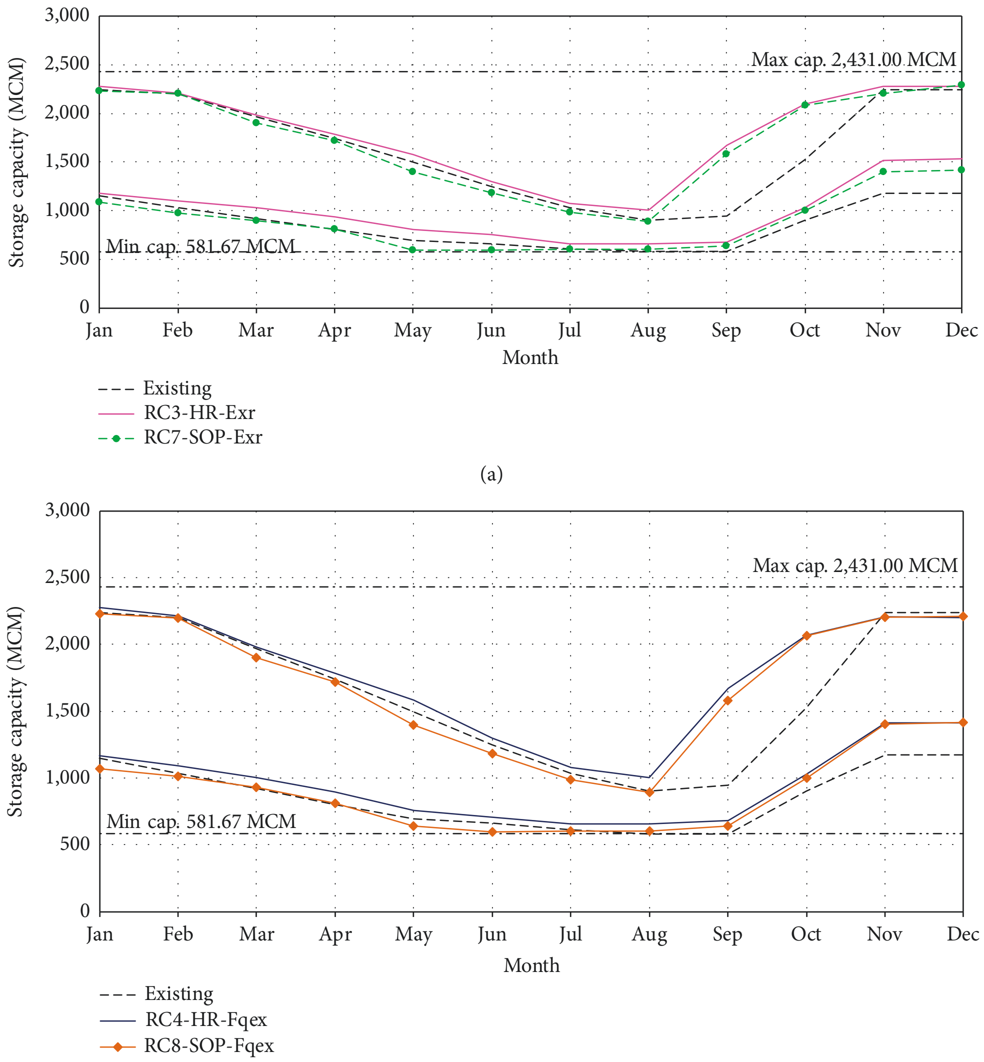
(b)

Figure 7: Optimal rule curves of the Ubolratana reservoir considering HR and SOP with objective functions of (a) the minimal average water shortage per year and (b) the minimal frequency of water shortage.

from MPA technique considering HR (RC1-HR-Avs, RC2-HR-Fqs, RC3-HR-Exr, and RC4-HR-Fqex) in reservoir condition were higher than the patterns of MPA technique considering SOP (RC5-SOP-Avs, RC6-SOP-Fqs, RC7-SOP-Exr, and RC8-SOP-Fqex) and current rule curves (existing). Moreover, the lower rule curves from using HR criteria were higher than lower rule curves when using SOP criteria especially in the dry season (April-May).

These mean that optimal rule curves from using HR attempt to retain water by limiting the water discharge during dry season according to the concept of using HR [15, 18]. It also indicates that the upper rule curves from using HR criteria are higher than upper rule curves when using SOP criteria in the end of rainy season (Oct.-Nov.). As a result, late rainy season storage capacity using HR is higher than that when using SOP and the existing rule curves for reducing severe water shortages in next dry season. This is the main purpose of applying HR criteria with rule curves for reservoir operation [14, 16].

The situations of water shortage and excess release that arise from using the new rule curves generated from the MPA with the HR criteria and SOP criteria are shown in Tables 2 and 3. It is seen that the situations of water shortage when using the historic inflow under the HR with the objective functions of the minimal average water shortage rule curves (RC1-HR-Avs) were the least as 115.769 MCM/year and 742.00 MCM/year for the average water shortage and the maximum water shortage, respectively, whereas the frequency of water shortage was the highest at 0.654 times/year as shown in Table 2. It is also clear that the situations of



(a)

(b)

Figure 8: Optimal rule curves of the Ubolratana reservoir considering HR and SOP with objective functions of (a) the minimal average excess water per year and (b) the minimal frequency of excess water.

excess water when using the historic inflow under the HR with the objective functions of the minimal average water shortage rule curves (RC1-HR-Avs) were the least at 1,107.54 MCM/year and 4,113.159 MCM/year for the average excess water and the maximum excess water, respectively, as shown in Table 3.

It is concluded that the situations of water shortage and excess water when using the obtained rule curves from MPA considering HR were fewer than situations of water shortage and excess water of using the obtained rule curves from MPA considering SOP. Therefore, the HR criteria control water release limitedly for saving water in order to alleviate water deficit in the next dry season [15, 18]. However, the SOP criteria control release of water in order to meet target demand for all considered duration times according to many previous studies [11, 30, 32, 33]. Hence, the SOP criteria are less suitable than HR criteria for reservoirs with high frequency of drought problems.

3.2. *The Efficiency of MPA Rule Curves considering Sedimentation Using HR and SOP.*

The optimal rule curves from MPA technique considering sedimentation with using HR and SOP are presented in Figures 9 and 10. It can be seen that the patterns of new optimal rule curves from MPA considering sedimentation and using HR (RC9s-HR-Avs, RC10s-HR-Fq, RC11s-HR-Exr, and RC12s-HR-Fqex) were higher than optimal rule curves using SOP (RC13s-SOP-Avs, RC14s-SOP-Fq, RC15s-SOP-Exr, and RC16s-SOP-Fqex) as well as current rule curves (existing). In addition, the lower rule curves from MPA considering sedimentation using HR criteria were higher than lower rule curves of using SOP criteria for the same condition. Furthermore, the lower rule curves from MPA considering sedimentation using HR criteria were higher than lower rule curves of using SOP criteria especially in the dry season (Mar.–May) as shown in both Figures 9 and 10. The figures also indicate that the upper rule curves from MPA considering sedimentation

Table 2: The situations of water shortage and excess water considering historic inflow 52 years using HR criteria.

Situations	Rule curves	Frequency (times/year)	Volume (MCM)		Time period (year)	
			Average	Maximum	Average	Maximum
Shortage	Existing	0.673	204.308	865.000	3.889	8.000
	RC1-HR-Avs	0.654	115.769	742.000	3.778	7.000
	RC2-HR-Fqs	0.635	129.558	760.000	3.667	7.000
	RC3-HR-Exr	0.615	124.692	772.000	3.556	7.000
	RC4-HR-Fqex	0.615	118.019	772.000	3.556	7.000
	RC5-SOP-Avs	0.692	126.865	832.000	3.600	7.000
	RC6-SOP-Fqs	0.577	140.231	962.000	2.727	7.000
	RC7-SOP-Exr	0.592	140.577	813.000	4.000	7.000
	RC8-SOP-Fqex	0.592	140.827	814.000	4.000	7.000
Excess water	Existing	0.923	1,230.310	4,126.736	9.600	21.000
	RC1-HR-Avs	0.865	1,107.549	4,113.159	6.143	10.000
	RC2-HR-Fqs	0.827	1,120.988	4,148.107	9.000	13.000
	RC3-HR-Exr	0.865	1,119.433	4,155.656	9.000	13.000
	RC4-HR-Fqex	0.865	1,113.160	4,150.361	9.000	13.000
	RC5-SOP-Avs	0.808	1,118.634	4,152.957	5.250	9.000
	RC6-SOP-Fqs	0.885	1,135.321	4,153.876	11.500	24.000
	RC7-SOP-Exr	0.885	1,139.487	4,158.318	11.500	24.000
	RC8-SOP-Fqex	0.885	1,139.624	4,158.318	11.500	24.000

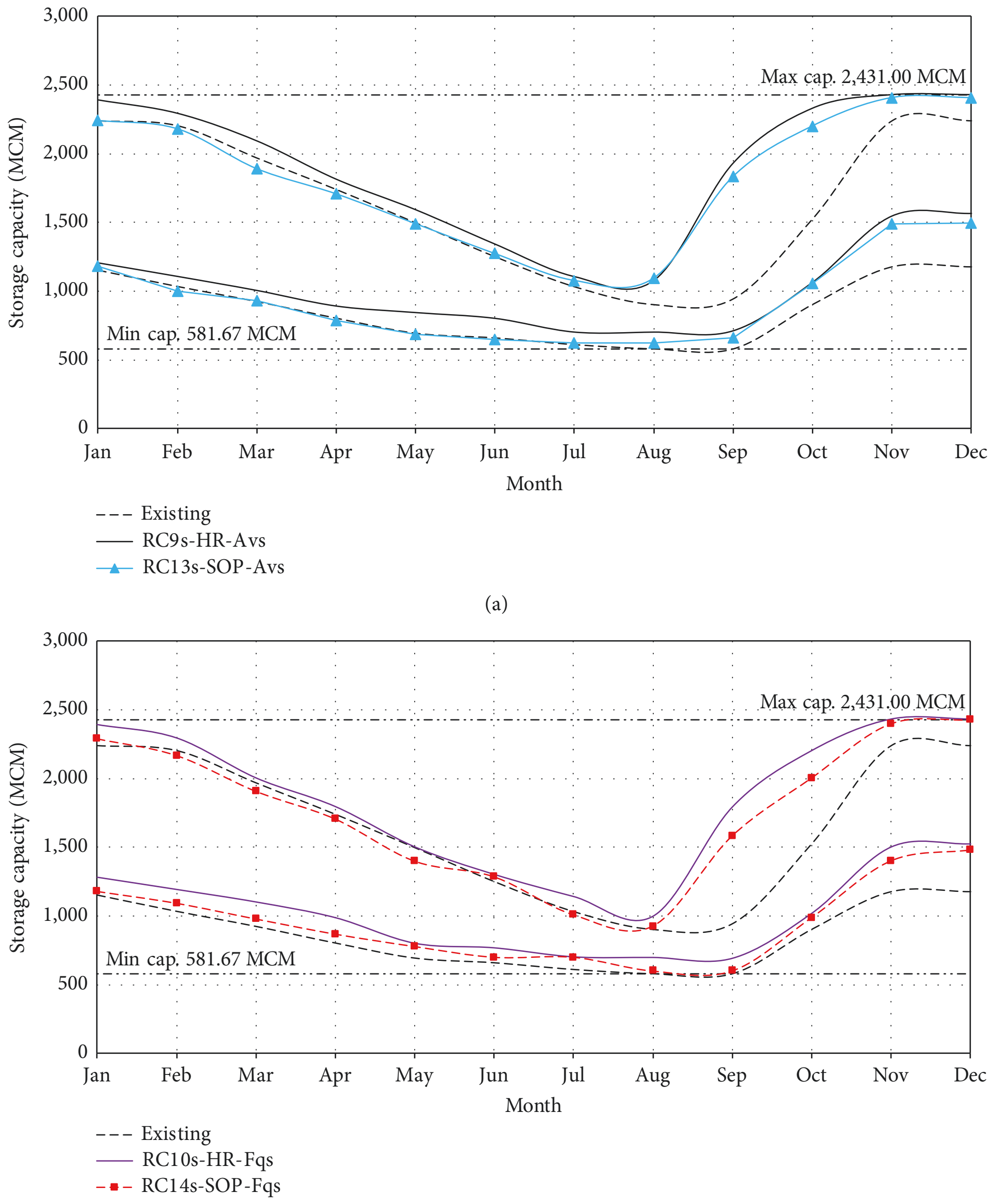
Table 3: The situations of water shortage and excess water considering historic inflow 52 years using SOP criteria.

Situations	Rule curves	Frequency (times/year)	Volume (MCM)		Time period (year)	
			Average	Maximum	Average	Maximum
Shortage	Existing	0.865	349.654	870.000	7.500	19.000
	RC1-HR-Avs	0.752	203.558	766.000	4.000	7.000
	RC2-HR-Fqs	0.730	205.712	790.000	4.000	7.000
	RC3-HR-Exr	0.750	209.481	791.000	3.889	7.000
	RC4-HR-Fqex	0.750	206.250	804.000	3.889	7.000
	RC5-SOP-Avs	0.673	247.962	900.000	4.111	7.000
	RC6-SOP-Fqs	0.662	232.769	891.000	4.875	8.000
	RC7-SOP-Exr	0.673	246.654	770.000	4.875	8.000
	RC8-SOP-Fqex	0.692	246.731	770.000	4.875	8.000
Excess water	Existing	0.962	1,189.589	4,150.361	16.667	25.000
	RC1-HR-Avs	0.942	1,191.718	4,113.159	16.000	25.000
	RC2-HR-Fqs	0.932	1,369.506	4,148.107	24.500	25.000
	RC3-HR-Exr	0.923	1,198.676	4,155.656	16.000	25.000
	RC4-HR-Fqex	0.923	1,196.486	4,126.736	16.000	25.000
	RC5-SOP-Avs	0.902	1,220.490	4,152.957	25.000	25.000
	RC6-SOP-Fqs	0.903	1,241.426	4,153.876	25.000	25.000
	RC7-SOP-Exr	0.905	1,241.520	4,158.318	25.000	25.000
	RC8-SOP-Fqex	0.902	1,241.657	4,158.318	25.000	25.000

using HR criteria were higher than upper rule curves of using SOP criteria at the end of rainy season (November). The optimal rule curves from MPA considering sedimentation using HR attempt to retain water by limiting the water discharge during the dry season (Mar.–May). Hence, the releases of water during March-May controlled by HR were smaller than releases controlled by SOP for all years.

This means that optimal rule curves from MPA considering sedimentation using HR attempt to retain water by limiting the water discharge during the dry season according to the concept of using HR [15, 18]. For this reason, the storage capacity at the end of rainy season using HR considering sedimentation was higher than that when using SOP and the existing rule curves for storing water in order to reduce severe water shortage in next dry season. This is the main purpose of applying HR criteria with rule curves for reservoir operation [14, 16].

The situations of water shortage and excess release when using the optimal rule curves from MPA technique and considering sedimentation and using HR and SOP are shown in Tables 4 and 5. They indicate that the circumstances of water shortage when evaluated by reservoir simulation under historic inflow using rule curves of HR considering sedimentation and objective functions of the minimal average water shortage (RC9s-HR-Avs) were the least at 95.558 MCM/year and 693.000 MCM/year for the average water shortage and the maximum water shortage respectively, whereas the frequency water shortage was the highest at 0.654 times/year as shown in Tables 4 and 5. The tables present that the situations of excess water when



(a)

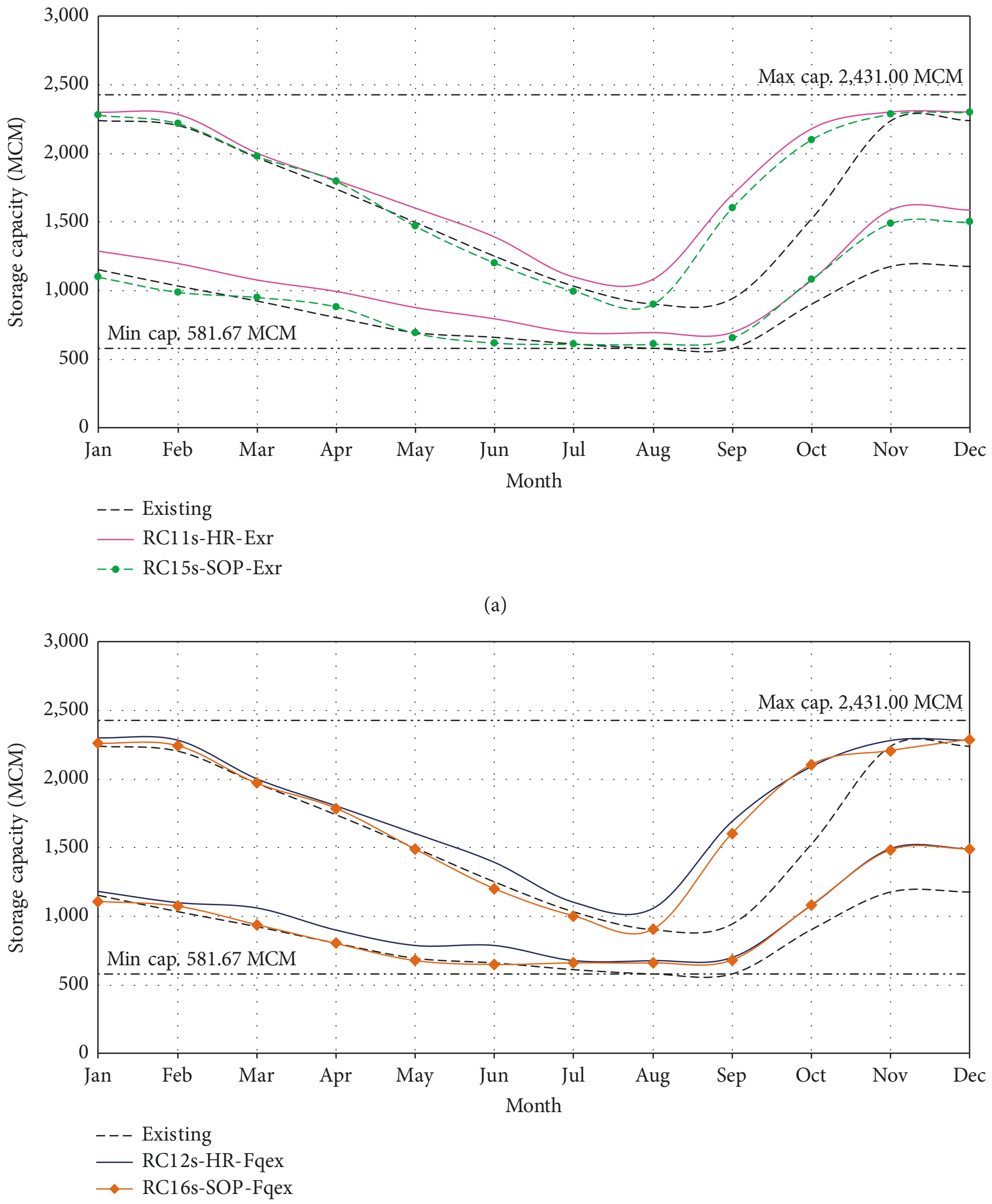
(b)

Figure 9: Optimal rule curves of the Ubolratana reservoir considering sedimentation with objective functions of (a) the minimal average water shortage per year and (b) the minimal frequency of water shortage.

evaluated by means of reservoir simulation under historic inflow using rule curves of HR considering sedimentation and objective functions of the minimal average excess water (RC9s-HR-Avs) were the least at 1,087.807 MCM/year and 4,105.658 MCM/year for the average excess water and the maximum excess water, respectively.

It is concluded that the situations of water shortage and excess water when using the obtained rule curves from MPA considering sedimentation and using HR were smaller than situations of water shortage and excess water of using the obtained rule curves from MPA considering sedimentation and using SOP. The HR criteria control water release limiting and saving water in order to alleviate water deficit in next dry season [15, 18]. Therefore, the rule curves from the MPA considering sedimentation with the HR can be applied to reduce the risk of unacceptably large damage from water shortage during the dry season.

In addition, the results from Tables 4 and 5 also indicate that the situations of water shortage and water excess were quite different, when sedimentation was or was not considered. The considering and not considering sedimentation cases were evaluated via the water surface area and the capacity curve [49]. The sediment accumulation from rainfall flowing into reservoir resulted in a decrease in reservoir capacity, so it is necessary to consider the reservoir's long-term sediment accumulation. Therefore, long-term reservoir operation considering sediment accumulation is an important operational parameter in order to



(a)

(b)

Figure 10: Optimal rule curves of the Ubolratana reservoir considering sedimentation with objective functions of (a) the minimal average excess water per year and (b) the minimal frequency of excess water.

ensure future accuracy and sustainability [21, 23, 24]. It can be concluded that the MPA linked with reservoir simulation using HR criteria and considering sedimentation can be used to effectively find optimal rule curves solution.

3.3. Comparison of Optimal Rule Curves Performance of MPA, GA, and FPA. The optimal rule curves from MPA, GA, and FPA techniques linked with reservoir simulation model considering sedimentation and using HR were plotted in Figure 11. They indicate that the patterns from the new rule curves obtained from the MPA, the GA, and the FPA are similar because of the seasonal inflow effect and the same conditions. The results also show that the upper rule curves of all techniques considering sedimentation (RC17-MPAs-HR, the RC18-GAs-HR, and the RC19-FPAs-HR for MPA, GA, and FPA, resp.) were higher than the existing upper rule curves.

These patterns can promote reduction of spill water and maintain full storage capacity full at the end of the rainy season. This will help prevent water shortages in the following dry season. However, lower rule curves of all techniques considering sedimentation during dry season (Jan.-May) were higher than the existing upper rule curves. They can control water discharge by reducing water release at lower levels than target demand according to the HR concept [14–16, 18].

The optimal rule curves from MPA, GA, and FPA techniques linked with reservoir simulation model considering

Table 4: The situations of water shortage and excess water considering historic inflow 52 years from MPA considering sedimentation and using HR criteria.

Situations	Rule curves	Frequency (times/year)	Volume (MCM)		Time period (year)	
			Average	Maximum	Average	Maximum
Shortage	Existing	0.673	204.308	865.000	3.889	8.000
	RC9s-HR-Avs	0.654	95.558	693.000	3.375	5.000
	RC10s-HR-Fq	0.519	128.058	722.000	3.778	7.000
	RC11s-HR-Exr	0.635	117.077	715.000	3.667	7.000
	RC12s-HR-Fqex	0.615	104.692	744.000	3.556	7.000
	RC13s-SOP-Avs	0.635	117.750	835.000	3.300	7.000
	RC14s-SOP-Fq	0.615	141.981	863.000	3.556	7.000
	RC15s-SOP-Exr	0.615	146.596	873.000	3.556	7.000
	RC16s-SOP-Fqex	0.615	115.981	717.000	3.556	7.000
Excess water	Existing	0.923	1,230.310	4,113.159	9.600	21.000
	RC9s-HR-Avs	0.865	1,087.807	4,105.658	5.250	9.000
	RC10s-HR-Fq	0.808	1,120.509	4,146.837	9.000	13.000
	RC11s-HR-Exr	0.846	1,111.388	4,156.169	7.333	13.000
	RC12s-HR-Fqex	0.846	1,101.828	4,157.411	7.333	13.000
	RC13s-SOP-Avs	0.827	1,106.682	4,143.346	6.143	10.000
	RC14s-SOP-Fq	0.885	1,134.931	4,150.620	11.500	24.000
	RC15s-SOP-Exr	0.885	1,142.790	4,154.135	11.500	24.000
	RC16s-SOPs-Fqex	0.846	1,118.288	4,158.341	7.333	13.000

Table 5: The situations of water shortage and excess water considering historic inflow 52 years from MPA considering sedimentation and using SOP criteria.

Situations	Rule curves	Frequency (times/year)	Volume (MCM)		Time period (year)	
			Average	Maximum	Average	Maximum
Shortage	Existing	0.865	349.654	870.000	7.500	19.000
	RC9s-HR-Avs	0.731	165.981	717.000	3.000	5.000
	RC10s-HR-Fq	0.692	201.596	797.000	4.000	7.000
	RC11s-HR-Exr	0.673	190.019	769.000	3.889	7.000
	RC12s-HR-Fqex	0.673	196.462	785.000	3.889	7.000
	RC13s-SOP-Avs	0.692	203.346	873.000	4.000	7.000
	RC14s-SOP-Fq	0.531	219.827	861.000	4.222	7.000
	RC15s-SOP-Exr	0.567	251.750	872.000	4.222	7.000
	RC16s-SOP-Fqex	0.577	247.423	868.000	4.222	7.000
Excess water	Existing	0.965	1,369.506	4,113.159	16.667	25.000
	RC9s-HR-Avs	0.962	1,147.727	4,105.658	11.750	24.000
	RC10s-HR-Fq	0.904	1,186.812	4,146.837	24.000	24.000
	RC11s-HR-Exr	0.923	1,176.389	4,156.169	15.667	24.000
	RC12s-HR-Fqex	0.923	1,185.039	4,157.411	16.000	25.000
	RC13s-SOP-Avs	0.923	1,187.500	4,143.346	16.000	24.000
	RC14s-SOP-Fq	0.942	1,212.770	4,150.620	24.500	25.000
	RC15s-SOP-Exr	0.962	1,244.219	4,154.135	25.000	25.000
	RC16s-SOPs-Fqex	0.904	1,240.496	4,158.341	25.000	25.000

sedimentation and using HR were used to evaluate the performance of mitigation water shortage and water excess situations by reservoir simulation considering historic inflow of 52 years; the results are shown in Table 6. They indicated that the situations of water shortage and water excess when using optimal rule curves from MPA, GA, and FPA techniques were slightly different because their patterns were similar and they had the same conditions. It can be concluded that the MPA linked with reservoir simulation model considering sedimentation and using HR can be used to find optimal rule curve solution effectively like GA and FPA techniques.

The efficacy of searching for rule curves solutions from MPA, GA, and FPA techniques was investigated by comparison of iteration number for all techniques. The results of searching iteration number are present in Figure 12 indicating that the optimal rule curves of MPA were obtained at 350 iteration number whereas the iteration number for GA and FPA techniques was 630 and 450, respectively.

It can be concluded that MPA technique had higher performance than GA and FPA techniques in reservoir rule curves searching. It may be inferred that, like the GA and FPA processes, the MPA methodology is effective in locating reservoir rule curves. However, while the outcomes are equivalent, the speed of search or the complexity of the system is also an essential factor, which MPA can handle better than other strategies.

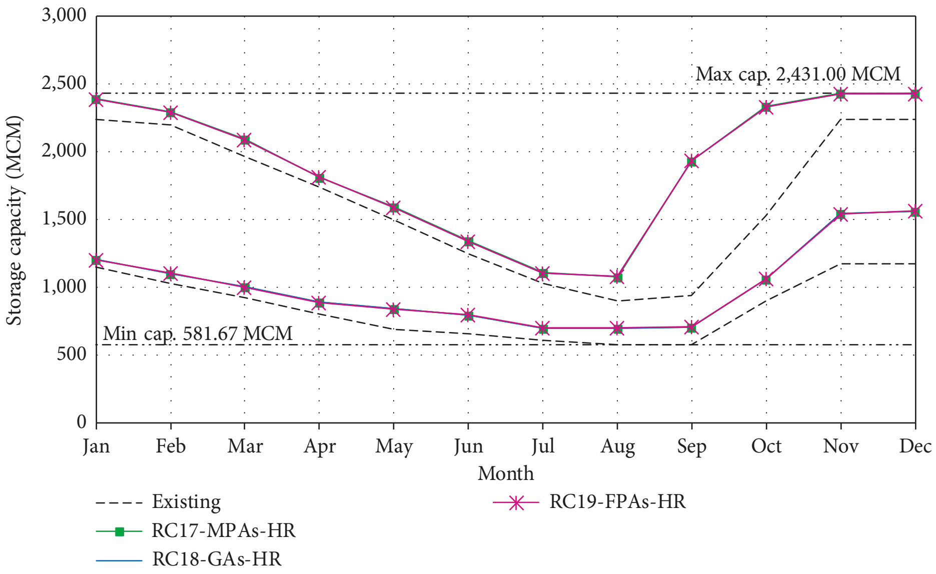


Figure 11: Optimal rule curves of the Ubolratana reservoir from MPA, GA, and FPA techniques.

Table 6: The situations of water shortage and excess water of using optimal rule curves from MPA, GA, and FPA techniques considering sedimentation and HR criteria.

Situations	Rule curves	Frequency (times/year)	Volume (MCM)		Time period (year)	
			Average	Maximum	Average	Maximum
Shortage	Existing	0.865	349.654	870.000	7.500	19.000
	RC17-MPAs-HR	0.654	95.558	693.000	3.375	5.000
	RC18-GAs-HR	0.731	95.556	693.000	3.375	5.000
	RC19-FPAs-HR	0.731	95.549	693.000	3.374	5.000
Excess water	Existing	0.965	1,369.506	4,113.159	16.667	25.000
	RC17-MPAs-HR	0.962	1,147.727	4,105.658	11.750	24.000
	RC18-GAs-HR	0.962	1,147.727	4,105.658	11.750	24.000
	RC19-FPAs-HR	0.962	1,147.726	4,105.656	11.750	24.000

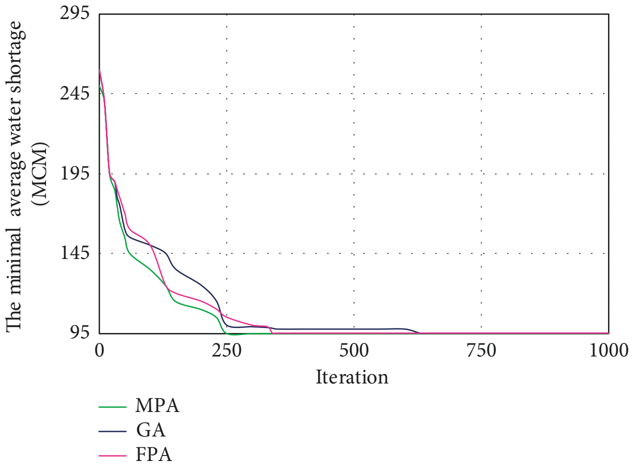


Figure 12: Iteration number of searching reservoir rule curves for MPA, GA, and FPA techniques.

4. Conclusions

This paper proposes the Marine Predators algorithm (MPA) linked to the reservoir simulation model considering hedging rule criteria and sedimentation in the reservoir for improving reservoir rule curves. The Ubolratana reservoir, located in Khon Kaen province, Thailand, was considered for this study. The release criteria of the standard operating rule (SOP) and hedging rule (HR) were applied to solve rule curves solution. The efficiencies of rule curves from three techniques (MPA, GA, and FPA) were evaluated.

The results revealed that the proposed model with four objective functions provided the new optimal rule curves. The patterns of optimal rule curves from MPA technique considering sedimentation in reservoir condition were higher than the patterns of existing rule curves for all other cases. The situations of water shortage from using optimal rule curves of HR criteria in terms of frequency were higher than those when using SOP criteria, whereas the average water shortage term of using HR criteria was less than that when using SOP criteria. This is the main objective of using HR criteria for determining release conditions. The results also showed that the optimal rule curves from considering sedimentation in the reservoir were more reasonable simulations than those not considering all cases of using historic inflow samples. In addition, the situations of water shortage and water excess were quite different from those concerning considering and not considering sedimentation cases. It can be concluded that sediment accumulation from rainfall flowing into reservoir must be considered to understand the reservoir's long-term sediment accumulation.

The results of the comparison for the rule curves search efficiency of the MPA technique and GA and FPA techniques showed that the optimal rule curves of MPA technique were similar to optimal rule curves of GA and FPA techniques. It can be concluded that the MPA with HR considering sedimentation can be used to find optimal reservoir rule curves effectively with both mitigating flood and drought situations. In addition, the MPA technique is faster in producing optimal rule curves compared with GA and FPA techniques.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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