Sedighkia, Mahdi, Datta, Bithin, and Abdoli, Asghar (2021) ***Design of optimal environmental flow regime at downstream of reservoirs using wetted perimeter-optimization method.*** **Journal of Hydro-Environment Research, 39 pp. 1-14.**

Design of optimal environmental flow regime at downstream of reservoirs using wetted perimeter-optimization method

Abstract

Conflicts between water demand and environmental flow requirements is a challenging aspect in the reservoir management. Hence, optimizing environmental flow regime is one of the most important tasks at downstream of the large dams. The present study proposes a coupled simulation-optimization method based on the wetted perimeter method as an assessment method of the environmental flow and optimization of the reservoir operation to minimize difference between habitat loss and water demand loss using different metaheuristic algorithms. Then, the fuzzy TOPSIS as the decision-making system was applied for ranking the optimization algorithms. Indices including reliability index, vulnerability index, root mean square error and mean absolute error were utilized as criteria to measure the system performance and to select the best algorithm. Based on the results, gravity search algorithm (GSA) was the best method to optimize environmental flow regime at downstream of the reservoir in the case study. The proposed method is able to optimize environmental flow to minimize conflicts between human's needs and aquatic's needs considering storage constraints in the reservoir management. The proposed method might minimize negotiations between environmental managers and stakeholders. Furthermore, it should be noted that original wetted perimeter method is not able to provide optimal environmental flow regime based on a balance between users and constraints in the reservoir management such as storage constraints. The proposed method converts wetted perimeter method from an assessment method to a simulation-optimization method for optimizing environmental flow at downstream of the reservoirs.

Keywords: Instream flow optimization, Wetted perimeter method, Non-animal inspired meta-heuristic algorithms, fuzzy TOPSIS

1-Introduction

Impacts of large hydraulic structures such as dams on the river ecosystem have been highlighted in recent decades. The most important impact is reduction of flow at downstream of dams which was the main reason for definition of environmental flow regime concept (Gillespie et.al, 2015). Offstream flow would be increased in the future years due to raising population (Postel, 1998). Different methods have been developed to assess environmental flow regime in rivers which could be categorized in three groups including historic flow record, hydraulic rating and habitat methods (Jowett,1997;Tharme,2003). Some methods for assessing minimum environmental flow regime have been discussed in the previous studies (Nikghalb et.al, 2016). It should be noted that some methods are economic and simple for using in the assessment of the environmental flow. Hence, their improvement might be advantageous for utilizing in the water resource management. Hydraulic rating methods are one of the most important methods to assess minimum environmental flow in rivers. The most known method in this group is wetted perimeter method (WP) (Shokoohi and Amini, 2014). It is possible to determine variation of wetted perimeter by its measurement in different flows in field studies (Gippel and Stewardson, 1998). It may be possible by calculation of water surface profile as well. It should be noted that WP method is a simple habitat hydraulic method that is an inexpensive tool to assess minimum environmental flow in rivers. In contrast, complex habitat hydraulic models such as PHABSIM is available that needs extensive ecological and geometric field studies combined with historic flow records and hydrological analysis (Waddle, 2001). Practical considerations might confine extensive ecological field studies. Hence, simple habitat hydraulic methods such as WP method are still applicable and important methods in the environmental flow assessment studies.

WP method generates a relationship between river flow and wetter perimeter. Regression model can be used as WP function to assess environmental flow. Break point of WP function has been proposed as minimum environmental flow that could provide sufficient environmental flow to protect aquatic habitats in the rivers. Identifying break point by observation method is impossible. Hence, two methods have been proposed to calculate break point in WP method. The first method is slope method (SP) which presents $dWP/dQ=1$ as the break point. Another method is curvature method (CM) which proposes maximum point of curvature function as the break point (Gippel and Stewardson, 1998). Shang, 2008 also proposed ideal point method (IPM). Its main advantage is simplicity of computation. Furthermore, it is applicable in a wider range of wetted perimeter-discharge relationship. However, it is not a known method to estimate break point.

It is required to review the ecological concept of the break point. Generally, minimum flow for mesohabitats including pool, riffle and run should cover a reasonable proportion of the bed area of riffles. The wetted perimeter

– discharge breakpoint has been used to determine minimum required flow for fish rearing (food production) in the US (Nelson, 1980), and Australia (Richardson, 1986; Gippel and Stewardson, 1998). According to these studies, when the instream flow is less than the lowest breakpoint in the curve, habitat conditions for aquatic organisms rapidly become unfavourable. In fact, small reduction of lower flow than flow of the breakpoint decreases wetted perimeter significantly that is not favourite for the organisms due to reducing available habitat area especially in the riffle habitats. Hence, the flow of the break point has been defined as the minimum environmental flow (Gippel and Stewardson, 1998).

Main challenge of the environmental flow assessment by WP method or similar methods is how to implement the method in practice. In fact, this method proposed a specific flow as the environmental requirement, which must be available in the river for all of the times. On the one hand, river flow might change during different seasons or dry and wet years. On the other hand, offstream flow might be changed due to increasing population. Moreover, technical issues are effective on available instream flow in rivers. For instance, dams are the most important structures to supply water demands in rivers. They might be useable as multipurpose reservoir for hydropower production, water supply, flood control and etc. Thus, we need an optimal operation in the reservoir in which benefits of the reservoir, environmental flow and constraints in the reservoir management should be considered simultaneously.

Many studies have been carried out to optimize release for supply of hydropower or water demands. Initial form of loss function has been proposed by Hashimito et.al, 1982 which defined difference between target and release as the loss for the system. This initial form has been improved considering practical constraints in the storage management to optimize reservoir operation (Datta and Houck, 1984). This form of loss function has been utilized in recent studies as well (e.g Ehteram et.al, 2017). Previous studies used evolutionary algorithms as and efficient method to optimize reservoir operation (eg. Karami et.al, 2018; Yaseen et.al, 2019). A long list of meta-heuristic algorithms has been used to optimize operation of the reservoirs. As a general classification, they can be classified into two classes including animal-inspired and non-animal inspired algorithms (Jahandideh et.al, 2019). Considering reservoir management constraints in the structure of the evolutionary algorithms might be possible using computational methods such as penalty function method (Yeniay, Ö., 2005). In fact, penalty functions increase the penalty of the reservoir operation. For example, when storage is less than minimum operational storage, penalty function increases the penalty of the system when storage is less than minimum operational level. Measurement the performance of the optimization system is necessary as well. Hashimoto et.al, 1982 developed two indices including vulnerability index and reliability index that could be used in each reservoir operation system. Reliability index measures how release from the reservoir is reliable to supply defined needs that might be described based on the summation of the target and release in the simulated period. Moreover, vulnerability index measures how the optimal solution is vulnerable in each time step. Generally, maximum difference between target and release could be considered as the vulnerability index.

Reservoir operation optimization with a focus on water demand has extensively been highlighted in the previous studies. However, optimization of the environmental flow at downstream of the reservoirs has rarely been addressed (Yin et.al, 2012; Cai et.al , 2013; Horne et.al , 2017). It should be noted that wetted perimeter method as one of the most important methods to assess environmental flow regime has not been utilized in a simulation-optimization framework to optimize environmental flow at downstream of the reservoirs. The focus of the present study is the environmental flow modelling. Hence, it might be useful to review some relevant concepts and recent studies in this regard. Using one dimensional hydraulic simulation is one of the applicable tools in the environmental flow modelling (Lamouroux et.al, 2017). One-dimensional hydraulic models are the applicable tools to develop hydrodynamic numerical models in rivers that utilize one-dimensional simulation along the centre line of river channel. These models generally solve one-dimensional Saint-Venant equation (Bazarov et.al, 2019). Moreover, two-dimensional hydraulic modelling might be applicable for simulating environmental flow regime in some cases (e.g Sedighkia et.al, 2021a). Mapping river depth and quantify hydraulic habitats at the catchment scale using high-resolution imagery is one of the recent advances that might be useful for assessing environmental flow in the river basin scale (O'Sullivan et.al, 2020). Investigation of changes in vegetation cover along the river might be needed in the environmental modelling as well that has been reviewed in the literature (Nallaperuma and Asaeda, 2019; Benjankar et.al, 2020). The seasonal pattern and the composition of downstream drift of fish eggs and larvae are important in the environmental management of the dams as well. The previous studies investigated their patterns through the fish ladder that could be applicable in dams (da Silva et.al, 2020). Moreover, recent studies highlighted the application of artificial intelligence methods for environmental flow modelling (e.g Sedighkia et.al, 2021b)

Main contribution of the present study is to propose a flexible framework to use wetted perimeter method as an applicable environmental flow assessment method to assess optimal environmental flow regime considering water supply and storage constraints in the reservoir. Moreover, system performance has been measured by different indices. Due to using different optimization algorithms in the present study, a decision-making system was applied to rank optimization methods. Proposed simulation-optimization method was utilized in a case study to test robustness of the method. This method might be useable to optimize environmental flow regime at downstream of reservoirs for reducing conflict between water demand and environmental requirements that is able to consider storage constraints as well.

2-Methods

2-1-Overview on the methodology

Due to complexities of the proposed method, it might be useful to have an overview on the method. Figure 1 displays the flowchart of the proposed method that should be described. At the first step, we collected recorded historic flow and wetted perimeter in the representative reach at downstream of the river before construction of dam. It was needed to complete data for developing wetted perimeter (WP) curve. Thus, 1D hydraulic simulation was utilized to simulate wetted perimeter in different flows. Total available data was applied to develop wetted perimeter curve. In the next step, habitat loss function was generated based on the WP curve. Moreover, water demand loss function was developed as well. Then, these loss functions were applied in the structure of the reservoir operation model to optimize environmental flow. Due to using different evolutionary algorithms in the optimization process, the decision-making system was applied to select the best algorithm and finalize the environmental flow in the case study.

2-2-Study Area and problem definition

Latian Dam is one of the important constructed dams in Tehran province, Iran. This dam is responsible to supply water demand that has been constructed on the Jajrood River. This river originates from Alborz mountains toward the salt lake with the length of 40 Km. Location of Jarood basin at the upstream of Latian dam has been displayed in Figure 2.

Due to increasing population, water supply in Tehran province is a challenging issue that means optimal management of water supply is a sensitive task for regional water authority. Moreover, environmental values of the Jajrood River is not negligible. Hence, supply of environmental flow should be highlighted as well. It is required to optimize release for environment and water supply simultaneously. Hence, environmental flow assessment methods should be converted to the simulation-optimization method. WP was selected as an acceptable method to assess environmental flow due to the following considerations. First, WP is a simple and inexpensive method. It is a proper method in many cases. Hence, development of a simulation optimization method based on the WP method might advantageous for our case study and other similar case studies. Secondly Available instream flow at downstream of the reservoir in the current condition is very low. Hence, ecological field studies were not possible that means habitat based methods are not implementable.

It is needed to explain the effectiveness of the present method in the case study. There is no diversion project at upstream river of the dam that means sufficient flow is available at the upstream river. Before construction of dam, the fishes were able to immigrate from the downstream of the Jajrood River to the upstream for reproduction. However, construction of dam disconnected the habitats at upstream and downstream. In fact, the fishes at downstream must utilize downstream river of the dam for reproduction in the current condition. Dam considerably changed hydraulic condition of the river. Due to high water demand from the dam, no flow or very low flow is considered as the environmental flow that means the biological activities of the aquatics have been stopped in the current condition. In other words, very low depth, velocity and habitat area at downstream river of the Latian dam is drastically destructive for river ecosystem in terms of several aspects. First, depth is not sufficient for hatching. Secondly, inappropriate depth and velocity reduces food sources for the fishes. Thirdly, due to low velocity, deposition of fine particles fills voids between the gravel particles that are necessary for reproduction process of the fishes. Thus, the presented method is an effective method that is able to provide proper hydraulic and geomorphological condition at downstream river habitats and optimal reservoir operation simultaneously.

2-3-Wetted perimeter method

Surveyed cross sections and recorded data before construction of dam was utilized to develop 1D hydraulic model. It should be noted that results of 1D hydraulic model was used to enhance used data for developing wetted perimeter (WP) curve. In fact, three cross sections were selected in the representative reach at downstream of the reservoir with length of 5000 meters in which hydrometric stations were available to measure flow and wetted perimeter. Recorded data before the construction of dam in these points was utilized to develop WP curve. Based on surveying at downstream cross sections, their shape was relatively close to rectangular. Results of hydraulic simulation demonstrated that logarithmic relationship between wetted perimeter and discharge is the best possible relationship which corroborated proposed relationship by Gippel et.al, 1998. Equation 1 shows proposed average wetted perimeter-discharge relationship at studied downstream reach.

$$NWP = 10.4Ln(MF) + 58.9 \qquad (1)$$

where NWP is normalized wetted perimeter(%) and MF is average monthly flow in million cubic meters. NWP considers maximum possible wetted perimeter 100% which approximately occurred in 52 mcm. In fact, WP was normalized based on the maximum wetted perimeter in the main channel. Based on the recorded data before construction of dam, it had been occurred in the 20.06 m^3/s. This value is equal to average monthly flow of 52 mcm. According to this equation, slope method and curvature method would define break point at 10.4 and 7.3 mcm respectively. These values considered as the best possible value for environmental flow requirement at downstream which would minimize habitat loss of downstream reach. Both of values have been used in optimization process and relevant analysis. It is necessary to clarify definition of the break point in the WP method. It is necessary to clarify definition of the break point in the WP method. Break point indicates required instream flow to minimize physical habitat loss in the river. In other words, basic study for developing WP method demonstrated when wetted perimeter is equal to break point; physical habitat loss is acceptable that might be considered as the optimum point in the assessment of environmental flow. The following equations indicate how break points by slope method and curvature method were computed respectively.

$$\frac{dP}{dQ} = \frac{10.4}{Q} = 1 \rightarrow Q = 10.4\,mcm \qquad (2)$$

$$k = \frac{\left|\frac{-10.4}{Q^2}\right|}{\left[1+(\frac{10.4}{Q})^2\right]^{1.5}} \rightarrow \frac{dk}{dQ} = 0 \rightarrow Q = 7.4\,mcm \qquad (3)$$

It is essential to explain regarding ecological evaluation of WP method. This method is a simplified method of physical habitat simulation that has been evaluated ecologically in the previous studies. In fact, it has been demonstrated that if instream flow is more than required flow equal to break point of the WP curve, suitable physical habitat is provided or physical habitat loss is acceptable that might be an optimum point in the environmental flow assessment. It might not be a perfect ecological assumption for all of the cases. However, it is a reliable assumption in the cases in which ecological field studies is not possible due to lack of instream flow for fish observations. In fact, WP method has originally been developed to assess environmental flow in cases that fish observations are not possible to apply physical habitat simulation (More details by Sedighkia et.al, 2017 and Gippel and Stewardson, 1998).

Figure 3 displays how equation 1 was developed. In the first step, relationship between daily flow and wetted perimeter was developed based on the recorded wetter perimeter in different flows before construction of the dam in the main channel of the river. Then, daily flow was converted to the monthly flow to develop proper relationship for applying in the reservoir operation optimization. Finally, WP was normalized based on the maximum wetted perimeter in the main channel of the river reported by regional water authority.

2-4-Objective function

Main component of optimization model was objective function. Hence, definition of favorite objective function was the most important step in optimization model. The main purpose of proposed methodology was to minimize conflict between water demands and environmental flow requirement by considering technical constraints. Hence defining loss function of habitats and water demand was necessary. Equation 1 considered as habitat loss function. Because based on wetted perimeter method, occurring maximum possible wetted perimeter in river would provide best habitat suitability in river (Shang, 2008). However, break point was considered as minimum requirement in initial form of this method. Equation 2 displays final defined habitat loss function

$$\begin{cases} HL = -10.4Ln(MF) + 41.0 & MF < 52 \\ HL = 0 & MF \geq 52 \end{cases} \tag{2}$$

where HL is habitat loss(%). This function demonstrated that when monthly flow is more than 52 mcm habitat loss would be zero. It is required to describe how threshold of 52 mcm was selected in the habitat loss function. In fact, maximum wetted perimeter method in the main channel is equivalent with 52 mcm as the average monthly flow in the river. The main assumption of the WP method is that relationship between biomass and the flow in the main channel might be direct and linear that means 52 mcm might provide zero habitat loss. It is the highest possible flow in the main channel of the river. It seems that this threshold is robust to define habitat loss function in the main channel of the river. It should be noted that break point might provide optimal habitat loss that is acceptable to assess environmental flow based on the literature.

The next loss function which is needed would be water demand loss function. According to available demands, maximum estimated water demand predicted 30 mcm monthly. Less possible values would reduce maximum possible covered population which means increase in water demand losses. Based on stated definition on water demand, loss function of water demand has been displayed in equation 3

$$\begin{cases} DL = -3.26(MF) + 100 & MF < 30 \\ DL = 0 & MF \geq 30 \end{cases} \tag{3}$$

Objective function was defined to minimize distance between habitat loss and demand loss which is displayed in Equation 4 in which HL is habitat loss and DL is water demand loss.

$$Minimize(OF) = \sum_{t=1}^{T}(HL_t - DL_t)^2 \tag{4}$$

It is also essential to explain how the optimal value of an environmental flow is assessed in the optimization model. Equations 2 and 3 were directly utilized in the optimization model. This model tries to minimize habitat loss and water demand loss simultaneously in each time step. The best value for the environmental flow is 52 mcm that could not be supplied due to constraints in the reservoir management in terms of storage and water demand supply. However, optimal value of the environmental flow in the WP method is rate of flow in the break point in which physical habitat loss is acceptable. In the present study, physical habitat loss in the break point is 20% approximately that seems acceptable ecologically (Figure 4). It should be noted that supply of rate of flow in the break point might not be possible due to constraints in the reservoir management and importance of maximum supply of water demand. Hence, the developed optimization model is able to provide a fair balance between demand and environmental flow. In fact, optimal environmental flow proposed by the optimization model was compared with the break point as the acceptable value for environmental flow. In fact, if optimized environmental flow is able to supply break point of the WP curve in each time step, the performance of the optimization model in that time step is perfect. In other words, break point was considered as the ideal environmental flow in the measurement of the optimization system.

The optimization model is able to provide a fair balance between human's needs and aquatic needs. However, it is not able to supply needs perfectly. In fact, losses are not zero in different time steps. If inflow is high (especially in the wet seasons), it might be possible to reduce losses close to zero. However, in the average inflow or dry seasons, it is not possible to supply ideal environmental flow or total water demand. Thus, losses might not be zero in many simulated period expect highly wet seasons. The optimization model is able to minimize conflicts by minimizing losses for human's needs and aquatic needs.

Some points should be noted regarding the definition of the objective function. Minimizing habitat loss and water demand loss is the ideal condition that might not be possible for study areas in arid and semi-arid regions such as our case study. In fact, low inflow and lack of sufficient storage capacity might escalate conflict of interests. This new form of the objective function might balance habitat loss and water demand loss fairly. Moreover, if we consider simultaneous minimization of losses by a multiobjective model, we will need a multiobjective optimization algorithm that might not be able to provide optimal solution for defined optimization model. More details are presented in the discussion regarding advantages of the proposed optimization model. Reservoir storage in each step was calculated based on equation 5 where S is storage, I is inflow to reservoir, RF is released environmental flow, D is water demand, SP is overflow, E is evaporation and A is surface area of reservoir

$$S_{i+1} = S_t + I_t - RF_t - D_t - SP_t - \left(\frac{E_t \times A_t}{1000}\right), t = 1,2,\dots,T \qquad (5)$$

It should be noted that total of released environmental flow and over flow could define as total environmental flow to downstream reach of river. Overflow would be estimated based on maximum storage of reservoir by equation 6

$$\begin{cases} if\left(S_i + Q_{in(i)} - \left(\frac{E_i \times A_i}{1000}\right)\right) \geq S_{max} \rightarrow Q_{SP(i)} = S_i + Q_{in(i)} - \left(\frac{E_i \times A_i}{1000}\right) - S_{max} \\ if\left(S_i + Q_{in(i)} - \left(\frac{E_i \times A_i}{1000}\right)\right) < S_{max} \rightarrow Q_{SP(i)} = 0 \end{cases} \qquad (6)$$

Storage has to be between minimum and maximum limitations as the constraint of defined objective function. To convert constrained optimization problem to unconstrained one which could be solved by disparate heuristic algorithms, penalty function method was used (Yeniay, 2005). Two main penalty functions were added to main objective function which are shown in equation 7 where c1 and c2 are coefficients which have be determined based on sensitive analysis (Ehteram et.al, 2017).

$$\begin{cases} if S_i > S_{max} \rightarrow P1 = c1\left(\frac{S_i - S_{max}}{S_{max}}\right)^2 \\ if S_i < S_{min} \rightarrow P2 = c2\left(\frac{S_i - S_{min}}{S_{min}}\right)^2 \end{cases} \qquad (7)$$

2-5-Metaheuristic algorithms

Four evolutionary algorithms have been used to solve objective function. The first algorithm was a recently developed called as atom search optimization (ASO) which has not been used in reservoir operation optimization (Zhao et.al,2019). Second algorithm was gravity search algorithm (GSA) which has been developed based on gravity law (Rashedi et.al, 2009). Its ability to optimize reservoir issues have been corroborated (Bozorg-Haddadet.al, 2016). It has not however been used in optimizing environmental flow regime. Third algorihtm was teaching learning-based optimization (TLBO) which has originally been developed by Rao and Kalyankar, 2011 and it has successfully been used in operating reservoir (Kumar and Yadav, 2018). Besides, genetic algorithm (GA) was also selected due its previous broad application in optimization of water resources system in order to compare outputs. Figures 5 to 8 display flowchart of disparate used algorithms respectively

2-6-Measurement of system performance

Some indices were selected to measure system performance of proposed optimized environmental flow regime at downstream of dam. The first index was reliability index which has originally been developed by Hashimito et.al, 1982. This index has been applied in reservoir optimization for water demand by Ehtream et.al, 2017. Equation 8 proposes designated form of this index for environmental flow regime optimization where AE is actual environmental flow and IE is ideal environmental flow by wetted perimeter method which would be evaluated based on SM and CM methods.

$$\alpha_E = \frac{\sum_{t=1}^{T} AE_t}{\sum_{t=1}^{T} IE_t} \qquad (8)$$

Second index which has been used to measure system performance is vulnerability index. It has also originally been developed and used by mentioned studies for previous index. Equation 9 proposes designated form of this index for environmental flow regime optimization

$$\gamma_E = Max_{t=1}^{T}\left(\frac{IE_t - AE_t}{IE_t}\right) \qquad (9)$$

Root mean square (RMSE) is another index as system performance in the present study which is displayed in equation 10. Another useful and applicable index to measure system performance was mean absolute error (MAE) which is displayed in equation 11(Chai and Draxler, 2014)

$$RMSE = \sqrt{\sum_{t=1}^{T} \frac{(IE_t - AE_t)^2}{T}} \tag{10}$$

$$MAE = \frac{\sum_{t=1}^{T} |IE_t - AE_t|}{T} \tag{11}$$

2-7-Decision Making System

Due to utilizing different evolutionary algorithms, one of the important purposes of the present study is to rank used methods for optimizing environmental flow regime at downstream of the reservoir which would be helpful for further studies on optimization of environmental flow regime. Fuzzy technique for order preference by similarity to ideal solution (F-TOPSIS) which has been used as applicable decision making systems in many branches of science was selected to prioritize of proposed solutions. Chen, 2000 has developed this method, which its flow chart is displayed in Figure 9 for an expert as decision maker.

3-Results and Discussion

Figure 10 displays optimal environmental flow regime by different heuristic algorithms. The first characteristic of the proposed environmental flow regimes is considerable different between some algorithms. As an illustration, GA proposes a wide range of environmental flow at different months where changes between relatively close to zero to 25 mcm. TLBO however proposes 20 mcm as maximum environmental flow; meanwhile ASO provides environmental flow between 1 to 10 mcm in different months. Moreover, GSA is minimally varied in proposed environmental flow regime at downstream of dam where can be seen that the minimum value of proposed environmental flow is 4 mcm and its maximum is 7 mcm.

Figure 11 presents supplied water demand regarding either GA or other non-animal inspired algorithms. Seemingly, performance of algorithms is different in supply of water demand. TLBO has the weakest performance in water demand, meanwhile either GSA or ASO is relatively similar in proposed supplied water demand. Different performance of algorithms in proposed environmental flow regime and water demand makes it necessary to measure system performance and selecting the best algorithm to optimize environmental flow regime. Figure 12 displays changes of the storage in the reservoir in the simulated period. GSA and ASO are the best methods due to less alteration of storage level in the simulated period. However, measuring the performance of the optimization system is to investigate the performance of the optimization system in terms of environmental flow supply as well. Figure 13 shows the reliability index of environmental flow supply. GA is the best method in terms of reliability of environmental flow supply. As presented, using other indices for measuring the performance of the optimization system in terms of environmental flow supply is essential. According to the figure 14, GSA is the best method for optimization of environmental flow in terms of vulnerability index. However, the performance of GA or TLBO is weak in this regard. Figures 15 and 16 displays RMSE and MAE of environmental flow supply. The better performance of GSA in terms of MAE and RMSE is observable. It seems that the performance of GA or TLBO is not robust in terms of RMSE and MAE as well as vulnerability index.

The difference between slope method and curvature method in measurement of performance should be discussed as well. According to the results, due to higher proposed environmental flow by slope method, all of the indices considerably have weaker performance. It should be noted that SM and CM are proposed computational methods to estimate the most favorable point of environmental flow by WP method; hence, there is no ecological evidence to identify premier computational method of break point. Results demonstrate that there is significant difference between these two methods in optimization of environmental flow especially in some indices. As an illustration, RI is considerably higher for CM in all of the used algorithms, which indicates using the SM would reduce reliability of environmental water requirement. It seems that it would be essential to investigate necessities of using slope method in assessment of environmental flow ecologically. As a general guideline of using WP method, the CM would assess ideal environmental flow lower than SM and it would be demonstrated in optimization process that CM provides more reliability in supply of environmental flow.

Vulnerability would be another story using CM and SM. Because it could be seen that there is not significant difference between two methods which needs to be interpreted. It is required to have focus on definition of vulnerability index to discern similarities on two methods. Hashimito et.al, 1982 proposed a precise definition on vulnerability index. According to this definition, it assesses possible magnitude of failure, which means maximum difference between ideal environmental flow and defined environmental flow by optimization process. Difference between two methods in assessment of favorite or ideal environmental flow is considerable. Given that technical issues in reservoir management and high volume of water demand, vulnerability index is not however significantly different. It would be an important point in reservoir management, because it demonstrates that methods that may have overestimation on environmental flow would not be pragmatically implementable in reservoir management and lack of directorial considerations in reservoir may make results of environmental flow assessment methods useless. It would deteriorate in river basin with populated users and water scarcities due to regular droughts.

Evaluation of habitat loss and water demand loss is another important technical issue in environmental flow optimization. Because the purpose of developed objective function, is minimization of habitat and water demand loss. In other words, best solution should be able to reduce loss of habitat and water demand, which minimally makes conflicts between water demand between community and environment. Figure 17 displays habitat loss due to applying different algorithms. According to results, GA experienced the worst performance among all of the used algorithms. Although its habitat loss is very low in some months such as January and August but its habitat loss in some month such as May is very high which means habitat may experience large losses. Some methods such as GSA and ASO experience an average habitat loss which is approximately 20% to 25%. It should be noted that TLBO has a close performance to GA in habitat loss evaluation. Changes of demand loss has been shown in Figure 18 that demonstrates that performance of GA is not at all acceptable among all of the used algorithms. It seems that TLBO has the second rank of performance, which is better considerably than GA. Unequivocally, performance of GSA and ASO is relatively similar, and it could not be judged which methods would have the best performance by observation.

Not only performance of used algorithms is quantitatively different, but it could also be observed that different indices would disparately prioritize methods. Hence, using a decision-making system of globally prioritization is indispensable. As discussed, fuzzy TOPSIS is an intellectual quantitative tool to prioritize possible alternatives for making the best decision. According to developed methodology of fuzzy TOPSIS, Figure 19 displays structure of fuzzy TOPSIS in the present study. Second row shows criteria to make decisions for prioritization. Furthermore, third row shows different possible alternatives which are included used algorithms in optimization or environmental flow. All of the indices have been utilized to maximize accuracy of selection process.

Given that using one expert has been considered for application of fuzzy TOPSIS in the present study, hence, proposed weight for each criterion has been displayed in Table 1. As can be seen, vulnerability index has the highest weight which is very high (VH), because aquatic habitats at downstream of dam would be sensitive to short-term damages and an immediate damage in a short-term period could destroy many inhabited aquatics and cease their biological activities such as reproduction. RMSE and MAE have similar weight, because their role is relatively the same in assessment of environmental flow. These indices focus on total difference between ideal environmental flow and actual environmental flow. Hence their weights have been considered as high(H). Reliability index has the lowest weight between indices. Because, it defines ratio of total actual environmental flow and ideal environmental flow annually without considering differences between instream flow in each month. As a result, it would have the lowest importance among indices.

Determining rating of candidates or alternatives for each criterion is another step to implement fuzzy TOPSIS method. Kind means how increasing or decreasing criteria would affect on appropriateness of each alternative. For example based on Table 2, reliability index should be considered as benefit, because its reduction would diminish suitability of candidates. According to this definition, relatively good (RG), very good (VG) and good (G) rating mean increasing benefit for system performance. It could however be observed that other criteria are cost for the system. For example VG rating means related candidate would have the lowest suitability pertaining to its relevant criterion. Rating values have been considered based on comparison of developed indices for each alternative.

Table 3 to 5 display integrated, normalized and weighted normalized matrices respectively. D+ and D- as final factors to calculate close coefficient have been displayed in Table 6. In addition to close coefficient method, modified TOPSIS method (Ren et.al, 2007) has been used to prioritize algorithms. According to Table 7 which is final result of prioritization by application of fuzzy TOPSIS method, it is demonstrated that outputs of TOPSIS and M-TOPSIS are similar. GSA is the best method to optimize environmental flow regime by using WP as simulation method.

Figure 20 shows proposed optimal environmental flow regime compared by ideal environmental flow regime. To complete discussion, it is needed to review and compare results of present study by previous studies on WP method. Shon ,2008 suggested that CM method is not a good method to assess environmental flow by WP method, meanwhile Sedighkia et.al, 2017 demonstrated that SM would have unacceptable results due to natural regime of studied river and CM was more close to natural regime of river and more implementable. It seems that choosing best method to estimate break point by WP method would be depended on natural regime of studied river. Moreover, when the goal of study is to assess environmental flow regime at downstream of large reservoirs, it is important to consider technical issues on reservoir management and water demands to finalize environmental flow regime. Optimization of environmental flow corroborated that CM is the better method to reduce conflicts between environmental requirements and water demands by stakeholders. Due to importance of the natural flow regime, Figure 21 displays monthly natural flow regime. Results corroborate that SM is not an appropriate method to assess environmental flow and it could not be supplied even in the natural flow regime without considering offstream flow.

Some points should be discussed regarding the proposed optimization framework. According to the results, wave-like fluctuations occur in the calculated environmental flow regime by some algorithms such as GA and TLBO. It should be noted that the main problem for using evolutionary algorithms in the optimization process for complex objective function such as defined function in the present study is lack of ability to guarantee the global optimization. Hence, some algorithms might provide unnatural responses for the complex optimization problems such as TLBO and GA in the present study. Interestingly, weaknesses of GA and TLBO are reflected in the RMSE and MAE. In fact, high RMSE for these algorithms demonstrates that they are not appropriate for the optimization process in the present study. Moreover, decision-making system indicates that these two algorithms are not appropriate for optimizing environmental flow in the proposed method.

Another solution for defined optimization problem is to apply a multiobjective optimization algorithm. In fact, minimization of habitat loss and water demand loss could be considered as two objective function in the system. At the first glance, it seems logical to utilize this type of the optimization. However, some points might weaken the applicability of the multiobjective model for the case study. From the technical view, Simultaneous minimization of losses in the case study is not possible due to lack of stream flow and storage capacity in the reservoir. In other words, multiobjective model might not be able to balance losses fairly. From the computational view, some drawbacks should be noted regarding the multiobjective model. First, evolutionary algorithms are not able to guarantee the global optimization that means using different algorithms is necessary in the optimization process. Unfortunately, limited number of multiobjective optimization algorithms have been developed that decreases efficiency of these algorithms. Higher computational complexities is another problem of the multiobjective models. It should be noted that low computational complexities are one of the main requirements for utilizing the optimization models in practical projects. Numerous simulations and covering long-term periods are the main requirements in projects that increase computational complexities. In contrast, many single objective optimization algorithms have been developed in the literature. Hence, the developed single objective optimization model is advantageous in terms of technical and computational considerations.

Two important issues should be discussed as well. First, how four algorithms are different in terms of environmental flow or ecological impact at downstream of the reservoir. Utilized measurement indices are useful to discuss on this question. RMSE and MAE indicate how optimization algorithm might mitigate ecological impacts averagely. In fact, high RMSE or MAE demonstrates that optimal environmental flow is considerably different from the ideal environmental flow. Hence, two algorithms including GA and TLBO are not reliable in this regard, because they are not able to provide a sustainable ecological status in the case study. In fact, ideal environmental flow might guarantee the sustainable ecological status in the river. Hence, high RMSE and MAE corroborate inability of the optimization method for providing sustainable ecological status in the river.

Another question is whether GSA as the best method could be considered as the best method for other case studies or addressing other methods of the environmental flow assessment. It should be noted that GSA was selected based on the defined criteria in the case study in the decision-making system. We determined weights of importance based on technical considerations in the case study. However, other cases might have other priorities in the management of the environmental flow. Thus, we do not claim that GSA is the best method for all the case studies or other methods of the environmental flow assessment. We tried to consider criteria and weight of importance perfectly in the case study that might appropriate for many cases. However, we recommend using the proposed method of optimization and decision-making system in each case study to select the best algorithm and finalizing the environmental flow regime.

4-Conclusions

The present study proposed a novel method to optimize environmental flow regime at downstream of large dams with focus on wetted perimeter (WP) as one of the principal methods to assess environmental flow. In other words, proposed method converts WP as inflexible method to assess environmental flow to a flexible method to optimize environmental flow regime with technical consideration in reservoir management with focus on minimization of difference between habitat loss and water demand loss. According to results, CM is a suitable method to assess ideal environmental flow at downstream of river. Although this could not provide sufficient water demand and technical limitations in reservoir management. Optimization method by utilizing different non-animal evolutionary algorithms could propose optimized environmental flow regime. Used algorithms were included genetic algorithm (GA), gravity search algorithm (GSA), atom search algorithm (ASO), and teaching-learning based optimization. What is more, a decision-making system based on fuzzy TOPSIS method has been used to select the best algorithm for optimizing environmental flow. As a result, gravity search algorithm (GSA) was selected as the best algorithm to optimize environmental flow regime by considering different criteria include reliability index, vulnerability index, root means square error and mean absolute error. Main innovation of present study is to present a coupled simulation-optimization method to optimize environmental flow regime at downstream of large dams which reduces controversial negotiations between environmental managers and stakeholders. Proposed regime could be a basic accurate estimation for further negotiations and finalizing environmental flow regime.

5-Acknowledgement

We would like to thank Mr Ahmadi for helps in the field studies

References

Bazarov, D.R., Vokhidov, O.F., Lutsenko, L.A. and Sultanov, S., 2019, November. Restrictions Applied When Solving One-Dimensional Hydrodynamic Equations. In International Scientific Conference on Energy, Environmental and Construction Engineering (pp. 299-305). Springer, Cham.

Benjankar, R., Woo, H. and Asaeda, T., 2020. Riparian vegetation processes–Knowledge, modeling and management.

Bozorg-Haddad, O., Janbaz, M. and Loáiciga, H.A., 2016. Application of the gravity search algorithm to multi-reservoir operation optimization. Advances in Water Resources, 98, pp.173-185.

Chai, T. and Draxler, R.R., 2014. Root mean square error (RMSE) or mean absolute error (MAE)?–Arguments against avoiding RMSE in the literature. Geoscientific model development, 7(3), pp.1247-1250.

da Silva, P.S., Celestino, L.F., de Assumpção, L., Makrakis, S., Dias, J.H.P., Kashiwaqui, E.A.L. and Makrakis, M.C., 2020. Ichthyoplankton drift through fishway in large dam: effect of hydrology, seasonal patterns and larvae condition. Journal of Ecohydraulics, 5(2), pp.165-174.

Datta, B. and Houck, M.H., 1984. A stochastic optimization model for real-time operation of reservoirs using uncertain forecasts. Water Resources Research, 20(8), pp.1039-1046.

Ehteram, M., Karami, H., Mousavi, S.F., El-Shafie, A. and Amini, Z., 2017. Optimizing dam and reservoirs operation based model utilizing shark algorithm approach. Knowledge-Based Systems, 122, pp.26-38.

Gillespie, B.R., Desmet, S., Kay, P., Tillotson, M.R. and Brown, L.E., 2015. A critical analysis of regulated river ecosystem responses to managed environmental flows from reservoirs. Freshwater Biology, 60(2), pp.410-425.

Gippel, C.J. and Stewardson, M.J., 1998. Use of wetted perimeter in defining minimum environmental flows. Regulated Rivers: Research & Management: An International Journal Devoted to River Research and Management, 14(1), pp.53-67.

Hashimoto, T., Stedinger, J.R. and Loucks, D.P., 1982. Reliability, resiliency, and vulnerability criteria for water resource system performance evaluation. Water resources research, 18(1), pp.14-20.

Jahandideh-Tehrani, M., Bozorg-Haddad, O. and Loáiciga, H.A., 2019. Application of non-animal–inspired evolutionary algorithms to reservoir operation: an overview. Environmental monitoring and assessment, 191(7), p.439.

Jowett, I.G., 1997. Instream flow methods: a comparison of approaches. Regulated Rivers: Research & Management: An International Journal Devoted to River Research and Management, 13(2), pp.115-127.

Karami, H., Mousavi, S.F., Farzin, S., Ehteram, M., Singh, V.P. and Kisi, O., 2018. Improved krill algorithm for reservoir operation. Water Resources Management, 32(10), pp.3353-3372.

Kumar, V. and Yadav, S.M., 2018. Optimization of reservoir operation with a new approach in evolutionary computation using TLBO algorithm and Jaya algorithm. Water Resources Management, 32(13), pp.4375-4391.

Lamouroux, N., Hauer, C., Stewardson, M.J. and Poff, N.L., 2017. Physical habitat modeling and ecohydrological tools. In Water for the environment (pp. 265-285). Academic Press.

Nallaperuma, B. and Asaeda, T., 2019. Long-term changes in riparian forest cover under a dam-induced flow scheme: the accompanying a numerical modelling perspective. Journal of Ecohydraulics, 4(2), pp.106-112.

Nelson, F.A. 1980. ‘Evaluation of four instream flow methods applied to four trout rivers in southwest Montana’,Draft Report toUS Fisheries and Wildlife Ser6ice. Montana Department of Fish Wildlife and Parks. p. 105

Nikghalb, S., Shokoohi, A., Singh, V.P. and Yu, R., 2016. Ecological regime versus minimum environmental flow: comparison of results for a river in a semi Mediterranean region. Water resources management, 30(13), pp.4969-4984.

O’Sullivan, A.M., Wegscheider, B., Helminen, J., Cormier, J.G., Linnansaari, T., Wilson, D.A. and Curry, R.A., 2020. Catchment-scale, high-resolution, hydraulic models and habitat maps–a salmonid's perspective. Journal of Ecohydraulics, 6(1), pp.53-68.

Postel, S.L., 1998. Water for food production: will there be enough in 2025?. BioScience, 48(8), pp.629-637.

Rao, R.V. and Kalyankar, V.D., 2011. Parameters optimization of advanced machining processes using TLBO algorithm. EPPM, Singapore, 20, pp.21-31.

Rashedi, E., Nezamabadi-Pour, H. and Saryazdi, S., 2009. GSA: a gravitational search algorithm. Information sciences, 179(13), pp.2232-2248.

Ren, L., Zhang, Y., Wang, Y. and Sun, Z., 2007. Comparative analysis of a novel M-TOPSIS method and TOPSIS. Applied Mathematics Research eXpress, 2007.

Richardson, B.A. 1986. ‘Evaluation of instream flow methodologies for freshwater fish in New South Wales’, in Campbell, I.C.(Ed.),Stream Protection,the Management of Ri6ers for Instream Uses. Water Studies Centre, Chisholm Institute of Technology,Caulfield. pp. 143 – 167.

Sedighkia, M., Datta, B. and Abdoli, A., 2021a. Minimizing physical habitat impacts at downstream of diversion dams by a multiobjective optimization of environmental flow regime. Environmental Modelling & Software, 140, p.105029.

Sedighkia, M., Datta, B. and Abdoli, A., 2021b. Utilizing classic evolutionary algorithms to assess the Brown trout (Salmo trutta) habitats by ANFIS-based physical habitat model. Modeling Earth Systems and Environment, pp.1-13.

Shang, S., 2008. A multiple criteria decision-making approach to estimate minimum environmental flows based on wetted perimeter. River research and applications, 24(1), pp.54-67.

Shokoohi, A.L.I.R.E.Z.A. and Amini, M.A.J.I.D., 2014. Introducing a new method to determine rivers’ ecological water requirement in comparison with hydrological and hydraulic methods. International Journal of Environmental Science and Technology, 11(3), pp.747-756.

Tharme, R.E., 2003. A global perspective on environmental flow assessment: emerging trends in the development and application of environmental flow methodologies for rivers. River research and applications, 19(5-6), pp.397-441.

Waddle, T., 2001. PHABSIM for Windows user's manual and exercises (No. 2001-340).

Whitley, D., 1994. A genetic algorithm tutorial. Statistics and computing, 4(2), pp.65-85.

Yaseen, Z.M., Allawi, M.F., Karami, H., Ehteram, M., Farzin, S., Ahmed, A.N., Koting, S.B., Mohd, N.S., Jaafar, W.Z.B., Afan, H.A. and El-Shafie, A., 2019. A hybrid bat–swarm algorithm for optimizing dam and reservoir operation. Neural Computing and Applications, 31(12), pp.8807-8821.

Yeniay, Ö., 2005. Penalty function methods for constrained optimization with genetic algorithms. Mathematical and computational Applications, 10(1), pp.45-56.

Zhao, W., Wang, L. and Zhang, Z., 2019. A novel atom search optimization for dispersion coefficient estimation in groundwater. Future Generation Computer Systems, 91, pp.601-610.

Table 1- Defined weights for different criteria

Criterion	**Reliability index**	**Vulnerability index**	**RMSE**	**MAE**
Weight	M	VH	H	H

Table 2- Rating values for alternatives in disparate criteria (VG, RG, G, F and RP mean very good, relatively good, good, fair and relatively poor respectively)

Criteria	**Kind**	**Candidates**	**Rating**
Reliability index	Benefit	ASO	RG
		GA	VG
		GSA	RG
		TLBO	G
Vulnerability index	Cost	ASO	RG
		GA	VG
		GSA	F
		TLBO	VG
RSME	Cost	ASO	RP
		GA	G
		GSA	RP
		TLBO	RG
MAE	Cost	ASO	RP
		GA	G
		GSA	RP
		TLBO	RG

Table 3- Integrated decision matrix

	W1			W2			W3			W4		
	0.3	0.5	0.7	0.9	1	1	0.7	0.9	1	0.7	0.9	1
	RI			VI			RMSE			MAE		
ASO	5	7	9	5	7	9	1	3	5	1	3	5
GA	9	10	10	9	10	10	7	9	10	7	9	10
GSA	5	7	9	3	5	7	1	3	5	1	3	5
TLBO	7	9	10	9	10	10	5	7	9	5	7	9

Table 4- Normalized decision matrix

	W1			W2			W3			W4		
	0.3	0.5	0.7	0.9	1	1	0.7	0.9	1	0.7	0.9	1

	RI			VI			RMSE			MAE		
ASO	0.50	0.70	0.90	0.33	0.43	0.60	0.20	0.33	1.00	0.20	0.33	1.00
GA	0.90	1.00	1.00	0.30	0.30	0.33	0.10	0.11	0.14	0.10	0.11	0.14
GSA	0.50	0.70	0.90	0.43	0.60	1.00	0.20	0.33	1.00	0.20	0.33	1.00
TLBO	0.70	0.90	1.00	0.30	0.30	0.33	0.11	0.14	0.20	0.11	0.14	0.20

Table 5- Weighted normalized decision matrix

	W1			W2			W3			W4		
	0.3	0.5	0.7	0.9	1	1	0.7	0.9	1	0.7	0.9	1
	RI			VI			RMSE			MAE		
ASO	0.15	0.35	0.63	0.30	0.43	0.60	0.14	0.30	1.00	0.14	0.30	1.00
GA	0.27	0.50	0.70	0.27	0.30	0.33	0.07	0.10	0.14	0.07	0.10	0.14
GSA	0.15	0.35	0.63	0.39	0.60	1.00	0.14	0.30	1.00	0.14	0.30	1.00
TLBO	0.21	0.45	0.70	0.27	0.30	0.33	0.08	0.13	0.20	0.08	0.13	0.20

Table 6- D+ and D- of candidates (D+ and D- mean distance of alternative from fuzzy positive ideal solution and distance of alternative from fuzzy negative ideal solution respectively)

Alternatives	D+	D-
ASO	2.50	2.10
GA	3.03	1.04
GSA	2.36	2.35
TLBO	3.01	1.09

Table 7- Finalized prioritization by fuzzy TOPSIS method

Alternatives	CC/R		Ranking	
	TOPSIS	M-TOPSIS	TOPSIS	M-TOPSIS
ASO	0.456	2.517	2	2
GA	0.255	3.302	4	4
GSA	0.499	2.357	1	1
TLBO	0.265	3.268	3	3

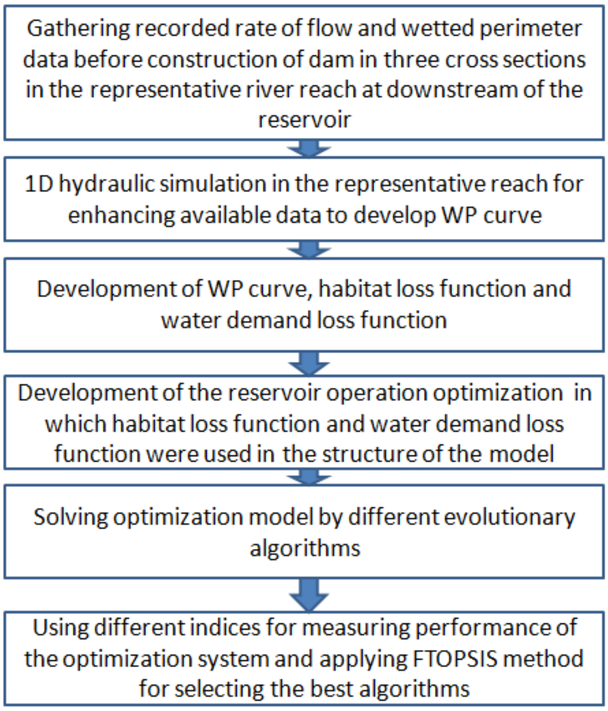


Figure 1- Flowchart of the proposed methodology

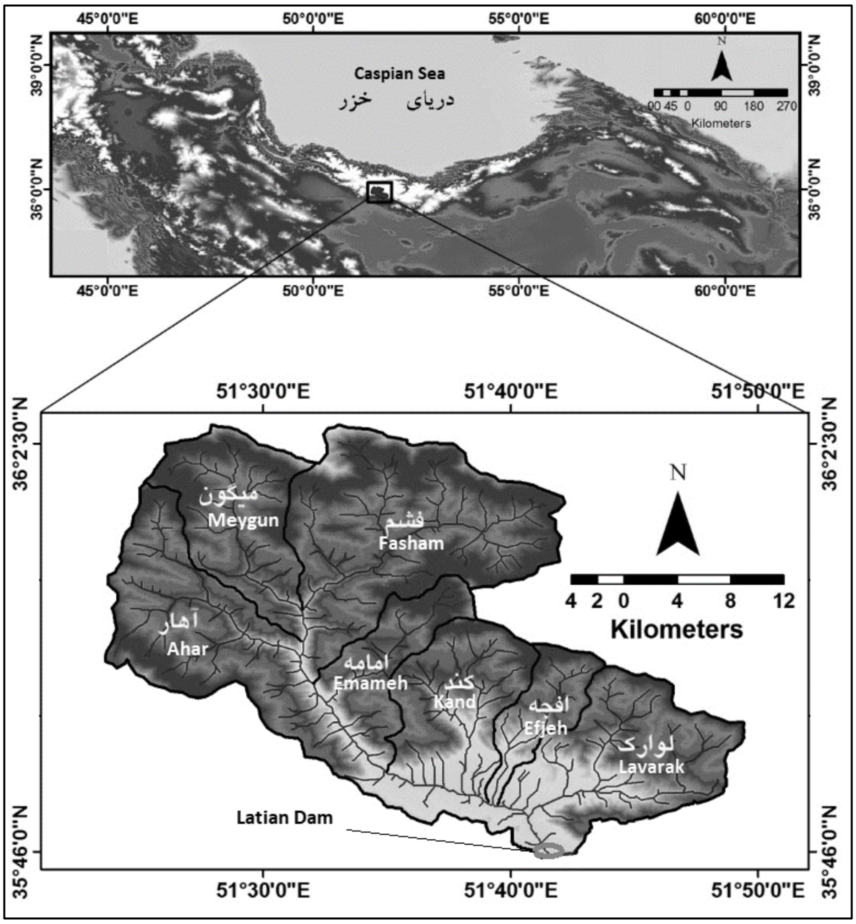
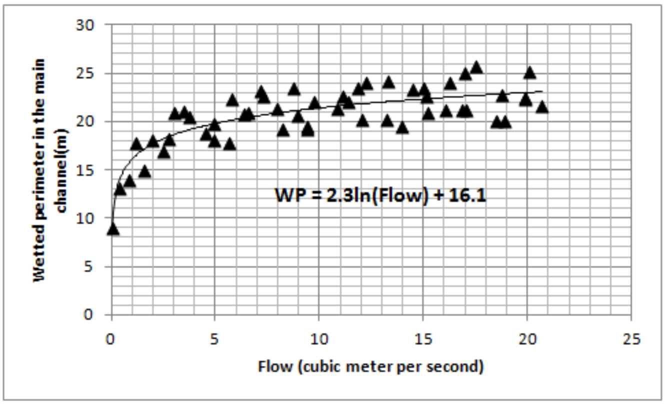
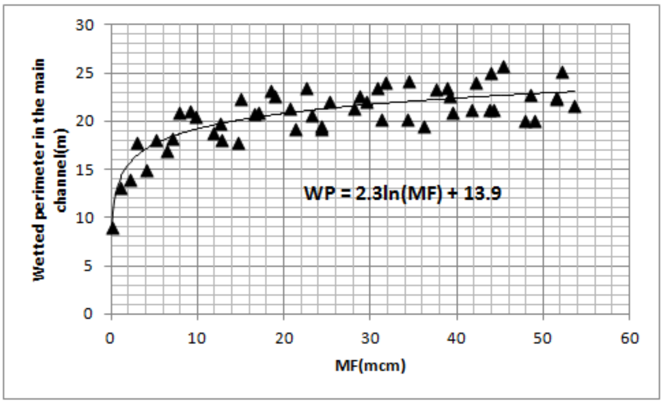


Figure 2-Jajrood river basin map



⇩



$$NWP = 10.4Ln(MF) + 58.9$$

Figure 3- Methodology of developing normalized wetted perimeter equation

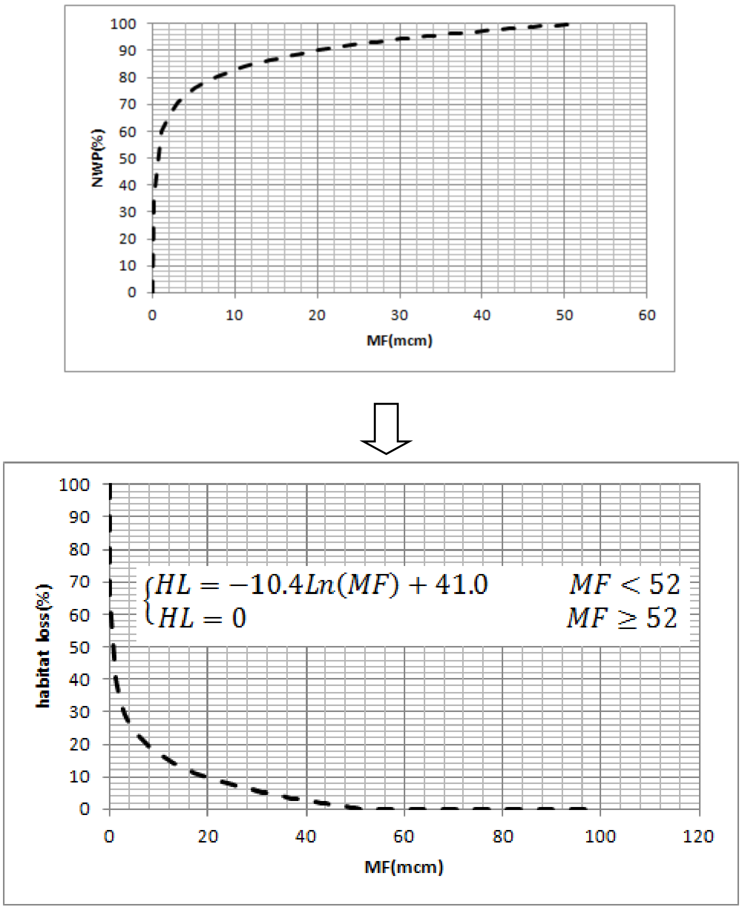


Figure 4- Development of habitat loss function in the optimization model

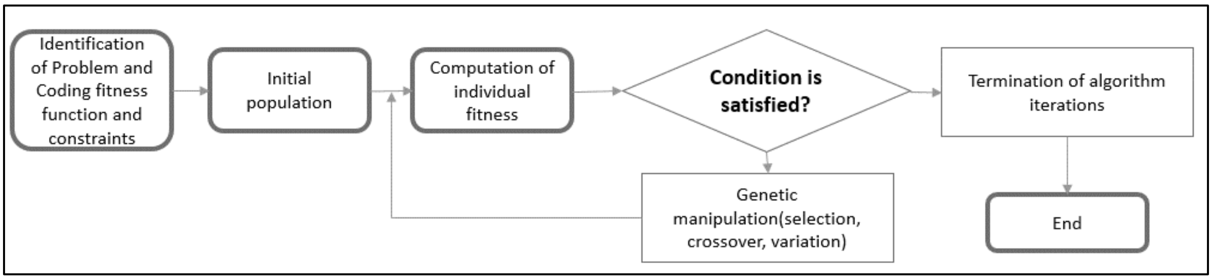


Figure 5-Flowchart of Genetic Algorithm (Whitley, 1994)

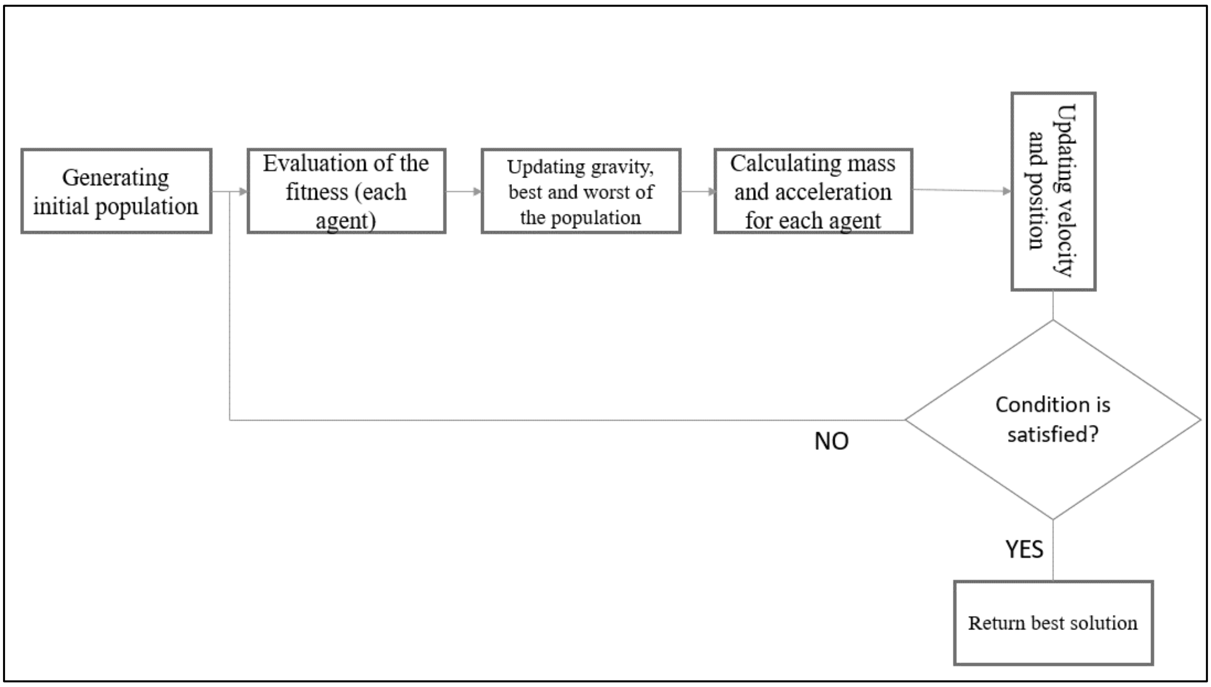


Figure 6-Flowchart of Gravity Search Algorithm (Rashedi et.al, 2009)

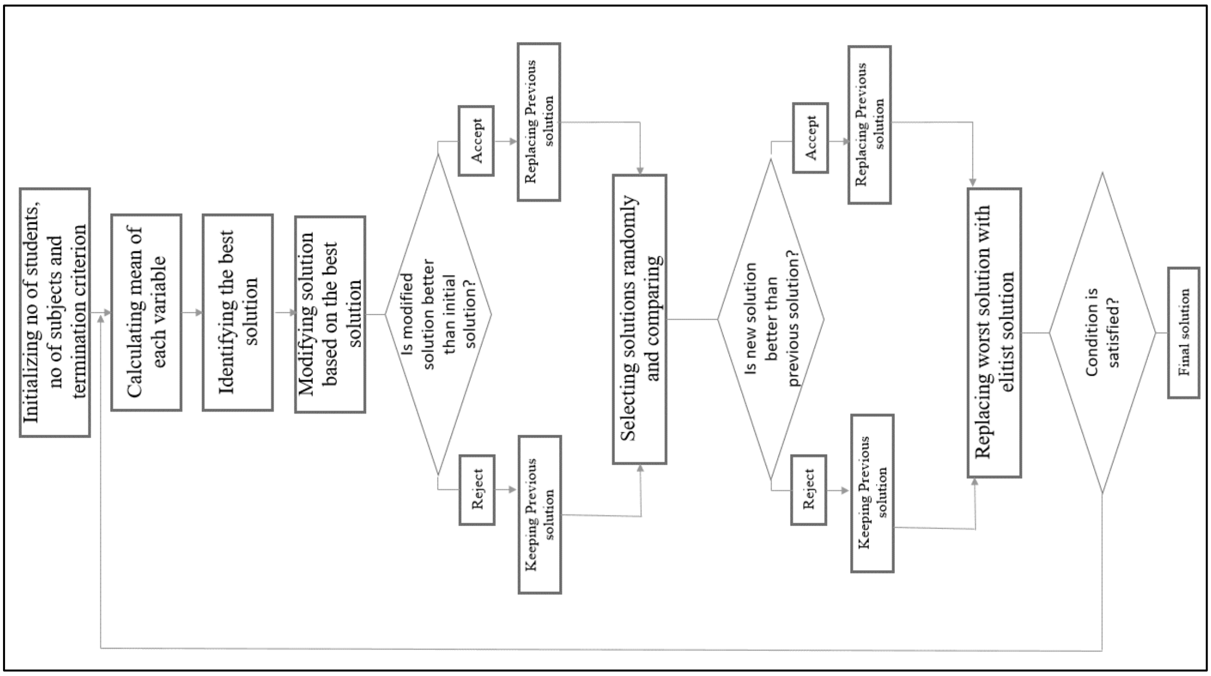


Figure 7-Flowchart of TLBO (Rao and Kalyankar, 2011)

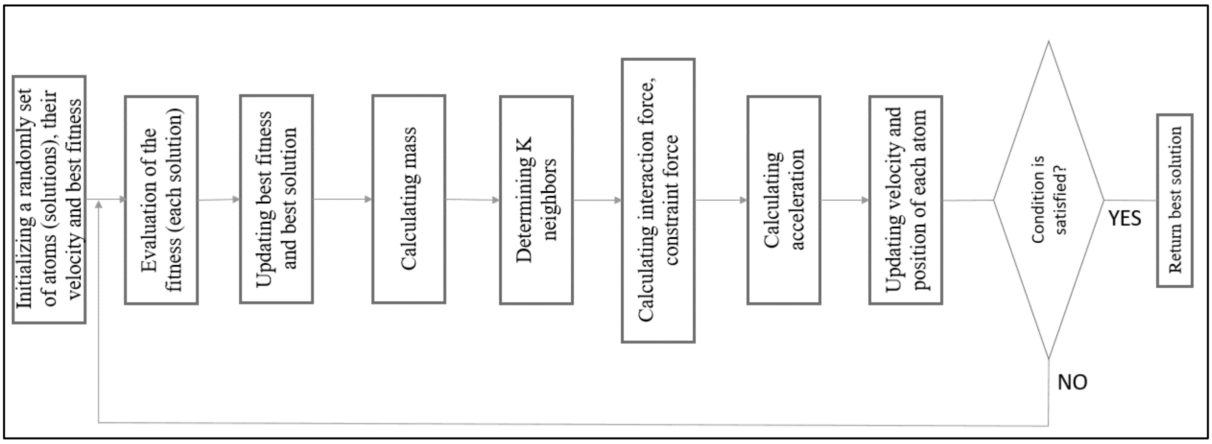


Figure 8-Flowchart of atom search optimization (Zhao et.al,2019)

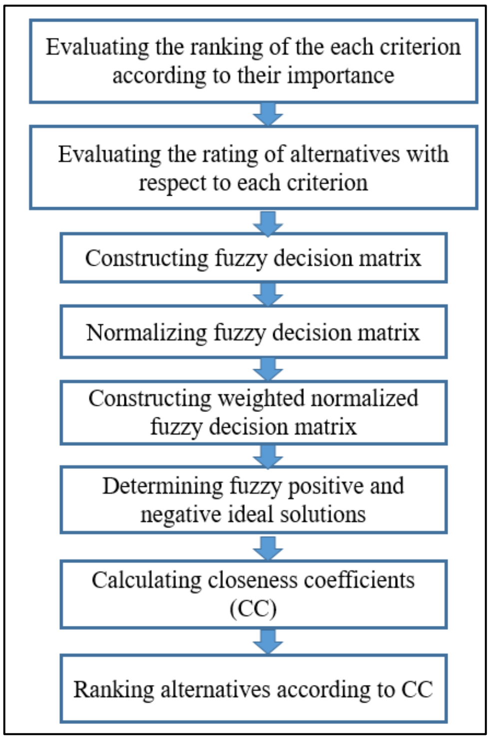


Figure 9-Flowchart of fuzzy TOPSIS (Chen,2000)

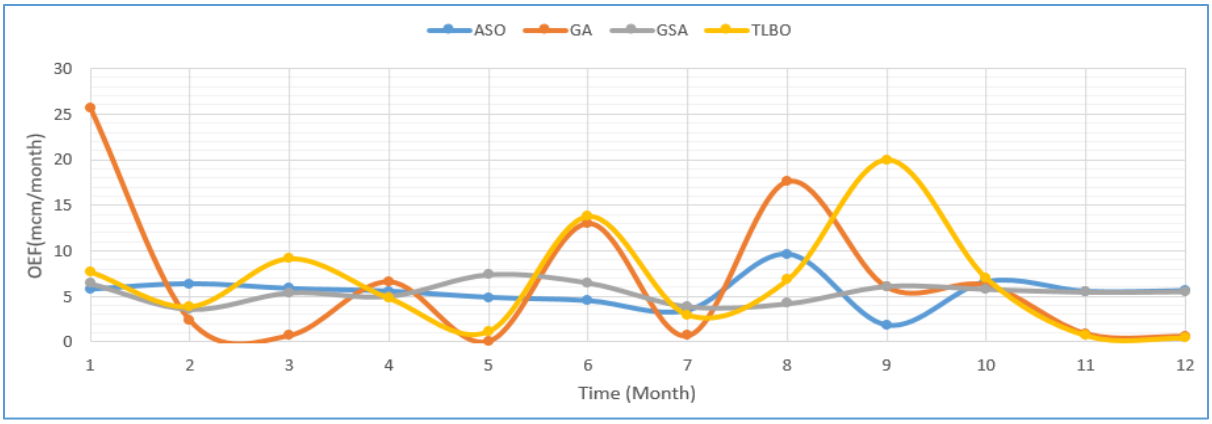


Figure 10-Proposed environmental flow regime by different algorithms

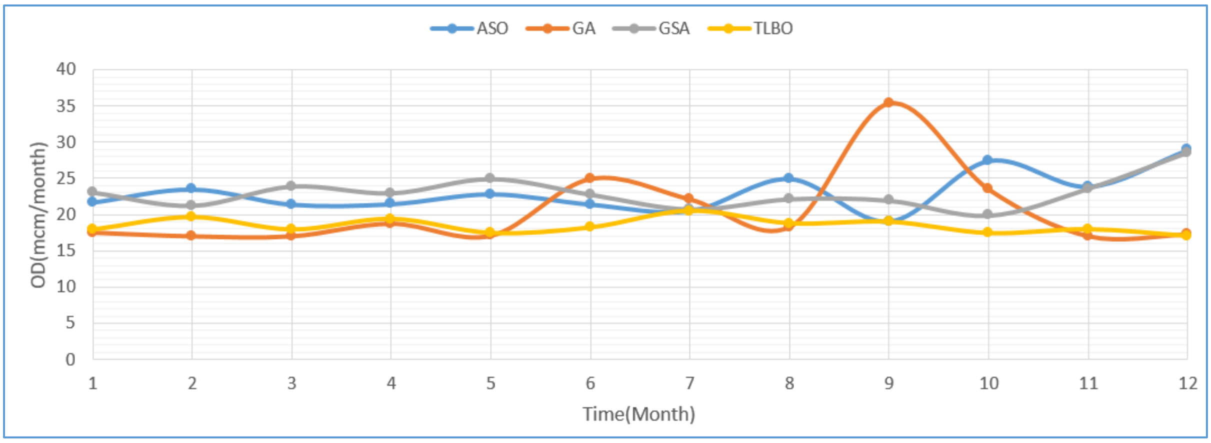


Figure 11-proposed water supply by different algorithms

.

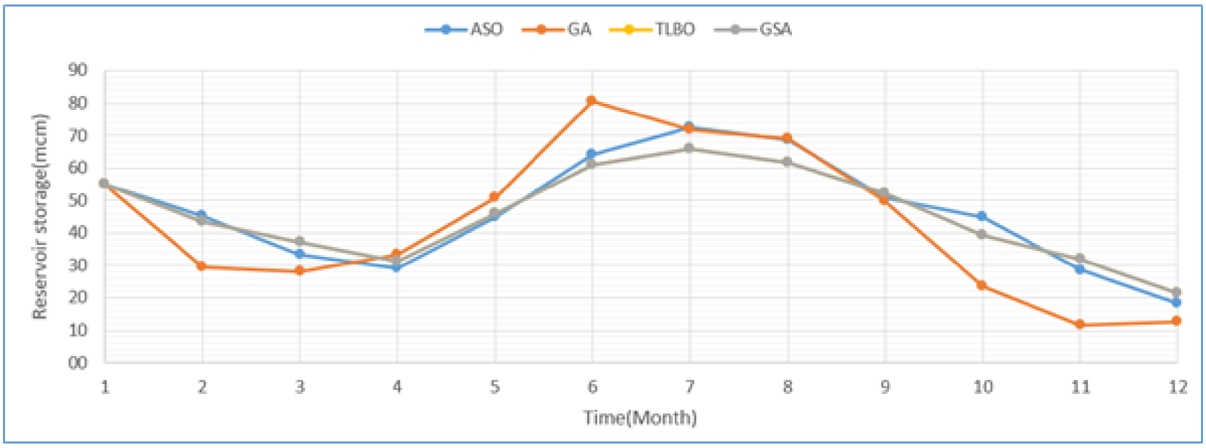


Figure 12-changes of reservoir volume by different algorithms

.

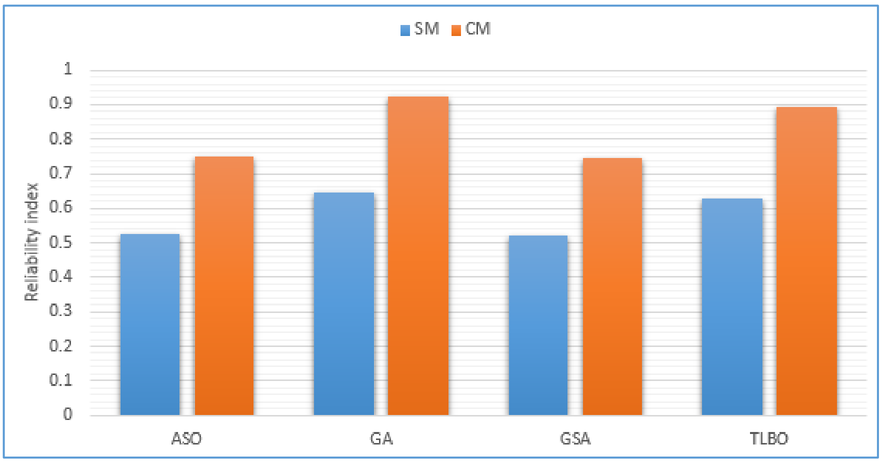


Figure 13-Reliability index (RI) for different algorithms

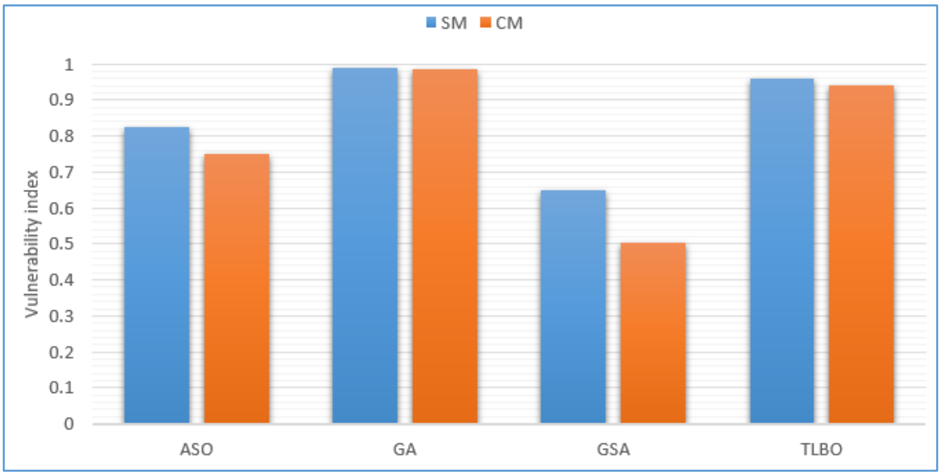


Figure 14-Vulnerability index (VI) for different algorithms

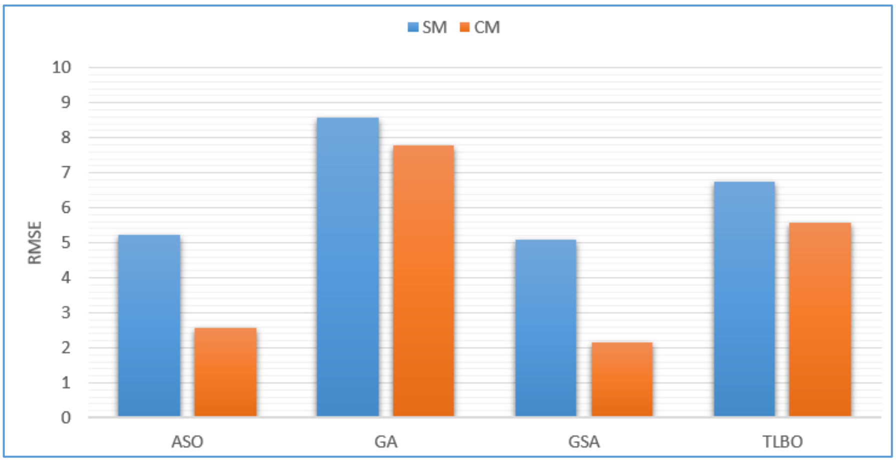


Figure 15-RMSE index for different algorithms

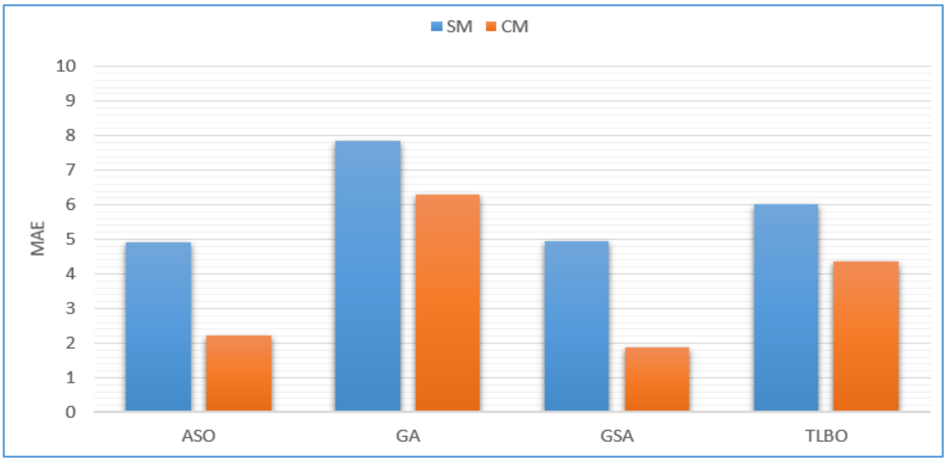


Figure 16-MAE index for different algorithms

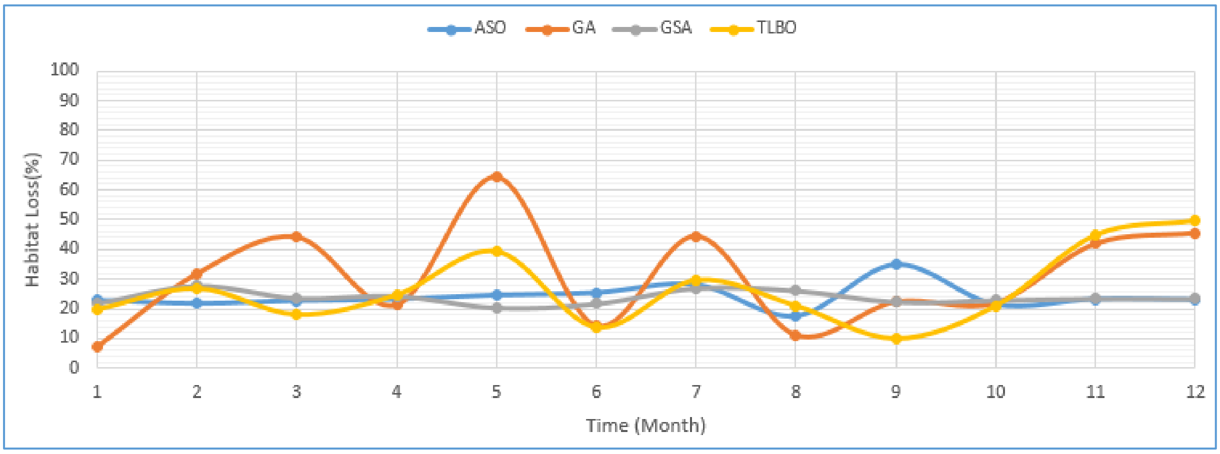


Figure 17-Habitat loss time series for different algorithms

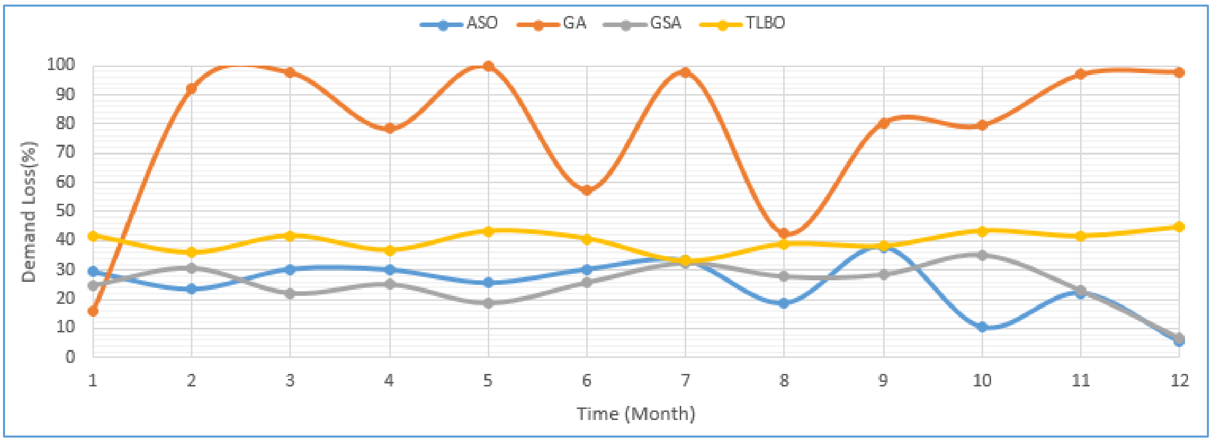


Figure 18-Water supply loss time series of different algorithms

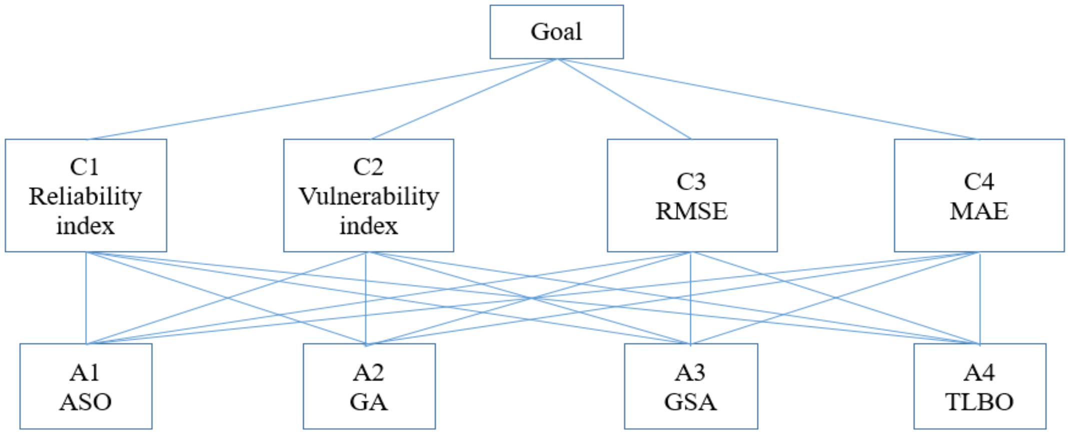


Figure 19-Developed hierarchical structure of fuzzy TOPSIS method

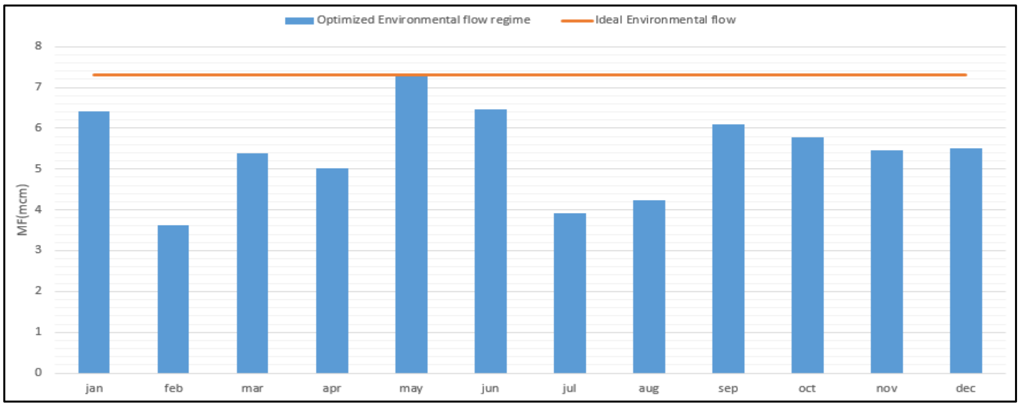


Figure 20-Finalized optimal environmental flow regime

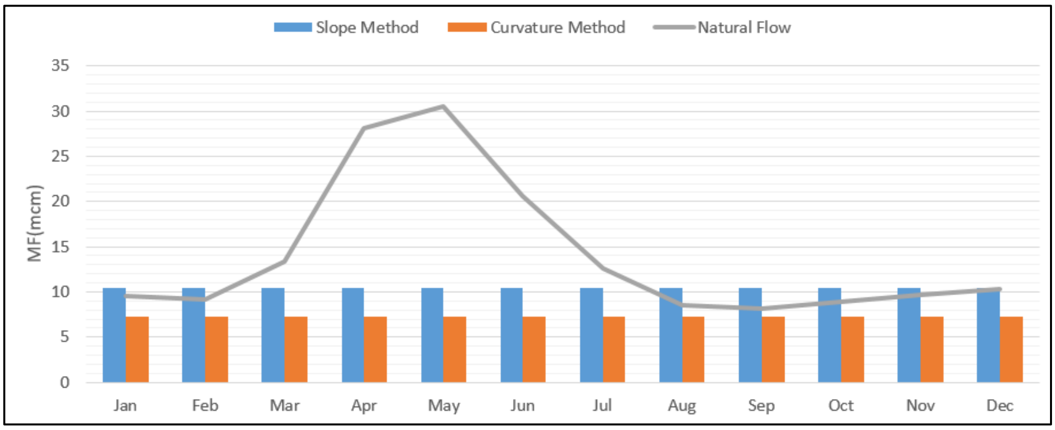


Figure 21-Natural flow regime at downstream of studied dam