



OPTIMIZATION OF WATER INFRASTRUCTURE SYSTEMS: INTEGRATING INVASIVE WEED ALGORITHMS WITH RESERVOIR SIMULATION MODELS

Anongrit Kangrang¹, *Anujit Phumiphan², Pinmanee Promaruk³, Rapeepat Techarungruengsakul⁴ and Nonthaphong Phonphuak⁵

^{1,4} Faculty of Engineering, Mahasarakham University, Mahasarakham, Thailand; ² School of Engineering, University of Phayao, Phayao, Thailand; ³ Water Management and Maintenance Division, Regional Irrigation Office 7, Ubonratchathani, Thailand; ⁵ Faculty of Engineering, Rajabhat Mahasarakham University, Mahasarakham, Thailand.

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ABSTRACT: Effective reservoir management is critical for maximizing the sustainable utilization of water resources. This study presents an innovative approach to improving reservoir operations by integrating the Invasive Weed Optimization (IWO) algorithm with a reservoir simulation model. The Phuttha Utthayan Reservoir in Amnat Charoen Province, Thailand, was selected as the case study, given its significance for agricultural irrigation, municipal water supply, and flood control in the region. The study focuses on developing optimized reservoir rule curves to address the challenges of fluctuating inflows and competing water demands. Using a synthetic dataset comprising 500 samples of inflow scenarios, the proposed IWO-based rule curves were evaluated against traditional control curves. Performance metrics, including water shortage frequency, overflow volume, and the duration of reservoir releases, were analyzed. The results demonstrate that the IWO algorithm outperforms conventional methods by significantly reducing water shortages and overflow events. This improvement highlights the efficacy of advanced optimization techniques in enhancing the operational efficiency of reservoirs. The findings underscore the potential of adopting IWO-derived rule curves to better adapt to dynamic water management needs and to support long-term sustainable water resource strategies.

Keywords: Reservoir Operations, Invasive Weed Optimization Algorithms, Genetic Algorithms, Water Infrastructure, Simulation Models

1. INTRODUCTION

Water is one of the most critical natural resources supporting human societies, ecosystems, and economies. Effective management of water resources has become increasingly important due to the imbalance between supply and demand driven by population growth, rapid urbanization, climate change, and intensified agriculture. Among the infrastructures developed for water management, reservoirs play a fundamental role in storing, regulating, and distributing water to meet diverse objectives, including municipal supply, irrigation, hydropower generation, industry, navigation, flood control, and ecosystem conservation [1-8]. The ability of reservoirs to perform these functions depends heavily on efficient operating strategies, especially in regions with highly variable inflows and uncertain hydrological conditions [9].

Reservoir operations are often guided by rule curves, which specify storage levels or release decisions under different conditions throughout the year. Traditional rule curves, developed from

historical inflows and long-term averages, are straightforward to implement but limited in addressing the nonstationary nature of hydrological processes influenced by climate variability and extreme events [10]. Prolonged droughts, sudden heavy rainfall, and seasonal shifts often render conventional rule curves suboptimal, resulting in shortages during dry seasons or excess releases during wet periods. These challenges underscore the need for advanced and adaptive methodologies capable of managing dynamic and uncertain inflows.

In recent decades, optimization techniques have emerged as promising tools for reservoir operation. Classical approaches often struggle with nonlinear, multiobjective, and stochastic system characteristics. Consequently, researchers have turned to metaheuristic algorithms, which mimic natural processes to search for near-optimal solutions in complex problem spaces. Algorithms such as Genetic Algorithms (GA), Particle Swarm Optimization (PSO), Differential Evolution (DE), and Simulated Annealing (SA) [11-12] have been applied to improve water supply reliability and mitigate flood risks. However,

each method has limitations: GA is prone to premature convergence, while PSO may converge quickly but risks losing diversity in high-dimensional problems [13].

Among the newer approaches, Invasive Weed Optimization (IWO) has emerged as a particularly promising algorithm. Inspired by the colonization behavior of weeds in nature, IWO combines the concepts of reproduction, spatial dispersal, and competitive exclusion to explore and exploit the search space effectively. The algorithm is characterized by its adaptability, robustness, and capacity to handle nonlinear, discontinuous, and multimodal functions. Several studies have highlighted IWO's superior performance compared to traditional metaheuristics in fields ranging from engineering design and scheduling to energy systems and environmental management. Despite its growing recognition, its application to reservoir operation remains relatively limited. This gap presents an opportunity to explore the potential of IWO in developing more efficient and adaptive rule curves that can enhance the performance of reservoir systems under uncertain hydrological conditions.

In Thailand, water resources management is vital due to the country's reliance on agriculture and its exposure to floods and droughts. Reservoirs play a key role in supporting irrigation, domestic use, and industry. Climate variability, however, has increased operational challenges. The Phuttha Utthayan Reservoir in Amnat Charoen Province illustrates these issues as it supports irrigation, municipal supply, and ecosystem needs. Like many medium-sized reservoirs, it struggles to balance reliable water supply with flood control. Traditional, non-adaptive rule curves often lead to shortages during dry periods or excessive releases during heavy rainfall, highlighting the need for more innovative management strategies.

Although past studies have used various optimization methods to improve reservoir rule curves, research specifically assessing the potential of IWO—especially for Thai reservoirs—remains limited. Most previous work has centered on GA or PSO, which, while effective, may not fully utilize IWO's stochastic search and its balance of exploration and exploitation. Additionally, many studies rely on limited historical inflow data, which may not capture long-term hydrological variability and can lead to underestimation of associated risks.

"The present study addresses these gaps by integrating the IWO algorithm with a reservoir simulation model to develop optimized rule curves for the Phuttha Utthayan Reservoir. A key originality of this work is its use of 500 synthetic inflow samples,

enabling a more comprehensive representation of hydrological variability and extreme events. This dataset provides a robust basis for evaluating the performance of IWO-based rule curves under diverse conditions, ranging from severe droughts to extreme floods. Through this approach, the study not only advances a novel application of IWO in reservoir operation but also offers methodological insights that may be applicable to other reservoirs in Thailand and elsewhere.

The contributions of this research are threefold. First, it advances the application of IWO in water resource management, demonstrating its effectiveness in generating operational rule curves. Second, it employs long-term synthetic inflow data, enhancing the robustness of performance evaluations compared with studies relying solely on historical records. Third, it offers practical insights for water managers and policymakers by providing a decision-support tool that strengthens reservoir resilience against growing hydrological uncertainty. The findings contribute to global discussions on sustainable water resource management by showcasing the potential of innovative optimization methods in addressing real-world challenges.

In summary, reservoirs are central to water security, yet traditional rule curves are increasingly inadequate in the face of climate variability and rising demands. Optimization algorithms—and particularly IWO—offer promising solutions. By applying IWO to the Phuttha Utthayan Reservoir with century-long synthetic inflow data, this study addresses key research gaps and contributes both methodological advances and practical tools for reservoir management under uncertainty.

2. RESEARCH SIGNIFICANCE

This research is significant as it introduces an innovative integration of the Invasive Weed Optimization (IWO) algorithm with reservoir simulation models to enhance water infrastructure management. By applying the method to the Phuttha Utthayan Reservoir in northeastern Thailand, the study demonstrates substantial improvements in balancing water allocation, flood control, and drought mitigation compared to conventional rule curves. The findings provide evidence that advanced optimization techniques can minimize water shortages and overflow risks, thereby promoting sustainable water resource utilization. This contribution is valuable for advancing computational approaches in hydrological engineering and supporting long-term water security strategies.

3. MATERIALS AND METHODS

This study focuses on the Phuttha Utthayan Reservoir, situated in Mueang District, Amnat Charoen Province, northeastern Thailand. The reservoir plays a crucial role in local water management and is characterized by the following features.

The reservoir encompasses a project area of 25.6 square kilometers, with an irrigation coverage of 23.38 square kilometers. Its water release mechanism is a box spillway with an ogee weir, designed with a crest length of 43.00 meters and a maximum discharge capacity of 69 cubic meters per second. The emergency spillway is positioned at a crest level of 175.61 meters above mean sea level (AMSL). The reservoir's normal water storage level is 174.11 meters AMSL, while the minimum operational water level is 153.41 meters AMSL. It has a usable storage volume of 14.558 million cubic meters and a minimum volume of 781,750 cubic meters. The reservoir reaches its maximum storage level at 174.61 meters AMSL, accommodating a total capacity of 21.94 million cubic meters. The intake structure, set at 168.11 meters AMSL, corresponds to a storage capacity of 19.32 million cubic meters. Annual inflow into the reservoir averages 27.861 million cubic meters. Geographically, the reservoir spans an area of 5.261 square kilometers, supported by a catchment area of 62 square kilometers. The region experiences an average annual rainfall of 1,486.4 millimeters.

For this study, a reservoir operation model was developed based on the principles of water balance. The model operates under the framework of a standard operating policy (SOP), which is described as follows:

The model integrates various water inflow sources, including rainfall, river inflows, and contributions from other streams, ensuring comprehensive consideration of water entering the reservoir system [14-19].

3.1 Water Outflow Components

The model accounts for all key outflow components, including evaporation, seepage, and various demands (irrigation, domestic/industrial, environmental). This ensures operations are managed holistically, balancing water availability with these competing demands.

Evaporation losses were estimated using the Pan Evaporation method. Monthly pan evaporation data was obtained from the nearest meteorological station (Data from the Royal Irrigation Department and the Thai Meteorological Department). A

standard pan coefficient was applied to this data to estimate the actual open-water evaporation from the reservoir's surface area.

3.2 Storage Dynamics

To maintain equilibrium, the model simulates changes in reservoir storage by balancing inflow and outflow components, thus ensuring the sustainable operation of the reservoir.

3.3 Standard Operating Policy (SOP)

The SOP provides specific guidelines for water storage and release, including:

Upper Rule Curve (URC): Defines the maximum permissible water level in the reservoir to mitigate the risk of flooding [20].

Lower Rule Curve (LRC): Specifies the minimum water level necessary to sustain critical needs, such as irrigation and domestic usage, during dry periods [21].

3.4 Seasonal Adaptations

The model incorporates adjustments for seasonal variations in water availability and demand, enabling optimization of water storage and release throughout the year.

3.5 Data Generation

To assess rule curve robustness, 500 sets of 13-year synthetic inflow data were generated, reflecting the 2011–2024 historical period. A first-order Markov model preserved monthly serial correlation, while inflow magnitudes were drawn from a Lognormal distribution parameterized with statistics from the 13-year record. This stochastic approach maintains essential historical characteristics but does not account for nonstationary trends or potential impacts of climate change.

For a standardized comparison, each of the 500 simulation runs was initialized with the reservoir at its normal water storage level (174.11 meters AMSL).

3.6 Model for the Simulation of Reservoir Operation

The reservoir system was modeled using the water balance principle, requiring hydrological data, reservoir characteristics, water demand information, and related inputs. Available water resources were quantified using Equation (1) based on this principle. Monthly discharge evaluation incorporated available

water, required releases, operating rules, and the defined Reservoir RORC as shown in Fig. 2.

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

The equation delineates the computation of the water resources accessible during the month τ , while considering various influencing factors. W_{τ} signifies the water availability for the month τ , whereas $S_{\tau-1}$ indicates the volume of water retained at the termination of the month $\tau - 1$, which is initially established at the maximum capacity of the reservoir. The computation is derived from the influx into the reservoir (I_{τ}), the volume of precipitation recorded during the month (P_{τ}), and the average evaporation losses incurred throughout the month (E_{τ}).

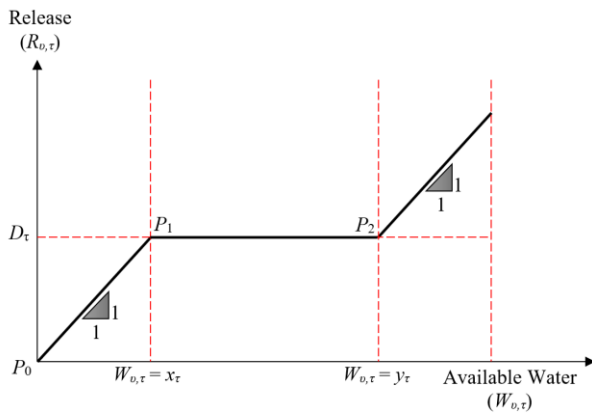


Fig. 1 Standard operating rule.

Subsequently, the monthly water release rate (R_{τ}) was determined to calculate water scarcity and excess water levels. These levels are represented by the average yearly excess water amount (the initial objective function in the search procedure) and the yearly frequency of excess water (the second objective function utilized during the search procedure), as shown in Equations 2 and 4, respectively. In these equations, x_{τ} refers to the lower RORC during month τ while y_{τ} denotes the upper RORC during month τ .

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

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

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

In this equation, Avg_i represents the average amount of excess water per year during iteration i , Sp_v denotes the excess water during year v , where releases exceed the target demand, Fre_i is the frequency of excess water, Sf_v indicates the number of annual floods, which is the year when releases exceed the target demand, D_{τ} represents the monthly goal demand from the reservoir, which is determined by utilizing data from previous studies and calculating the water demand in the downstream area. The variable i represents the iteration number.

To determine the optimal rule curve, the Invasive Weed Optimization (IWO) algorithm is utilized, taking into account variations in irrigation water requirements. The procedural steps for employing IWO to derive the Optimal Rule Curve are outlined in Fig. 2. This flowchart illustrates the systematic approach for optimizing reservoir management rule curves using the IWO method, highlighting its potential to enhance water resource allocation and operational efficiency.

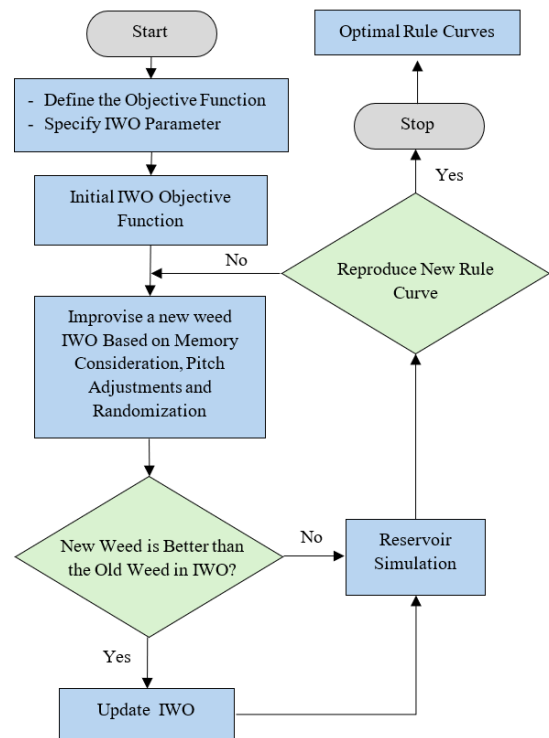


Fig. 2 Flowchart of applying the Invasive Weed Optimization (IWO) to find optimal rule curves.

3.7 Performance Evaluation Metrics

To quantitatively evaluate and compare the performance of the existing and optimized rule curves, simulation outputs from the 500 synthetic 13-year datasets were analyzed. Five key metrics, computed for both water shortage and excess water events, were employed for this assessment. These metrics are operationally defined as follows:

- 1) Frequency (times/year): Measures the average annual occurrence of deficit or surplus events. An event is any continuous period of one or more months with observed water shortage or excess. It is calculated by dividing the total number of discrete events by the total number of simulation years.
- 2) Average volume (MCM): Represents the mean magnitude (in Million Cubic Meters) of a single event. It is computed by dividing the total cumulative volume (shortage or surplus) across all events by the total number of events.
- 3) Maximum volume (MCM): Indicates the single worst-case event magnitude observed across the entire 500-sample simulation ensemble. This metric serves as an indicator of system vulnerability to extreme conditions.
- 4) Average time period (year): Measures the mean continuous duration of an event. This is calculated as the sum of all event durations (in months) divided by the total number of events, subsequently converted to years. This metric relates to system resilience or recovery time.
- 5) Maximum time period (year): Represents the longest continuous duration (in years) recorded for a single shortage or surplus event within the 500-sample simulation ensemble. This metric indicates the worst-case temporal persistence of a failure or surplus condition.

4. RESULTS AND DISCUSSION

4.1 Optimal Rule Curves

The application of the Invasive Weed Optimization (IWO) algorithm for the Phuttha Utthayan Reservoir yielded optimal rule curves that enhance reservoir operations under varying conditions of water shortage and excess. Figs. 3 – 5 illustrate the proposed rule curves compared to the currently implemented ones, highlighting subtle yet significant differences.

4.1.1 Optimal rule curve under average annual water shortage conditions

Fig. 3 presents the optimal rule curve derived from IWO for average annual water shortage conditions over 13 years.

During the dry season (November–April), the existing Lower Rule Curve (LRC) enforces a higher minimum storage level to secure irrigation and other essential demands. In contrast, the IWO-Avg Lower allows a reduced threshold, providing greater flexibility in water allocation when inflows are limited. This adaptability helps optimize resource use without compromising supply reliability. Meanwhile, the optimized upper rule curve enhances flood resilience during the wet season. Together, the refined upper and lower curves achieve a balanced strategy, reducing flood risks while improving overall water use efficiency.

4.1.2 Optimal rule curve for annual average shortage conditions

Fig. 4 illustrates the optimal rule curve under conditions of average annual shortages using 13 years of monthly irrigation data.

During the rainy season (May–October), the existing URC sets a lower maximum water retention threshold, limiting the reservoir's ability to store stormwater. In contrast, the IWO-Est Upper raises this threshold, increasing storage capacity and thereby reducing flood risks.

In the dry season (November – April), the existing LRC secures a higher minimum retention level to meet water demands. The IWO-Est Lower, however, allows a reduced minimum threshold, creating greater flexibility for irrigation and other uses. Together, these improved curves enhance stormwater retention in the wet season and optimize water allocation in the dry season, effectively addressing both flood risks and water scarcity.

4.1.3 Optimal rule curve under average overflow conditions

Fig. 5 shows the optimal rule curves under conditions of annual average overflow using 13 years of irrigation data.

During the rainy season (May–October), the existing Upper Rule Curve (URC) demonstrates a lower maximum retention threshold compared to the optimized curves derived from the IWO-Avg Upper and GA-Avg Upper. This limitation reduces the reservoir's capacity to store rainfall and manage stormwater effectively. By contrast, the optimized curves significantly enhance rainwater retention

capacity, thereby mitigating flood risks and improving flood resilience.

In the dry season (November–April), the existing Lower Rule Curve (LRC) maintains a relatively high minimum retention threshold, which ensures sufficient water supply to meet dry season requirements. However, this approach may constrain operational flexibility. The optimized curves, represented by the IWO-Avg Lower and GA-

Avg Lower, reduce the minimum storage threshold, allowing more efficient allocation of water resources for irrigation and other uses while maintaining essential supply security.

Overall, the optimized rule curves generated using the IWO and GA algorithms exhibit significant improvements compared to the existing control curves currently in use.

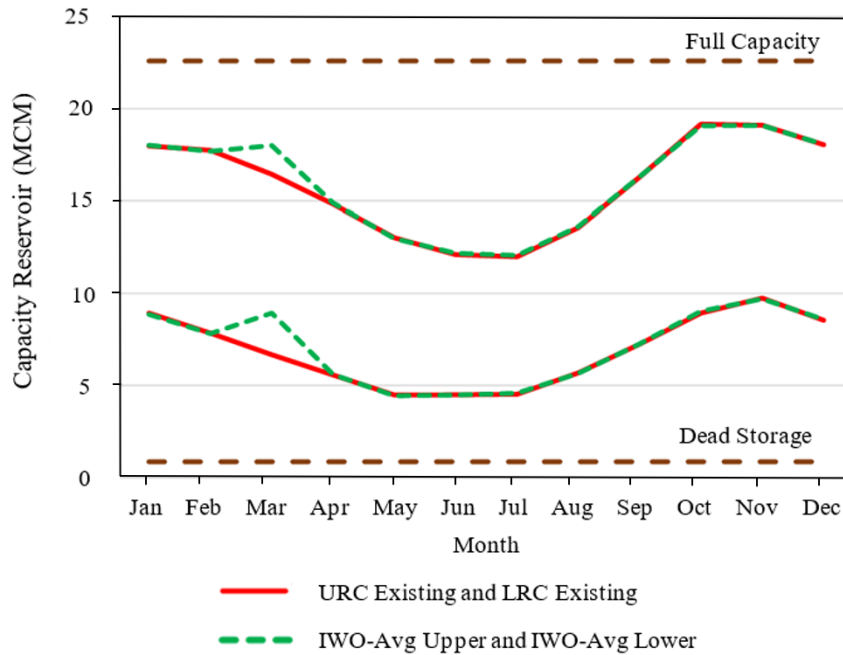


Fig. 3 Rule curve of Phuttha Utthayan reservoir situation of average annual water shortage per years using the average water use for irrigation total of 13 years.

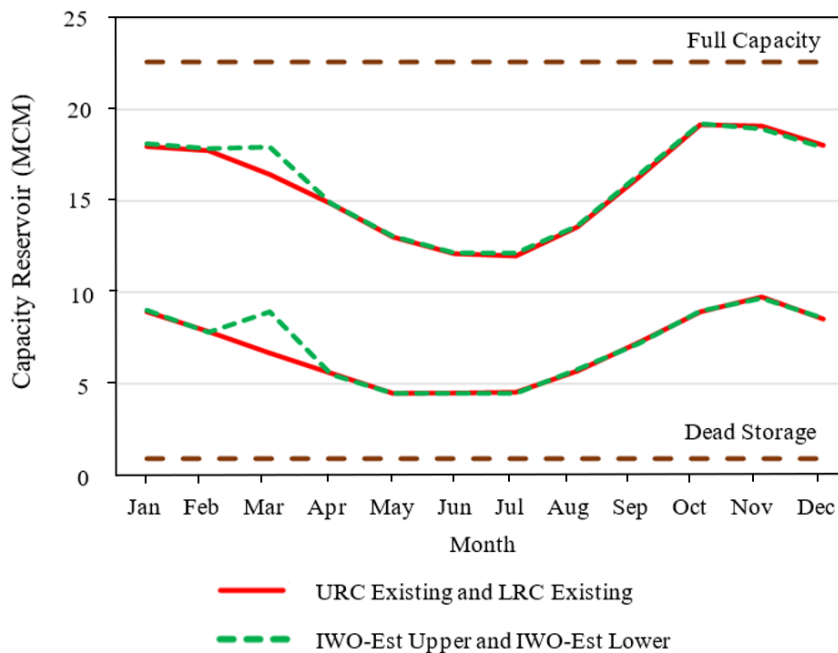


Fig. 4 Rule curve of Phuttha Utthayan reservoir situation of annual average shortage per years using the average water use for irrigation total of 13 years.

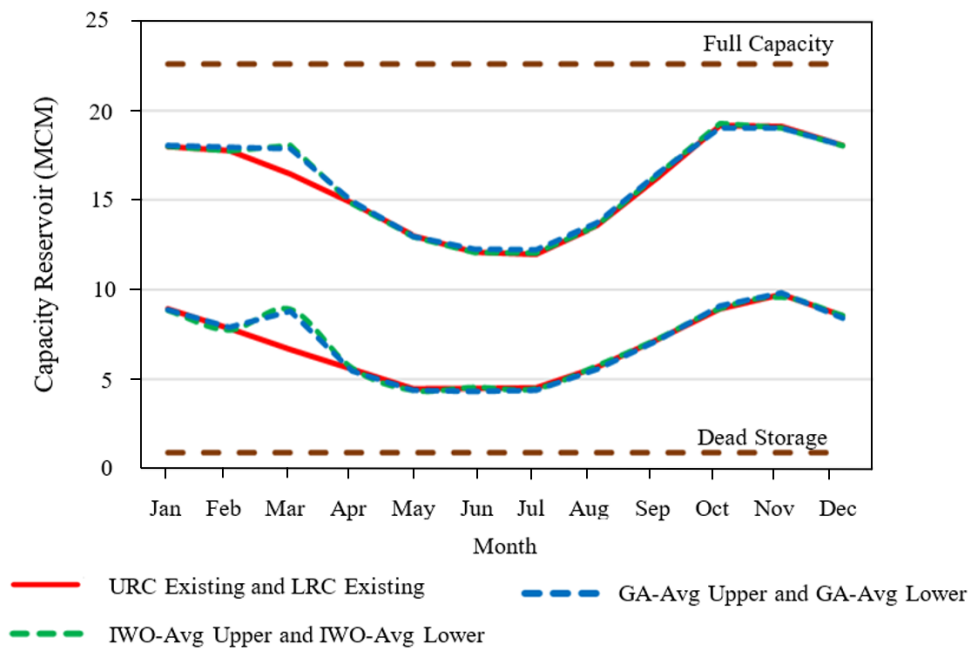


Fig.5 Rule curve of Phuttha Utthayan reservoir situation of average annual excess release per years using the average water use for irrigation total of 13 years.

These optimized curves not only enhance water storage capacity during the rainy season but also contribute to more efficient water allocation throughout the dry season, ensuring that available resources are distributed more effectively to meet agricultural, domestic, and ecological demands. In addition, the improved rule curves strengthen the reservoir’s ability to operate under increasingly variable hydrological conditions, providing greater flexibility in responding to unexpected inflow patterns. Such adaptability is essential as climate variability continues to intensify uncertainties in reservoir management. The findings therefore underscore the considerable potential of advanced optimization techniques in supporting more sustainable and resilient reservoir operations. By helping to balance the dual challenges of reducing flood risks during periods of excessive rainfall and mitigating water scarcity during prolonged dry spells, these methods offer promising pathways for improving long-term water resource reliability.

4.2 Evaluation of the Performance of Rule Curves

The performance of the optimized and existing rule curves was assessed using historical and synthetic water inflow data over a 13-year period (2011 – 2024). These evaluations aimed to measure the frequency, volume, and duration of water shortages and surpluses under different management scenarios, with results presented in

Tables 1 and 2.

Table 1 presents the analysis of water shortage and surplus conditions at the Phuttha Utthayan Reservoir, based on 500 sets of synthetic inflow data for irrigation demands. The results indicate that none of the evaluated rule curves—namely Existing, GA-Excess, GA-Frequency_Excess, IWO-Shortage, IWO-Excess, IWO-Frequency_Shortage, and IWO-Frequency_Excess—led to water shortages; however, all demonstrated varying degrees of excess water. Specifically, the frequency of excess water occurred approximately 0.89 – 0.90 times per year, with an average excess volume ranging from 1.06 – 1.09 million cubic meters annually and maximum volumes reaching 6.95 – 7.28 million cubic meters. In terms of temporal characteristics, the average duration of excess water extended for 6.73 – 6.93 years, while the maximum duration was observed between 8.75 – 8.89 years.

These results indicate that while the reservoir avoids shortages across all management rules, excess water events are a persistent issue. On average, excess water occurs 0.9 times per year, with an annual surplus of 1.08 million cubic meters. The highest recorded excess volume was 7.2 million cubic meters, persisting for up to 8.87 years.

Table 2 presents a comparative analysis of water shortage and surplus metrics based on the same dataset, focusing on statistical measures such as mean and standard deviation. The results indicate that the frequency of surplus events averages 0.90 –

0.91 times per year, with standard deviations of 0.08 – 0.09. The average surplus volume ranges from 1.07 to 1.09 million cubic meters (SD = 0.13), while the maximum surplus volume peaks between 7.09 and 7.33 million cubic meters (SD = 0.37 – 0.44). In terms of temporal characteristics, the mean duration of surplus extends 7.23 – 7.67 years (SD = 3.74 – 3.88), and the maximum duration reaches 9.01 – 9.40 years (SD = 2.93 – 3.08). These findings reinforce that water shortages are effectively avoided under all rule curves, but surplus water events remain a persistent challenge.

A closer comparison across all evaluated rule curves shows that average surplus volumes are relatively consistent, with GA-Excess and IWO-Excess slightly reducing surplus compared to the Existing curve. The frequency of surplus events varies minimally between 0.89 and 0.91 times annually. Maximum surplus volumes are highest under IWO-Excess and lowest under IWO-Shortage, while average surplus durations are comparable across all curves, with GA and IWO marginally exceeding Existing. Maximum surplus duration is longest for Existing and shortest for IWO-Shortage.

Overall, the existing rule curve for reservoir

operation indicates a higher risk of excess water, which can lead to uncontrolled releases and potential flooding, highlighting the urgent need for more effective and adaptive water management strategies. In contrast, optimization methods such as Genetic Algorithm (GA) and Invasive Weed Optimization (IWO) demonstrate superior performance by minimizing the risks of surplus water while simultaneously providing greater operational flexibility for irrigation scheduling and water allocation across different sectors. These advanced methods can adapt to variable inflow patterns and uncertain hydrological conditions, allowing reservoir operators to make more informed decisions. The results of comparative studies emphasize that applying such sophisticated optimization algorithms can significantly improve reservoir performance, enhance water storage efficiency, and promote a balanced management approach that simultaneously addresses flood mitigation and resource allocation. This underscores the critical role of modern computational techniques in sustainable water resources management and operational planning.

Table 1. Situation of water shortage and excess water of the Phuttha Utthayan reservoir considering synthetic historical inflow data of 13 years for 500 samples using the actual water use for irrigation.

Rule curve		Shortage					Excess water				
		Frequency (times/year)	Average volume (MCM)	Maximum volume (MCM)	Average time period (year)	Maximum time period (year)	Frequency (times/year)	Average volume (MCM)	Maximum volume (MCM)	Average time period (year)	Maximum time period (year)
Existing	μ	0.00	0.00	0.00	0.00	0.00	0.90	1.08	7.20	6.89	8.87
	σ	0.00	0.00	0.00	0.00	0.00	0.08	0.13	0.44	3.63	2.96
GA-Excess	μ	0.00	0.00	0.00	0.00	0.00	0.90	1.06	7.00	6.87	8.85
	σ	0.00	0.00	0.00	0.00	0.00	0.08	0.13	0.45	3.66	2.98
GA-Frequency_Excess	μ	0.00	0.00	0.00	0.00	0.00	0.90	1.07	7.10	6.86	8.83
	σ	0.00	0.00	0.00	0.00	0.00	0.08	0.13	0.44	3.63	2.98
IWO-Shortage	μ	0.00	0.00	0.00	0.00	0.00	0.90	1.07	7.11	6.93	8.89
	σ	0.00	0.00	0.00	0.00	0.00	0.08	0.13	0.44	3.66	2.97
IWO-Excess	μ	0.00	0.00	0.00	0.00	0.00	0.89	1.06	6.95	6.78	8.75
	σ	0.00	0.00	0.00	0.00	0.00	0.08	0.13	0.44	3.64	2.99
IWO-Frequency_Shortage	μ	0.00	0.00	0.00	0.00	0.00	0.90	1.09	7.28	6.84	8.84
	σ	0.00	0.00	0.00	0.00	0.00	0.08	0.13	0.44	3.62	2.96
IWO-Frequency_Excess	μ	0.00	0.00	0.00	0.00	0.00	0.89	1.07	7.08	6.73	8.75
	σ	0.00	0.00	0.00	0.00	0.00	0.08	0.13	0.44	3.59	2.96

μ = mean

σ = standard deviation

5. CONCLUSION

This study's findings demonstrate that the Invasive Weed Optimization (IWO) algorithm effectively enhances reservoir operations by

addressing the specific hydrological challenges of the Phuttha Utthayan Reservoir. A key finding, derived from 500-sample simulation analysis, is that the reservoir's primary operational challenge is not water shortage (which was zero across all scenarios)

but excess water management. The IWO-derived curves significantly outperformed the existing rules by mitigating this surplus risk.

The specific mechanism for this improvement was twofold. First, the IWO-optimized Upper Rule Curve (URC) intelligently raised the maximum retention threshold during the wet season (May–October) . This adjustment allows the reservoir to capture and retain more inflow, enhancing flood control capacity and reducing uncontrolled spillway discharge. Second, the optimized Lower Rule Curve (LRC) provided greater operational flexibility by lowering the minimum storage threshold during the dry season (November – April), without compromising water supply reliability.

These findings demonstrate that the IWO algorithm successfully identifies and implements a more balanced operational strategy. By raising the URC, it mitigates flood occurrences , and by lowering the LRC, it increases allocation flexibility. This achieves a more stable and efficient operational equilibrium compared to the existing rules, which is critical for bolstering agricultural productivity, supporting economic resilience, and fostering

sustainable water resource management in the region.

By providing an adaptable and effective strategy for reservoir operations, this research underscores the potential of optimization algorithms like IWO in addressing the complex challenges of water management and contributing to the long-term sustainability of vital water resources.

While this study successfully demonstrated the potential of the IWO algorithm for optimizing reservoir operations at the Phuttha Utthayan Reservoir, several limitations are acknowledged, which in turn provide directions for future research.

This study focused on applying the standard IWO algorithm without conducting a comprehensive sensitivity analysis of its parameters or comparing its computational cost with other metaheuristics. Future research could examine how IWO parameter settings affect solution quality and benchmark its performance against other hybrid metaheuristic algorithms. Such investigations would provide deeper insights into optimizing IWO for reservoir management and clarify its advantages and limitations relative to alternative optimization approaches.

Table 2. Situation of water shortage and excess water of the Phuttha Utthayan reservoir considering synthetic historical inflow data of 13 years for 500 samples using the average water use for irrigation total of 13 years.

Rule curve	Shortage						Excess water				
	Frequency (times/year)	Average volume (MCM)	Maximum volume (MCM)	Average time period (year)	Maximum time period (year)	Frequency (times/year)	Average volume (MCM)	Maximum volume (MCM)	Average time period (year)	Maximum time period (year)	
GA-Excess_AvgIrr	μ	0.00	0.00	0.00	0.00	0.90	1.07	7.09	7.30	9.04	
	σ	0.00	0.00	0.00	0.00	0.09	0.13	0.44	3.86	3.08	
GA-Frequency_Excess_AvgIrr	μ	0.00	0.00	0.00	0.00	0.91	1.09	7.33	7.67	9.40	
	σ	0.00	0.00	0.00	0.00	0.08	0.13	0.39	3.81	2.97	
IWO-Shortage_AvgIrr	μ	0.00	0.00	0.00	0.00	0.90	1.08	7.28	7.23	9.01	
	σ	0.00	0.00	0.00	0.00	0.09	0.13	0.44	3.85	3.07	
IWO-Excess_AvgIrr	μ	0.00	0.00	0.00	0.00	0.90	1.08	7.28	7.37	9.12	
	σ	0.00	0.00	0.00	0.00	0.08	0.13	0.44	3.88	3.07	
IWO-Frequency_Shortage_AvgIrr	μ	0.00	0.00	0.00	0.00	0.90	1.08	7.23	7.42	9.16	
	σ	0.00	0.00	0.00	0.00	0.09	0.13	0.44	3.88	3.08	
IWO-Frequency_Excess_AvgIrr	μ	0.00	0.00	0.00	0.00	0.91	1.09	7.33	7.45	9.25	
	σ	0.00	0.00	0.00	0.00	0.08	0.13	0.37	3.74	2.93	

μ = mean

σ = standard deviation

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