Hindawi Publishing Corporation
Mathematical Problems in Engineering
Volume 2016, Article ID 1316038, 7 pages
http://dx.doi.org/10.1155/2016/1316038

Research Article

Optimization of Reservoir Operation Using Cuckoo Search Algorithm: Example of Adiguzel Dam, Denizli, Turkey

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Received 22 September 2015; Revised 10 February 2016; Accepted 17 February 2016

Academic Editor: Carla Roque

The Adiguzel Dam is located in Denizli in the western part of Turkey. It was built for irrigation purposes, but it also produces energy at the same time. The dam's energy-production regime is not regular since there are no reservoir-operating rules. Thus, this study develops a reservoir optimization rule to generate a corresponding gain in energy production. It is well known that operating a reservoir is a complex problem that depends on many parameters such as inflow, storage capacity, water elevation, tailwater elevation, and evaporation. Therefore, in order to optimize energy production, there is a need to use heuristic algorithms such as the Cuckoo Search (CS). This study develops a CS algorithm-based solution to optimize the reservoir's operational system and generate an optimal operation rule curve. Results show that the CS algorithm improves the system operation, and the energy production will be increased by about 10% to a value of 160000 MWh with a corresponding economic gain of about $\$12 \times 10^6$ in total for 183 months.

1. Introduction

As in many countries, energy demand has been increasing for many years. Building new power plants is costly and takes a long time. In addition to developing new production facilities for meeting the energy demand, it is obvious that the existing hydroelectric facilities should be used effectively. One of Turkey's primary energy-generating resources is hydroelectric power. In order to improve energy-production efficiency, there is a need to develop an optimal operation rule specific to each power plant like the Adiguzel Dam in Turkey. By developing such optimization techniques, it would be possible to achieve maximum benefits without the need for additional investment.

Demand is an important issue for reservoir management since it is used for environmental preservation, water supply, irrigation, and energy production. A number of factors need to be considered in reservoir operations including inflow, outflow, elevation, and evaporation. Traditional operational systems for reservoirs might not reflect today's various demand parameters on reservoirs. The application of optimization theory to reservoir operations for planning purposes is an important research area that delivers the advantages of producing energy and maximizing economic benefits.

With the development of computers within the last 40 years, optimization techniques have increasingly been refined, especially for managing and operating complex reservoir systems. Other literature shows that optimization techniques are a great help in solving various aspects of reservoir management systems. Yeh [1], Wurbs [2], Chau and Albermani [3], and Labadie [4] have provided an extensive literature review looking at the evaluation of various optimization methods and intensive research on the optimization of reservoir system operations.

A lot of literature describes the use of dynamic programming (DP), linear programming (LP), nonlinear programming (NLP), and Genetic Algorithms (GAs) [5] for developing reservoir-operating rules in water management. For example, Wardlaw and Sharif [6] employed the GA method to study a deterministic, finite horizon, multireservoir system operation and concluded that the approach could be easily applied to nonlinear and complex systems.

L.-C. Chang and F.-J. Chang [7] and Chang et al. [8] used GAs to search for an optimal reservoir-operating schedule and showed that this had produced superior results compared to traditional methods. Cheng et al. [9] proposed a hybrid method that combined a parallel, genetic algorithm with a fuzzy optimal model on a cluster of computers. Chang et al. [10] demonstrated that the optimization of operating curve rules using GAs is effective for flushing schedules in a reservoir.

Shrestha et al. [11] constructed a fuzzy rule-based model to derive operation rules for a multipurpose reservoir. Panigrahi and Mujumdar [12] presented a fuzzy rule-based reservoir operation model for a single-purpose reservoir. The approach adopted was essentially the same as that of Russell and Campbell [13] and Shrestha et al. [11], with the difference that the expert knowledge for framing the fuzzy rules was derived from an explicit stochastic model. A fuzzy rule-based control model for multipurpose real-time reservoir operation was constructed by Dubrovin et al. [14]. Jain et al. [15] presented a study aimed at the application of artificial neural networks for reservoir inflow prediction and operation. Neelakantan and Pundarikanthan [16] used a back-propagation neural network for training to approximate the simulation model developed for the city of Chennai's water supply problem. The neural network was used as a submodel in a Hooke and Jeeves nonlinear programming model to find near optimal policies.

Nagesh Kumar and Janga Reddy [17] presented an elitist-mutated particle swarm optimization technique to derive reservoir operation policies for multipurpose reservoir systems. Afshar et al. [18] proposed the honeybee mating optimization (HBMO) algorithm for solving the single reservoir operation optimization problems. Bozorg Haddad et al. [19] applied the HBMO algorithm to extract linear monthly operation rules for both irrigation and hydropower reservoirs.

It can be seen in the literature that many heuristic methods have been used for optimizing the reservoir-operating system, but there are no studies on the application of the Cuckoo Search (CS) method, even though it is computationally efficient and it has advantages of not being trapped on local optima. Thus, this study proposes the CS algorithm for optimizing the reservoir operation system and sets operation rules for energy production in an example reservoir. In order to initialize the water-management parameters such as water elevation level at storage, water losses, inflow, and outflow are set up with the sequential streamflow routing method. The CS algorithm is applied to improve the performance of the Adiguzel Dam, which has no reservoir-operating rules. The main objective of the study is to develop an optimal operation rule for the Adiguzel Dam for energy production. The Adiguzel Dam has about 1×10^9 m^3 of storage capacity, the crest elevation is 460 m, the gross head is 144 m, and its irrigation area is about 94825 ha.

2. Reservoir Operation Management

Reservoir operation management can be defined as a balancing of available water resources and demand, such as energy production and irrigation. The balanced operation is a complex task that requires a reservoir operation policy, since each reservoir has different limitations and requirements. Operating rules are commonly developed as a guide for real-time reservoir operation.

2.1. Problem Formulation. Reservoir elevations, as a target level, at the end of each month are the decision variables in the optimization problem for the CS algorithm. The amount of water to be released for energy production for each month is decided, based on these target elevations.

The optimization problem is composed of an objective function and a number of constraints. Two turbines produce energy in the Adiguzel Dam. Both turbines have a design flow of 32 m^3/s. The objective is to maximize the total energy production. The energy-production equation is given as

$$W = \eta \gamma Q H \Delta t, \tag{1}$$

where W is power generation, η is turbine efficiency, γ is the specific weight, Q is the power discharge rate, H is the net head, and Δt is the working hours of the turbine.

The objective function and their corresponding constraints are given as

$$Z_{\max} = \sum_{j=1}^{183} \left(W_{1,j} + W_{2,j} \right), \quad j = 1, 2, \ldots, 183, \tag{2}$$

subject to

$$S_{j+1} - S_j = I_j + P_j - E_j - R_j^*, \quad j = 1, 2, \ldots, 183, \tag{3}$$

$$\begin{gathered} x_{\min} \leq x_k \leq x_{\max}, \quad k = 1, 2, \ldots, 12, \\ S_{\min} \leq S_k \leq S_{\max}, \quad k = 1, 2, \ldots, 12, \\ Q_{1,\min} \leq Q_1 \leq Q_{1,\max}, \\ Q_{2,\min} \leq Q_2 \leq Q_{2,\max}, \end{gathered} \tag{4}$$

where $Z_{\max}$ is the objective function that is to be optimized as a total power generation (TWh), $W_{1,j}$ and $W_{2,j}$ are the power generation for turbines 1 and 2 (TWh), respectively, i is an index that shows the turbine number, j is an index that refers to data over a period of one month, $x_{\min}$ and $x_{\max}$ express the minimum and maximum reservoir operation levels, S_{j+1} indicates the real storage volume at the end of the period, S_j depicts the storage volume at the beginning of the period, and I_j, P_j, E_j, and R_j^* represent monthly inflow, precipitation, evaporation, and real release volumes at the end of each period, respectively. The value k is an index that represents the months within the year, x_k is the target reservoir operation level (m), and $Q_{1,\min}$ and $Q_{2,\min}$ are the minimum discharge rates for the turbines. The values $Q_{1,\max}$ and $Q_{2,\max}$ identify the maximum discharge rates for the turbines. The values Q_1 and Q_2 express the estimated discharge rates for turbines. Expression (3) represents the continuity equation, while (4) are the constraints.

2.2. Cuckoo Search Algorithm. The CS method was first used by Yang and Deb [20]. It is inspired by the cuckoo species that lay their eggs in the host's nest, which belong to birds of other species. At this stage, if a host bird recognizes that

```
Generate initial population of $n$ nests $x_i$, $i = 1, 2, \ldots, n$
for $i = 1 : n$
    Determine fitness value $F_i = f(x_i)$
end for
while (stopping criterion is not satisfied)
    Generate a cuckoo egg ($x_j$) from random nest by Lévy flights
    Determine fitness value $F_j = f(x_j)$
    Select a random nest $i$
        if $F_j > F_i$ then
        $x_i \leftarrow x_j$
        $F_i \leftarrow F_j$
        end if
    Abandon a fraction $p_a$ of the worst nests
    Build new nests by Lévy flights
    Compare fitness of new nests and keep best nest
end while
```

Algorithm 1: Cuckoo Search algorithm.

the eggs belong to other birds, there are two choices: the first one is that these alien eggs are moved away, and the second one is that the host bird leaves the nest and builds a new nest in a different place. This behavior clearly decreases the probability of their eggs being abandoned and thus their chances of hatching are increased [21]. Additionally, although it does not seem possible, a cuckoo chick is able to imitate the call of the host chicks in order to get more feeding opportunities [22]. Also, the so-called guest cuckoo eggs hatch much earlier than the host eggs. Once the cuckoo chick hatches, its first behavior is to blindly push the host eggs out of the nest. This behavior definitely increases the chance of the cuckoo chick being fed [21]. As summarized, the CS algorithm idealizes cuckoo's breeding behavior and thus can be applied to solve different optimization problems as proved in the relevant literature [23].

In the light of the literature reviewed, the following fundamental rules can be used for solving a given optimization problem using the CS algorithm:

(i) Choosing the best solution by means of picking the best nests.

(ii) Replacement of host eggs depending on the quality of the new solutions.

(iii) Discovery of some cuckoo eggs by the host birds and replacement based on the quality of local random walks [24].

The CS algorithm steps are based on these rules and given in Algorithm 1 [23].

One of the most important steps in the algorithm is the use of Lévy flights for random searches. The Lévy flight is a type of random walk and described by a sequence of jumps determined from a probability density function [25, 26]. The step size α, which controls the random search process in Lévy flight, is generally selected between the intervals 0 and 1. Setting $\alpha = 0.1$ may produce efficient results, especially for small-sized optimization problems [26]. The other important parameter in the CS algorithm is p_a, which resembles the discovery of the cuckoo eggs by the host birds. Yang and Deb [27] emphasized that the convergence rate of the algorithm was not strongly affected by the p_a value; hence they recommend setting $p_a = 0.25$. The number of nests (n) and the maximum number of generations have been set to 20 and 1000, respectively.

The vector of the new nest is generated from randomly selected ith nest by Lévy flights using

$$\text{new\_nest}_i^t = \text{nest}_i^t + \alpha L \left(\text{nest}_i^t - \text{nest}_{\text{best}}^t\right), \tag{5}$$

where new_nest_i^t is the new nest generated by Lévy flights, nest_i^t is a randomly selected nest from the population, $\text{nest}_{\text{best}}^t$ is the best nest obtained so far, α is step size, and L is the step length or Lévy flights vector.

After determining the new nest, the objective function values of two nests are calculated using (2) and the best nest is kept.

Step length L can be determined as follows:

$$L = \frac{u}{|v|^{1/\beta}}, \tag{6}$$

where β is the scale parameter and the recommended range is between 1 and 2. The β value is set to 1.5 in this study. The values u and v are obtained from normal distribution as

$$\begin{gathered} u = N\left(0, \sigma_u^2\right), \\ v = N\left(0, \sigma_v^2\right), \end{gathered} \tag{7}$$

where N denotes normal distribution; σ_u and σ_v can be calculated by using the following equation [23]:

$$\begin{gathered} \sigma_u = \left\{ \frac{\Gamma(1+\beta)\sin(\pi\beta/2)}{\Gamma\left[(1+\beta)/2\right]\beta 2^{(\beta-1)/2}} \right\}^{1/\beta}, \\ \sigma_v = 1, \end{gathered} \tag{8}$$

where Γ denotes the gamma function.

The exploration of alien eggs is performed for all the eggs using the probability matrix P, which is produced as

$$p_{ij} = \begin{cases} 1, & \text{if } \operatorname{rand}(0,1) < p_a \\ 0, & \text{otherwise,} \end{cases} \tag{9}$$

where p_{ij} is the discovery probability for the jth variable of the ith nest in the matrix of P. The value of p_a is compared with the value provided by using rand (0, 1) to determine whether a local random walk is considered or not. After determining the discovery probabilities, new nests are produced using

$$\text{new\_nest}^t = \text{nest}^t + K * P, \tag{10}$$

where K is the matrix of local step size produced by using

$$\begin{aligned} K = \operatorname{rand}() * (&\text{nests}[\text{permute 1}[i]][j] \\ &- \text{nests}[\text{permute 2}[i]][j]). \end{aligned} \tag{11}$$

The value rand() is a random number generator with an interval between 0 and 1 and permute 1 and permute 2 are different rows permutation functions applied to the nests matrix [28]. Finally, the existing and new objective function values are compared for each nest and the best nest is used for the next generation according to the simple rule given in

$$\text{nest}_i^{t+1} = \begin{cases} \text{nest}_i^t, & \text{if } F(\text{nest}_i^t) < F(\text{new\_nest}_i^t) \\ \text{new\_nest}_i^t, & \text{otherwise.} \end{cases} \tag{12}$$

The generation of new nests and the steps of discovering the alien eggs are repeated until a stopping rule is satisfied or the maximum number of generations is reached.

3. Case Study

Adiguzel Dam is located in the province of Denizli, in western Turkey on the Great Menderes River. The dam was completed in 1993 and came into operation in 1996. The main function of the dam is for irrigating an area of 94825 ha. It also serves to generate power while irrigating the land.

The minimum water elevation of Adiguzel Dam is 403.25 m and the maximum water elevation is 453.25 m. The total reservoir capacity is 1.075 billion m^3. The active capacity at maximum level is 849 million m^3. Energy is generated by two different turbine units of 31 MW (2 × 31). The maximum net head of water in the power plant is 136.535 m and the minimum net head is 86.35 m. The tailwater chute base elevation is 316.90 m. The cross-sectional view of the Adiguzel Dam is shown in Figure 1.

Monthly average data measured for 183 months from October 1998 to December 2013 is used in this study. Monthly average inflow, irrigation, and evaporation values are shown in Figure 2.

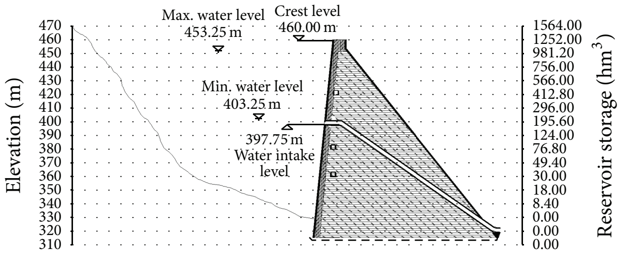

FIGURE 1: Cross-sectional view of Adiguzel reservoir.

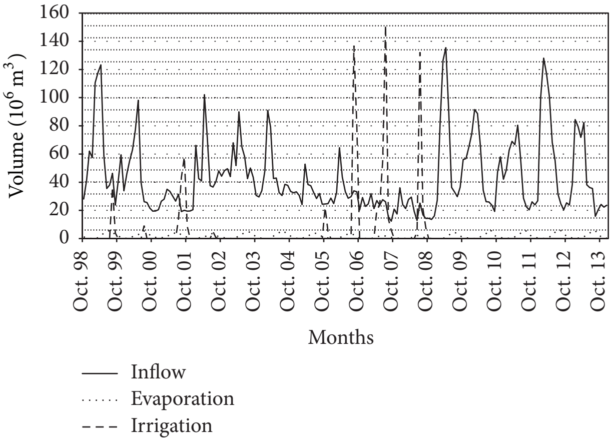

FIGURE 2: Monthly mean inflow, irrigation, and evaporation values.

The water taken into the turbines is used for the irrigation of downstream agricultural lands. Reservoir operation is carried out only to supply the irrigation water demands without any consideration of maximizing energy production. The power plant produced 1.70 TWh of energy in 183 months according to the State Hydraulic Works (DSI) [29].

The application of the CS algorithm is carried out with data provided on the Adiguzel Dam by DSI [29]. The convergence graph of the CS algorithm is given in Figure 3.

The CPU time takes about 10 hours. The CS algorithm was coded using the Matlab 7.8 software package and run on a Windows 7, 128 GB RAM, 2.80 GHz dual-processor workstation. As can be seen in Figure 3, the convergence of the algorithm reaches the global or near global optimum after 2000 generations. The CS algorithm showed a steady convergence for this problem. The $Z_{\max}$ value on the y-axis in Figure 3 shows the best-fitness values for total energy production.

After the convergence, the final average values of the targeted elevations are given in Table 1 on a monthly basis.

In order to compare the final values of the average elevations obtained from the CS algorithm, the energy-production values and their corresponding elevations with measurements provided by the Electricity Generation Company (EUAS) [30] are given in Figure 4. The average operating elevations from EUAS are far lower than those calculated in this study. Therefore, if this dam is operated using the proposed operating rules, there will be higher energy production than with the current operational conditions without any extra cost.

Figure 5 shows the cumulative energy production predicted by EUAS and calculated in this study.

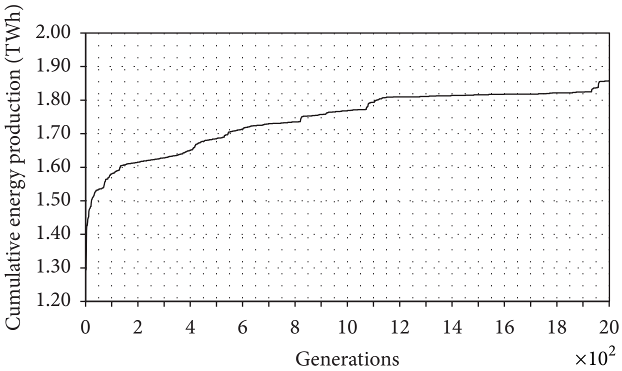

Figure 3: Convergence graph for CS algorithm.

Table 1: Average elevations obtained with CS algorithm.

Months	Optimal average elevations (m)
October	445.84
November	447.59
December	452.86
January	451.02
February	449.39
March	447.26
April	445.29
May	450.50
June	451.13
July	445.33
August	452.98
September	442.60

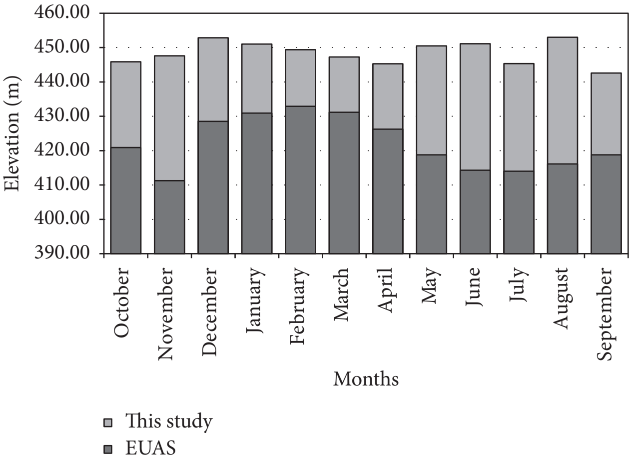

Figure 4: Comparison of average elevations calculated in this study with those provided by the EUAS.

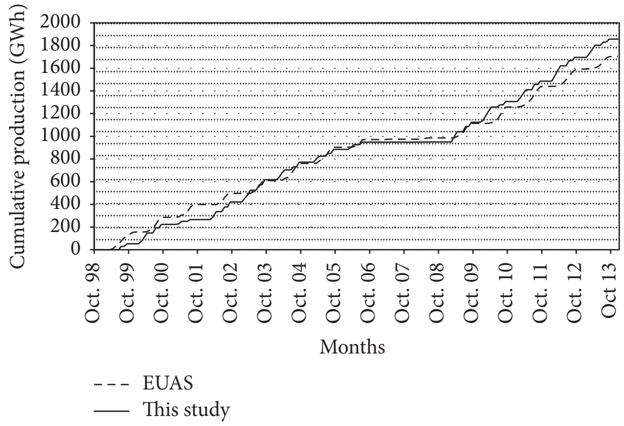

Figure 5: Comparison of the EUAS and the CS algorithm for cumulative energy production.

As can be seen in Figure 5, at the end of 2013, EUAS produced about 1.70 TWh and the CS algorithm about 1.86 TWh, an increase of 160.000 MWh. This value indicates an economic gain of about $\$12 \times 10^6$ in total. As known, there are two basic variables in calculating the hydroelectric energy production: flow and head. It is not possible to increase the flow. It is obvious that production can only be increased by increasing the net head of water. The amount of production in the early years was observed to be higher than the proposal put forward in this study when the cumulative production curve was assessed. The reason for this was the storing of water in the reservoir to increase the head by satisfying the irrigation requirements. After the water level in the reservoir rose to the desired level, CS based solution method provides higher amount of energy production than those obtained by EUAS. Note that this was achieved by the same amount of water passing through the turbines.

4. Conclusions

The Cuckoo Search (CS) algorithm, which is one of the most powerful nature-inspired algorithms, was developed for solving global optimization problems. The CS is inspired by the breeding behavior of some cuckoo species. In recent years, because of its simplicity and efficiency, the CS has been applied to engineering optimization problems. The reason for its superiority is underpinned by the fact that the CS algorithm requires fewer parameters that need to be fine-tuned compared to most other similar algorithms. Thus, in this study, the CS algorithm is used to solve the optimal elevation values for the reservoir-operating system. The proposed algorithm evaluates the reservoir-operating system by considering the irrigation demand on reservoir management. The following conclusions were drawn from this study:

(1) The proposed CS algorithm showed a steady convergence in finding a solution for the reservoir-operating system and the optimal or near optimal operating rule curve has been successfully obtained.

(2) By applying the optimized operating rules, energy production will be increased by about 10% to a value of 160000 MWh with an economic gain of about $\$12 \times 10^6$ in total for 183 months.

(3) The results may help operators to efficiently apply new reservoir-operating rules for energy production

without any extra effort or additional cost. It is also easy to update the CS algorithm with new data, when available, while the reservoir is in operation.

(4) Different pricing is implemented at different times to balance the supply and demand in Turkey. The price is high when the consumption rate is high and low when the consumption is low. Within this study, energy maximization was achieved by considering the average energy pricing. Rather than energy maximization, profit maximization can be preferred by considering the supply and demand balance in a future study.

(5) Statistically, the best rule curve can be obtained by using the longest available data set. Using the rule curve obtained with the 183-month data set for the whole-life cycle of the dam may lower the efficiency. In order to increase the efficiency, the rule curve must be updated by using new data measured at certain periods.

(6) There are several studies in literature to assist in estimating the possible results of climate change and its effects on water resources quantity. It would be beneficial to revise the rule curves by considering these estimations and benefiting from these studies and their different consequences.

(7) Finally, the performance of the CS algorithm should be tested for multireservoir-operating systems.

Conflict of Interests

The author declares that there is no conflict of interests.

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