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Improvement of Optimal Multi-Purpose Reservoir Operations by Atom Search Optimization Technique: A Case Study of Nong Han Kumphawapi Reservoir

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A B S T R A C T

The research objective is to develop a decision support system for finding the optimal rule curve of a reservoir using an optimization technique model, in conjunction with the Hedging rule (HR) and Standard operating policy (SOP) criteria, and to evaluate the performance of the resulting rule curve. The monthly inflow data of the reservoir from 1,000 synthetic historical data sets, presented in the form of frequency, event timing, average water quantity, and maximum water quantity, both in water shortage and overflow situations, are used. These data are then used to create a set of solutions for three different situations: low water quantity, high water quantity, and average water quantity situation. The study area is the Nong Han Kumphawapi Reservoir in Udon Thani Province, which is a multipurpose reservoir with the objectives of water allocation for domestic water supply, ecosystem conservation (red water lily sea), agriculture, and industry. The research results found that the rule curve of the reservoir developed using optimization techniques with Genetic Algorithm (GA) and Atom Search Optimization (ASO) methods shows similar URC and LRC curve characteristics. From the evaluation of the performance of the rule curve obtained from the model, in alternative 1, for a high-water year (80 percentile), the rule curve considering HR discharge using GA technique is the most efficient, with only 302.644 million cubic meters of excess water discharged. In alternative 2, for an average water year, the rule curve considering HR discharge using both GA and ASO techniques is the most efficient, with the GA technique avoiding water shortages and resulting in 180.965 million cubic meters of excess water. In alternative 3, for a water shortage year (20 percentile), the rule curve considering HR discharge using GA and ASO techniques is the most efficient, by reducing water shortages in the case of a low water year to 4 million cubic meters per year.

1. INTRODUCTION

Water resource development using large-scale construction is currently in a downward trend, which is mainly due to the need for large operating budgets and environmental impact factors or land acquisition [1,2]. As a result, there must be a need to change the management guidelines of the existing water resources development plan to be more efficient by using methods that do not use construction [3] What can be done immediately is reservoir management, which involves planning and managing the reservoir to achieve its objectives, including considering the amount of water flowing through the reservoir to be balanced with the demand for water at the end of the reservoir [4] The main problem of reservoir management is how to ensure that the amount of available water can satisfactorily and sustainably meet the water demand at various times to prevent flooding or water shortages. From the definition of water shortage, it is when the amount of water released for use according to demand is less than the amount of water required, which makes it difficult to always release water according to the demand for water at the end of the reservoir. This is because the amount of water remaining in the reservoir at different times is not the same [5]. This problem causes gaps in reservoir management in actual operations. Therefore, a water release plan must be devised in order to provide maximum benefit to water users at the back of the reservoir and to prevent impacts from water quantity problems as much as possible.

One of the non-construction reservoir management methods that have come into play and are very useful in the current era is decision support systems [6, 7]. This will be a system that is an integration between technology and data management to create a system to help explain the problem. The results that will occur in an event or situation and the decision to choose a course of action [8-10]. It is a system suitable for problems with uncertain structure or semi-structured problems [11]. The water resource system is a complex system, especially for the management of multi-purpose reservoirs or multi-purpose reservoirs where various factors and relationships must be considered. Therefore, this decision support system is an appropriate aid for application in water allocation of multi-purpose reservoirs [12-17].

In reservoir management, it is directly related to reservoir operations, which means storing water in the reservoir and delivering water from the reservoir for various purposes, such as consumption needs, irrigation, industry, transportation, tourism and ecological preservation. Therefore, reservoir management is of great importance and one important and necessary tool is the reservoir operating rule curve, which is obtained by calculating statistical data. Such operational rule curves consist of at least two lines: the Upper Rule Curve (URC) and the Lower Rule Curve (LRC) [18]. Reservoir management will ensure that the average water volume is between the two lines and will not let the water volume be lower than the lowest storage threshold line. The two rule curves are only the upper and lower limits of the reservoir water level control range. It will try to control the water level in the reservoir as close to the upper and lower limits as possible in the rainy and dry seasons. In preparing the reservoir operating curve of most reservoirs, both system simulation techniques and optimization techniques are used in developing such tools. However, methods for creating a reservoir operating criteria curve that rely on knowledge and simple development concepts include the Probability Based Rule Curve and the Minimum Vacancy Storage Requirement Rule Curve. Reservoir operations are therefore considered an important part and must be developed in the project planning stage. After that, it will be gradually adjusted to be consistent with the actual situation.

Optimization techniques include linear programming, nonlinear programming, and dynamic programming. It is a popular technique used in solving problems in water resources engineering. This is especially true in reservoir operations, where it is necessary to know the best water release strategy at different times in order to best meet project objectives under complex system constraints. The technique of finding the best value can be applied to find the appropriate operating curve of the reservoir. Techniques for finding the optimum value have been widely applied, such as genetic algorithm, Flower Pollination Algorithm, Tabu search, Honey-Bee Mating Optimization, Harris Hawks Optimization [6, 19]. The application of those techniques to the problem of interest. The answer values will be similar. However, if new techniques are invented that can be used conveniently and provide answers that are similar to other techniques that have been used before [20]. It is considered an interesting technique that will be applied further [3, 21].

Therefore, in this research, the researcher aims to create a decision support system for finding the most appropriate reservoir operating curve for the management of Nong Han Kumphawapi Reservoir, Udon Thani Province. It is a multi-purpose reservoir and an important source of water resources in Udon Thani Province. The objective is to allocate water for consumption, ecosystem preservation, agriculture, and industry.

2. MATERIALS AND METHODS

Decision support system for finding the most suitable reservoir operating curve. By applying an optimization technique that determines the objective function of the minimum water shortage mean, minimum water shortage frequency, to find the most suitable reservoir operating curve. Reservoir operating curves can be used to manage multipurpose reservoirs adequately to meet water demand [19, 22]. This is an efficient way to manage reservoirs without using buildings.

2.1 Study area

The Nong Han Kumphawapi Reservoir study area is located in Udon Thani Province, in the Chi River Basin. There is a catchment area above the basin of 1,486 square kilometers (Figure 1). There is an average annual rainfall that falls in the catchment area of 1,300 mm. It has a storage capacity of 102 million cubic meters (MCM). The average amount of water flowing into the reservoir is 638 MCM/year. Allocation of water from reservoirs for irrigation purposes. Flood control, consumption, and preserving the ecosystem around the reservoir and Lam Pao River. Figure 2 provides a schematic illustration of the reservoir, highlighting its role in supporting downstream water demands. These demands include electricity generation, irrigation, flood control, industrial needs, domestic water supply, and environmental conservation.

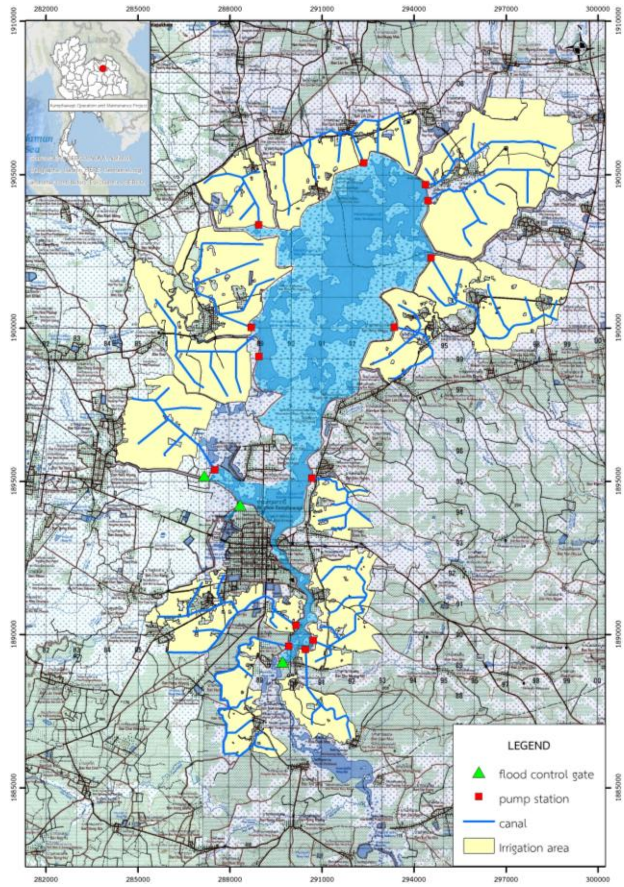


Fig. 1. The location of Nong Han Kumphawapi reservoir.

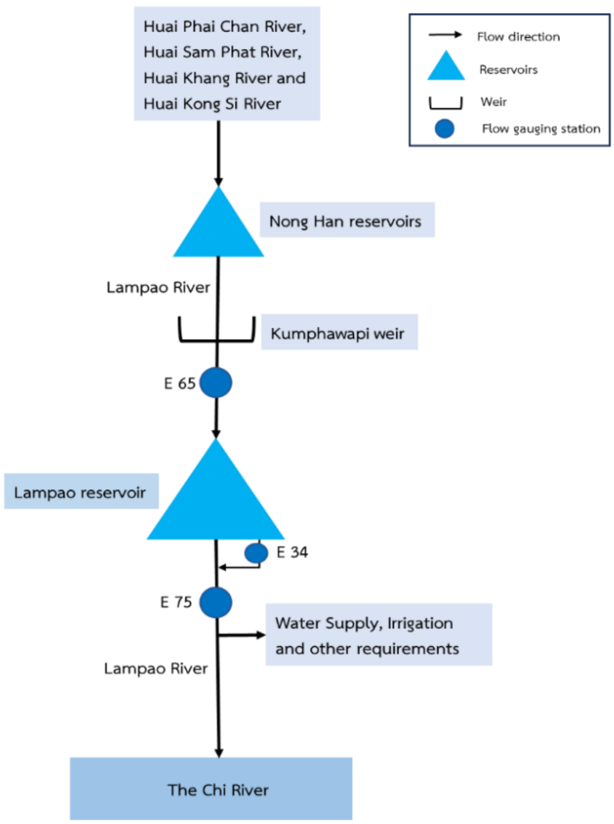


Fig. 2. Schematic diagram of the Nong Han-Kumphawapi reservoir.

2.2 Optimization Technique

The atom search optimization method (ASO) was first proposed by Weiguo Zhao and colleagues in 2018 using the atomic force motion model in molecular dynamics [23]. ASO is classified as inspired by the physics of particle swarm algorithms, which require fewer parameters and are capable of global optimization [24].

Genetic Algorithm (GA) is a method of finding the appropriate answer using the principles of natural selection from simulating the concept of evolution of living things [25]. The genetic algorithm can be summarized in 5 steps: creating a prototype population; genetic processes; Calculating the suitability value; Selection and verification of stopping conditions. The key steps in genetic methods are selection of populations suitable to survive in the next generation and chromosome editing, which is carried out by crossover and mutation processes.

The modelling steps include a simulation model of a reservoir system and optimization techniques using atomic search and genetic algorithms by applying both methods together to find the most appropriate rule curve [26]. The details can be explained as follows.

2.3 Model for Simulating Reservoir Equilibrium Conditions

Reservoir systems generally consist of runoff flowing into a reservoir with either a single-purpose or multi-purpose reservoir covering a watershed area. Reservoirs are normally operated under standard water release criteria, and monthly reservoir rule curves for long-term operations have been found to be the most used reservoir rule curve solutions for reservoir operations [27]. The reservoir system simulation model was created based on the water balance concept and can be used to effectively simulate the operation of the reservoir as well as the Nong Han Kumphawapi Reservoir. The reservoir operation policy is based on the monthly rule curve of the reservoir and the principle of the water balance equation under the reservoir model. The reservoir system operates according to the policy under standard water release criteria as shown in Equation (1) and Figure 3 and Hedging Rules water release criteria as shown in Equation (2) and Figure 4:

$$R_{\upsilon,\tau} = \begin{cases} D_\tau + W_{\upsilon,\tau} - y_\tau, \text{ for } W_{\upsilon,\tau} \geq y_\tau + D_\tau \\ D_\tau, \text{ for } x_\tau \leq W_{\upsilon,\tau} < y_\tau + D_\tau \\ D_\tau + W_{\upsilon,\tau} - x_\tau, \text{ for } x_\tau - D_\tau \leq W_{\upsilon,\tau} < x_\tau \\ 0, \text{ otherwise.} \end{cases} \quad (1)$$

where $R_{\upsilon,\tau}$ is the amount of water released from the reservoir (MCM) during the year υ of month τ (τ = 1 to 12, representing January to December); D_τ is the demand for water at the end of the reservoir for the month τ (MCM); x_τ is the lower bound of the rule curve of the month τ; y_τ is the upper bound of the rule curve of the month τ; and $W_{\upsilon,\tau}$ is the available cost water volume of the basin in month τ (MCM).

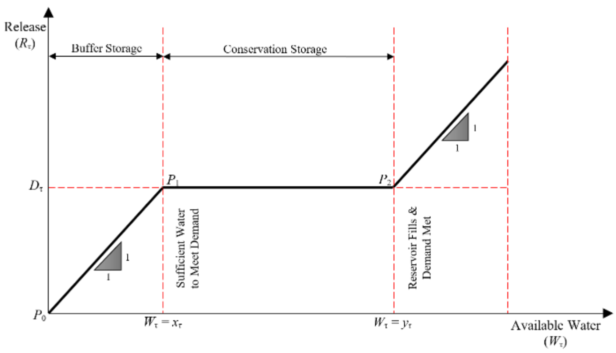


Fig. 3. Criteria for Releasing Water According to Standard Rules.

$$R_{\upsilon,\tau} = \begin{cases} WA_\tau & \text{if } WA_\tau < SWA_\tau \\ D_\tau + (SWA_\tau - D_\tau)\dfrac{WA_\tau - EWA_\tau}{SWAt_\tau - EWA_\tau} & \text{if } SWA_\tau \leq WA_\tau \leq EWA_\tau \\ D_\tau & \text{if } EWA_\tau \leq WA_\tau < D_\tau \\ WA_\tau & \text{if } WA_\tau \geq D_\tau \\ 0, \text{ otherwise.} \end{cases} \quad (2)$$

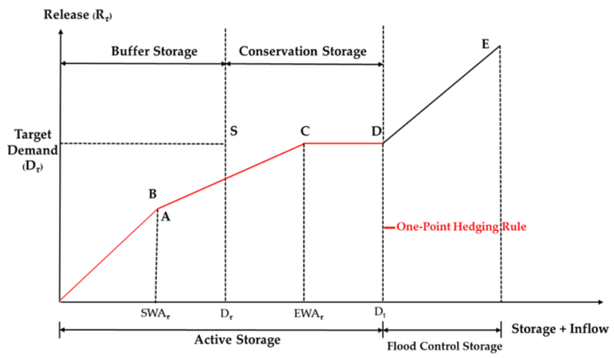


Fig. 4. Criteria for Releasing Water According to Hedging Rules.

where SWA_τ is the initial water volume of the total reservoir at time τ ; EWA_τ is the end of water volume of the total reservoir at time τ ; D_τ is the water demand for the water distribution system at time τ. Then calculate the available water budget of the reservoir for the next month using the following water balance equation (3):

$$W_{\upsilon,\tau+1} = S_{\upsilon,\tau} + Q_{\upsilon,\tau} - R_{\upsilon,\tau} - E_\tau - DS \quad (3)$$

where $S_{\upsilon,\tau}$ is the reservoir's water storage volume at the end of the month τ (MCM); $Q_{\upsilon,\tau}$ is the monthly runoff volume flowing into the basin; E_τ is the monthly average evaporation value; and DS (Dead Storage) is the unused storage volume (MCM).

In Equation (1), if the amount of water budget is between the upper and lower rule curves, water can be released according to the demand for water at the end of the reservoir but must not be released to the lowest storage level. If the available cost of water in the reservoir beyond the upper rule curve is greater than the water demand at the end of the reservoir, water will be released from the reservoir up to the level of the upper rule curve. When the amount of available cost water of the reservoir beyond the upper rule curve is less than or equal to the demand for water at the end of the reservoir, water can be released according to the demand for water at the end of the reservoir. If the available cost water quantity of the reservoir is lower than the lower rule curve, water shall be released only as needed. But the release must not reach the lowest storage level and if the water level drops to the lowest storage level, no water will be released from the reservoir ($W_{\upsilon,\tau}$) to reduce the risk of water shortages in the future, when $0 \le W_{\upsilon,\tau} < x_\tau - D_\tau$ under long-term operation.

After performing all monthly inflow periods considering the total monthly reservoir drainage (R_τ monthly reservoir drainage), it is used to calculate the objective function in the search step. The results of each objective function are recorded and used in the ASO model until the stopping criteria are met and an appropriate reservoir rule curve is obtained as described. The details of each objective function are described in the next section.

Calculating the rule curve values from the ASO and GA technique models by defining the objective function of the work, the number of work cycles, creating the initial population by creating a set of initial answers is to select the rule curve values for each month both 12 months, 24 values, create the initial rule curve values. After that create a set of possible close answers. Select the closest answer set. Condition Check: Determine the desire criteria by specifying the conditions for considering the set of neighbouring solutions and checking the duty cycle. Then use the obtained rule curve values to carry out reservoir operations and calculate the amount of water that must be released each month under this set of rule curves in order to evaluate the water shortage situation according to the objective function of searching for answers. This study uses the average of the least water shortage (H) in Equation (4) and the least average water overflow (P) in Equation (5) as the objective function of finding the answer in the case of using normal water, shown in the equation (4) and (5)

$$\text{Fitness} = \text{Min}\, H_{(avr)} = \frac{1}{n}\sum_{v=1}^{n} Sh_v \quad (4)$$

$$\text{Fitness} = \text{Min}\, P_{(avr)} = \frac{1}{n}\sum_{v=1}^{n} Sp_v \quad (5)$$

where n is the length of the water budget data set, Sh_v is the amount of water lacking in year v (the amount of water released is less than the water demand), Sp_v is the amount of excess water released in year v (the amount of water released is greater than the water demand) and i is the number of iterations.

The study uses an optimization technique combined with a reservoir simulation model to find the most appropriate rule curve developed using MATLAB programming. Then, the rule curve of the appropriate reservoir operating basin obtained from the model will be used in long-term reservoir operation with the water flowing into the reservoir using 1,000 sets of synthesized data. Using the HEC-4 model, it covers events that are expected to occur as well as past events that have occurred in the past. In order to simulate the rule curve condition of the reservoir in the long term as well. Then carry out a reservoir operating simulation to study the behaviour of the system from the rules of management and control, and then calculate the amount of water that must be released each month under the curve of the reservoir operating criteria. It is displayed as water shortage and overflow situations (frequency, magnitude, duration) and compared with existing law curves and between the ASO model, GA model, and reservoir model under the same conditions. Moreover, the new rule curve can be evaluated in other situations, such as increasing irrigation area. In order to predict how it will affect future operations.

Please use only drawings and photographs of excellent quality. It is especially important that all numbers and characters appearing in your figures are of good quality and well-readable size (≈ 8–10 pt), i.e. approximately of the same size as your text. Figure axis labels are often a source of confusion. Axes labels must be clearly denoted.

3. RESULTS AND DISCUSSION

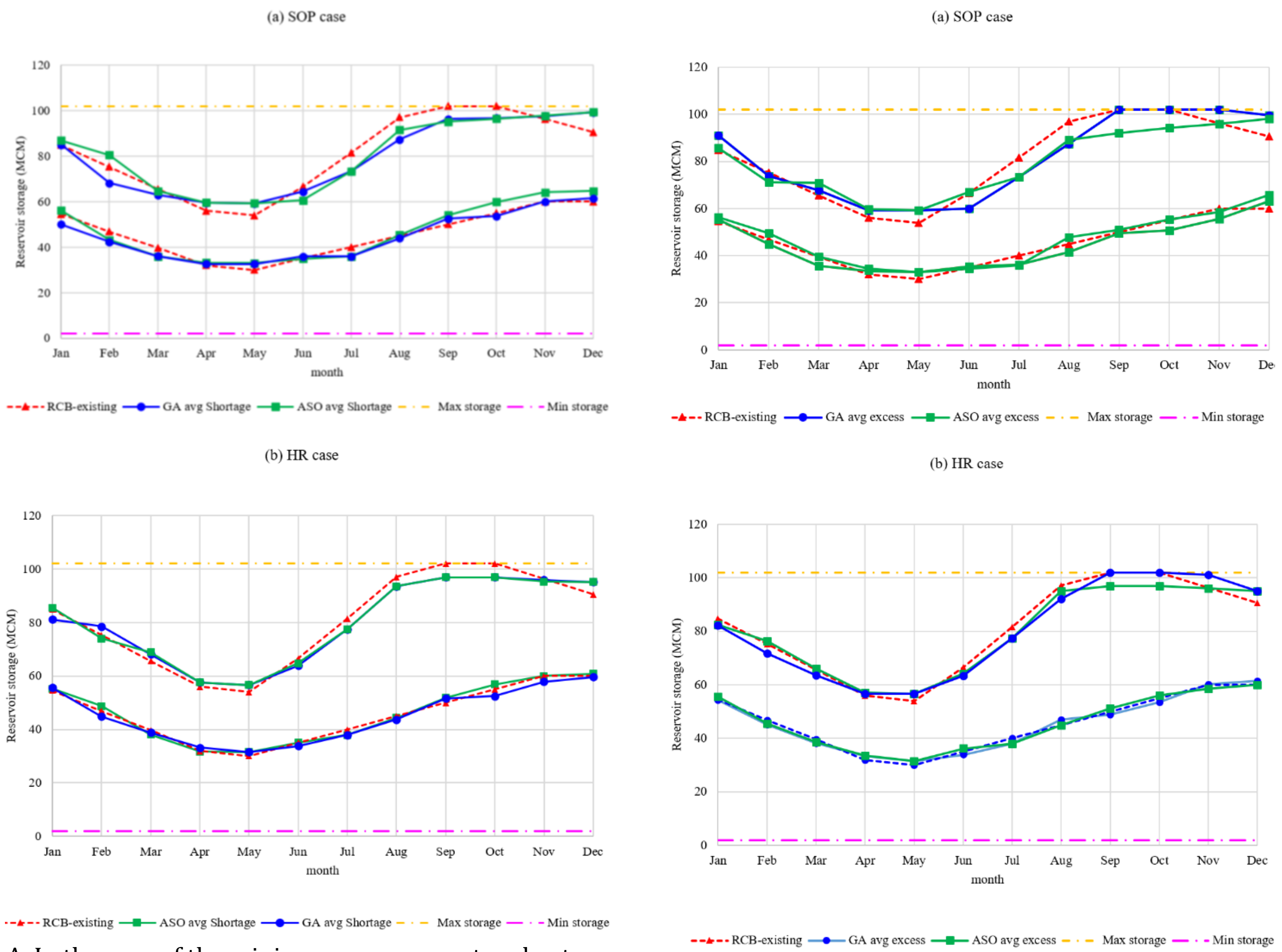
The model's optimal control curve obtained by processing historical data includes reservoir flow data, evaporation data, water demand data and monthly rainfall data. The control curve of the ASO model is compared with the control curve of the GA model, and the existing rule curve shows the results of the control curve pattern obtained from ASO, GA and existing rule curve are similar. But the upper bounds of ASO and GA are lower than the existing rule curve at the beginning of the rainy season (June-August) in order to release more water to increase the volume of water storage for flood protection. Meanwhile, during October-November, the upper bounds of ASO and GA are higher than the existing rule curve due to the reduced overflow volume. Therefore, we began to store water to fill the reservoir at the end of the rainy season, which will help alleviate water shortage problems next year. The form of the control curve obtained in the study is similar to that of other reservoirs in Thailand and in other studies due to similar seasons [28-33].

The proposed ASO and GA models are another optimal search technique, so the results are similar to the optimal search techniques of other search techniques under the same conditions. However, many researchers have studied the effectiveness of each of the techniques mentioned in the introduction.

The performance evaluation results of the new reservoir operating curve based on monthly synthetic data of 1000 event sets in water shortage situations are shown in Table 1. The results show that in the water shortage situation, the average water shortage frequency of the HR water release criteria with ASO and GA techniques has the best values of 0.964 and 0.963 times per year, respectively, which is less than the existing rule curve, which has a value of 0.999 times /year. The average water shortage of SOP water release criteria using ASO and GA techniques has the best values of 10.578 and 10.627 MCM/year, respectively, which is less than the existing rule curve, which has a value of 13.348 MCM/year. In the excess water situation, it is shown in Table 2. The results show that in the excess water situation, the average frequency of overflow of SOP water release criteria with ASO and GA techniques has the best values equal to 0.995 and 0.995 times/year, respectively. Which is less than the existing rule curve which is equal to 0.996 times/year. The average overflow volume of the SOP water release criteria using the GA technique has the best value equal to 258.722 MCM/year, respectively, which is lower than the existing rule curve which is equal to 268.414 MCM/year.

The results of evaluating the efficiency of ASO's reservoir operating curves are based on the frequency and average water shortage volume. The value is similar to GA, but slightly higher than GA and lower than the value obtained from the existing rule curve, which means the rule curve obtained from the optimization model performs better than the existing rule curve.

The results of the alternative analysis of the decision support system in alternative 1 in the case of a high-water year (80 percentile) Rule curve that considers HR water release using the GA technique has the best efficiency, being able to drain excess water to only 302.644 MCM. Alternative 2, in the case of the average water year, rule curve that considers HR water release using the GA technique and considers HR water release using the ASO technique has the best efficiency without causing water shortages and having excess drainage water of 180.965 MCM for rule curve that considers HR water release using GA techniques. Alternative 3, in the case of low water years (20 percentile), Rule curve that considers HR water release using GA technique and HR water release using ASO technique has the best efficiency. It can reduce water shortages in low water years to 4 MCM/year.



A. In the case of the minimum average water shortage objective function

B. In the case of the minimum average excess water objective function

Figure 5. Rule curve from the case of using water release criteria using standard operating rules and hedging rules.

Table 1. Rule curve efficiency evaluation results in water shortage situation.

Drainage criteria	Rule curve	Frequency (Times/year)	Volume (MCM/year)		Time period (year)	
			Average	Maximum	Average	Maximum
	Existing	0.999442	13.34849	24.116	15.991	15.991
SOP	SOP GA Average shortage	0.997768	10.62668	22.741	15.724	15.840
	SOP ASO Average shortage	0.998450	10.57774	22.647	15.855	15.916
HR	HR GA Average shortage	0.963291	11.33031	23.543	15.350	15.386
	HR ASO Average shortage	0.963542	11.72093	23.878	15.368	15.393

Table 2. Rule curve efficiency evaluation results in excess water situation.

Drainage criteria	Rule curve	Frequency (Times/year)	Volume (MCM/year)		Time period (year)	
			Average	Maximum	Average	Maximum
	Existing	0.996290	0.996290	268.414	634.742	15.304
SOP	SOP GA Average excess	0.995037	0.995037	258.722	624.736	15.397
	SOP ASO Average excess	0.995097	0.995097	263.180	629.721	15.399
HR	HR GA Average excess	0.995223	0.995223	260.552	634.331	15.423
	HR ASO Average excess	0.995471	0.995471	265.231	639.274	15.449

4. CONCLUSION

Improving the operating curve of a reservoir from a model of the optimization technique can be developed as an alternative to support a multi-purpose reservoir water management decision system. This is another option that can be used in reservoir management decisions. Results of improving the operating curve of the reservoir from the model, techniques for finding the most appropriate value and evaluating the efficiency of the operating curve of the reservoir obtained from the model. The rule curve that considers the hedging rule water release criterion is more effective than the standard water release criterion (SOP). Therefore, there are 3 different situations to choose from: the situation of a low water year; The high-water year situation and the average water year situation were found to be the best choice in decision making with 3 water situations for reservoir management with 5 choices out of 16 alternatives, most of which are from the rule curves caused by HR water release criteria, which alleviates water shortage and water overflow situations well, both in SOP and HR water release criteria. However, there are other forms of reservoir management decision support systems that can be applied in conjunction with the decision support systems from this research, such as using artificial intelligence (AI) systems to predict the amount of water flowing into the reservoir and forecasting water demand, etc.

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