

# Hedging rule-based optimized reservoir operation using metaheuristic algorithms

## *Fonctionnement optimisé du réservoir basé sur des règles de couverture à l'aide d'algorithmes métaheuristiques*

Mojtaba Shourian<sup>1\*</sup>, and Javad Jamshidi<sup>1</sup>

<sup>1</sup>Faculty of Civil, Water and Environmental Engineering, Shahid Beheshti University, Tehran, Iran

**Abstract.** In this study, optimal operation of a reservoir by incorporation of the hedging policy and the Bat Algorithm (BA) is investigated. The deficit in water supply by the dam is minimized as the objective function and the optimal monthly releases from the reservoir are determined and compared in three hedging-based operation rules. In the first rule, which has a single decision variable, a constant monthly release is considered for all 240 months of the operation period. In the second scenario, one fixed release is determined for each month of the year and is repeated in successive operating years which results 12 decision variables for the problem. In the third rule, all monthly releases are varied as the decision variables resulting 240 unknowns for the problem. The developed models are utilized for the Zhvagh reservoir in west of Iran. Results show that while BA is a suitable algorithm to be applied for optimal reservoir operation planning, the amount of water deficit is lower when a higher degree of freedom is defined for the operating rules.

**Résumé.** Dans cette étude, le fonctionnement optimal d'un réservoir par incorporation de la politique de couverture et du Bat Algorithm (BA) est étudié. Le déficit d'approvisionnement en eau du barrage est minimisé, car la fonction objective et les rejets mensuels optimaux du réservoir sont déterminés et comparés dans trois règles d'exploitation basées sur la couverture. Dans la première règle, qui a une seule variable de décision, une libération mensuelle constante est prise en compte pour les 240 mois de la période d'exploitation. Dans le second scénario, une version fixe est déterminée pour chaque mois de l'année et est répétée au cours des années d'exploitation successives, ce qui donne 12 variables de décision pour le problème. Dans la troisième règle, toutes les versions mensuelles sont modifiées en tant que variables de décision résultant de 240 inconnues pour le problème. Les modèles développés sont utilisés pour le réservoir de

---

\* Corresponding author: [m\\_shourian@sbu.ac.ir](mailto:m_shourian@sbu.ac.ir)

Zhaveh à l'ouest de l'Iran. Les résultats montrent que, bien que BA soit un algorithme approprié à appliquer pour la planification optimale de l'exploitation du réservoir, le montant du déficit en eau est plus faible lorsqu'un degré de liberté plus élevé est défini pour les règles d'exploitation.

## 1 Introduction

Although a systematic approach for water resources planning is not limited to mathematical modeling, but these models can effectively reveal the internal relations and interactions between the elements of a water resources system. Moreover, use of mathematical models allows estimation of physical and economic consequences of various operation policies for water storage and transfer structures. The main goal for reservoir operation is to supply water for the demands in a way that the lowest deficits occur during the operation period. This issue becomes more complicated in drought periods or arid regions. Mathematical simulation and optimization models are useful tools to deal with this problem [1].

As one of the common policies for reservoirs operation is the hedging policy which aims to ration the reservoir's storage for meeting the downstream demands. In this field, Draper and Lund stated that the hedging rules for reservoir storage result an acceptable level of water deficit over a long period of operation [2]. Tu et al. optimized hedging rules for reservoir operations [3]. They reevaluated and updated the existing hedging rules to incorporate changes that have taken place in the reservoir system, as well as the demand characteristics. Dariane and Karami combined artificial neural networks, hedging rules and a heuristic algorithm to optimize operation of the reservoirs system in Tehran [4]. Huang et al. analyzed optimal hedging rules for operation of a dual-purpose reservoir based on economic and multi-level environmental objectives and achievement of a balance between environmental and downstream water supply purposes [5]. Spiliotis et al. optimized a reservoir operation in Spain by using the hedging rules and the particle swarm optimization algorithm [6]. Kranthi and Srinivasan introduced generalized two-point linear hedging rules for operation of a reservoir which are identified based on two possibilities for the initial and ending water storages [7]. Shenava and Shourian used a novel optimization-simulation approach for optimal reservoir operation with water supply enhancement and flood mitigation objectives [8].

Recently, Bat Algorithm (BA) which acts based on position and sound of bats is applied in engineering optimization problems as an efficient metaheuristic method. The bats use echolocation ability for finding a prey. Yang found global optimum solutions well by applying the bat algorithm for benchmark functions [9]. Reddy and Manoj applied the bat algorithm for finding the optimum capacitor placement to reduce loss of energy [10]. For energy optimization, Niknam et al. showed the bat algorithm led to better distribution and management of power energy than did the genetic algorithm [11]. Ethteram and et al. incorporated BA with different ordered rule curves for dam-reservoir operation [12]. Ahmadianfar et al. optimized multireservoir operation by hybridizing bat algorithm and differential evolution [13]. Zarei et al. optimized reservoir operation using bat and particle swarm algorithm and game theory based on optimal water allocation among consumers [14].

In the present study, application of the hedging policy for optimal operation of the Zhaveh Dam in Iran using the bat algorithm is investigated. Zhaveh Dam is one of the most important dams to be constructed in west of Iran. The height of the dam and operation of the reservoir due to its downstream users are some of the challenging subjects. Therefore, optimum operation of the reservoir is assessed in this study. Three hedging-based rules are defined for the reservoir operation and the water supply deficit is minimized as the objective function.

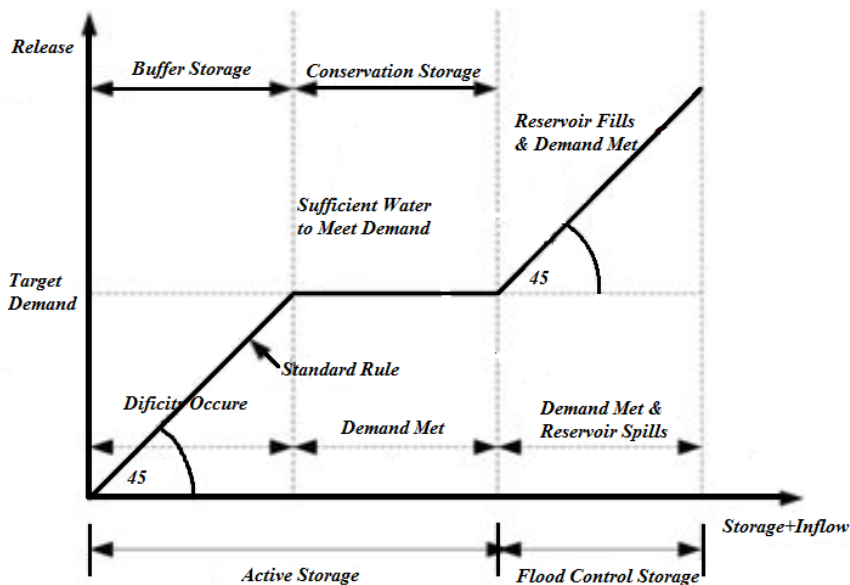
## 2 Methodology

### 2.1 Reservoir Operation Policy

A reservoir operation policy is a decision support tool that provides guidance for reservoir operations to meet the requirements of various users [15]. In general, it is widely known in the following forms.

#### 2.1.1 Standard Operating Policy

A standard operating policy (SOP) is the simplest and most often-used reservoir policy that releases, if possible, only the demand required in each period, and does not preserve water for future requirements. If sufficient water is not available to meet demand, the reservoir is emptied. If there is excess water, the reservoir will fill and then spill the excess water as shown in Figure 1. Thus, standard operating policy is the optimal operating policy with the objective to minimize the total deficit over the time horizon [16].

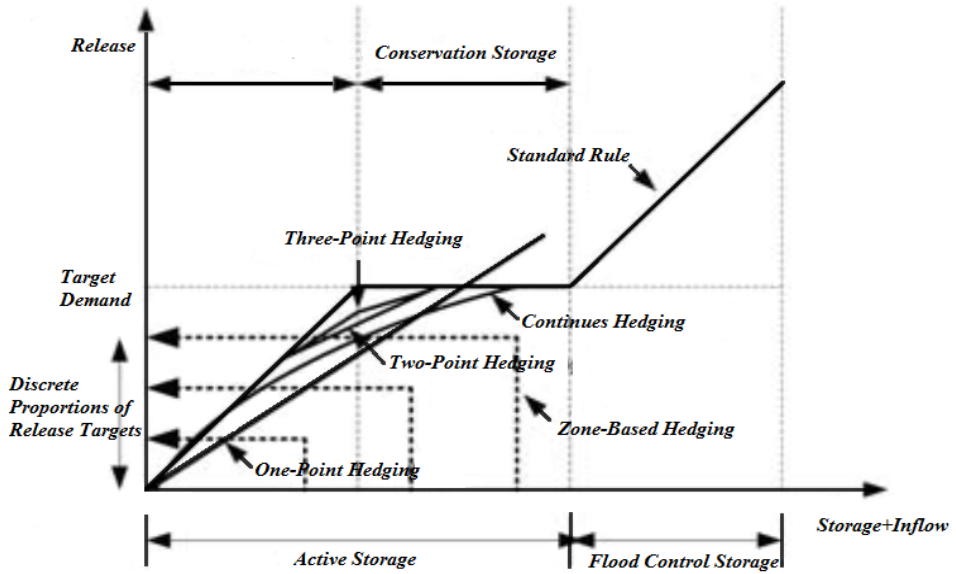


**Fig. 1.** Standard operating policy.

#### 2.1.2 Hedging Policy

The concept of a hedging policy has been formulated since the 1980’s and has been further emphasized in water resources planning and management up to the present. A hedging policy attempts to retain existing water storage for use in later periods. In principle, some water is stored, even when there is enough water for target demand in the present period. The common forms of hedging are described in the following manners [2]:

- (1) One-point hedging; release begins at the origin in Figure 2 and increases linearly until it intersects with the target level of release.



**Fig. 2.** Types of hedging rule for reservoir operation.

(2) Two-point hedging; a linear hedging rule begins from a first point occurring somewhere up from the origin in the shortage portion of the standard operation policy, to a second point occurring where the hedging slope intersects the target release.

(3) Three-point hedging; an intermediate point is specified in the above rule, introducing two linear portions to the hedging portion of the overall release rule.

(4) Continuous hedging; the slope of the hedging portion of the rule can vary continuously.

(5) Zone-based hedging; hedging quantities are discrete proportions of release targets for different zonal levels of water availability.

## 2.2 Bat Algorithm

Bats, the only winged mammals, can determine their locations while flying using sound emission and reception, which is called echolocation. Most bats are insectivores and use a type of sonar, called echolocation, to detect prey, avoid obstacles, and locate their roosting crevices in the dark. Bats emit sound pulses while flying and listen to their echoes from surrounding objects to assess their own location and those of the echoing objects. Each pulse has a constant frequency and lasts a few thousandths of a second. About 10 to 20 sounds are emitted every second with the rate of emission up to approximately 200 pulses per second when they fly near their prey while hunting. As the speed of sound in air is typically  $v = 340$  m/s, the wave length ( $\lambda$ ) of the ultrasonic sound bursts with a constant frequency ( $f$ ) and is given by:

$$\lambda = \frac{v}{f} \tag{1}$$

In simulations, we have to use virtual bats. We have to define the rules how their positions  $x_i$  and velocities  $v_i$  in a d-dimensional search space are updated. The new solutions  $x_i^t$  and velocities  $v_i^t$  at time step t are given by [9]:

$$f_i = f_{min} + (f_{max} - f_{min})\beta \tag{2}$$

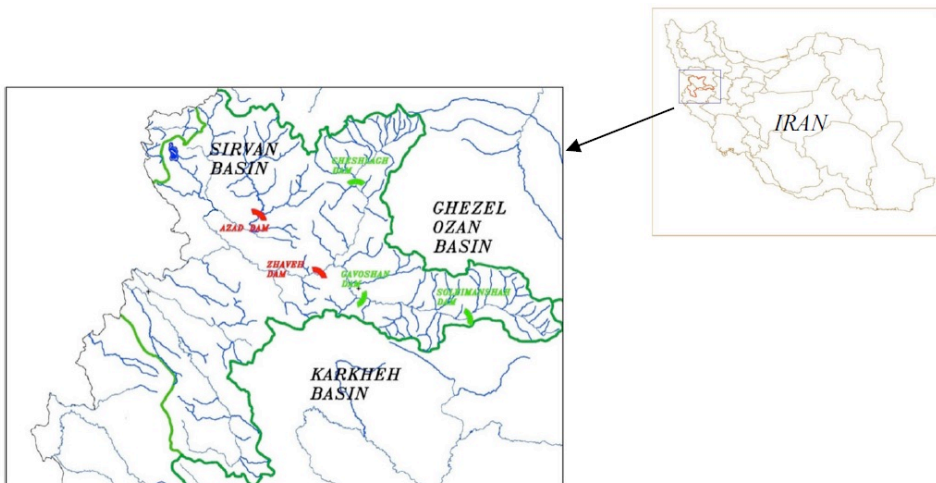
$$v_i^t = v_i^{t-1} + (x_i^t - x_*)f_i \tag{3}$$

$$x_i^t = x_i^{t-1} + v_i^t \tag{4}$$

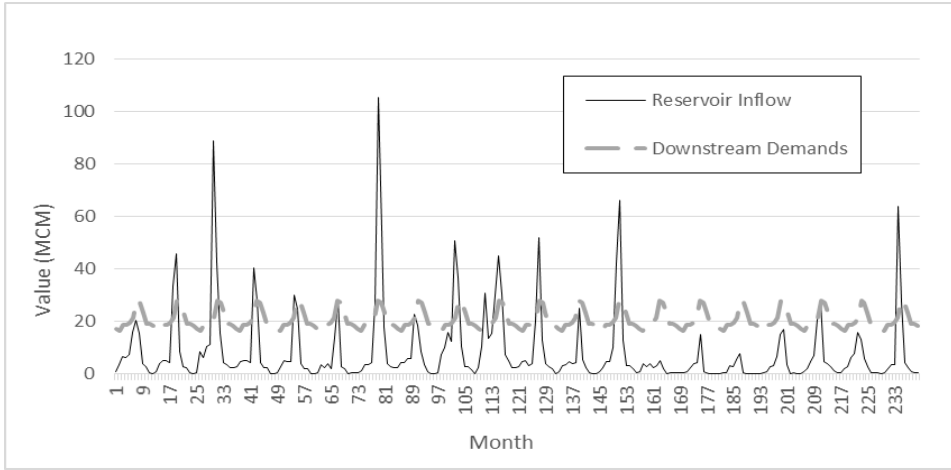
where  $\beta \in [0,1]$  is a random vector drawn from a uniform distribution. Here  $x_*$  is the current global best location (solution) which is located after comparing all the solutions among all the n bats. As the product  $\lambda_i f_i$  is the velocity increment, we can use  $f_i$  (or  $\lambda_i$ ) to adjust the velocity change while fixing the other factor,  $\lambda_i$  (or  $f_i$ ), depending on the type of the problem of interest. In our implementation, we will use  $f_{min} = 0$  and  $f_{max} = 1$ , depending on the domain size of the problem of interest. Initially, each bat is randomly assigned a frequency which is drawn uniformly from  $[f_{min}, f_{max}]$ . For the local search part, once a solution is selected among the current best solutions, a new solution for each bat is generated locally using random walk [2].

### 3 Case Study

The Zhavveh Reservoir is located on the Sirvan River in west of Iran. The maximum storage capacity of the reservoir is 169 million cubic meters (MCM). In Figure 3, location of the Zhavveh Dam in the Sirvan River Basin is shown. Average discharge of the Sirvan River at the dam site is 0.26 cubic meters per second ( $m^3/s$ ) which produces an average annual inflow of 8.11 MCM to the reservoir. In Figure 4, the time series of the monthly inflows to the Zhavveh reservoir and the downstream demands are plotted. The reservoir's maximum and minimum storages are 169 and 27 MCM, respectively.



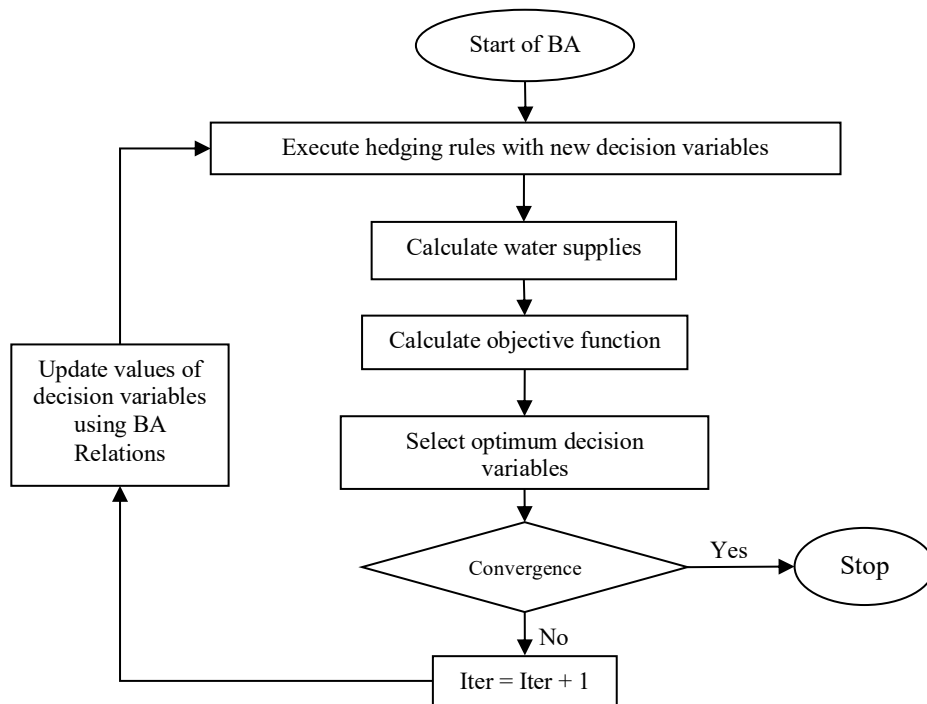
**Fig. 3.** Location of the Zhavveh Dam in the Sirvan River Basin, Iran.



**Fig. 4.** Time series of the monthly inflows and downstream demand of the Zhaveh Dam.

## 4 Formulation of the Problem

For optimal reservoir operation, the goal is to determine the reservoir releases in a way that the objective function which here is the deficit of water supply for the demands is minimized. According to hedging rule curve, the decision variables are  $K_p$  values (the gradient of the release curve) which through determination of them, the amounts of releases are known. By obtaining the releases, the objective function's value which is the deficit of water supply is then calculated for each set of the produced decision variables. The set of  $K_p$ 's which result the minimum objective function is used by the bat algorithm for generating the new values for the decision variables and this procedure is repeated until one of the convergence criteria defined for the algorithm is met. These criteria are repeating of the best solution in 25 successive iterations after iteration no. 100 or reaching to maximum number of searching iterations which is defined equal to 300 here. In Figure 5, the workflow of the BA-hedging rule process is presented.



**Fig. 5.** Workflow of the BA-hedging rule process for optimal reservoir operation.

The objective function is to minimize the water supply deficit. The decision variables are  $Kp$  values (hedging coefficients) which produce the reservoir releases according to Eq. 8. The deficit which is to be minimized as the objective function is defined in Eq. 5.

$$Def = \sum_{t=1}^T \left( \frac{D(t)-R(t)}{D(t)} \right)^2 \tag{5}$$

In Eq. 5,  $D(t)$  is the monthly demand,  $R(t)$  is the reservoir's monthly release and  $T$  is the number of operation time steps.  $R(t)$ 's are unknown and the reservoir operation goal is to release water in a way that  $Def$  is minimized. The continuity constraint for the reservoir storages should be satisfied as in Eq. 6:

$$S(t + 1) = S(t) + I(t) - R(t) - E(t) - Sp(t) \tag{6}$$

where  $S(t)$  is the reservoir's storage in beginning of month  $t$  and  $I(t)$ ,  $E(t)$  and  $Sp(t)$  are the inflow, evaporation and spill in month  $t$ , respectively. The reservoir's storage should be in the feasible domain as shown in Eq. 7:

$$S_{min} \leq S(t) \leq S_{max} \tag{7}$$

where  $S_{min}$  and  $S_{max}$  are the reservoir's minimum and maximum storage capacities. If through Eq. 6,  $S(t)$  finds a value out of the feasible domain then it is restricted to the corresponding boundary and  $R(t)$  is decreased or  $Sp(t)$  is increased accordingly. Monthly reservoir releases are determined by the hedging relation as shown in Equations 8.

$$R(t) = \left(\frac{1}{K_p}\right) * (S(t) + I(t)) \tag{8}$$

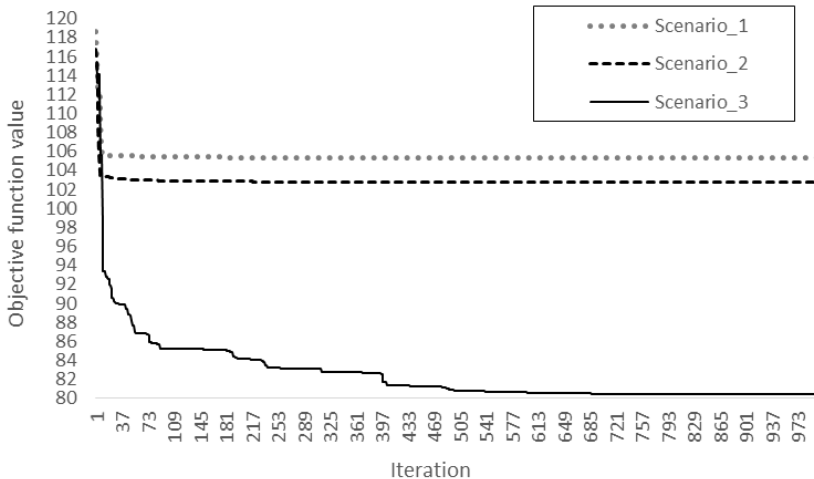
where  $K_p$  is the hedging rule curve gradient coefficient. By defining  $K_p$ , other variables are determined. Therefore,  $K_p$ 's are introduced as the BA's decision variables and finding their optimum values is the purpose of using the optimization algorithm. In this research, three scenarios for the reservoir operation rules are defined. In the first scenario, a constant  $K_p$  is considered for all months. In the second state,  $K_p$ 's have 12 values varying in different months of a year but are the same in 20 years of the reservoir operation. So, the problem has 12 decision variables in this state. And in the third scenario,  $K_p$ 's are relaxed to vary in all 240 months of the operation period which faces the problem with 240 decision variables. Therefore, in these three states, the reservoir operation rule curve finds more degree of freedom to search for the optimum solution in the search space of the problem. In Table 1, the differences between three scenarios defined for the reservoir operation are stated.

**Table 1.** Hedging rule-based reservoir operation optimization scenarios.

Scenario	Rule	Decision Variable
1	$R(t) = (1/K_p) \times (S(t) + I(t))$ $t = 1, 2, \dots, 240$	One $K_p$ constant for all months
2	$R(t) = (1/K_p(m)) \times (S(t) + I(t))$ $t = 1, 2, \dots, 240,$ $m = 1, 2, \dots, 12$	12 $K_p$ repeating every year
3	$R(t) = (1/K_p(t)) \times (S(t) + I(t))$ $t = 1, 2, \dots, 240$	240 $K_p$ variable in all months

### 5 Results and Discussion

By execution of the BA-hedging rule model, the optimum values for the decision variables of the problem which are  $K_p$ 's in the defined scenarios, are obtained. The optimization procedure is run at least five times in each state for reassurance of convergence of the bat algorithm to the global optimum. The results obtained by the model in various executions are close to each other indicating the consistency of the algorithm. In Figure 6, the convergence trend of the best objective function obtained by the bat algorithm in three defined scenarios is shown.



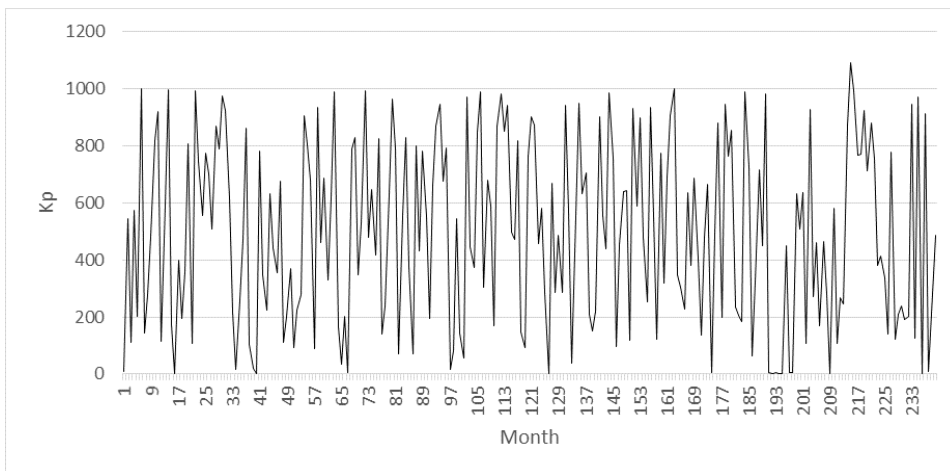
**Fig. 6.** Convergence trend of the best objective function in hedging rules scenarios.



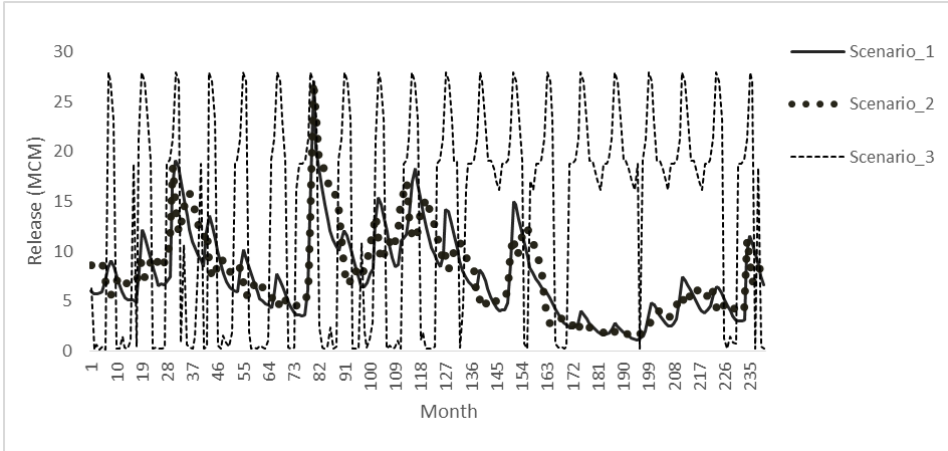
According to the results, the optimum values for the objective function are 105.3 for the first scenario, 102.8 for the second state and 80.5 for the third scenario. This states that by increase of the degree of freedom for the optimization algorithm, it is able to find a better solution in terms of the objective function. In other words, the hedging model performs more successfully in determining reservoir releases when a larger number of variables are employed by the bat algorithm. The objective function declines from the first to the third scenario with increases in the number of hedging coefficients (indicating the higher efficiency of the third scenario comparing the other two). The optimum values for the decision variable in the first and second scenario are reported in Table 2. Also, these values are presented in Figure 7 for the third scenario. In Figure 8, time series of the optimum reservoir releases in three scenarios of hedging rule-based operation are shown.

**Table 2.** Optimum values for  $K_p$  in the first and second scenarios.

Scenario	Value of $K_p$											
1	9.1											
	Month											
2	1	2	3	4	5	6	7	8	9	10	11	12
	6.27	5.76	5.66	5.32	4.93	7.07	10.82	12.98	11.54	9.19	8.27	6.73

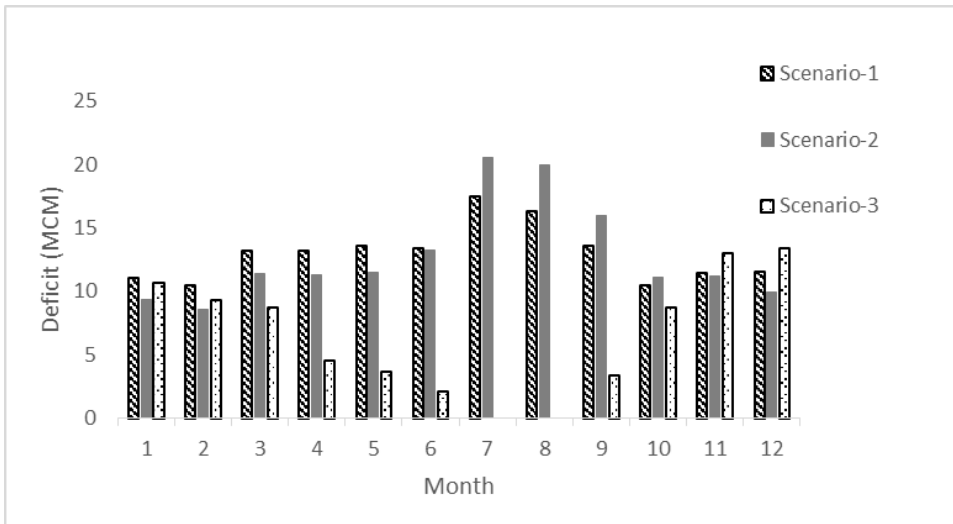


**Fig. 7.** Optimum values obtained for  $K_p$  in scenario 3.



**Fig. 8.** Time series of the Zhaveh reservoir’s optimum releases in hedging rules scenarios.

As seen in Fig. 8, the reservoir releases are almost close in scenarios 1 and 2 but they vary differently in scenario 3 where the optimization algorithm is allowed to select an optimum value for the release in each month of the operation period. In Figure 9, the average monthly deficits for the reservoir downstream demands are shown.



**Fig. 9.** Average monthly deficits for the reservoir demands in hedging rules scenarios.

According to Fig. 9, the average annual deficits for the Zhaveh reservoir downstream demands are 155.5, 154 and 73.5 MCM in scenarios 1, 2 and 3, respectively. The average annual deficit is 1% lower in the second scenario comparing the first state while it is 52% lower in the third scenario compared to scenario 2. This indicates that by increasing the dimension of the optimization problem from 12 (scenario 2) to 240 (scenario 3), the average annual deficit for the reservoir downstream demands is decreased more than 50%.

It is seen that the first scenario does not perform well for a 20-year operation period which includes wet and dry months because it employs a single rule, while the second scenario performs better where the hedging coefficients vary in the months of a year leading to better

solution. The third scenario outperforms the other states because it is able to vary all monthly reservoir releases to find the best solution.

## 6 Concluding Remarks

Optimal reservoir operation involves diverse aspects for which a single optimum solution rarely exists, and there are usually a number of answers based on the purpose of the defined problem. In the present study, optimum operation of the Zhavah reservoir in west of Iran using the hedging policy and the bat algorithm is determined. Three scenarios for optimizing the hedging coefficients are defined to minimize the deficit of water supply for the downstream demands. Results show that as the flexibility of the hedging rules increases, the total deficit decreases. Optimality of the results obtained by the bat algorithm is assessed through solving the problem with a nonlinear programming procedure which is able to find the global optimum. Closeness of the results showed the ability of BA to solve the real word engineering optimization problems.

## References

1. A. Singh, S.N. Panda, Optimization and simulation modelling for managing the problems of water resources, *Water Resources Management*, 27(9), 3421-3431 (2013)
2. A. J. Draper, J. R. Lund, Optimal hedging and carryover storage value, *Water Resources Planning and Management*, 130(1): 83-87 (2004)
3. M.Y. Tu, N.S. Hsu, F.T.C. Tsai, W.W.G. Yeh, Optimization of hedging rules for reservoir operations, *Water Resources Planning and Management*, 134(1): 3-13 (2008)
4. A. B. Dariane, F. Karami, Deriving hedging rules of multi-reservoir system by online evolving neural networks, *Water Resources Management*, 28(11), 3651-3665 (2014)
5. C. Huang, J. Zhao, Z. Wang, W. Shang, Optimal hedging rules for two-objective reservoir operation: balancing water supply and environmental flow, *Water Resources Planning and Management*, 142(12): 04016053 (2016)
6. M. Spiliotis, L. Mediero, L. Garrote, Optimization of hedging rules for reservoir operation during droughts based on particle swarm optimization, *Water Resources Management*, 30(15), 5759-5778 (2016)
7. K. Kranthi, K. Srinivasan, Generalized linear two-point hedging rule for water supply reservoir operation, *Water Resources Planning and Management*, 144(9), 04018051 (2018)
8. N. Shenava, M. Shourian, Optimal reservoir operation with water supply enhancement and flood mitigation objectives using an optimization-simulation approach, *Water Resources Management*, 32(13), 4393-4407 (2018)
9. X. S. Yang, A new metaheuristic bat-inspired algorithm, In: Gonzalez JR et al. (eds.) *Nature inspired cooperative strategies for optimization*, *Studies in Computational Intelligence*, Vol. 284, pp 65-74, Springer, Berlin (2010)
10. V.U. Reddy, A. Manoj, Optimal capacitor placement for loss reduction in distribution systems using bat algorithm. *IOSR J. Eng.* 02(10): 23–27 (2012)
11. T. Niknam, S. Sharifinia, R. Azizipanah-Abarghooee, A new enhanced bat-inspired algorithm for finding linear supply function equilibrium of GENCOs in the competitive electricity market, *Energy Convers Manage.* 76:1015–1028 (2013)

12. M. Ethteram, S.F. Mousavi, H. Karami, S. Farzin, R. Deo, F. Binti Othman, K. Chau, S. Sarkamaryan, V. P. Singh, A. El-Shafie, Bat algorithm for dam-reservoir operation, *Environmental Earth Sciences*, 77:510 (2018)
13. I. Ahmadianfar, A. Adib, M. Salarijazi, Optimizing multireservoir operation: hybrid of bat algorithm and differential evolution, *Water Resources Planning and Management*, 142(2), 05015010 (2016)
14. A. Zarei, SF. Mousavi, Eshaghi Gordji, M. et al., Optimal reservoir operation using bat and particle swarm algorithm and game theory based on optimal water allocation among consumers, *Water Resources Management*, 33(9): 3071-3093 (2019)
15. A. Rittima, Hedging policy for reservoir system operation: A case study of Mun Bon and Lam Chae reservoirs, *Kasetsart J. (Nat. Sci.)* 43: 833 – 842 (2009)
16. T. R. Neelakantan, N. Pundarikanthan, Hedging rule optimization for water supply reservoirs system, *Water Resources Management*, 13(6): 409-426 (1999)
17. O. Bozorg-Haddad, I. Karimirad, S. Seifollahi-Aghmiuni, H.A. Loáiciga, Development and application of the bat algorithm for optimizing the operation of reservoir systems, *Water Resources Planning and Management* 141(8), 04014097 (2014)