

Research Article

Optimization of the Operation Rule Curves for Cascade Reservoirs Using the Cuckoo Search Algorithm

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Received 28 August 2021; Revised 10 December 2021; Accepted 14 March 2022; Published 6 April 2022

Academic Editor: Vagelis Plebris

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Reservoir operation optimization models are based on the hydrological cycle principle. These models determine the inflow and outflow necessary to meet the demands for drinking water, irrigation water, etc. Rather than optimizing each reservoir separately in cascaded reservoir systems, more efficient results are obtained if the reservoirs are optimized as a whole. In this study, the optimal operation rule curves for cascaded reservoirs were obtained by using the cuckoo search algorithm, which is a soft computing method. Both the irrigation and flood control constraints of the Adiguzel and Cindere dams in Denizli (Turkey) were satisfied by utilizing these rule curves, and the total energy production was maximized. In addition, these rule curves considered turbine efficiency, which significantly contributes to published literature. The total energy obtained with the proposed operation rule curves was 14% higher than that currently produced by the Adiguzel and Cindere dams.

1. Introduction

Water and energy are two of the most important needs of society. Fresh water has become considerably more important due to global climate change. It is therefore crucial to use fresh water efficiently and produce maximum energy from it. As in all developing countries, Turkey's need for water and energy increases year by year because the population and level of development increase. Therefore, the water resources available in Turkey must be used optimally and be able to produce more energy every year.

Most of the energy produced in Turkey comes from imported and consumable resources such as oil and natural gas. This causes dependency on external energy resources and increases the unit cost of energy production. Accordingly, sustainable domestic and renewable energy resources with lower unit costs are important for energy production.

Hydroelectric energy is the most important renewable energy source in Turkey and meets 32% of Turkey's total energy needs [1]. Thirty percent of the electrical energy installed power in Turkey consists of hydrological resources.

Approximately 70% of the facilities established on hydrological resources in Turkey consist of storage dams. Therefore, these reservoirs should be used efficiently to meet the energy demand [2].

Various factors, such as inflow, outflow, water elevation, and evaporation, directly affect the operation of reservoirs. Using traditional methods for reservoir operation can lead to failure in meeting some of these demands. Therefore, reservoir operation studies of various optimization techniques aimed at maximizing energy production and economic benefits are important research topics today. Due to the development of computer technology, especially in the last 40 years, various optimization techniques have been developed to manage and operate single- and multireservoir systems. These optimization techniques are comprehensively presented in studies by Yeh [3], Wurbs [4], Chau and Albermani [5], and Labadie [6]. These studies indicated that optimization methods developed using dynamic programming, nonlinear programming, and various soft computing algorithms are suitable for the optimal operation of cascade reservoirs.

Karamouz et al. [7] applied discrete dynamic programming to a multireservoir water resource system in the Gunpowder River basin near Baltimore. The study investigated the operation of reservoir systems using stochastic dynamic programming and Bayesian decision theory.

Li et al. [8] suggested an improved decomposition-coordination optimization method and discrete differential dynamic programming to effectively solve a large-scale hydropower system problem. The proposed method was applied to the long-term optimal dispatch of the large-scale hydropower system in the Yangtze River basin. The method performed effectively, not just for total power generation but also for optimizing the large-scale hydropower system operation.

In a study by Bozorg Haddad et al. [9], two problems with single and cascade reservoirs were selected to demonstrate the applicability and performance of the honey bee mating optimization (HBMO) algorithm in the nonconvex hydropower system design and operation. The problems were solved with both HBMO and gradient-based LINGO 8.0, and their results were compared. HBMO produced feasible and near-optimal solutions for both the single- and multireservoir problems, but LINGO 8.0 did not produce feasible solutions for the multireservoir problem.

Afshar et al. [10] presented an improved HBMO algorithm to obtain optimal operation rules for multireservoir systems. The performance of the proposed model was tested through sensitivity analysis, and its results were compared with a real-coded genetic algorithm for a 60-month single-reservoir operation problem. The improved model was then used to derive the release rule and storage balance functions that set the operational policy for the multireservoir system's water supply and hydropower generation.

Oliveira and Loucks [11] used real-coded genetic algorithms to implement multireservoir operation policies. These genetic algorithms utilize real-value vectors, including the information needed to define both the system release and the individual reservoir storage volume. The proposed algorithm was tested on sample reservoir systems used for water supply and hydropower. Sharif and Wardlaw [12] presented a genetic algorithm approach for optimizing multireservoir systems. The approach was demonstrated by applying it to a reservoir system in Indonesia, considering both the existing development situation in the basin and two future water resource development scenarios. The results obtained with the genetic algorithm were compared with those of discrete differential dynamic programming.

Hinçal et al. [13] investigated the efficiency and effectiveness of the genetic algorithm in optimizing cascade reservoirs. Three reservoirs in the Colorado River Storage Project were optimized to maximize power generation. The results obtained compared real operational data with the effectiveness of the genetic algorithm and showed that it could be used as an alternative to traditional optimization techniques.

Yang et al. [14] proposed several improvement strategies to prevent early convergence of the genetic algorithm in multireservoir optimization problems. The performance of these proposed strategies was tested on the optimal operation of the cascade reservoirs of the Three Gorges Dam.

Meng et al. [15] proposed a new multipurpose cuckoo search algorithm to overcome its existing deficiencies. A multipurpose hydropower plant operation optimization model for the Xiaolangdi and Xixiyuan-cascaded hydropower plants in the Lower Yellow River was constructed and used to validate the effectiveness of these algorithms along with five benchmarking problems.

SeethaRam [16] presented a genetic algorithm optimized rule curve (GA-RC) model for monthly operation of a multipurpose reservoir, which maximizes the hydropower produced while reliably meeting the irrigation demands. Instead of the usual single target storage for each period, the GA-RC model considers three sets of target storage, namely, dry, normal, and wet storage, based on the storage level at the beginning of the period.

Yuan et al. [17] proposed an improved cuckoo algorithm that featured a new neighbor sequence algorithm for global search and a variable neighborhood descent algorithm for local search, and then applied the improved cuckoo algorithm to optimize the characteristics for the operation of cascaded reservoir power generation.

Determining reservoir operation policies and optimizing reservoir operation to use the storage dams efficiently is an important part of planning and managing water resources. For example, to meet irrigation needs, the turbine efficiency is increased by using the same amount of water from a higher head. Much higher electricity production can be achieved by operating the spillway at a minimum level. Many studies in published literature have created optimal rule curves to maximize electricity production. If an optimal operation rule curve specific to each power plant is developed to increase energy production efficiency, the maximum benefit can be achieved without any additional investment [2].

Unfortunately, most of the many hydroelectric production facilities in Turkey are operated without following any optimal operation rules. The Adigüzel and Cindere cascaded dams are operated in this manner. Both the Adiguzel Dam and hydroelectric power plant (HEPP), and the Cindere Dam and hydroelectric power plant on the Büyük Menderes River were therefore selected as the sample study areas.

This study examined reservoir operations to maximize the energy produced by multipurpose cascaded reservoirs while meeting their water demands. The method suggested is based on the cuckoo search algorithm, which is a bio-based metaheuristic alternative to the methods suggested in the above studies.

Adiguzel Dam is inside the borders of Denizli and Usak. It was designed for irrigation, energy production, and flood control. The hydroelectric power plant has a total installed power of 62 MWe and an annual electricity generation potential of 280 GWh.

Cindere Dam is in the southern district of Denizli, downstream from Adiguzel Dam. The Directorate General for State Hydraulic Works (DSI) designed the dam for irrigation and energy production. The Cindere hydroelectric power plant has a total installed capacity of 29.31 MWe and an annual energy production of 88.10 GWh, according to feasibility calculations.

Yasar [2] developed a CS algorithm-based solution to optimize the reservoir's operational system and generate an optimal operation rule curve. The results showed that the CS algorithm improved the system operation, and the energy production would be increased by about 10%. The significant success of the CS algorithm for single-reservoir operation is the main motivation for this study. For this purpose, this study was carried out to test the success of the CS-based optimization model developed by Yasar [2] in operating cascade reservoirs. The study aimed at producing the most energy with the least water consumption within the specified constraints of the multipurpose cascaded reservoirs. The optimization experiments used metaheuristic methods to create reservoir operation rule curves. The average inflow of Adiguzel Dam and average monthly intermediate basin flow between the Adigüzel and Cindere Dams from 1999 to 2017 were used. Basic rules for reservoir operation were determined by considering variables such as the inflow, outflow, water loss, and storage capacity used in the sequential streamflow routing method. In the past 228 months (1999–2017) of flow data from the Adiguzel and Cindere Dams, the cascaded reservoirs were operated using codes and functions written in the MATLAB program primarily using the sequential streamflow routing method.

2. Materials and Methods

In this study, the method used for optimal operation of cascaded reservoirs consisted of three main steps. In the first step, the cascaded reservoirs are operated using the sequential streamflow routing method; in the second step, the optimum turbine flow was determined for maximizing turbine efficiency in reservoir operation, and in the third step, the objective function was optimized using the cuckoo search algorithm by considering all constraints in the cascaded reservoir operation model. After these three steps, the operation rule curves for the cascaded reservoirs were obtained.

2.1. Operating Cascaded Reservoirs with the Sequential Streamflow Routing Method. When planning a reservoir system, the system performance has to meet the existing variable water demands. The purpose of the operation and planning of a reservoir system is to maximize benefits, minimize costs, and meet variable water demands under mass balance equations and other constraints [18].

The reservoir operation is established by calculating the inflow, outflow, and loss using mass balance equations. The first step in establishing how the reservoir operates is to apply the sequential streamflow routing method, using the continuity equation to evaluate the operation of the reservoir's storage system. This method aims at reaching the targeted storage capacity by successive applications throughout the operation period. The sequence-trial streamflow routing method can be applied monthly, daily, or hourly by using the reservoir input-output data and considering the operational purposes of the reservoir. This method is based on the continuity equation given as follows:

$$\Delta V = I - O - L, \quad (1)$$

where ΔV is the change in the volume of the water stored in the reservoir, I is the amount of inflow, O is the amount of outflow, and L is the amount of water lost in the reservoir due to evaporation, leakage, and similar reasons.

This method can be used in storage hydroelectric power plant projects where the head changes, regardless of the flow, although it is quite complex. Weekly or monthly intervals are often used because collecting daily calculations for longer periods is time-consuming [19].

In this study, the operation of the cascaded reservoirs in the system was measured monthly using the sequential streamflow routing method. The reservoir data obtained for each month after operating the cascaded reservoirs were used as the initial reservoir data for the following month. In the sequential streamflow method, the area-volume-elevation values of reservoirs, tailwater channel flow elevation values, and turbine efficiency curve equations were used along with the hydrological data.

The elevation-area-volume curve of a reservoir shows the changes in the reservoir basin and its volume, depending on the water elevation in the reservoir. Land topography directly affects the storage capacity of the reservoir. When operating the cascaded reservoirs in this study, the water elevations and basin area changes corresponding to those for the volume of the reservoirs were determined by the interpolation method, using the existing elevation-area-volume values obtained from the DSI of the Aydin Regional Directorate. The area-volume-elevation values for the Adiguzel and Cindere Dam reservoirs are summarized in Figures 1 and 2, respectively.

One of the most important variables affecting the energy production of hydroelectric power plants is the net head. The head of a hydroelectric power plant is obtained by determining the difference between the water elevation in the reservoir and that in the tailwater channel. Therefore, the water elevation in the tailwater channel directly affects energy production. In this study, to calculate the net head more precisely for the operational optimization of cascaded reservoirs, the water elevation in the tailwater channel was considered based on the turbine flow. Tailwater channel models were created by examining the technical properties of the tailwater channels of both dams and obtaining tailwater rating curves.

The Adiguzel hydroelectric power plant operates between flows of $10 \text{ m}^3/\text{s}$ and $64 \text{ m}^3/\text{s}$, while the Cindere hydroelectric power plant operates between flows of $7.50 \text{ m}^3/\text{s}$ and $70.20 \text{ m}^3/\text{s}$. To optimize reservoir operation, when the turbine water was operated at the relevant flows for each power plant, the water elevations in their tailwater channels were obtained from the tailwater rating curves shown in Figures 3 and 4. The data on the tailwater channel water elevations for the Adiguzel and Cindere hydroelectric power plants were obtained from the Aydin Regional Directorate of State Hydraulic Works in the CD format. The graphs presented in Figures 3 and 4 were obtained with the help of these data.

One of the important variables affecting energy production is turbine efficiency. It varies according to the

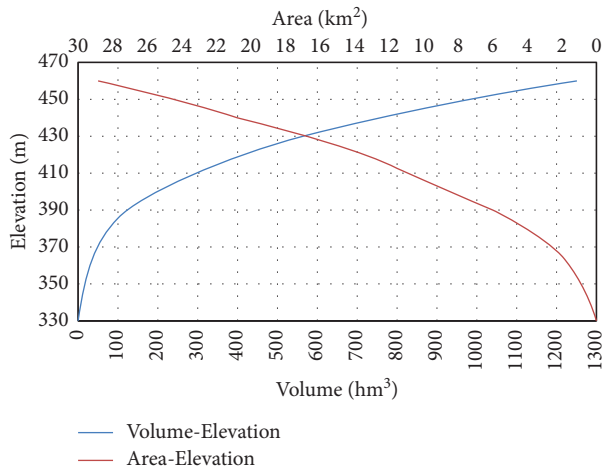


FIGURE 1: Area-volume-elevation curve of Adiguzel Dam.

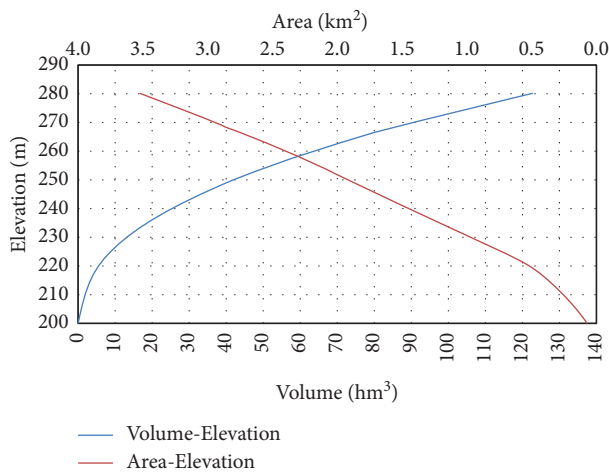


FIGURE 2: Area-volume-elevation curve of Cindere Dam.

turbine flow and turbine type. After achieving the required head and flow in the reservoir, the amount of turbine flow during operation directly affects the energy production.

Technical information about the turbines used in Adiguzel and Cindere Dam hydroelectric power plants was obtained from the DSI Aydın Regional Directorate. Francis-turbines are used in both dams.

While modeling the reservoir operation with the sequential streamflow routing method, the ratio of the monthly turbine flow (Q_t) to the turbine design flow (Q_d) was calculated after distributing the turbine volume. This ratio was used as a function input to obtain the turbine efficiency coefficient as the output of the function. Monthly turbine efficiency coefficients were used in calculating monthly energy production. The turbine efficiency curves of the Adiguzel and Cindere Dams were based on the technical data and calculation reports obtained from the DSI Aydın Regional Directorate. Data on turbine efficiency curves presented in Figures 5 and 6 were not available online. Relevant data were obtained from the State Hydraulic Works in the CD format upon a written request and payment of a fee.

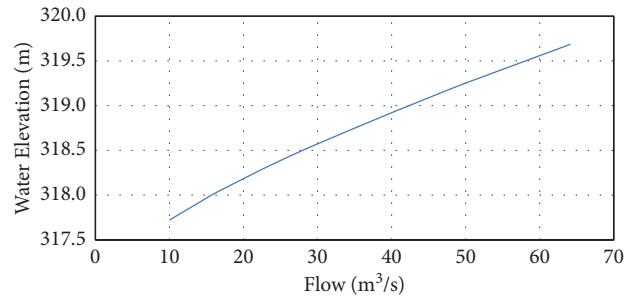


FIGURE 3: HEPP tailwater rating curve of Adiguzel Dam.

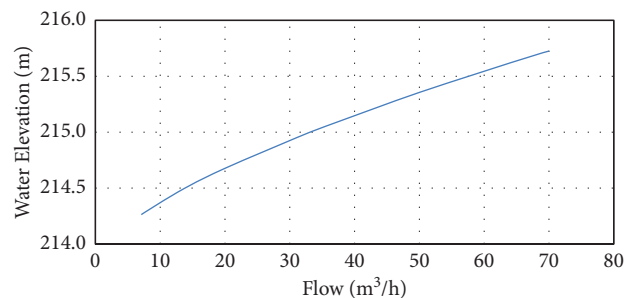


FIGURE 4: HEPP tailwater rating curve of Cindere Dam.

The turbine efficiency curves and equations given in Figures 5 and 6 were considered in the energy production calculations for the reservoir operation optimization studies.

These results were used to create the reservoir operational model with the sequential streamflow routing method. This was the first step in optimizing the reservoir operation to obtain the rule curves. The cascaded reservoirs in this study were operated to meet irrigation demands, which was their primary objective, and then water elevation changes in the tailwater channel and turbine efficiency curves were included in the monthly energy production calculation.

2.2. Calculating Optimum Turbine Flow. In previous studies on the development of operation rule curves, the effect of turbine efficiency on energy production was usually not taken into account in a realistic way. Regardless of the amount of turbine flow, the effect of the efficiency curve on energy production was ignored by taking the turbine efficiency coefficient to be constant. However, in this study, turbine efficiency equations were derived for both power plants to obtain the operation rule curves. The intention was that the turbines should operate with the highest possible efficiency during reservoir operation.

To determine the optimum turbine flow, models were created based on the constraints determined by the number of turbines in each power plant and by turbine design criteria. In optimizing the cascaded reservoir operation to obtain the reservoir operation rule curves, the monthly turbine volume was distributed to the turbines according to these models by considering the turbine efficiency. The model developed to determine the optimum turbine flow had the following constraints:

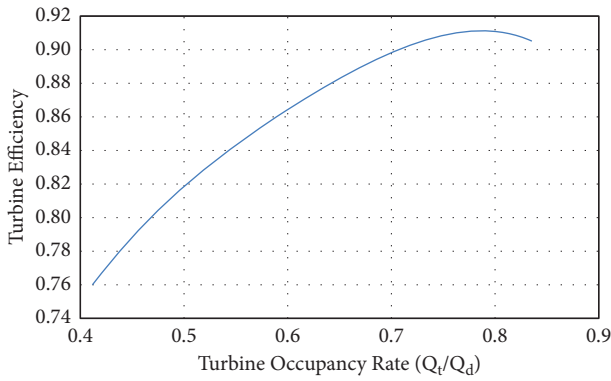


FIGURE 5: HEPP turbine efficiency curve of Adiguzel Dam.

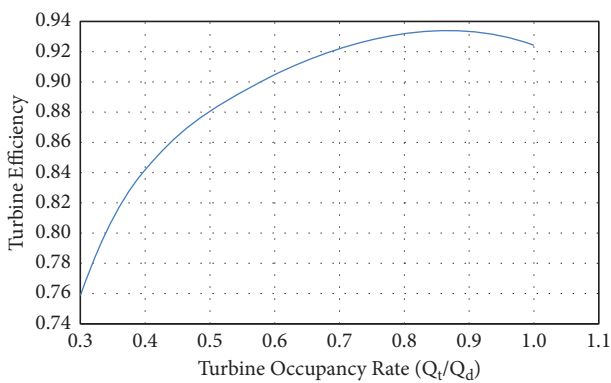


FIGURE 6: HEPP turbine efficiency curve of Cindere Dam.

- (1) If the turbine flow was less than the minimum single turbine flow, the power plant was operated on a stop-and-go principle in the range that generated the highest turbine efficiency and energy. However, the optimum turbine flow to be used was determined by considering the irrigation need. Thus, energy production was carried out during a specific part of the day, not all day. At the same time as meeting the irrigation needs, energy was therefore produced at high efficiency.
- (2) If the turbine flow was between the minimum single turbine flow and the maximum single turbine flow, energy was produced using only one turbine.
- (3) If the turbine flow was greater than the maximum single turbine flow and less than the plant design flow, the turbine flow was sent to the existing turbines equally, and energy was produced in both turbines.

In obtaining the operation rule curves for cascaded reservoirs, maximizing the turbine efficiency coefficient in the reservoir operation optimization achieved results closer to the actual production. Therefore, instead of using a constant turbine efficiency coefficient in the reservoir operation studies, it was necessary to determine a turbine's optimum flow by using the turbine efficiency curves.

2.3. Cuckoo Search Algorithm. The cuckoo search algorithm is a metaheuristic algorithm developed by Xin She Yang and Suash Deb. It is a new generation of optimization algorithm inspired by the brood parasitism and random flights of some cuckoo species [20]. The cuckoo bird is fascinating because of its aggressive brooding strategy and charming voice. The Ani and Guira species of cuckoo lay their eggs in other birds' nests, and they drop the other birds' eggs to increase the likelihood of their own eggs hatching. This parasitic behavior using other birds' (and mostly other species) nests as sites to lay eggs are followed by many other species. The pseudocode in Figure 7 summarizes the main steps of the cuckoo search (CS) algorithm.

Random search is particularly important in metaheuristic algorithms. The cuckoo search algorithm conducts random searches via the Lévy flight process. Lévy flight is a process that includes a series of random sequential steps. Mathematically, there must be two consecutive stages for the Lévy flight to generate random numbers. In the first stage, the steps are created, and in the second stage, a random direction is selected. The following equation is used to generate new solutions for the Lévy flight:

$$x_i^{j+1} = x_i^j + \alpha L(x_i^j - x_{best}^j), \tag{2}$$

where x_i^j is the current solution, x_i^{j+1} is the next solution, x_{best}^j is the best solution generated up to that step, α is the parameter used to control step size, and L is the step length.

The current solution—the first term of Equation (2)—and the transition probability—the second term of Equation (2)—are the only parameters that the next step in the Markov Chain is dependent on, and it can generally be considered a random walk. Using Lévy flight and random walk together, longer step-sizes investigate the search space more efficiently [21]. One of the most efficient and simplest methods is using the Mantegna algorithm. The L -step size in this algorithm can be calculated by the following equation [21]:

$$L = \frac{u}{|v|^{1/z}}, \tag{3}$$

where z is a parameter that takes values between 1 and 2—assumed to be 1.5 in this study. The terms u and v are calculated through a normal distribution function in the following equation:

$$u = N(0, \sigma_u^2), v = N(0, \sigma_v^2), \tag{4}$$

where σ_u and σ_v are obtained via the formula below:

$$\sigma_u = \left\{ \frac{\Gamma(1+z) \sin(\pi z/2)}{\Gamma[(1+z)/2] z 2^{(z-1)/2}} \right\}^{1/z}, \tag{5}$$

$$\sigma_v = 1,$$

where Γ represents the gamma function.

Although there is a similar random walk in other heuristic algorithms, this walk explores the search space with the cuckoo algorithm more effectively because the Lévy flight achieves longer steps [21]. The Lévy flight produces some

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Objective Function  $f(x)$ ,  $x = (x_1, x_2, \dots, x_d)^T$ 
Generate initial population of  $n$  host nests  $x_i$ 
While ( $t > \text{MaxGeneration}$ ) or (stopping criteria)
    • Get a cuckoo randomly generated solution by Levy flights and then evaluate its quality/fitness  $F_i$ 
    • Choose a nest among  $n$  (say,  $j$ ) randomly
        If ( $F_i > F_j$ )
            • Replace  $j$  by the new solution
        end
        • A fraction ( $p_a$ ) of worse nests are abandoned and new ones/solutions are built /generated
        • Keep best solution (or nests with quality solutions)
        • Rank the solution and find current best
    end while
Postprocess results and visualization

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FIGURE 7: Pseudo-code of the cuckoo search algorithm.

new solutions that are closer to the best solution, which accelerates the local search. In addition, most of the new solutions are produced far enough from the best solution to eliminate the local minimum problem.

The main drawback of the CS algorithm is that its evolutionary operators may not adequately preserve the diversity of its population during the evolution process, and this may cause it to converge earlier than expected and deliver suboptimal solutions. Many studies have been carried out to eliminate this disadvantage. Abed-alguni [22] introduced an improved variation of CS called island-based CS with polynomial mutation (iCSPM) that adapts two improvements to CS. Abed-alguni [23] proposed a new action-selection method called cuckoo action-selection (CAS) method based on the cuckoo search algorithm. Abed-alguni and Paul [24] experimentally evaluated the performance of the CS algorithm after replacing the Lévy flight method in the original CS algorithm with seven different mutation methods. Abed-alguni et al. [25] introduced a variation of CS called exploratory CS (ECS), which incorporates three modifications to the original CS algorithm to enhance its exploration capabilities. Alawad and Abed-alguni [26] presented a variation of iCSPM (island-based Cuckoo Search with highly disruptive polynomial mutation) called discrete iCSPM with an opposition-based learning strategy (DiCSPM) for scheduling workflows in cloud computing environments based on two objectives: computation and data transmission costs. Salgotra et al. [27] are proposed three modified versions of CS to improve the properties of exploration and exploitation. All these versions employ Cauchy operator to generate the step size instead of Lévy flights to efficiently explore the search space. Moreover, two new concepts, division of population and division of generations, are also introduced in CS so as to balance the exploration and exploitation. Salgotra et al. [28] are proposed a new self-adaptive CS (SACS) algorithm to improve

its performance. The algorithm employs adaptive parameters and hence no parameter tuning is required to be done. Only two parameters exist for monitoring the performance of the CS algorithm: α and p_a . The interval $[0, 1]$ is used to select the step size α : the controller of the random search in Lévy flight. Small-sized optimization problems were reported to be solved successfully with a step size of $\alpha = 0.1$ [29]. An important parameter in the CS algorithm, p_a , represents the fraction of cuckoo eggs discovered by the host birds in the real-life phenomenon. In mathematical applications, the convergence rate of the algorithm was reported not to be strongly affected by this parameter and a value of $p_a = 0.25$ was suggested [30]. In this study, a parameter-free CS algorithm (PFCS) proposed by Karahan et al. [31] was preferred. The parameters of the PFCS algorithm (α , p_a) were selected randomly as shown below:

$$p_a = 0.1 + 0.2 * \text{rand}, \quad (6)$$

$$\alpha = 0.1 + 0.9 * \text{rand}. \quad (7)$$

2.4. Determination of the Optimal Rule Curves for Cascaded Reservoirs Using the Cuckoo Search Algorithm. To obtain the operation rule curves for optimal reservoir operation in the two cascaded dams, the codes written in the MATLAB program for the operation model were based on the constraints of the reservoirs, the operational purposes of the sequential streamflow routing, and the optimum turbine flow steps. The objective function was optimized using the cuckoo search algorithm.

The water elevation in the reservoir was kept at the highest possible level to maximize energy production in the cascaded reservoirs. The target water elevations were determined in the reservoir operations every month, taking the irrigation water demands and other constraints into consideration, and the

reservoirs were kept at these elevations. The amount of water used for energy production each month was determined according to the target water elevation.

In obtaining operation rule curves for cascaded reservoirs, the main decision variable of the problem is their target water elevation. Moreover, the optimum turbine flow and energy production times of the units are the design variables of this problem. The objective function created to solve this optimization problem is given in Equation (3), and the design variables used are briefly explained as follows.

2.5. Objective Function.

$$E_{\max} = \sum_{i=1}^{228} (E_{A,i}^1 + E_{A,i}^2) + \sum_{i=1}^{228} (E_{C,i}^1 + E_{C,i}^2 + E_{C,i}^3), \quad (8)$$

where E_{\max} is the total energy production — which is the objective function to be optimized, i is the number of months of operation, $E_{A,i}^1$ and $E_{A,i}^2$ are the monthly energy outputs of Adiguzel Dam's two turbines, and $E_{C,i}^1$, $E_{C,i}^2$, and $E_{C,i}^3$ are the monthly energy outputs of the Cindere Dam's three turbines.

While optimizing the objective function of the problem, the following were considered the constraints of the problem: the maximum storage volume, the maximum and minimum operation elevations and the reservoir volumes corresponding to these operation elevations, the targeted operation elevations at the end of the period, the minimum and maximum turbine flows, and finally, the flows based on energy production. The constraints of the problem are given in Equations (4)-(10) and explained in detail as follows.

2.6. Constraints.

$$S_{i+1} - S_i = I_i - P_i - E_i - IW_i - NV_i, \quad i = 1, 2, \dots, 228, \quad (9a)$$

$$\text{if } S_{i+1} < 0 \text{ then } S_{i+1} = 0, \quad (9b)$$

$$\text{if } NV_i > V_{TM} \text{ then } S_O = NV_i - V_{TM} \text{ else } S_O = 0, \quad (9c)$$

where S_{i+1} is the storage volume at the end of the period, S_i is the storage volume at the beginning of the period, I_i is the monthly reservoir inflow, P_i is the precipitation in the reservoir basin, E_i is the monthly evaporation in the reservoir basin, IW_i is the monthly amount of irrigation water to be released from the reservoir, and NV_i is the net volume to be released from the reservoir at the end of the period, S_O is the overflow volume at the end of the period, and V_{TM} is the maximum turbine volume:

$$h_{1,\min} \leq h_{1,T} \leq h_{1,\max}, \quad (10)$$

$$h_{2,\min} \leq h_{2,T} \leq h_{2,\max}, \quad (11)$$

$$S_{1,\min} \leq S_{1,T} \leq S_{1,\max}, \quad (12)$$

$$S_{2,\min} \leq S_{2,T} \leq S_{2,\max}, \quad (13)$$

$$Q_{A,\min} \leq Q_{A,1}, Q_{A,2} \leq Q_{A,\max}, \quad (14)$$

$$Q_{C,\min} \leq Q_{C,1}, Q_{C,2}, Q_{C,3} \leq Q_{C,\max}, \quad (15)$$

where $h_{1,\min}$ is the minimum operation elevation of Adiguzel Dam, $h_{1,\max}$ is the maximum operation elevation of Adiguzel Dam, $h_{1,T}$ is the target operation elevation of Adiguzel Dam for the month, $h_{2,\min}$ is the minimum operation elevation of Cindere Dam, $h_{2,\max}$ is the maximum operation elevation of Cindere Dam, $h_{1,T}$ is the target operation elevation of Cindere Dam for the month, $S_{1,\min}$ is the reservoir volume of Adiguzel Dam at its minimum operation elevation, $S_{1,\max}$ is the reservoir volume of Adiguzel Dam at its maximum operation elevation, $S_{1,T}$ is the reservoir volume in Adiguzel Dam at the monthly targeted operation elevation, $S_{2,\min}$ is the reservoir volume in Cindere Dam at its minimum operation elevation, $S_{2,\max}$ is the reservoir volume of Cindere Dam at its maximum operation elevation, $S_{2,T}$ is the reservoir volume in Cindere Dam at the monthly target operation elevation, $Q_{A,\min}$ is the minimum turbine flow in Adiguzel Dam, $Q_{A,\max}$ is the maximum turbine flow in Adiguzel Dam, $Q_{A,1}$, $Q_{A,2}$ are the energy production-based monthly flows for Adiguzel Dam, $Q_{C,\max}$ is the minimum turbine flow in Cindere Dam, $Q_{C,\min}$ is the maximum turbine flow in Cindere Dam, and $Q_{C,1}$, $Q_{C,2}$, $Q_{C,3}$ are energy production-based monthly flows for Cindere Dam.

Considering all these constraints, the objective function is maximized and optimal rule curves were obtained. The following stopping criterion were used to check the convergence of the solutions obtained with successive iterations:

$$|f_{\text{best}} - f_{\text{worst}}| \leq \varepsilon, \quad (16)$$

where ε is a small threshold value ($1E-9$), and f_{best} and f_{worst} denote the best and the worst convergence values in the objective function.

3. Results and Discussions

This study demonstrated that the water resources available in Turkey can be used more efficiently and more energy can be produced merely by creating new operational policies in Turkey's existing hydropower storage plants. Unlike other studies conducted in this cascaded reservoir operation study, an optimum turbine flow concept was used. As can be seen from the turbine efficiency curves shown in Figures 5 and 6, the optimum flow is the one that provides an approximately 90% turbine occupancy rate. To determine the optimum turbine flow, models were created using the constraints specified in Section 2.3 according to the number of turbines and turbine design criteria in each power plant. In the cascaded reservoir operation optimization study carried out to develop the reservoir operation rule curves, the monthly turbine volume was distributed among the turbines according to these models by considering the turbine efficiency.

To maximize the total energy production, the sequential streamflow routing method was applied, the objective function created by considering the constraints of each

cascaded reservoir was optimized by the cuckoo search algorithm in the MATLAB program, and the elevations of the reservoir operation rule curves were obtained.

As a result of determining the best reservoir operation policy for each dam, reservoir operation rule curves showing the optimum reservoir operation elevations for each period were obtained.

Tables 1 and 2 with Figures 8 and 9 show the operation elevations currently used and those proposed in this study of the Adiguzel Dam and the Cindere Dam, respectively. Since the current operating levels of Adiguzel Dam and Cindere Dam cannot be obtained online, they were obtained from the Aydın Regional Directorate of State Hydraulic Works in the CD format.

As a result of the optimization study, the proposed operation elevations for Adiguzel Dam are higher than the existing operation elevations in Table 1. Therefore, more energy can be produced without increasing water consumption with the proposed operation elevation. This possibility reveals the importance of reservoir operation policy.

Figure 8 compares the existing operation rule curve with the operation rule curve obtained for the Adiguzel Dam achieved by optimizing the cascaded reservoir operation with the outlined method.

The optimized operation elevations proposed for the Cindere Dam are generally slightly higher than its existing operation elevations, as seen in Table 2. Energy production can be increased by obtaining more head with the proposed operation elevations.

Figure 9 compares the existing operation rule curve with the operation rule curve obtained for the Cindere Dam as a result of optimizing cascaded reservoir operation. As can be seen from Figures 8 and 9, the existing operation elevations are lower than those of the operation rule curves obtained by the optimization study. In addition to contributing to energy production, this allows cascaded reservoirs to have more volume in potential dry periods, thus eliminating the possibility that cascaded reservoirs do not meet the irrigation demands in those periods.

Adiguzel Dam, with an active volume of 821 million cubic meters, is the main storage dam of the cascaded dam system optimized in this study. With the optimization results, Adiguzel Dam operation elevations were increased by approximately 17 m in some months. This increased the cascaded dam system's active storage amount and eliminated the risk that irrigation demands cannot be met during dry periods.

According to the information provided by the DSI Aydın Directorate, Adiguzel Dam achieved 2171.07 GWh of energy production between 1999 and 2017, while Cindere Dam produced 378.97 GWh of energy between 2012 and 2017. In comparison, 2550.04 GWh of energy was produced by these two dams with existing operational policies.

If Adigüzel and Cindere Dams had been operated according to the rule curves obtained by this study, the energy that would have been produced annually as a result of the optimized reservoir operation of the cascaded dams is shown in Tables 3 and 4, respectively.

TABLE 1: Existing and proposed operation elevations for the Adigüzel Dam in meters.

Month	Existing operation elevations	Proposed operation elevations
October	435.30	449.29
November	435.30	452.03
December	435.30	450.44
January	437.25	447.47
February	440.44	448.42
March	443.55	451.92
April	446.10	453.25
May	447.96	453.25
June	448.61	453.25
July	447.20	453.25
August	441.91	445.91
September	435.83	446.96

TABLE 2: Existing and proposed operation elevations for the Cindere Dam in meters.

Month	Existing operation elevations	Proposed operation elevations
October	266.22	265.55
November	266.30	266.13
December	266.30	267.00
January	266.46	267.00
February	266.46	267.00
March	266.46	267.00
April	266.39	267.00
May	266.50	267.00
June	266.30	267.00
July	266.11	267.00
August	266.11	267.00
September	266.11	266.40

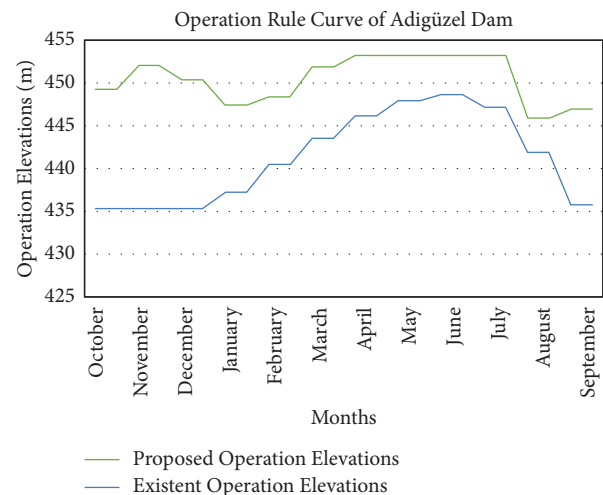


FIGURE 8: Comparison of the existent and proposed monthly operation elevations for the Adiguzel Dam.

The current cumulative energy production of the Adiguzel and Cindere Dams, and the cumulative energy production obtained with the optimal rule curve are

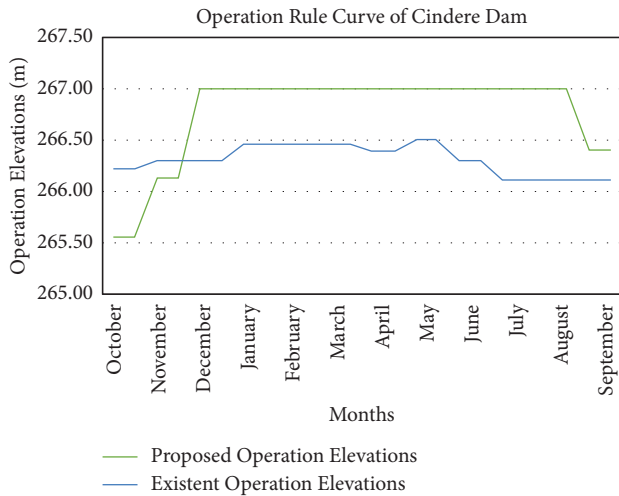


FIGURE 9: Comparison of existent and proposed monthly operation elevations of the Cindere Dam.

TABLE 3: Potential energy production achieved by the Adiguzel Dam optimization.

Year	Energy production (GWh)
1999	102.40
2000	125.21
2001	113.75
2002	122.13
2003	196.67
2004	171.27
2005	132.21
2006	111.09
2007	112.81
2008	101.47
2009	112.58
2010	201.38
2011	170.49
2012	219.03
2013	173.23
2014	113.29
2015	148.01
2016	166.49
2017	101.98
TOTAL	2695.46

TABLE 4: Potential energy production achieved by the Cindere Dam optimization.

Year	Energy production (GWh)
2012	91.44
2013	72.22
2014	48.11
2015	62.91
2016	69.69
2017	55.18
TOTAL	399.54

presented in Figures 10 and 11. These data can be accessed from the website <http://www.enerjiatlas.com> [26]. Adiguzel Dam could have produced 2695.46 GWh of energy

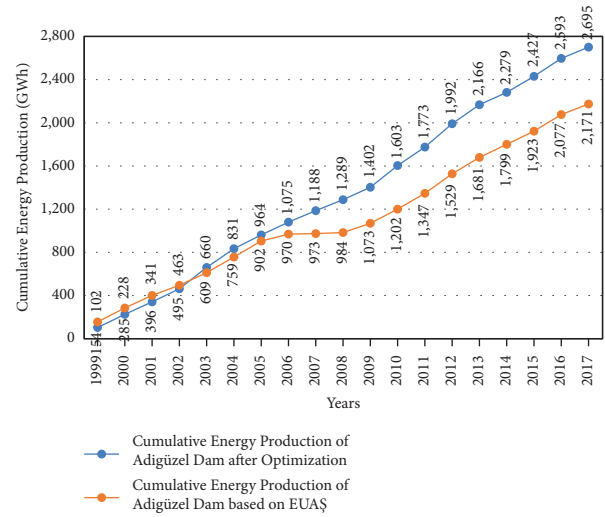


FIGURE 10: Comparison of the existing and proposed cumulative energy production by the Adiguzel Dam.

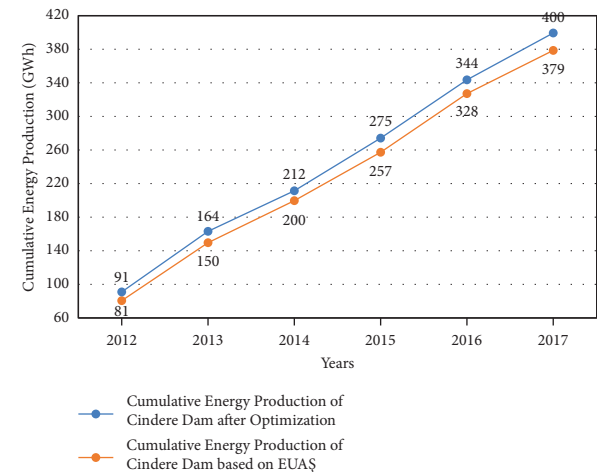


FIGURE 11: Comparison of the existing and proposed cumulative energy production by the Cindere Dam.

between 1999 and 2017, and the Cindere Dam could have produced 399.54 GWh of energy between 2012 and 2017. If they had been operated according to the proposed rule curves, 3095.01 GWh of energy would have been produced by the Adiguzel and Cindere Dams together. All water demands would have been met, and 544.97 GWh more energy would have been produced. This excess energy, potentially produced due to optimization, increases the total energy production of both dams by approximately 18%. Thus, the operational policies developed within the scope of this study confirmed that multipurpose cascaded dams could maximize energy production to meet the primary demands for drinking water, irrigation, and flood control.

Considering the efficient use of existing water resources and the contribution of hydroelectric energy production to the national economy, 544.97 GWh of excess energy would provide a surplus value of approximately USD39.8 million at

a unit price of USD0.073/kWh. It is obvious that by merely by changing the operational policies — without making any extra investment — these cascaded dams can produce more energy and thus contribute more to the national economy.

4. Conclusions

This study was performed not only to optimize the efficiency of freshwater use, which has become more significant due to global climate change, but also to increase the efficiency of hydroelectric power plants and reduce the carbon emissions that are known to be the main driving force behind climate change.

When evaluating the results of this study, operating cascaded dams established on large rivers based on the operation rule curves obtained by more advanced methods instead of storage dams meets all irrigation demands and significantly increases energy production.

Since the results of this study performed on a sample study area make a significant contribution to the national economy, performing this study on all technically appropriate storage hydroelectric power plants in Turkey would add significant value to the national economy.

Moreover, applying the proposals in this study would enable more efficient use of the existing water resources in periods when the water resources and rivers in Turkey are suffering from drought.

Further studies, which were not considered within the scope of the study but may be beneficial, are summarized as follows:

- (1) After obtaining the rule curves, the operation studies should be refreshed by adding the actual monthly data to obtain more up-to-date rule curves.
- (2) This study examined the reservoir operations of two storage dams on the main Büyük Menderes River. The facilities located on the tributaries of the river were not considered. The study can be repeated for all storage facilities in the basin.
- (3) The future operation of reservoirs can be predicted by considering climate change scenarios.
- (4) This study can be repeated using other optimization algorithms.

Data Availability

Relevant data can be obtained from the authors upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

Authors' Contributions

I.A. and M.Y. conceptualized the study; I.A. and M.Y. helped the methodology; I.A. provided software; I.A. and M.Y. validated the study; I.A. and M.Y. did formal analysis; I.A.

investigated the study; I.A. and M.Y. curated the study; I.A. visualized the study; and M.Y. supervised the study.

Supplementary Materials

The provided supplementary materials include the following: Supplementary File S1 (energy productions and operation elevations of Adiguzel and Cindere Dams) related to Tables 1-2 and Figures 8-9, Supplementary File S2 (tail water rating curve of Adiguzel Dam) related to Figure 3, Supplementary File S3 (tail water rating curve of Cindere Dam) related to Figure 4, Supplementary File S4 (turbine efficiency curve of Adiguzel Dam) related to Figure 5, and Supplementary File S5 (turbine efficiency curve of Cindere Dam) related to Figure 6. (*Supplementary Materials*)

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