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Optimization of energy management and conversion in the multi-reservoir systems based on evolutionary algorithms

Mohammad Ehteram [a,*], Hojat Karami [a], Sayed-Farhad Mousavi [a], Saeed Farzin [a], Ozgur Kisi [b]

[a] Department of Water Engineering and Hydraulic Structures, Faculty of Civil Engineering, Semnan University, Semnan, Iran
[b] School of Natural Sciences and Engineering, Ilia State University, Tbilisi, Georgia

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ABSTRACT

Concerning water and energy crisis, energy management and correct utilization of resources are important. In the present study, utilization of a multi-reservoir system was addressed with an approach to improve production of hydroelectric energy. For this purpose, Monarch Butterfly Algorithm (MBA), which is a new evolutionary algorithm, was used. Three periods of dry (1963–64), wet (1951–52) and normal (1985–86) conditions were considered in the operation of a 4-reservoir system. Results showed that MBA was capable of generating more energy as compared to Particle Swarm Optimization (PSO) algorithm and Genetic Algorithm (GA). For instance, MBA improved the accuracy of GA and PSO in generating energy by 1.16 and 0.88 percent in the wet year, 1.28 and 1.2 percent in the dry year and 1.34 and 0.88 percent in the normal year, respectively. Moreover, quality of the responses obtained from the MBA was better than those of the other two algorithms, because coefficients of variation of the responses in MBA were less.

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1. Introduction

Human being has always been concerned with water and energy crisis. Regarding the global population growth and increased demands, managing energy and resources is of a great importance (Zou et al., 2017). One of the important energies used by the humans is hydroelectric energy (Al-falahi et al., 2017). The hydroelectric energy produced by power plants and the related turbines are utilized based on water reception from upstream dams (Aali et al., 2017). Therefore, the issue of exploitation of power plants and electricity generation is associated with the amount of the input water to the turbines (Jafarian et al., 2017; Dahunsi et al., 2017). How the water is released from single-reservoir and multi-reservoir systems of dams, such that the amount of power-plant energy is adequate for supplying hydroelectric demands, have significant importance (Bellos et al., 2017). The issue of energy production is closely linked to the issue of exploitation of reservoirs (Mathimani et al., 2017). Calculating the output of multi-reservoir water systems, so that the energy production is maximal regarding the input water to the turbines, is one of the objectives of interest for researchers (Lv et al., 2017). During the recent years, researchers have used various mathematical models in order to calculate dams' water release, aiming at maximizing energy production in the downstream power plants. One of the important issues in this field is utilization of multi-reservoir water systems with the purpose of increasing power generation in the downstream power plants. The evolutionary algorithms have recently gained a good position in the field of solving the problems related to the utilization of power plants and dams. Labadie (2004) used a nonlinear approach in order to maximize energy production from a dam's reservoir. This approach was properly able to perform water management for energy production, in addition to the simplicity of the calculations. Ballester and Carter (2017) used GA for utilizing a multi-reservoir system in order to maximize energy production. This method resulted in greater power production in the downstream power plant, as compared to the nonlinear method. Chang et al. (2010) used GA to maximize energy production in a reservoir. Results indicated that this algorithm gave higher energy in the downstream power plant, as compared to dynamic programming method. Afshar (2012) used PSO algorithm to increase the profit from hydroelectric energy production in multi-reservoir systems. Results showed that PSO algorithm had high capability in energy

* Corresponding author.
E-mail address: mohammdehteram@semnan.ac.ir (M. Ehteram).

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generation, compared to GA. Afshar et al. (2015) used Ant Colony Algorithm (ACA) for operation of multi-objective systems with the aim of producing more energy in the downstream power plants. Results revealed that a higher energy was obtained by applying ACA, as compared to other evolutionary algorithms.

A successful algorithm that has recently been developed by Wang et al. (2015) in the field of engineering optimization is the Monarch Butterfly Algorithm (MBA). Wang et al. (2015) applied this algorithm in optimizing complex mathematical functions. Also, this algorithm has high efficiency in other engineering fields. It converges fast and the obtained responses are close to the absolute optimized answer.

In fact, there are different methods for operation of multi-reservoir systems. Traditional methods include linear programming, dynamic programming, and nonlinear methods. However, each method has its own limitations. For instance, in the problems of operating multi-reservoir systems, the use of nonlinear objective functions makes the linear method non-applicable when there are a lot of decision variables, or dynamic programming method requires high computations time. Therefore, metaheuristic algorithms are recommended for solving the important problems of operating multi-reservoir systems (like water release rates, hydroelectric production, flood storage, etc.).

2. Problem statement and innovation

The meta-heuristic algorithms are of different problems. For instance, some of them fall into the trap of local optimizations and find the local optimal answer instead of finding the absolute optimal answer. Moreover, there are some other algorithms that are of low convergence speed. In addition, one another problem is the lack of balance between exploration and exploitation capabilities. The exploration capability is the ability of the evolutionary algorithm in free search without any consideration of its findings during the searching process. In contrary, the exploitation capability is known as the amount of the algorithm attention paid to its achievements during the searching process. Obviously, the more the exploration capability in a searching algorithm, the more random and unexpected behavior the algorithm will have. In contrast, enhancement of the exploration in an algorithm causes it to have a more cautious and counted behavior. The lack of balance between the exploration and exploitation capabilities is observed in a large number of the evolutionary algorithms (Amini et al., 2017). The Monarch Butterfly algorithm can adjust a balance between the exploration and exploitation capabilities by using migration and adjustment operators and applying parallel processing. Also, unlike other evolutionary algorithms, the Monarch Butterfly algorithm accelerates the calculation process by the help of simpler operators compared with other evolutionary algorithms. One of the important factors is the adjustment of random parameters of the evolutionary algorithms. By having less number of parameters relative to other evolutionary algorithms, the Monarch Butterfly algorithm is also of a better process in the determination of random parameters. Therefore, the new Monarch Butterfly algorithm is of more efficiency in the optimization process.

The present study aims to maximize energy production in downstream power plants of a multi-reservoir water system. Water level in the reservoirs is considered as decision variable. Moreover, in order to solve this complex optimization problem with non-convex, nonlinear objective function, the MBA is used. Outputs of the above problem include the amount of produced hydroelectric energy by the power plants, the hydraulic head, and the reservoirs' water level. Hence, the novelty of this research is application of a new algorithm in order to improve the efficiency of energy production in a multi-reservoir system.

3. Materials and methods

3.1. Monarch butterfly algorithm

One of the important species of butterflies in North America is monarch butterfly. These butterflies are distinguished from other butterflies by their colorful wings. Butterflies of the Southeast of North Americas are known by their remarkable ability to migrate from America and southern Canada to Mexico and travel thousands of kilometers. Accordingly, the following assumptions are used in simulating the behavior of monarch butterflies, and their migration, in solving the optimization problems:

1 Monarch butterflies include total population of monarch butterflies in lands 1 and 2. The monarch butterflies migrate from land 1 to land 2 in April and return to land 1 in September.
2 The migration operator produces each child of the monarch butterfly in lands 1 and 2.
3 To keep the population of monarch butterflies constant, older ones are removed and younger butterflies are born.
4 Monarch butterflies with better objective function are automatically transferred to the next generation. Thus, the superior butterflies are never removed due to population regeneration.

3.2. Migration operator

To simplify the calculations, it is assumed that monarch butterflies live in land 1 from April to August and in land 2 from September to March. Therefore, population of monarch butterflies in land 1 is equal to $NP_1 = rou(p \times NP)$ and in land 2 is equal to $NP - NP_1$, where *rou*rounds $p \times NP$ to the nearest integer number, NP is total number of monarch butterflies and p is the ratio of monarch butterflies in land 1 to total population of monarch butterflies. The monarch butterflies in lands 1 and 2 are specified as subpopulations 1 and 2, respectively. The migration is based on the following equation:

$$x_{i,k}^{t+1} = x_{r_1,k}^{t} \quad (1)$$

where, $x_{i,k}^{t+1}$ is the kth element of the generation x_i in the generation $t+1$, which represents the location of ith butterfly. Similarly, $x_{r_1,k}^{t}$ is the kth element of x_{r1}, which is the new location of butterfly r_1. The r_1 monarch butterfly is selected from subpopulation 1. When $r \le p$, the kth element in the new generation of the butterflies is produced based on equation (1) that r is calculated according to the following equation:

$$r = rand*peri \quad (2)$$

where, *peri* denotes the migration period, usually taken as 1.2 (Wang et al., 2015) and *rand* is a random number of uniform distribution. On the other side, if $r > p$, the k element in the new population is determined by the following relation:

$$x_{i,k}^{t+1} = x_{r_{2,k}}^{t} \quad (3)$$

where, $x_{r_{2,k}}^{t}$ is the kth element of x_{r2}. Also, the monarch butterfly r_2 is from subpopulation 2. It is observed from the above analyses that the direction of migration operator is adjusted by p rate. If the mentioned parameter is large, then more butterflies are selected from land 1, and subpopulation of land 1 plays an important role in producing new butterflies. If the mentioned parameter is small, then more butterflies are selected from land 2 and subpopulation of

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