Optimization of multipurpose reservoir system operation (Case study: Sefidrud and Shahryar reservoir dams)

Optimisation du fonctionnement du système de réservoir polyvalent (Étude de cas: barrages réservoirs de Sefidrud et Shahryar)

Naeemeh Abolvaset [1], *Simin* shahradfar [1*], and *Atosa* Mihandoost [1]

[1]Dam Department, Ashenab Consulting Engineers Company, Tabriz, Iran

Abstract. Nowadays, effective water management becomes more vital all over the worlds. Due to the effect of climate change and population growth, reservoirs play a more important role in water resources management. Reservoirs can be used for multiple purposes such as irrigation, industrial water supply, hydropower generation, flood protection, water quality management, recreation and so on. In this paper, an optimized model have been considered and solved based on the goal programming method for the optimal operation of a multi-objective two reservoir systems in Sefidrud watershed. Release for irrigation demand and environment, flood controlling and recreation are represented as objectives. Then, to consider uncertainties and also for achieving the general method for reservoirs operation, because of the considerable advantages of linguistic rules in better inferring and interpretation of systems, an adaptive neuro based fuzzy inference system (ANFIS) approach is used to construct operation rules for these multipurpose reservoirs. The results of the ANFIS models show that they can be applied successfully to provide high accuracy for the management of the reservoirs system.

Résumé. De nos jours, une gestion efficace de l'eau devient plus vitale partout dans le monde. En raison des effets du changement climatique et de la croissance démographique, les réservoirs jouent un rôle plus important dans la gestion des ressources en eau. Les réservoirs peuvent être utilisés à des fins multiples telles que l'irrigation, l'approvisionnement en eau industrielle, la production d'énergie hydroélectrique, la protection contre les inondations, la gestion de la qualité de l'eau, les loisirs, etc. Dans cet article, un modèle optimisé a été considéré et résolu sur la base de la méthode de programmation par objectif pour le fonctionnement optimal d'un système multi-objectif à deux réservoirs dans le bassin versant de Sefidrud. Les rejets pour la demande d'irrigation et l'environnement, le contrôle des crues et les loisirs sont représentés comme des objectifs. Ensuite, pour tenir compte des incertitudes et aussi pour obtenir la méthode générale de fonctionnement des réservoirs, en raison des avantages considérables des règles linguistiques pour une meilleure inférence et interprétation des systèmes, une approche de système d'inférence floue basée surun neuro adaptatif (ANFIS) est utilisée pour construire des règles de fonctionnement pour ces réservoirs polyvalents. Les résultats des modèles ANFIS montrent qu'ils peuvent être appliqués avec succès pour fournir une grande précision pour la gestion du système de réservoirs.

* Corresponding author: ashenab.icold@email.com

1 Introduction

Dam construction is one of the most important ways of using surface water. Considering water demands in different areas, storage system could be made on rivers as a one-reservoir system or multi-reservoir systems. Meanwhile, as well as the construction of dams, the way of operation of these reservoir systems is very important. In other words, appropriate operation is possible from existing dams, instead of building several new dams with high cost to compensate the water shortage. Existing uncertainties in prediction of water resource of watersheds in future, variability of rainfall and river flow regimes in different years, represent the adopting a strategy for optimal operation of the reservoirs with scientific methods. Optimal reservoirs operation is a topic that includes a large volume of researches and in this regard, recently, several optimization models are developed and used by the researchers. Loganathan and Bhattacharya (1990) applied five goal programming schemes for optimal reservoir operations to the Green River basin, these methods minimize deviations from a set of preferred target storage and flow values are considered: (1) Preemptive goal programming; (2) weighted goal programming; (3) min max goal programming, (4) fuzzy goal programming; and (5) interval goal programming [1]. Russell et al. (1996) applied using both fuzzy logic programming and fixed rules to finding operating procedures for a single-purpose hydroelectric project, where both the inflows and the selling price for energy can vary [2]. Eschenbach et al. (2001) used goal programming decision support system for multi-objective operation of reservoir systems. They adopted preemptive GP for modeling the system and for this purpose they used River Ware software as a suitable tool for optimization and simulation multi reservoir systems for daily operation [3]. Labadie (2004) assesses the state-of-the-art in optimization of reservoir system management and operations and consider future directions for additional research [4]. Application of heuristic programming methods using evolutionary and genetic algorithms are described, along with application of neural networks and fuzzy rule-based systems for inferring reservoir system operating rules. Abdelaziz Foued and Sameh (2001) used application of stochastic goal programming approach to operate and control of multipurpose reservoir systems in the north of Tunisia [5]. Uncertainty in hydrological phenomena requires the use of tools that are capable of considering uncertainties and subtleties in these phenomena. Recently, many investigations are done for simulation of uncertainty in hydrological phenomena using intelligent systems such as Fuzzy Inference System (FIS) and Adaptive Neuro-Fuzzy Inference System (ANFFIS). Following researches are done in the field of using ANFIS for simulating the uncertainty in hydrological phenomena; Regarding the modeling of rainfall – runoff, simulation of suspended sediment (Kişi. 2005 and Rajaee et al. 2009), Ground waters (Dixon, 2005) and the optimal operation of reservoirs (Mousavi et al. 2007) [6-9]. In this paper, an optimized model have been considered and solved based on the goal programming method for the optimal operation of a multi-objective two reservoir systems. Then, to consider uncertainties and also for achieving the general method for reservoirs operation, because of the considerable advantages of linguistic rules in better inferring and interpretation of systems, an adaptive neuro based fuzzy inference system (ANFIS) approach is used to construct operation rules for these multipurpose reservoirs.

2 Methodology

2.1 Goal Programming

Goal Programming (GP) is a well-known mathematical model for solving multi-criteria problems which can be said that it is the oldest existing model of multi-objective decision models that has wide applications in various fields. Goal-programming methods also require specified target values, along with relative losses or penalties associated with deviations from these target values. The objective is to find the plan that minimizes the sum of all such losses or penalties. Assuming for this illustration that all such losses can be expressed as functions of deviations from target values, and again assuming each objective is to be maximized, the general goal-programming problem is to minimize: (Eq. 1 to 3)

$$\textit{Minimize} \quad \sum_j v_j D_j + w_j E_j \tag{1}$$

subject to

$$g_i(x) = b_i \qquad i = 1,2,\dots,m \tag{2}$$

$$Z_j(x) = T_j^* - D_j + E_j \tag{3}$$

Where, the parameters v_j and w_j are the penalties (weights) assigned to objective value deficits or excesses, as appropriate. The weights and the target values, T_j^*, can be changed to get alternative solutions, or tradeoffs, among the different objectives (Loucks and Van Beek, 2005).

2.2 Adaptive Neuro Fuzzy Inference System

Despite the many successes that have been achieved in the operation of reservoirs, applicability of optimization techniques faces many problems. Therefore, efforts to improve and simplify the computational operations cannot be effectively and application of a model that is compatible with the understanding of exploiter must be considered in the selection of model. In recent decades, fuzzy logic is proposed to model reservoir management, and resolve its ambiguous features. A mathematical model which in some way uses fuzzy sets is called a fuzzy model. In system identification, rule-based fuzzy models are usually applied. One of the most important fuzzy modeling is the fuzzy inference system which based on: fuzzy set theory, fuzzy if then rules and fuzzy reasoning. There are three types of fuzzy inference systems (Mamdani, Sugeno and Tsukamoto) that the differences between these lie in the consequents of their fuzzy rules, and thus their aggregation and defuzzification procedures differ accordingly. Although the fuzzy inference system has a structured knowledge representation in the form of fuzzy if-then rules, it lacks the adaptability to deal with changing external environments. Thus, Jang (1993) incorporate neural network learning concepts in fuzzy inference systems, resulting in neuro-fuzzy modeling [10]. Adaptive neuro fuzzy inference system (ANFIS), representing both the Sugeno and Tsukamoto fuzzy models, decompose the parameter set to facilitate the hybrid learning rule. ANFIS can be used to optimize membership functions to generate stipulated input–output pairs and has the advantage of being able to subsequently construct fuzzy "if–then" type rules representing these optimized membership functions.

2.2.1. ANFIS Structure

Let the membership functions of fuzzy sets A_i, B_i, i=1,2, be , μ_{Ai}, μ_{Bi}. Consider a Sugeno type of fuzzy system having the rule base:

- If x is A1 and y is B1, then $f_1=p_1x+q_1y+r_1$
- If x is A2 and y is B2, then $f_2=p_2x+q_2y+r_2$

Which the fuzzy inference system under consideration has two inputs x and y and one output z for a first-order Sugeno fuzzy model. In evaluating the rules, choose product for T-norm (logical and).
Evaluating the rule premises results in $w_i = \mu_{A_i}(x).\mu_{B_i}(y)$, i=1,2.
Evaluating the implication and the rule consequences gives. $f=\frac{w_1f_1+w_2f_2}{w_1+w_2}$

3 Case study

The study area of this research consists of two storage dams; Sefidrud and Shahryar dams which are located in the Sefidrud catchment. This sub-basin has an area of 60015 square Kilometers. Sefidrud Dam is a buttress dam on the SefidRud near Manjil in Gilan Province, Iran. It was constructed to store water for irrigation and produce hydroelectric power. It is 106 m tall and forms a reservoir with a capacity of 1.82 km^3.

Shahriar dam is a double curvature concrete arch dam with 135 meters height from foundation. The dam is capable to supply the needed water for the regions of the downward lands and 120000 hectares of Mianeh lands. The above mentioned dam also aids Sefidrud dam to provide water needed for agriculture and industry in Gilan province. In addition to control Qhzlozan flood water and due to raise the efficiency of removing the sediment in Sefidrood dam the reservoir may provide artificial water-floods. Decreasing the sediments entering sefidrud dam and providing 27 MWH, electricity annually are among the consequences of constructing this dam. In the Fig. 1 and 2 the Schematic diagram of the location of Sefidrud and Shahryar dams and also a view of the Sefidroud River Basin are shown.

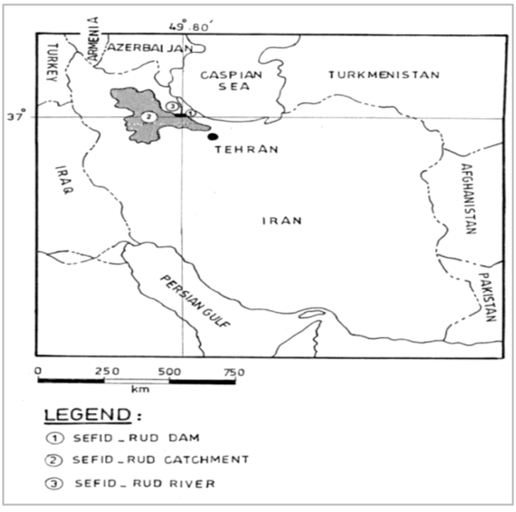

Fig 1. Sefidrud River Basin

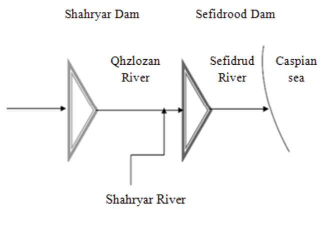

Fig 2. The Schematic diagram of The location of Sefidrud and Shahryar dams

4 Proposed model structure

In this paper, first, Goal Programming (GP) method is used for optimal operation of a two reservoir systems, then, using the results of the GP optimization model, ANFIS model is applied in order to enter the uncertainties as well as to obtain a general method of operation. In fact, Adaptive Neuro-Fuzzy Inference System (ANFIS) is used due to its ability in utilization of artificial neural network for making the rules of Fuzzy Inference System. To obtain the optimal multi-objective model of the system, three objectives are generally considered: downstream water demand (agriculture and environment), flood controlling and recreational using. Table 1. Shows the downstream water demand of the Shahryar dam.

Table 1. Downstream water demand (agriculture and environment) of Shahryar dam (MCM)

Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.
22	13	13	13	13	13	25	160	168	130	50	14

Mathematical structure of optimization model I, are given as Eq. 4 to 19, note that in the all given equations, index 1 is related to the Shahryar dam and index 2 is related to the Sefidrud dam.

Minimize:

$$C=(aw\times OF_I)+(bw\times OF_{II})+(cw\times OF_{III}) \quad (4)$$

$$\text{Subject to}$$

$$OF_I=\sum_{y=1}^{48}\sum_{t=1}^{12}\left(Ad_1^+(y,t)+Ad_1^-(y,t)\right)+\sum_{y=1}^{48}\sum_{t=1}^{12}\left(Ad_2^+(y,t)+Ad_2^-(y,t)\right) \quad (5)$$

$$OF_{II}=\sum_{y=1}^{48}\sum_{t=1}^{12}\left(Fd_1^+(y,t)+Fd_1^-(y,t)\right)+\sum_{y=1}^{48}\sum_{t=1}^{12}\left(Fd_2^+(y,t)+Fd_1^-(y,t)\right) \quad (6)$$

$$OF_{III}=\sum_{y=1}^{48}\sum_{t=1}^{12}\left(Rd_1^+(y,t)+Rd_1^-(y,t)\right)+\sum_{y=1}^{48}\sum_{t=1}^{12}\left(Rd_2^+(y,t)+Rd_2^-(y,t)\right) \quad (7)$$

$$R_1(y,t)=D_1(y,t)+Ad_1^+(y,t)\text{-}Ad_1^-(y,t) \quad (8)$$

$$R_2(y,t)=D_2(y,t)+Ad_2^+(y,t)\text{-}Ad_2^-(y,t) \quad (9)$$

$$S_1(y,t)=Fl_1(t)+Fd_1^+(y,t)\text{-}Fd_1^-(y,t) \quad (10)$$

$$S_2(y,t)=Fl_2(t)+Fd_2^+(y,t)\text{-}Fd_2^-(y,t) \quad (11)$$

$$S_1(y,t)=Rl_1(t)+Rd_1^+(y,t)\text{-}Rd_1^-(y,t) \quad (12)$$

$$S_2(y,t)=Rl_2(t)+Rd_2^+(y,t)\text{-}Rd_2^-(y,t) \quad (13)$$

$$S_1(y,t+1)=S_1(y,t)+Q_1(y,t)\text{-}R_1(y,t) \quad (14)$$

$$S_2(y,t+1)=S_2(y,t)+Q_2(y,t)+kR_1(y,t)\text{-}Q_1(y,t)\text{-}R_2(y,t) \quad (15)$$

$$S_{min}\leq S_1(y,t)\leq S_{max} \quad (16)$$

$$R_{min}\leq R_1(y,t) \quad (17)$$

$$S_{min}\leq S_2(y,t)\leq S_{max} \quad (18)$$

$$R_{min}\leq R_2(y,t) \quad (19)$$

In this research for modeling the multi-objective two reservoir systems, the combination of all above-mentioned purposes is intended. Also in these models to formulate the optimization relations (objective functions and constraints) following Hydrological data and assumptions are considered; Data related to inflow of reservoirs, agriculture and environment water demands are used as monthly data, and also these constraints are assumed; Limitations of reservoirs volume to maximum and minimum volume. Limitation of release from reservoirs, limitation of proper water level in the reservoirs for flood controlling, limitation of proper water level in the reservoirs for recreational using.

It should also be noted that the mathematical form of the objective function and the constraints used in the models II and III is the same as model I but the only difference is the relative weights that are applied to the objective function. In other words, the abovementioned objectives don't have the same priorities from the view of decision makers. As well the differences in the models are in the conventional water levels for the mentioned purposes. In all models, according to the opinion of decision makers priorities of the agriculture and environment water demand supply due to their special importance are considered more than purpose of flood controlling and recreational using. The weight of the flood controlling purpose in Model I is applied greater than the recreational using, in Model II, the same and in the Model III reverse the case of the model I.

Eq. 4 is the main equation of the objective function of the model, where, OFI, OFII and OFIII are the objective functions of GP model (Eq. 5 to Eq. 7). It should be noted that aw, bw and cw are considered as the relative weights of the objective functions of the model.
The sum of these weights must be equal to one. Eq. 8 to 13 show the constraints of the Goal Programming model, where, D(y,t) is the water demand, Rl(t) is equal volume of water level for recreational using, Fl(t) is equal volume of water level for flood controlling, Ad^{-} (y,t), Ad^{+} (y,t) , Fd^{+} (y,t) , Fd^{-} (y,t), Rd^{+} (y,t) and Rd^{-} (y,t) are the values deficits or excesses of the GP model. Eq. 14 and Eq. 15 are the continuity equations, in fact the most important constraints in the problem of reservoir operation. Where, S(y,t) represents storage volume of reservoirs for the month t, Q(y,t) represents inflows for reservoirs for the month t and R(y,t) represents release from reservoirs for the month t. the assumptions of the continuity equation are considered as following, The evaporation and seepage losses and also rainfall to the reservoirs are ignored. In the continuity equation of Sefidrud dam, reservoir inflow is considered from Shahrud River and a third of Shahryar dam release.

Finally, Eq. 16 to 19 represents the minimum and maximum limits of reservoir volumes and releases. In Fig. 3 to 6, the results of the Models I, II and III, are shown for a statistical period of 48 years (1956-2004), Monthly outputs of these models are as follows; storage volume in reservoirs in the specified statistical period, the amount of water released by the dams during the specific statistical period and the values deficits or excesses of GP model. As can be seen, in the models I, II and III, changes in the storage volume of the reservoirs are evident. In the Shahryar dam, storage volume in the months of September and October is minimum and in the months of May and June is maximum. The status of Sefidrud dam is almost the same as the Shahryar dam so that in the reservoir of this dam, the storage volume in the month of September is the lowest and in the months of June and July has the highest value. However in the models I, II and III, The results show the negligible changes in the release of the dams, and so that it will be discussed in the next session, the performance criteria for the models in supplying the objectives of this two-reservoir system are almost suitable

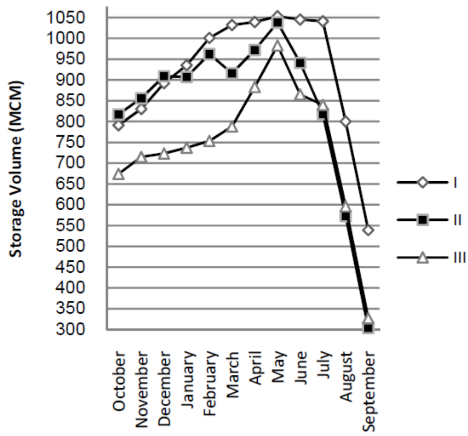

Fig 3. Storage volume in Sefidrud reservoir for models I, II, III

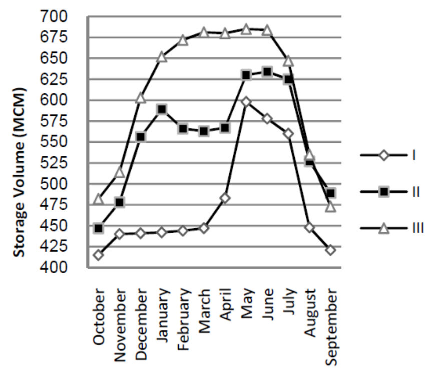

Fig 4. Storage volume in Shahryar reservoir for models I, II, III

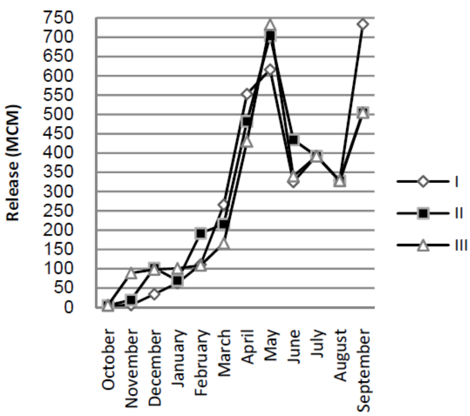

Fig 5. Release of Sefidrud reservoir for models I, II, III

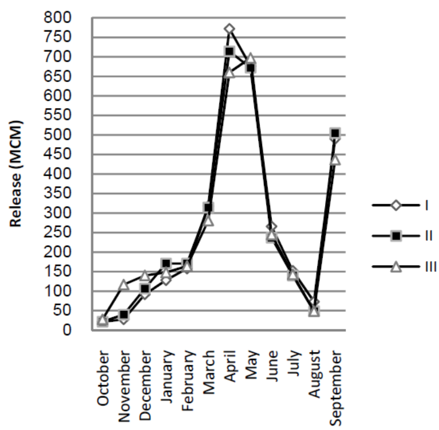

Fig 6. Release of Shahryar reservoir for models I, II, III

5 Performance criteria

These characteristics can be captured by the measures of reliability, resilience and vulnerability.

5.1 Reliability

Reliability is the term given to that aspect of the analysis which shows the probability of a reservoir being in a satisfactory state of operation. Mathematically it is defined as Eq. 20,

$$\delta = \left(1 - \frac{f}{T}\right) \tag{20}$$

Where, δ, is defined as the satisfactory states $(0 \leq \delta \leq 1)$, f, is the total number of failed periods and T is the total number of operational period.

5.2 Resilience

Resilience, the measure of how quickly a reservoir system is able to recover from a failure state, may be equated to the following formula; Eq. (21),

$$\lambda = \frac{1}{\frac{f}{fs}} \tag{21}$$

Where, λ is the speed of reversibility, f_s is the maximum number of consecutive failure states and f is the number of failure states.

5.3 Vulnerability

When a failure state occurs, it is useful to have some method by which to measure the degree of failure which has occurred. The term designated to describe this facet of an investigation is vulnerability. The equation used to determine the degree of failure which occurred in the reservoir simulation is Eq. 22,

$$\eta = \frac{(\sum_{t\epsilon f} R_t^* - \sum_{t\epsilon f} R_t)}{\sum_{t\epsilon f} R_t^*} \tag{22}$$

Where, η is the maximum penalty for a time of failure, R_t^* is the desired release, Rt is the actual amount of release. An unsuccessful state of operation occurred whenever there was water in the flood-control pool, due to the run storage exceeding the level set by the rule curve. The case in which the actual downstream flow was less than the downstream demands was also considered inadequate. The occurrence of either or both of these events within a given month of examination constituted a failure of the reservoir (Loucks and Van Beek, 2005) [11]. Loucks in 1997 to determine the stability in design and operation of the reservoirs, combined the reliability, resilience and vulnerability as Eq. 23 [12],

$$\varphi = \delta\lambda(1 - \eta) \tag{23}$$

Where, φ is the sustainability index. According to these criteria, it could be say that in general, the performances of the studied reservoirs in supplying the objectives of the system were appropriate. This index is very good in comparing the policies and operation of reservoir systems. In the operation of storage systems the most ideal policy operation occurs when the reliability and resilience of the system is the highest but the vulnerability is the lowest. Although, having such a system due to the interaction between the reservoir performance criteria, it is rarely possible. Fig. 7 and 8 show the performance criteria of the Sefidrud and Shahryar reservoir systems. As it can be seen, it could be said that in general, the performance of the studied reservoirs are suitable, and also performance of the multi objective optimization model II is better than models I and III of the research.

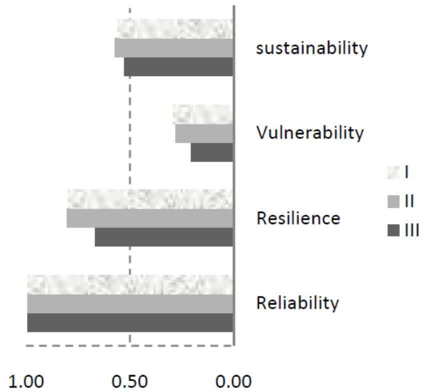

Fig 7. performance criteria of the Shahryar reservoir

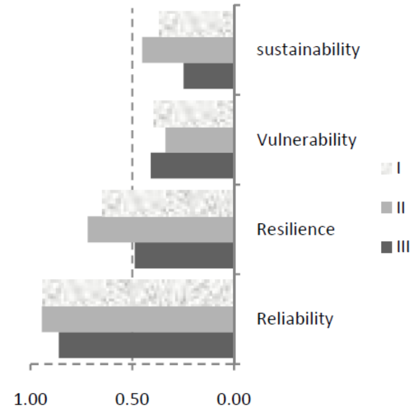

Fig 8. performance criteria of the Sefidrud reservoir

6 Application of ANFIS model in the operation of reservoir systems

ANFIS model is applied in order to enter the uncertainties as well as to obtain a general method of operation. In fact, Adaptive Neuro-Fuzzy Inference System (ANFIS) is used due to its ability in utilization of artificial neural network for making the rules of Fuzzy Inference System. So, for simulation, data classification was performed for the training, checking and testing in different scenarios. Finally, the data set is divided into three parts: the first 70% of total data (Data relating to the results of the optimization model II) are used as training set and the second 20% are used for checking and the last 10% of data are used for testing the models. The input and output variables for the present study were scaled between 0.05 and 1 to eliminate their dimensions and to ensure that all variables receive equal attention during training of the models as Eq. 24,

$$\acute{x}_i = 0.05 + 0.95\frac{x_i - x_{min}}{x_{max} - x_{min}} \qquad (24)$$

Where, $\acute{x}_i$ is the normalized value, x_i is the original value and x_{min} , x_{max} are the minimum and maximum of variable i, respectively.

In the premise part of fuzzy model, the reservoir inflow, storage volume and downstream water demand (monthly) are considered and in the consequent part, monthly release is considered as models variables. After the construction of models with different kinds of membership functions (Triangular, trapezoidal and Gaussian), and also with different numbers of membership functions (three, four and five) for each input, finally, ANFIS model with Gaussian membership function and five membership function for each input was selected as the best model.

In this paper, the performance of the models was evaluated utilizing R^2 and RMSE. In brief, the models predictions are optimum if R^2 and RMSE are found to be close to 1 and 0, respectively. The R^2 parameter clarifies relation between observed and predicted values and RMSE evaluates the residual between observed and predicted. The formulas of these criteria are given as Eq. 25 and 26,

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(x_i - y_i)^2}{n}} \qquad (25)$$

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(x_i - y_i)^2}{\sum_{i=1}^{n}(y_i - \bar{x}_i)^2} \quad (26)$$

Where, y_i is the data related to model results, xi is related to model input, y_i و x_i describe the mean of mentioned data. Values of these two criteria for both Sefidrud and Shahryar dams are presented in Table 2. Here, the output of the model II is used as observed data for comparison with the results of the ANFIS model (the amount of water release from Sefidrud and Shahryar dams)

Table 2. Values of evaluation criteria for both Sefidrud and Shahryar dams

Dam	Modeling stage	Evaluation Criteria		Dam	Modeling stage	Evaluation Criteria	
		RMSE	R^2			RMSE	R^2
Shahryar	Train	0.03	0.97	Sefidrud	Train	0.03	0.96
	Check	0.04	0.95		Check	0.05	0.86
	Test	0.05	0.84		Test	0.03	0.91

In Fig. 10 and 11 also a comparison between the output data of ANFIS model and Model II

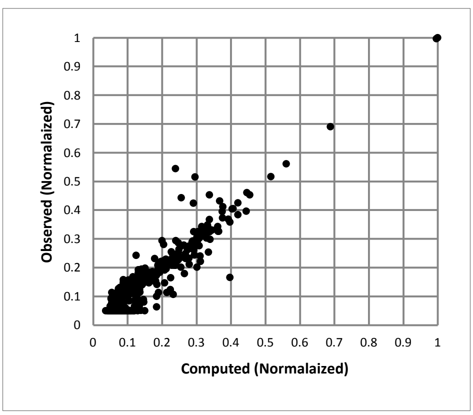

Fig 10. Comparison of ANFIS Results and model II , Sefidrud (R2=0.91)

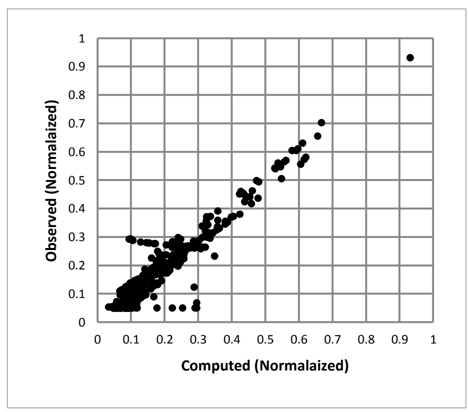

Fig 11. Comparison of ANFIS Results and model II , Shahryar (R2=0.84)

7 Conclusion

The results of Goal Programming (GP) model indicated that, in the models I, II and III, changes in the storage volume of the reservoirs are evident. In the Shahryar dam, storage volume in the months of September and October is minimum and in the months of May and June is maximum. The status of Sefidrud dam is almost the same as the Shahryar dam so that in the reservoir of this dam, the storage volume in the month of September is the lowest and in the months of June and July has the highest value. However in the models I, II and III, The results show the negligible changes in the release of the dams. According to The performance criteria for the models, it could be said that in general, the performances of the studied reservoirs in supplying the objectives of the system are appropriate, and also performance of the multi-objective optimization model II is better than models I and III of the research.

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