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Extracting Optimal Operation Rule Curves of Multi-Reservoir System Using Atom Search Optimization, Genetic Programming and Wind Driven Optimization

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Abstract: This research aims to apply optimization techniques using atom search optimization (ASO), genetic programming (GP), and wind-driven optimization (WDO) with a reservoir simulation model for searching optimal rule curves of a multi-reservoir system, using the objective function with the minimum average quantity of release excess water. The multi-reservoir system consisted of five reservoirs managed by a single reservoir that caused severe problems in Sakon Nakhon province, Thailand, which was hit by floods in 2017. These included Huai Nam Bo Reservoir, the Upper Huai Sai-1 Reservoir, the Upper Huai Sai-2 Reservoir, the Upper Huai Sai-3 Reservoir, and the Huai Sai Khamin Reservoir. In this study, the monthly reservoir rule curves, the average monthly inflow to the reservoirs during 2005–2020, the water demand of the reservoirs, hydrological data, and physical data of the reservoirs were considered. In addition, the performance of the newly obtained rule curves was evaluated by comparing the operation with a single reservoir and the operation with a multi-reservoir network. The results showed situations of water shortage and water in terms of frequency, duration, average water, and maximum water. The newly obtained rule curves from the multi-reservoir system case showed an average water excess of 43.722 MCM/year, which was less than the optimal curves from the single reservoir case, where the average water excess was 45.562 MCM/year. An analysis of the downstream reservoir of the multi-reservoir system, which diverts water from the upstream reservoirs, was performed. The results showed that the new optimal rule curves of ASO, GP, and WDO operated as a multi-reservoir system performed better than when operated as a single reservoir. Therefore, this research is suitable for sustainable water management without construction.

Keywords: multi-reservoir system; reservoir rule curves; atom search optimization; genetic programming; wind-driven optimization

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1. Introduction

Water management is a process for ensuring that sufficient water resources are available for efficient and equitable allocation and use of water for various purposes, and includes addressing both quantity and quality issues [1,2]. As a result, water management tools have been invented and developed. There are two approaches; to use the structure or not to use it. Management tools using the structure method involve reserve reservoirs, irrigation weirs, water diversion tunnels, ponds in the fields and gardens, etc. Management tools, that involve not using structures include the application of computer programs for decision support systems for planning and analyzing consumer water allocation data, including flood and drought data [3,4]. Reservoir management is currently an important part of water resource management in Thailand. Reservoirs are classified based on their intended use [5]. From one point of view, reservoirs can be classified into two categories: single-purpose reservoirs and multipurpose reservoirs [6–8]. Reservoir classification based on physical or management characteristics of the watershed is also possible. Single reservoir and multi-reservoir systems are the two types of reservoir systems that exist [9,10]. However, there are still difficulties because of the ongoing shifts in these temporal patterns and the quantity of water required. The reservoir operation rules must be revised and the water release policy must be adjusted in light of the water demand patterns to ensure the sustainable functioning of water released from a water system's dams and reservoirs [11,12], and under climate change [13].

Reservoir operation rules are thus a crucial instrument for effective reservoir management and provide increased confidence in water release decisions [14–16]. There is a risk of reservoir failure, particularly during reservoir critical times, due to both excess water overflow and a lack of water supply to meet demand, resulting in water shortages. As a result, guidelines are required to ensure that the reservoir operates as intended. Most reservoir operating rules are in the form of rule curves. This consists of an Upper Rule Curve (URC) and a Lower Rule Curve (LRC), which must control the water level and release the water under the upper and lower boundaries during various time periods. They are extracted using a combination of system simulation and optimization techniques [17–19]. Reservoir operation is a critical component that must be designed during the project planning stage. In terms of a multi-reservoir system operation, a multi-reservoir system's joint reservoir operation is more advantageous than operating a single reservoir by reducing the amount of uncontrolled outflow from the system [20,21].

Optimization techniques, such as linear programming, non-linear programming, and dynamic programming, are widely used in the field of water resource engineering to solve problems and predictions. Currently, there are many applications of optimization techniques to find the optimal rule curves such as dynamic programming and the other optimization techniques derived from evolutionary theory [22–24]. They are effective techniques to find solutions such as genetic algorithm [19,25], Flower Pollination Algorithm [26], Tabu search [27,28], Honey-Bee Mating Optimization [29], Harris Hawks Optimization [30], where researchers have applied these techniques in their searches for finding optimal reservoir rule curves.

Nowadays, one of the alternative optimization techniques that can be adapted to find appropriate value is a wind-driven optimization (WDO) technique. WDO is an evolutionary adaptive of the air parcel in the atmosphere, finding the best pressure to balance the atmosphere [31]. This technique is a highly effective technique and is appropriate for searching for optimal reservoir rule curves. Recently, genetic programming (GP) is an alternative technique for the application of a variety of engineering. The numerical problem-solving used GP for resizing the structure in order to find the optimal cross-section and the connection of the joints to achieve the minimum weight [32]. However, it is not commonly used to find the optimal rule curves. Hence, it is an interesting technique that is introduced to apply to a reservoir simulation model for solving rule curves optimization problems.

Another effective technique for finding optimal solutions is the atom search optimization (ASO) technique. ASO is a heuristic algorithm that is inspired by basic molecular dynamics. Based on the literature review conducted by the authors, the performance of ASO has not been evaluated for solving reservoir operation problems. The ASO imitates atom movement governed by reaction forces. Later, tests with various comparison functions were run on hydrogeological parameter estimation solutions to verify qualitative and quantitative validity. The findings demonstrate that ASO outperforms both traditional and novel algorithms and which can be accounted as an alternative approach for solving various engineering problems [33]. ASO has also been applied in electronic engineering with the objective of improving ASO's ability by combining it with other algorithms in a hybrid method [34–37]. However, this method is not widely used, but it is another one that quickly and efficiently converges on an answer that can be used to find reservoir rule curves.

Recent reservoir rule curve improvement studies are frequently carried out as single reservoir management studies involving large-sized reservoirs with historical data spanning several years. However, it is currently more difficult to construct a reservoir for use as a water management tool because of rules, laws, or permission to work on the construction site [38]. As a result, certain problems were solved by constructing a network reservoir by connecting several small reservoirs in the same sub-basin. If the multi-reservoir system is managed by a single reservoir management method, this will cause the downstream reservoir to suffer from water shortage when the upper reservoir does not release water. If the upstream reservoir drains too much water downstream, it will overflow the lower reservoir. One example of a multi-reservoir system managed by a single reservoir causing severe problems is the Sakon Nakhon province, Thailand which experienced flooding in 2017 [39]. This was due to the amount of water overflowing from the upper multi-reservoir systems. It flowed into the Huai Sai Kamin reservoir situated downstream of the multi-reservoir system, resulting in the being unable to drain the floodwaters in time, water overflowed onto the soil dam, causing dam damage and flooding. Therefore, new techniques must be studied in order to manage the multi-reservoir systems to reduce excess water flow.

The objective of this research is to examine optimal water management strategies. To achieve optimal multi-reservoir system rule curves, the atom search optimization (ASO), genetic programming (GP), and wind-driven optimization (WDO) are coupled to a reservoir simulation model. The objective function of the optimization problem is designed to minimize the average value of the excess released water, over the simulation period. Following that, the efficiency of the achieved rule curves of the multi-reservoir system is evaluated.

2. Materials and Methods

2.1. Study Area and Data Collection

A multi-reservoir system in the Nam Oon sub-basin of the Mekong River Basin, Sakon Nakhon Province, Thailand is considered as the case study. The topography of the study area is shown in Figure 1. The schematic diagram of the five-reservoir system is shown in Figure 2 including the Huai Nam Bo reservoir, the Upper Huai Sai-1 reservoir, the Upper Huai Sai-2 reservoir, the Upper Huai Sai-3 reservoir, and the Huai Sai Kamin reservoir. The details of the physical characteristics of the reservoirs are shown in Table 1 consists of a type of dam, the first year of operation, the catchment area, the height from the foundation, the crest length, the normal storage capacity, the irrigation area, the spillway maximum discharge capacity and the average annual inflow.

Table 1. The Physical Characteristics of the System's Reservoirs.

Characteristics	Huai Nam Bo	Upper Huai Sai-1	Upper Huai Sai-2	Upper Huai Sai-3	Huai Sai Kamin
Type of dam	Earth dam	Earth dam	Earth dam	Earth dam	Earth dam
First year of operation	1964	1991	1986	1985	1956
Catchment area (km^2)	9.87	6.63	5.6	0.6	29.00
Height from foundation (m)	17	13.5	12.9	8	8.30
Crest length (m)	950	575	690	450	1300
Normal storage capacity (MCM)	2.2	2.1	2.1	0.21	3.18
Irrigation area (km^2)	4.8	6.4	6.08	1.12	6.40
Spillway discharge capacity (m^3/s)	15	25	21.3	1.9	85.50
Average annual inflow (MCM)	9.04	2.38	1.54	0.40	45.77

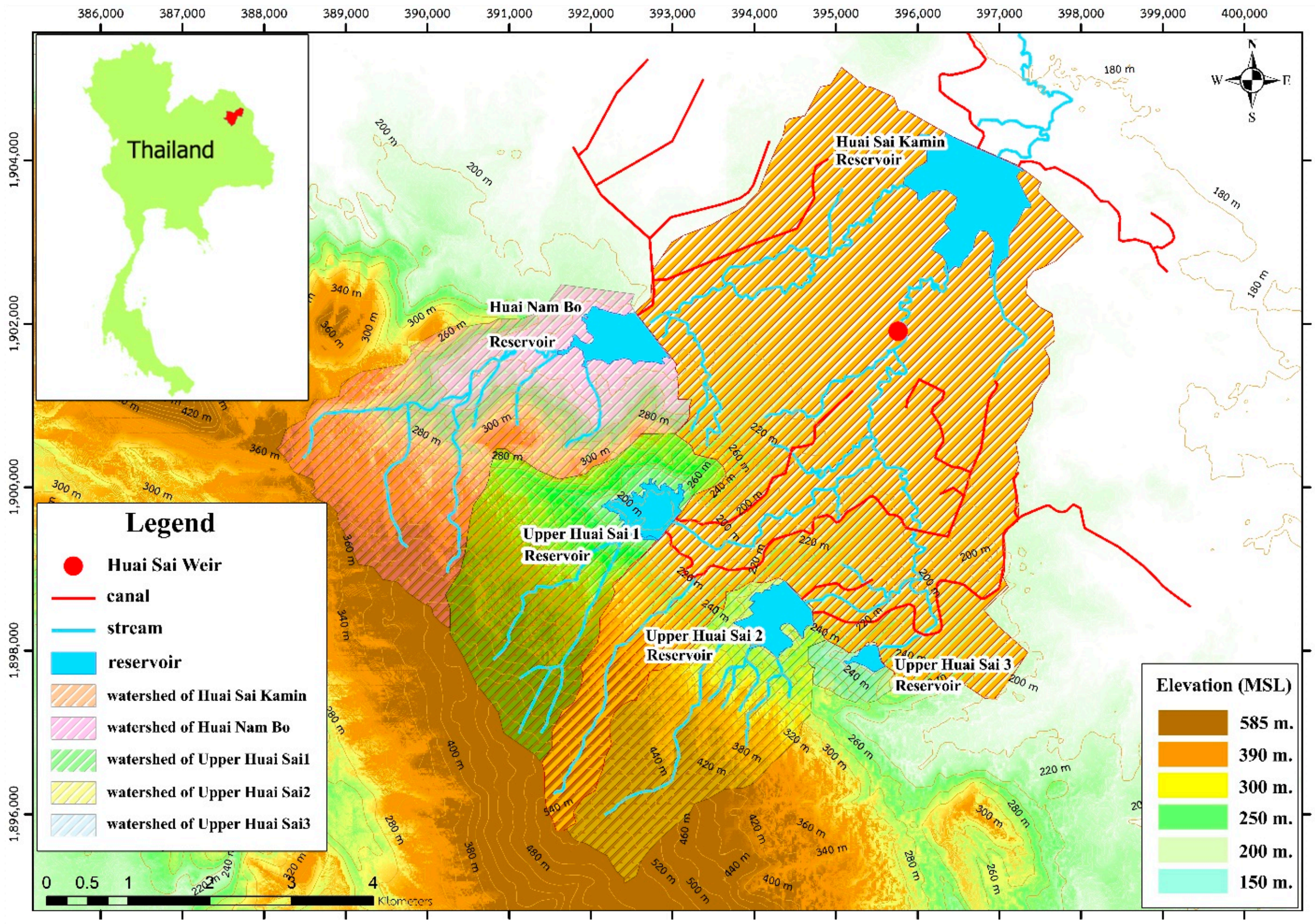

Figure 1. Topography of The Multi-Reservoir System.

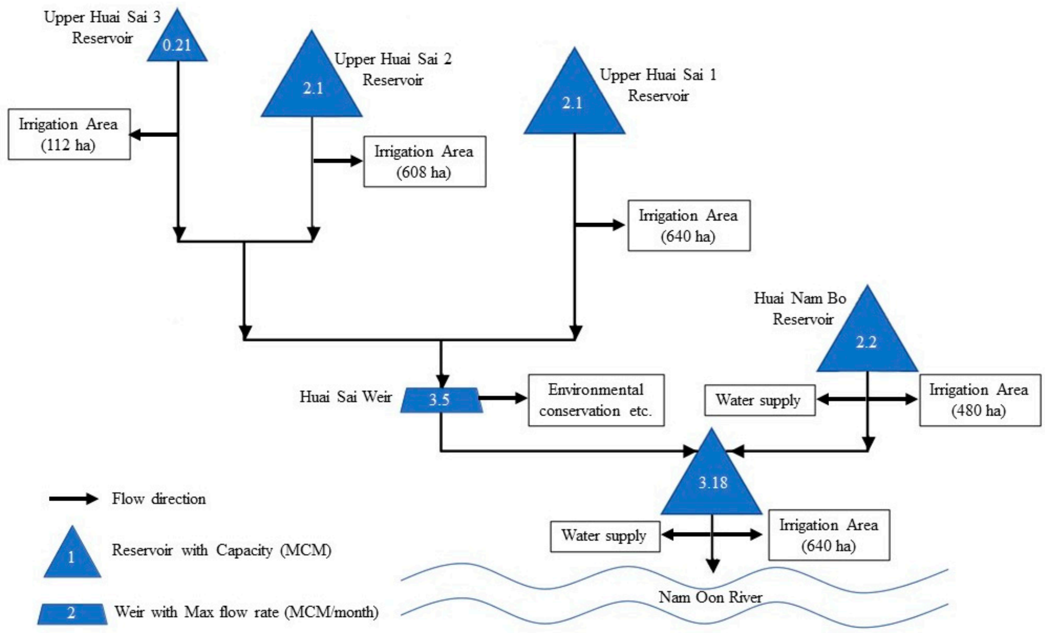

Figure 2. Schematic Diagram of the Multi-Reservoir System in Thailand.

In this study, the meteorological data including the average monthly rainfall, the effective rainfall, the monthly evaporation, were continuously measured by the Thai Meteorlogical Department (TMD). The data on irrigation water requirements and the average monthly inflows into the multi-reservoir system, the data from the Royal Irrigation Department (RID) is shown in Table 2, a period of 16 years from 2005 to 2020 was selected as the baseline period.

Table 2. Average monthly inflows into the Multi-Reservoir System (2005 to 2020).

Reservoir	Average Monthly Inflow (MCM/Month)											
	January	February	March	April	May	June	July	August	September	October	November	December
Huai Nam Bo	0.130	0.128	0.215	0.151	0.282	1.008	1.777	1.643	1.857	1.452	0.266	0.137
Upper Huaisai-1	0.044	0.047	0.052	0.047	0.147	0.250	0.360	0.425	0.479	0.408	0.074	0.051
Upper Huaisai-2	0.087	0.038	0.045	0.038	0.086	0.167	0.315	0.286	0.197	0.159	0.083	0.043
Upper Huaisai-3	0.002	0.002	0.004	0.006	0.075	0.124	0.055	0.070	0.060	0.182	0.008	0.005
Huai Sai Kamin	0.878	0.683	0.779	0.374	0.555	2.415	8.161	11.654	12.053	6.321	1.401	0.499

2.2. The Proposed Computational Approach

Generally, a reservoir system comprises available water that flows into the reservoir and a single or multiple purposes downstream the reservoir which should be supplied. The reservoirs are usually operated under water usage criteria and reservoir rule curves with weekly, monthly, or annual data for long-term performance. The reservoir rule curves have been found to offer the most equitable solution to all operational problems. In this study, a modified reservoir operation model is constructed on the concept of water balance, and it can be used to simulate reservoir operation effectively.

This conceptual approach is extended for multi-reservoir systems with more complexities. The reservoir operation policies are defined based on the monthly rule curves of individual reservoirs and the principles of the water balance equation embedded within the reservoir simulation model. Meanwhile, the single reservoirs are operated under the standard operating policy [13,27] as expressed in Equation (1).

$$W_{v,\tau} = S_{v,\tau} + Q_{v,\tau} - R_{v,\tau} - E_{\tau} \quad (1)$$

where $W_{v,\tau}$ is the available water during year v and period τ (τ = 1 to 12, representing January to December); $S_{v,\tau}$ is the stored water at the end of month τ during year v; $Q_{v,\tau}$ is monthly reservoir inflow during year v and period τ; $R_{v,\tau}$ is the released water from the reservoir during year v and period τ; and E_{τ} is the average value of evaporation loss.

After operation for all months along the considered inflow period, all monthly releases of water from the reservoir are used to calculate the objective function in the searching procedure. Results of each objective function are recorded and used in the optimization (i.e., ASO, GP, and WDO) models until satisfying the stopping criteria and so, the optimal rule curves are obtained as the final results. The detail of the objective function calculation is described in the next section.

2.3. Atom Search Optimization Algorithm for Finding Operation Rule Curves

The ASO was created and coupled to the reservoir simulation model. The ASO was developed using the same principles as the previously studied. The procedure started by creating an initial population of rule curves (X), boundary search, objective function, and stopping criteria. Then the population of initial rule curves were sent to the reservoir simulation model one by one, for operating the reservoir by considering input data and physical information of the reservoir. The time series of monthly releases were calculated using initial rule curves along the simulation period. Then, all monthly releases were used to calculate the objective function and to evaluate the set of initial rule curves for accepting the first iteration. Next, the newly accepted rule curves were used to replace the initial population. This procedure was repeated until the newly accepted rule curves were appropriate and the stopping criteria were satisfied as shown in Figure 3.

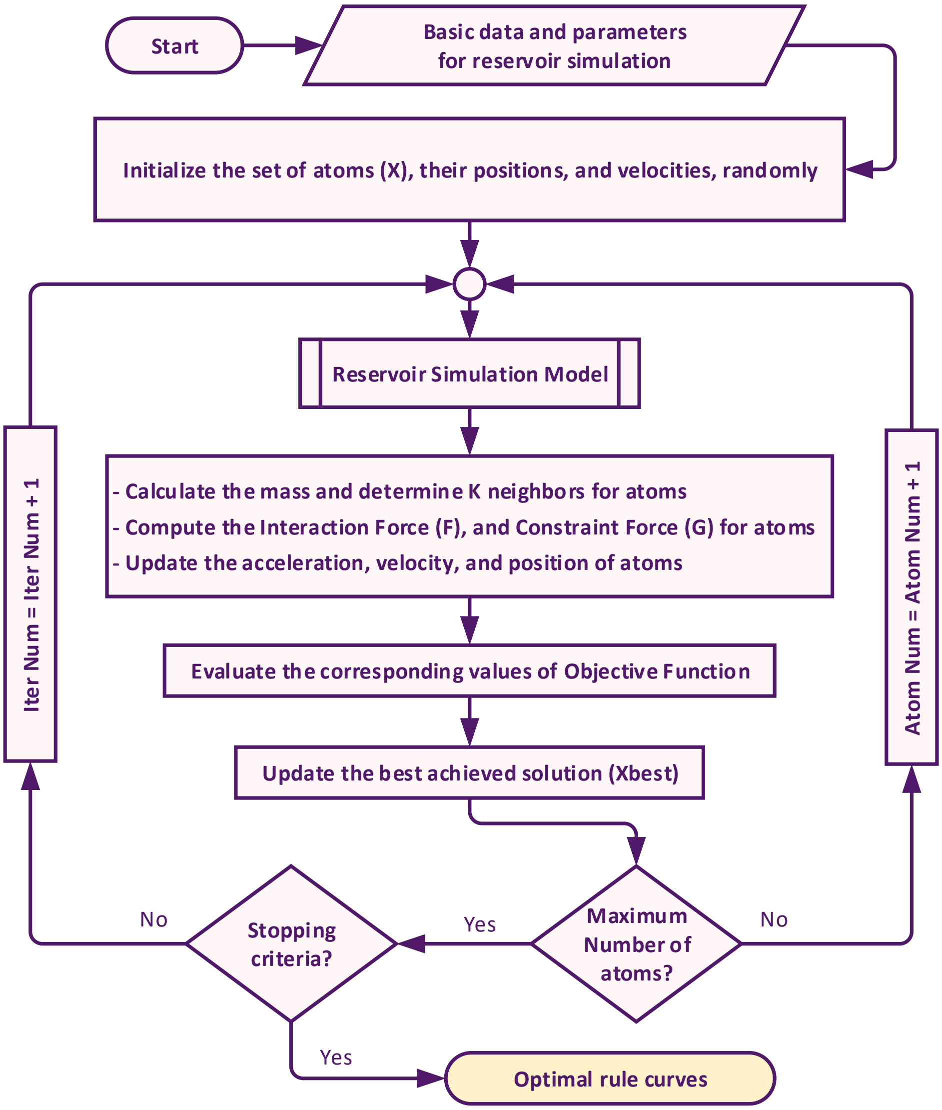

Figure 3. Atom Search Optimization with Reservoir Simulation to Search for optimal Rule Curves.

The minimum average quantity of excess released water per year (U) is used as the objective function of the optimization problem subject to the constraints on the simulation model, where water must be allocated to suit the water needs and not cause water shortages. These values were then taken as the values of the reservoir rule curves in the simulation study model and calculated monthly water discharge volumes in this the rule curves as in the following:

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

$$\text{if } R_\tau > D_\tau ; \text{Then } Sp_v = \sum_{\tau=1}^{12} (R_\tau - D_\tau) \ \text{ Else } Sp_v = 0 \quad (3)$$

where n is the maximum number of simulated years, D_τ is the water demand of month τ, Sp_v is the quantity of excess released water during years v (a year, in which released water is higher than the water demand), and i is the iteration number.

2.4. Genetic Programming for Finding Operation Rule Curves

The process of GP starts with a random initial population of a computer program. An individual program present in the population refers to a parse tree, which is generated by the combination of its functions (nodes) and terminals (leaves) that are defined in a function set and terminal set, appropriate to the problem, respectively. A function set may consist of basic arithmetic operators, mathematical functions, conditional operators, Boolean operators, iterative functions and any user-defined functions or operators, while a terminal set contains the arguments for the functions. Once the initial population has been created, the next step is repeatedly replacing the current population with a new population (or new generation) by means of applying genetic operators (reproduction, crossover and mutation) probabilistically until the best fitness of the population has reached the desired level, or the maximum number of generations has been reached. The genetic operators applied in a GP are the basic GA operators. Reproduction is the process of copying the selected individual program to the new population. The crossover operation creates a new offspring program for the new population (see Figure 4).

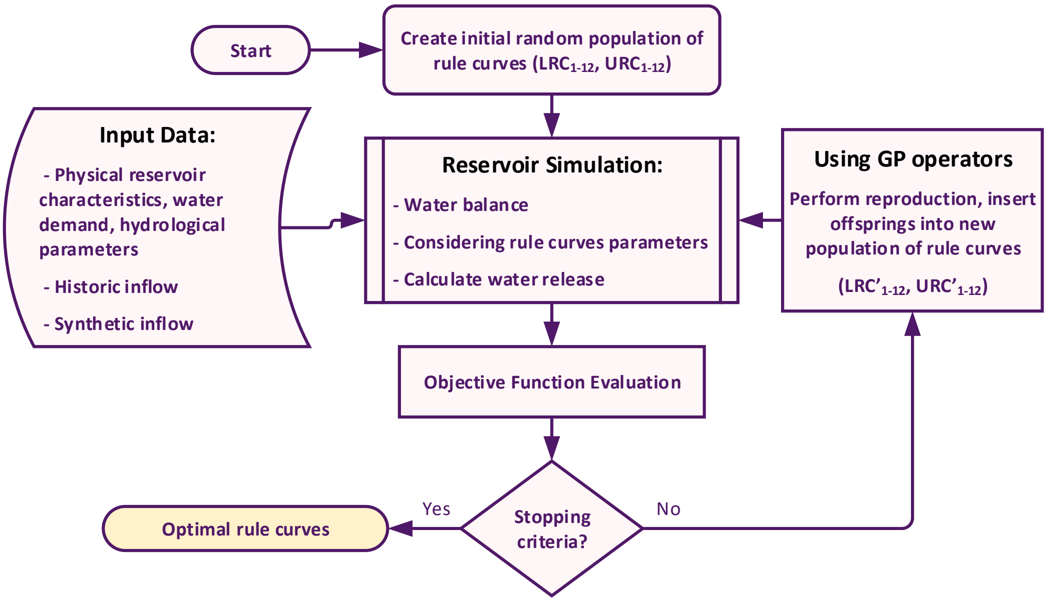

Figure 4. Genetic Programming with Reservoir Simulation to Search for optimal Rule Curves.

2.5. Wind-Driven Optimization for Finding Operation Rule Curves

The proposed approach to connect WDO optimization algorithm with the reservoir simulation model is presented as follows: the WDO starts with a set of initial population {X1, X2, ..., Xn} that is created randomly within the feasible space. The feasible space is assumed between the dead storage capacity and the normal storage water level of the considered reservoir. There are 24 decision variables. For this study, each decision variable represents the monthly rule curves in the reservoirs, which are defined as the upper bound and the lower bound (rule curves variables for both upper and lower) for each reservoir. The feasible solution of the iteration is represented as $Xi = [xi_1, xi_2, ..., xi_{24}]$. The application of WDO and reservoir simulation models for searching the rule curves is described in Figure 5 as a computational flowchart.

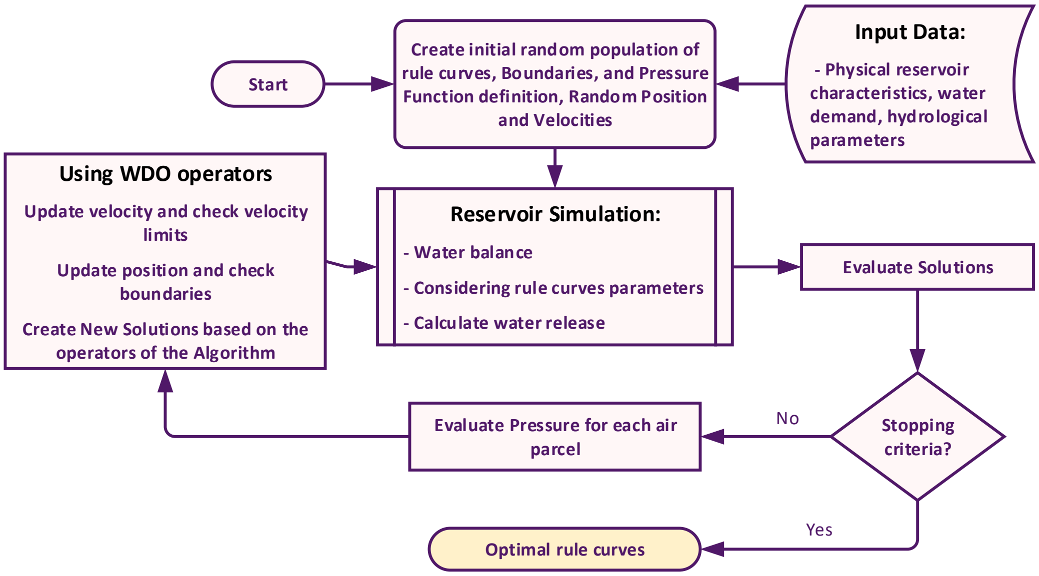

Figure 5. Wind Driven Optimization with Reservoir Simulation to Search for optimal Rule Curves.

2.6. Rule Curve Performance Assessment

Various operating scenarios were simulated to evaluate the performance of the obtained rule curves. As the amount of inflows to the considered system is much greater than the storage capacity, minimization of the excess releases is so important to the system managers. Therefore, the performance of the operation rule curves was determined from the excess water content of the rule curves comparing a single reservoir and a multi-reservoir system. The minimum average overflow forms the objective function and was separately considered as follows.

1. The performance of the proposed model was evaluated with historical inflow data for 2005–2020 and monthly synthetic inflow data across 1000 incident sets with the standard operating rule of release criteria.
2. A comparison of the performance of the rule curve obtained by the ASO with the current rule curves, genetic programming (GP) and wind-driven optimization (WDO) using the least mean excess water content.
3. The water situation when considering the amount of water discharged from the Upper Huai Sai-1 reservoir, the Upper Huai Sai-2 reservoir and the Upper Huai Sai-3 reservoir when combined flows are limited by the capacity of the Huai Sai Weir (that can drain the maximum 3.5 MCM/months) before flowing into the Huai Sai Kamin reservoir was evaluated.

3. Results

3.1. The Multi-Reservoir Rule Curves Search

The ASO, GP, and WDO were used to find the rule curves of the multi-reservoir system; the optimal rule curves were obtained. These obtained rule curves were plotted in order to compare them with the existing rule curves of the system for both single-reservoir and multi-reservoir system cases. LRC-existing for the lower rule curve; URC-existing for the upper rule curve; S-LRC-ASO, S-LRC-GP, and S-LRC-WDO for the lower rule curve of single reservoir consideration using ASO, GP, and WDO, respectively; S-URC-ASO, S-URC-GP, and S-URC-WDO for the upper rule curve of single reservoir consideration using ASO, GP, and WDO, respectively; M-LRC-ASO, M-LRC-GP, and M-LRC-WDO for the lower rule curve of multi-reservoir consideration using ASO, GP, and WDO, respectively; M-URC-ASO, M-URC-GP, and M-URC-WDO for the upper rule curve of multi-reservoir consideration using ASO, GP, and WDO, respectively. Figure 6 depicts the Huai Sai Kamin reservoir rule curve results.

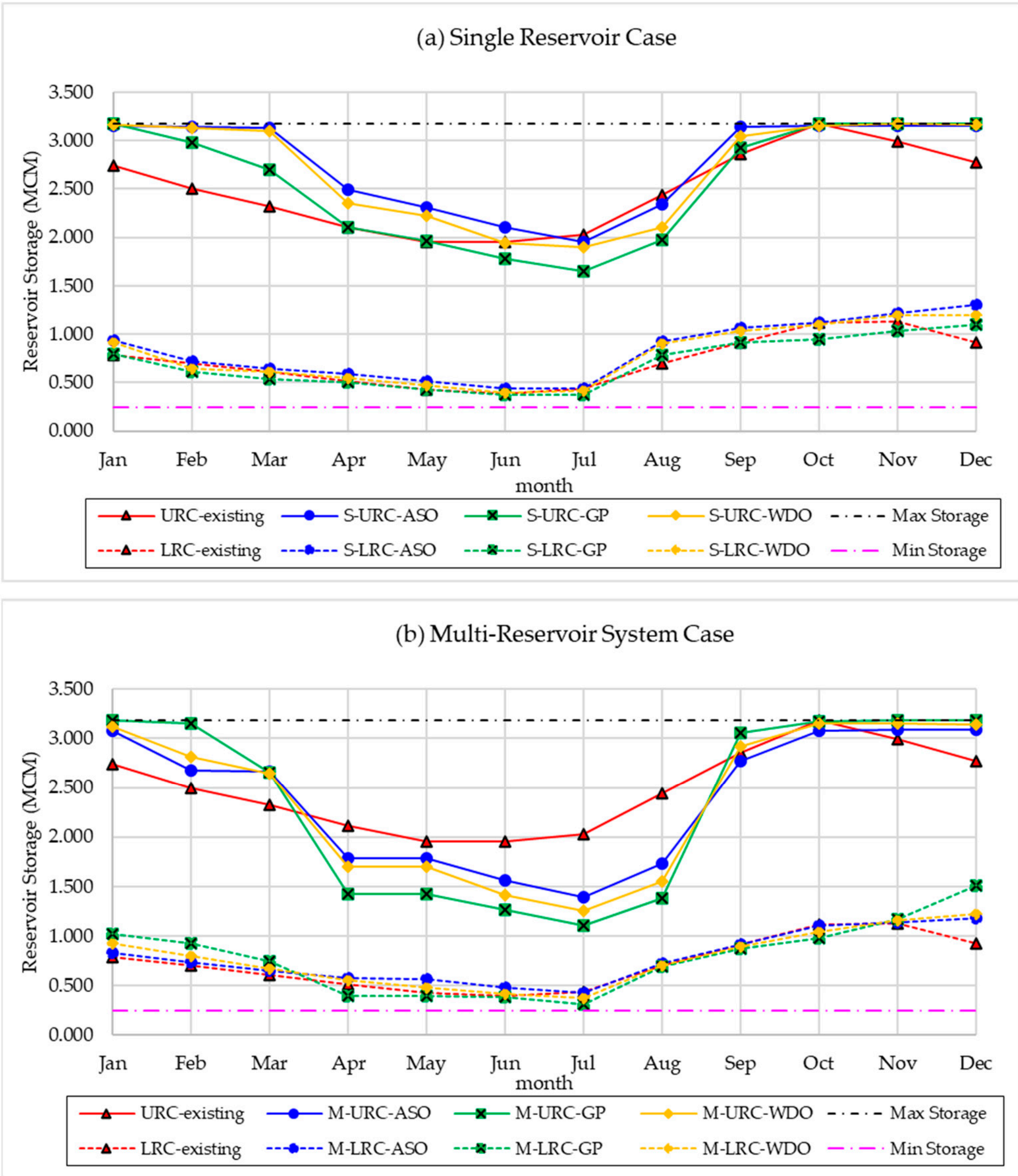

Figure 6. Optimal Reservoir Rule Curves of The Huai Sai Kamin Reservoir Obtained from ASO, GP, and WDO for Considerations (**a**) a Single Reservoir Case and (**b**) Multi-Reservoir System Case.

The proposed ASO model is another search optima technique, and the results were near optimality and were close to the results of the other search techniques based on the same condition according to the previous studies [40,41]. However, the efficiency of each technique has been investigated in many studies.

3.2. Assessment of the Amount of Inflow into the Huai Sai Kamin Reservoir Obtained from the Newly Obtained Rule Curves

Assessment of the amount of water flowing into the Huai Sai Kamin reservoir (downstream of the system) from the drainage of the Upper Huai Sai-1 reservoir, the Upper Huai Sai-2 reservoir, and the Upper Huai Sai-3 reservoir found that the amount of water discharged from using the rule curves of the water data in 2017, resulted in an overflow in the area of the Huai Sai Weir as shown in Figure 2. This is consistent with the actual situation in 2017 as shown in Table 3 and Figure 7. It can be seen that the RC-existing rule curves exceeded the stream capacity in August and September. The amount of water flowing through the Huai Sai Weir was 4.175 MCM/month (modeled) and 4.741 MCM/month (actual).

The S-RC-ASO (Single Reservoir rule curves created by ASO) rule curves exceeded stream capacity in August and September. The amount of water flowing through the Huai Sai Weir was 3.835 MCM/month (modeled) and 4.716 MCM/month (actual). The S-RC-GP (Single Reservoir rule curves created by GP) rule curve exceeded stream capacity in August and September. The amount of water flowing through the Huai Sai weir was 3.759 MCM/month (modeled) and 4.866 MCM/month (actual). The S-RC-WDO (Single Reservoir rule curves created by WDO) rule curves exceeded stream capacity in August and September. The amount of water flowing through the Huai Sai weir was 3.840 MCM/month (modeled) and 4.816 MCM/month (actual). The rule curves M-RC-ASO (Muti-Reservoir rule curves created by ASO) exceeded stream capacity in September. The amount of water flowing through the Huai Sai weir was 4.726 MCM/month. The rule curves M-RC-GP (Muti-Reservoir rule curves created by GP) exceeded the dam capacity in September. The amount of water flowing through the Huai Sai weir was 4.751 MCM/month and the rule curves M-RC-WDO (Muti-Reservoir rule curves created by WDO) exceeded the dam capacity in September. The amount of water flowing through the Huai Sai weir was 4.732 MCM/month.

Table 3. The Amount of Inflow into The Huai Sai Kamin Reservoir from Search Techniques with ASO, GP, and WDO between Single Reservoir Case and Multi-Reservoir System Case.

Rule Curves		Volume of Inflow through Huai Sai Weir (MCM/Month)											
		January	February	March	April	May	June	July	August	September	October	November	December
Single Reservoir	RC-Existing	0.000	0.000	0.392	0.626	0.959	1.962	2.668	4.175	4.741	1.342	0.559	0.223
	S-RC-ASO	0.005	0.004	0.238	0.383	0.585	1.862	2.806	3.835	4.716	1.332	0.509	0.135
	S-RC-GP	0.005	0.000	0.238	0.395	0.747	1.712	2.766	3.759	4.866	1.202	0.559	0.135
	S-RC-WDO	0.005	0.004	0.238	0.380	0.590	1.860	2.786	3.840	4.816	1.232	0.539	0.135
Multi Reservoir	M-RC-ASO	0.005	0.000	0.238	0.383	0.581	1.192	2.026	3.409	4.726	1.572	0.619	0.135
	M-RC-GP	0.005	0.000	0.238	0.395	0.581	1.192	2.066	3.445	4.751	1.512	0.579	0.135
	M-RC-WDO	0.005	0.000	0.238	0.385	0.581	1.162	2.03	3.412	4.732	1.552	0.609	0.135

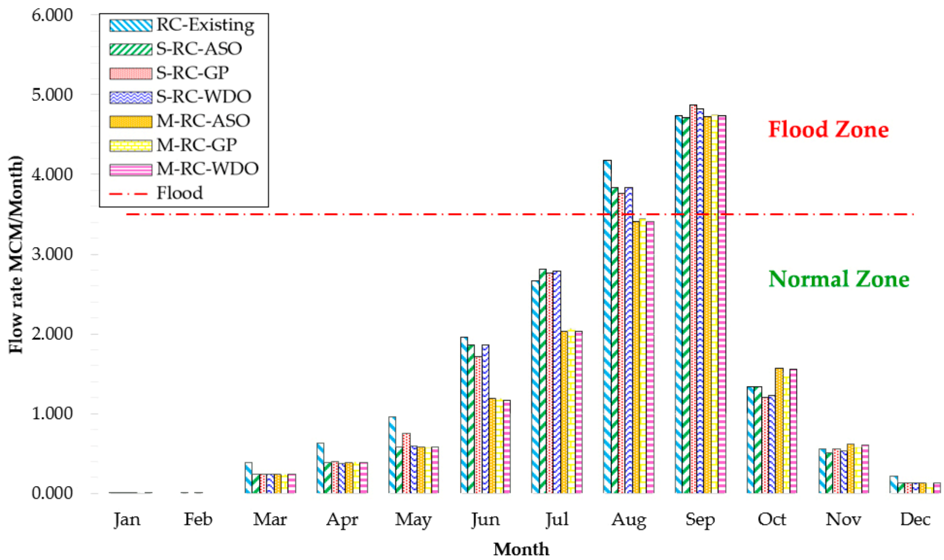

Figure 7. The Amount of Inflow into The Huai Sai Kamin Reservoir from Search Techniques with ASO, GP, and WDO between Single Reservoir Case and Multi-Reservoir System Case.

In summary, in situations of the total overflow flowing through the Huai Sai Weir using the M-RC-ASO, M-RC-GP, and M-RC-WDO rule curves, the reservoir network model was considered by the objective function of the minimum average overflow. The time interval and total overflow flowing through the Huai Sai weir can be reduced more than in the RC-existing rule curves and the rule curves considering single reservoir S-RC-ASO, S-RC-GP, and S-RC-WDO. They can reduce overflow times better than single reservoir considerations. It may be concluded that the ASO approach, like the GP and WDO procedures, is useful in finding networked reservoir rule curves.

3.3. Performance of Optimal Rule Curves in Monthly Historical and Synthetic Inflow Data across 1000 Incident Sets

The evaluation of the performance of the rule curves of the Huai Sai Kamin reservoir, which is the reservoir located downstream of the multi-reservoir system, was based on the development with ASO, GP, and WDO, both in the single reservoir case and the multi-reservoir system cases. The results of evaluating the efficiency of the rule curves in the case of using monthly historical inflow data are shown in Table 4. It was found that the efficiency of the rule curves of the Huai Sai Kamin reservoir, considered as a single reservoir using ASO (S-RC-ASO), GP (S-RC-GP) and WDO (S-RC-WDO), had average excess water of 45.602 MCM/year 45.562 MCM/year and 45.588 MCM/year, respectively, which is less than the RC-existing rule curve with average excess water of 45.788 MCM/year. The efficiency of the rule curves of the Huai Sai Kamin reservoir, which was considered a multi-reservoir system model using ASO (M-RC-ASO), GP (M-RC-GP), and WDO (S-RC-WDO), showed that the rule curves M-RC-ASO, M-RC-GP, and M-RC-WDO were found. The average excess water was 43.828 MCM/year, 43.722 MCM/year, and 43.822 MCM/year, respectively, which was less excess water than the original rule curves and the rule curves that were considered as a single reservoir with an average of 4.28–4.51%.

Table 4. Situations of Excess Release of The Huai Sai Kamin Reservoir Considering Monthly Historical Data between Single Reservoir Case and Multi-Reservoir System Case.

Criteria for Consideration	Rule Curves	Frequency	Magnitude of Excess Release Water (MCM/Year)		Duration (Year)	
		(Times/Year)	Average	Maximum	Average	Maximum
Single Reservoir	RC-existing	1	45.788	90.945	16	16
	S-RC-ASO	1	45.602	90.550	16	16
	S-RC-GP	1	45.562	90.408	16	16
	S-RC-WDO	1	45.588	90.502	16	16
Multi Reservoir	RC-existing	1	45.788	90.945	16	16
	M-RC-ASO	1	43.828	88.345	16	16
	M-RC-GP	1	43.722	88.794	16	16
	M-RC-WDO	1	43.822	88.455	16	16

The evaluation of the performance of the rule curves of the Huai Sai Kamin reservoir with monthly synthetic inflow data is presented in Table 5. It was found that the efficiency of the rule curves of the Huai Sai Kamin reservoir considered as a single reservoir using ASO (S-RC-ASO), GP (S-RC-GP), and WDO (S-RC-WDO) yielded results consistent with the assessment in Section 3.2. The S-RC-ASO, S-RC-GP, and S-RC-WDO rule curves had average excess water of 45.536 $\pm$ 3.869 MCM/year, 45.495 $\pm$ 3.868 MCM/year, and 45.533 $\pm$ 3.869 MCM/year, respectively, which were less than the RC-existing rule curves with an average overflow of 45.639 $\pm$ 3.769 MCM/year. Examining the efficiency of the rule curves of the Huai Sai Kamin reservoir considering the multi-reservoir system model, revealed that the rule curves M-RC-ASO, M-RC-GP, and M-RC-WDO also showed results consistent with the assessment in 3.2, i.e., the average excess water was 43.833 $\pm$ 3.697 MCM/year, 43.673$\pm$3.798 MCM/year, and 43.734 $\pm$ 3.705 MCM/year, respectively.

Table 5. Situations of Excess Release of The Huai Sai Kamin Reservoir Considering Monthly Synthetic Inflow between Single Reservoir Case and Multi-Reservoir System Case.

Criteria for Consideration	Rule Curves		Frequency	Magnitude of Excess Release Water (MCM/Year)		Duration (Year)	
			(Times/Year)	Average	Maximum	Average	Maximum
Single Reservoir	RC-existing	μ	1	45.639	75.388	16	16
		σ	0	3.769	10.006	0	0
	S-RC-ASO	μ	1	45.536	74.834	16	16
		σ	0	3.869	9.569	0	0
	S-RC-GP	μ	1	45.495	74.793	16	16
		σ	0	3.868	9.569	0	0
	S-RC-WDO	μ	1	45.533	74.828	16	16
		σ	0	3.869	9.569	0	0
Multi Reservoir	RC-existing	μ	1	45.639	75.388	16	16
		σ	0	3.769	10.006	0	0
	M-RC-ASO	μ	1	43.833	72.389	16	16
		σ	0	3.697	9.286	0	0
	M-RC-GP	μ	1	43.673	72.893	16	16
		σ	0	3.798	9.939	0	0
	M-RC-WDO	μ	1	43.734	72.445	16	16
		σ	0	3.705	9.546	0	0

μ, Mean; σ, standard deviation.

The M-RC-ASO, M-RC-GP, and M-RC-WDO rule curves derived from multi-reservoir system considerations had a good performance and are suitable for normal water events, according to these findings. The average overflow can be reduced more effectively than the active rule curves and the rule curves derived from a single reservoir consideration at present.

4. Conclusions

This study applied atom search optimization (ASO), genetic programming (GP), and wind-driven optimization (WDO) connecting with the reservoir simulation system and the minimal average excess water per year was used as the objective function for finding optimal rule curves of the multi-reservoir system. The optimal rule curves of the multi-reservoir system were searched when considering a single reservoir system and when considering the multi-reservoir system. The upper and lower rule curves of ASO were discovered to be similar to GP and WDO methods. The results showed that the rule curves considering the multi-reservoir system model can reduce the amount of water flowing into the last, downstream reservoir of the Huai Sai Kamin reservoir. As a result, the overflow of the water stream around the Huai Sai Weir from the overflow period of 2 months for the original rule curves and the rule curves considered as a multi-reservoir system remaining overflow period of 1 month only. It can reduce overflow times better than single reservoir considerations.

The efficiency of the rule curves of the multi-reservoir system was also evaluated. Efficiency was estimated using the average overflow from the Huai Sai Kamin Reservoir downstream of the multi-reservoir system. It was found that the rule curves of the multi-reservoir system were more effective in reducing the average overflow of the lowest reservoirs than those of the single reservoirs. In addition, the rule curves of the multi-reservoir system can control the overall drainage of the upper reservoir with effects that exceed the capacity of the downstream reservoir. It can reduce overflow times better than considering single reservoirs.

However, there are also constructions for water management, such as the water gate, that work as a network in the basin as well as the reservoir network, and which are used to control water in the river for drought and flood management. There is a relationship between the drain water of the upstream gate to the drainage rate of the downstream water gate. The optimization technic is therefore another interesting approach to apply in river management in the future.

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