Consideration of climate conditions in reservoir operation by using fuzzy inference system (FIS)

H. R. SAFAVI, M. A. ALIJANIAN & M. H. GOLMOHAMMADI
Department of Civil Engineering, Isfahan University of Technology, Isfahan, Iran
hasafavi@cc.iut.ac.ir

Abstract Operation of reservoir obviously is sensitive to climate conditions. When operation rules are formulated based on stationary climate, any intervening climate change may modify final outcomes of the policies for better or worse. Previous research on reservoir operation has seldom identified the effects of climate change on the relationship between crop yield and irrigation. The rather complicated nature of mathematical modelling of reservoir operation under conditions of climate change warrants the use of intelligent computing tools such as the Fuzzy Inference System (FIS) approaches. Fuzzy Inference Systems are based on if-then rules which allow expert experience and knowledge to be included in the relationships between input and output variables. FIS can be used for forecasting such uncertain conditions as are typically encountered under conditions of climate change. This paper uses the FIS method to the operation of the Zayandehrood Dam Reservoir under conditions of climate change. The study area is the Zayandehrood River Basin located in west-central Iran. A great portion of the basin being of the arid and semiarid climate type, agriculture in this region depends almost entirely on irrigation water from surface and groundwater resources. The bulk of the surface water in the basin flows through the Zayandehrood River which is controlled by the 1400 MCM Zayandehrood Dam. A historical low rainfall in the head region of the basin over the past 10 years, combined with a growing demand for water, has triggered great changes in the water management in the basin with special effects on the operation of the dam reservoir. In this paper, the Fuzzy Inference System is used to develop a model for the operating of the Zayandehrood Dam and for planning of downstream agricultural crop farms for different climate conditions. The model consists of three parts: in the first part, the storage volume of the reservoir in the last month of the solar year, Esfand (February-March), is predicted based on the input flow to the reservoir during the last three months of the year and on the Southern Oscillated Index (SOI) using the Adaptive Network Fuzzy Inference System (ANFIS). The SOI and the input flow are model inputs while the storage volume of the reservoir is the model output. The second part involves forecasting the annual release in the following year as the model output using the storage of the reservoir in the last month of the previous year and the amount of snow both as the FIS inputs. This value will be different for different climate conditions. As the annual release from the reservoir has definitive effects on the cropping schedule, it may be regarded as a defining factor for climate conditions. The optimized planning of crops for the following year will be developed based on the annual release from the dam as forecasted by the fuzzy rules in the third part of the model. The three parts of the model operate on an "if-then" principle, where the "if" is a vector of the fuzzy permits and "then" is the fuzzy result. The model is developed based on data from 1990 to 2006.
Keywords fuzzy inference system; reservoir operation; southern oscillated index (SOI); crop planning

INTRODUCTION

Actually the operation of water resources is an essential aspect in semi arid countries like Iran. Reservoirs are the source for saving and supplying the water requirements during the year. This system provides the ability to save the water in rainy seasons and use it in drought periods. Furthermore there are the other applications such as producing electric power, fishing, and even recreation camps around reservoirs. In recent decades the management of reservoir is one of the fundamental problems in water resources management. There are lots of researchers who work on programming the reservoir and use diverse methods. The most important aspect which must be considered in modelling of reservoir operation is the randomly hydrological events.

Because of these random properties, most of the methods which have been used for simulation and optimization are based on stochastic concepts. Yeh (1985) presented the state of the art and discussed in detail various models for reservoir operation. He cited the application of linear programming (LP), dynamic programming (DP), nonlinear programming (NLP) and simulation models for various multipurpose, multireservoir cases. Simonovic (1992) has discussed the limitations in the reservoir operation models and remedial measures to make them more acceptable to operators. Russel and Campbell (1996) also emphasized that due to the 'high degree of abstraction' necessary for efficient application of optimization techniques.

The uncertainty which is the innate characteristic of the most of the hydrological variations approaches the researchers to use some stochastic or statistical methods for modelling the operation of dam. Since the application of Dynamic programming (DP) has been stabilized for operating the reservoirs, the extension of this method by stochastic viewpoints has been produced and Stochastic Dynamic Programming (SDP) has been widely used, Tejada-Guibert et al.(1993, 1995). The managers and reservoir operators are uncomfortable with the sophisticated optimization techniques used in the models, which are made more complex by the inclusion of stochasticity of hydrologic variables. The fuzzy logic approach may provide a promising alternative to the methods used for reservoir operation modelling, because the approach is more flexible and allows incorporation of expert opinions which could make it more acceptable to operators, Russel and Campbell (1996). On the other hand, although inflow to reservoir is a continuous variable, only discrete transitions between states of this variable are allowed in the frame work of SDP model. Mousavi et al. (2004) used fuzzy set theory (FST) to deal with errors associated with discretization process of variables in an SDP model. Chang et al. (1997) used Multipurpose Fuzzy Programming (MFP) for considering the optimization methods in operating the reservoir and the use of water on the lands under its cover. They applied their method for operating the Tweng-Wen reservoir. Liu and Odanaka (1999) used the Dynamic Fuzzy Criterion (DFC) model for optimizing the operation of reservoir. Their goal was to get the best operation base on supplying all of the requirements. Bender and Simonovic (2000) used the Fuzzy Compromise method and modelled the operation with attention to uncertainty. They also verified they method with comparison to the result of ELECTRE method for Tisza River in Poland and got good conclusions.

Among all of fuzzy methods, fuzzy rule-based models have been used to derive if-then operating rules. "if" contains a vector of fuzzy or crisp explanatory variables called premise variables such as, inflow, storage, and demand, otherwise "then" is a fuzzy or crisp consequence like release from the reservoir. There are lots of researches done based on this approach. Sugeno (1999) simulated the discharge of Deniper River by use of data from its upstream river, Niman. Dubrovin et al. (2002) established a fuzzy ruled method, Total Fuzzy Similarity, and modelled the operation of a multipurpose reservoir. Jamali and Abrishamchi (2006) use Fuzzy Inference System (FIS) for operation of the reservoir of Zayandehrood Dam.

One of the problems that managers and stakeholders face on it is climate condition and the influences of its change on their decision. Modelling the effects of climate change on supplying of water requirement is useful for most of the managers. Safavi and Alijanian (2008) modelled the optimal cropping area and the optimal irrigation program based on the release of dam in each year. They believe that climate condition has direct effect on the amount of release from a dam and on the other hand cultivators consider current climate condition and decide how much area they will cultivate and which crops will be better for that condition. They used FIS method for modelling eight various climate conditions and prepared different cropping program for each condition.

Historical data base for each hydrological variation is an essential parameter for simulation and optimization of water quantities. Using of ANN has been spreading in many water resources problems. The most important ability of ANN is predicting base on a historical data base of the problem. So ANN is widely applied for river stage forecasting, rainfall forecasting, and also deriving operating policies of a river (Cancelliere et al., 2002; Chandramouli and Raman, 2001; French et al., 1992; Hsu et al., 1995; Karunanithi et al., 1994; Raman and Chandramouli, 1996; Rogers and Dowla 1994; Saad et al., 1994). The combination of fuzzy ruled method and ANN has been developed in an approach called Adaptive Neuro- Fuzzy Inference System. This method has been widely used for deriving the operation of reservoir because it has both of the advantages of ANN and Fuzzy-Ruled methods.

In this paper, the Fuzzy Inference System is used to develop a model for the operating of the Zayandehrood Dam and for planning of downstream agricultural crop farms for different climate conditions. The model consists of three parts: in the first part, the storage volume of the reservoir in the last month of the solar year, Esfand (February-March), is predicted based on the input flow to the reservoir during the last three months of the year and on the Southern Oscillated Index (SOI) using the Adaptive Network Fuzzy Inference Systems (ANFIS). The SOI and the input flow are model inputs while the storage volume of the reservoir is the model output. The second part involves forecasting the annual release in the following year as the model output using the storage of the reservoir in the last month of the previous year and the amount of snow both as the FIS inputs. This value will be different for different climate conditions. As the annual release from the reservoir has definitive effects on the cropping schedule, it may be regarded as a defining factor for climate conditions. The optimized planning of crops for the following year will be developed based on the annual release from the dam as forecasted by the fuzzy rules in the third part of the model. The three parts of the model operate on an “if-then” principle, where the “if” is a vector of the fuzzy permits and “then” is the fuzzy result. The model is developed based on data from 1990 to 2006.

CASE STUDY

The approach previously discussed is used for modelling of operation of the Zayandehrood reservoir located on the Zatandehrood River streaming in the Zayandehrood basin of Isfahan province, Iran. Figure 1 shows the Zayandehrood River basin and the location of Zayandehrood Dam in Iran. It is a multipurpose reservoir which is used for hydropower energy, flood control, irrigation and supply the running water which is operated since 1971. Since it is the only constant river in the centre of Iran, it has a prominent influence on human life such as cultivation. The major crops grown in the command area are wheat, rice, corn, orchards and potato. There are both surface water which is released from Zayandehrood and groundwater for irrigation the cropping lands which are around 100000 hec. The maximum amount of yearly demand water for irrigation is 2884.63 MCM and its minimum amount is 1315.05 MCM. Between 60 percent and 80 percent (averagely 70 percent) of this demand is supplied by the released water from reservoir. The reservoir has the gross storage capacity of 1470 Mm^3 and a live storage capacity of 1090 m $m^{3.}$ A water year (from September 1 to August 31) is divided into 24, 15-day periods. Table 1 shows the average inflows, releases and irrigation demands of this reservoir.

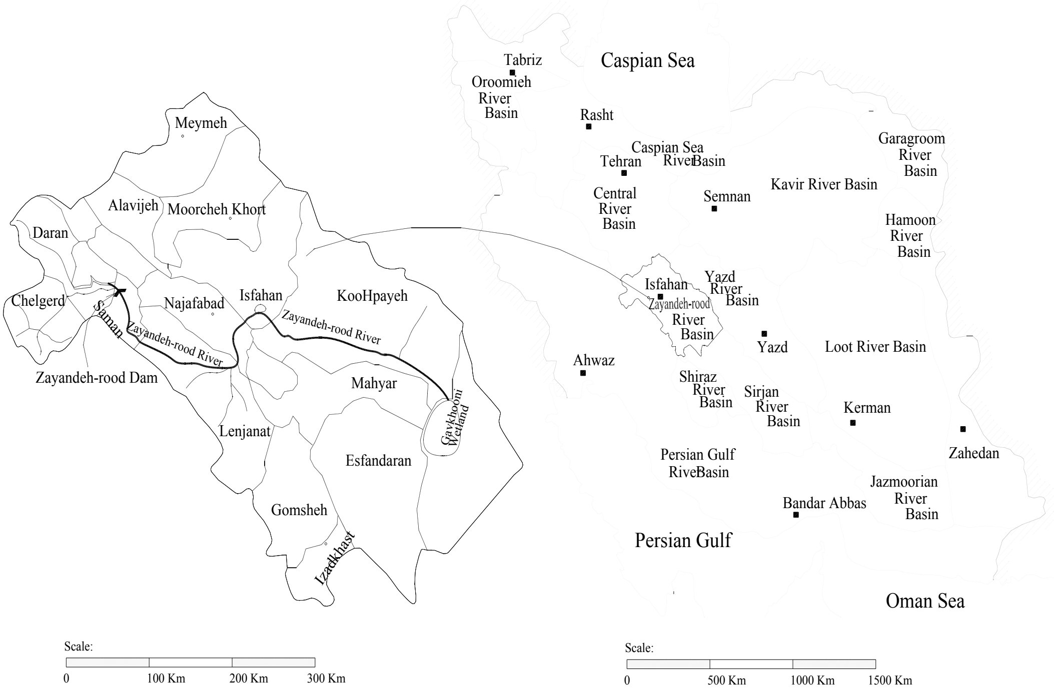


Fig. 1 Zayandehrood River basin

Table 1. The average inflows, releases and irrigation demands of Zayandehrood Dam

Month	Inflow (MCM)	Release (MCM)	Demand (MCM)
September	39.84624	107.351	129.81
October	56.75656	103.981	77.47
November	65.97583	92.1595	252.02
December	62.81385	46.4865	234.99
January	73.59206	30.9324	30.76
February	142.0152	55.2324	84.37
March	314.7018	138.176	136.08
April	294.3572	204.427	306.64
May	187.2198	193.23	347.13
Jun	119.4994	169.684	298.24
July	72.03527	168.616	238.94
August	44.58766	152.9	183.02

METHODOLOGY

The Fuzzy Set Logic theory is expounded by Professor L. A. Zadeh, the Iranian-American professor of the University of Berkeley. In most of the systems, there are some kinds of ambiguity that cause some problems in understanding, inference and decision on them. Fuzzy Set theory is a workable and useful method for solving these ambitions. One of the most important abilities of fuzzy set theory is the development of rule based models. Since fuzzy Set theory has the ability to work on linguistic variables, the rules based on knowledge and experiences of experts can be developed by this approach. Fuzzy-rule based modelling is a qualitative modelling scheme where the system behaviour is described using a natural language (Sugeno and Yasukawa, 1993). They called this model Fuzzy Inference Systems (FIS). FIS models can decide based on experts' experiences but they could not test and train on data base and the experts must introduce the rules which are used in the models. On the other hand, the Annual Neural Networks has this opportunity to work on data base and develop the relation between inputs and outputs by training and testing. Jang combined these two advantages in a system. In one hand, this system can work on linguistic variables and develop the if-then rules. On the other hand it can train the rules between data base by neural networks. These systems are called the Adaptive Network Fuzzy Inference Systems (ANFIS). ANFIS models are always developed by using a Takagi-Sugeno-Kang (TSK) in a feed forward network. The general structure of the ANFIS is presented in Figure 2. Selection of the FIS is the major concern when designing an ANFIS to model a specific target system (Nayak et al. 2004).

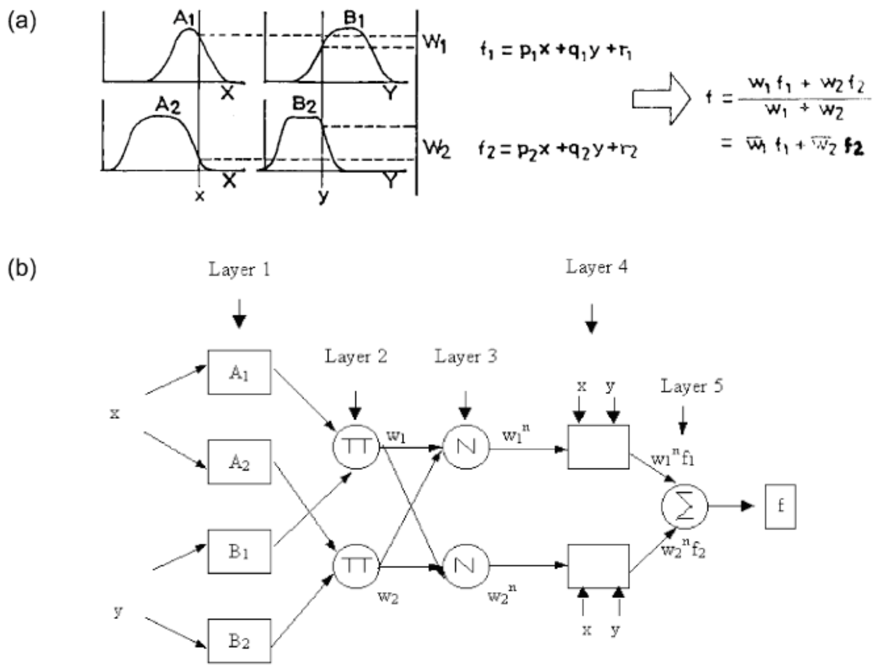


Fig. 2 (a) Fuzzy inference system. (b) Equivalent ANFIS architecture (Nayak et al. 2004)

The corresponding equivalent ANFIS architecture is presented in Figure (2.b), where nodes of the same layer have similar functions. The functioning of the ANFIS is as follows (Nayak et al. 2004):

Layer 1: Each node in this layer generates membership grades of an input variable. The node output OP_i^1 is defined by:

$$OP_i^1 = \mu_{Ai}(x) \; for \; i = 1,2 \; or \; OP_i^1 = \mu_{B_{i-2}}(y) \; for \; i = 3,4 \quad (1)$$

Where x (or y) is the input to the node; A_i (or B_{i-2}) is a fuzzy set associated with this node, characterized by the shape of the Membership Functions (MFs) in this node and can be any appropriate functions that are continuous and piecewise differentiable such as Gaussian, generalized bell shaped, trapezoidal shaped and triangular shaped functions. Assuming a generalized bell function as the MF, the output OP^1_i can be computed as:

$$OP_i^1 = \mu_{Ai}(x) = \frac{1}{1+\left(\frac{x-c_i}{a_i}\right)} \quad (2)$$

Where $\{a_i, b_i, c_i\}$ is the parameter set that changes the shapes of the MF with maximum equal to and minimum equal to 0.

Layer 2: Every node in this layer multiplies the incoming signals, denoted as Q, and the output OP^2_i that represents the firing strength of a rule is computed as:

$$OP_i^2 = w_i = \mu_{Ai}(x)\mu_{Bi}(x), \quad i = 1,2. \quad (3)$$

Layer 3: The *i*th node of this layer, labeled as N, computes the normalized firing strengths as:

$$OP_i^3 = \bar{w}_i = \frac{w_i}{w_1 + w_2}, \quad i = 1,2 \quad (4)$$

Layer 4: Node *i* in this layer compute the contribution of the *i*th rule towards the model output, with the following node function:

$$OP_i^4 = \bar{w}_i f_i = \bar{w}_i(P_i x + q_i y + r_i) \quad (5)$$

Where w is the output of layer 3 and $\{p_i, q_i, r_i\}$ is the parameter set.

Layer 5: The single node in this layer computes the overall output of the ANFIS as:

$$OP_i^5 = Overal\ output = \sum_i \bar{w}_i f_i = \frac{\sum_i w_i f_i}{\sum_i w_i} \quad (6)$$

In this article we follow a three step model for operating the Zayandehrood Dam and developing an optimized plan for cultivation of downstream lands in diverse climate conditions. Figure 3 illustrates the schema of these steps.

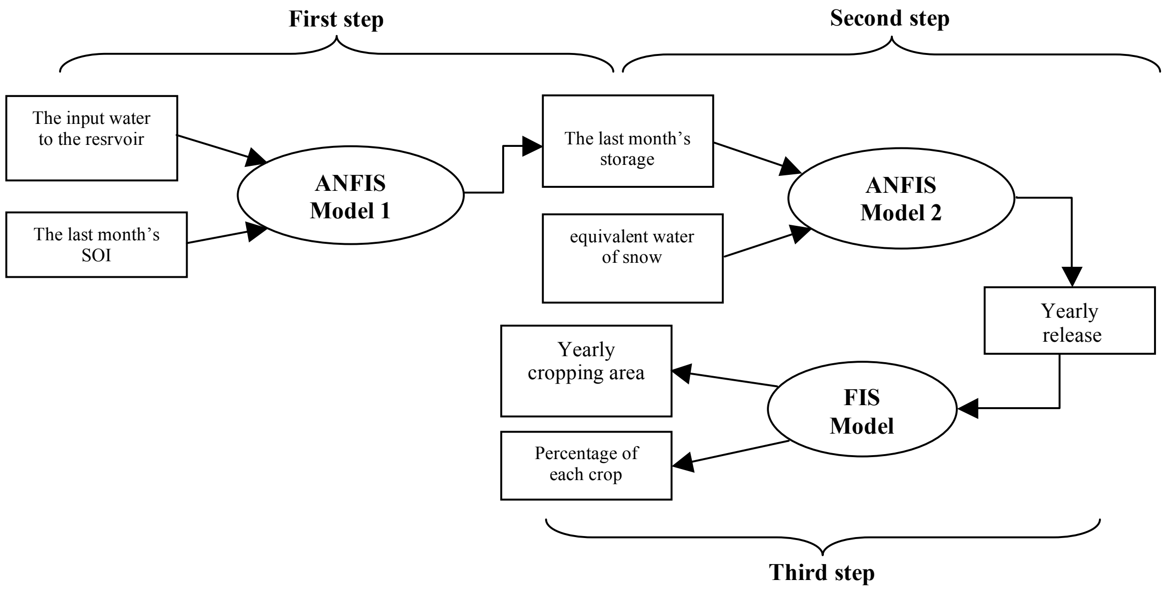


Fig. 3 The schema of the model's steps

At first step, an ANFIS model is developed to predict the storage of reservoir in the last solar month of year, Esfand (February-March). The input volume to the reservoir in the last three months of year and the Southern Oscillated Index (SOI) in the last month of year are the inputs of model while the storage volume of last month of year is the output of the model. The data are used from 1971 to 2004. 80 percent of data is used for training and the rest are used for testing and verifying the model.

The second step of model forecasts the annual release in the next year as the output of model by using the storage volume in the last month, which is obtained as the output of first step, and the equivalent water of snow of that month as the inputs of this step. This step is modelled by ANFIS too. The period of data base is from 1989 to 2004. Table 2 shows the statistics of data base which is used in both steps.

The structure of ANFIS model developed for the first step with different MFs is prepared in the table 3. Since the model with seven three angular MFs and 500 iterations is the most simple model with the best results, this model is selected for the first step.

Table 4 shows the specifications of different models which are make for the second step. According to the results the model with five three angular MFs and 500 iteration in training is the simplest model while it has the best results.

Table 2. Statistics' parameters used in the both ANFIS models

Parameter	Period	Average	Maximum	Minimum	Variance	Deviation
SOI	1971-2004	-0.2	2	-4.6	2.6	1.61
Input (MCM)	1971-2004	9476.6	490.7	133.8	266.7	16.33
Volume (MCM)	1971-2004	896.7	1239	198	71816.8	267.99
equivalent water of snow (cm)	1989-2004	102.5	288.3	11.3	7686.7	87.67
Release (MCM)	1989-2004	1496.4	2543.4	567.5	169967.3	412.27

Table 3. The structure of different models used for the first step.

MF type	Num. of MF	Epoch	Error		
			RMSE	MAE (%)	R^2
Gaussian	9	500	4.14	1.69	0.99
Gaussian	5	1000	4.61	2.24	0.987
Gaussian	7	500	4.15	1.79	0.99
Bell MF	5	1000	4.68	2.28	0.987
Bell MF	7	500	4.14	1.72	0.99
Triangular MF	9	500	4.15	1.72	0.99
Triangular MF	7	500	4.15	1.71	0.99
Triangular MF	5	500	4.53	2.23	0.988

Table 4. The results of different models used for the second step.

MF type	Num. of MF	Epoch	Error		
			RMSE	MAE(%)	R^2
Gaussian	9	500	2.01	1.66	0.99
Gaussian	7	500	1.93	1.5	0.99
Bell MF	7	500	1.95	1.5	0.99
Triangular MF	5	500	2.26	2.06	0.99
Triangular MF	7	500	2.5	2.27	0.99

The third step is used for developing a plan for suggesting the kind of crops which are better to cultivate. This model is developed by FIS. Farmers choose their crops and their cropping area with attention to the climate conditions. Admittedly if they understand or even predict that the flowing weather will not be good, they will cultivate some kinds of crops that needs little amount of water and reduce their cropping area, and vies versa. For identifying the climatic conditions or water conditions, the annual release of Zayandehrood Dam is considered as input set. So the annual release of Zayandehrood Dam is divided into eight triangular fuzzy sets. The amplitude of these sets are between 500 (MCM) to 2150 (MCM) which are remarked, by linguistic values, very bad, bad, fairly bad, normal, fairly good, good, very good and excellent. The consequents of the problem are the total annual cropping area and the lean of farmers to basic crops. These sets are considered by analyzing a data base of crops from 1991 to 2006 and are divided to eight fuzzy sets too. The Figure 4 shows the MFs of release from Dam as the input parameter while figure 5 and figure 6 show the cropping area and the percentage of wheat and rice, the two most important crops, as outputs. Table 5 shows the characteristic of each crop. According to this table some crops such as wheat, rice and orchards have fuzzy character and the lean of farmers to cultivate them is different in various climate conditions. On the other hand, farmers have the same willing to crop other kind of crops and the percent of area which is allocated to them is constant in different climate condition. But, actually the total cropping area of all of the crops is various in each different climate condition and the effect of climate condition on each crop are considered in total area of cultivation.

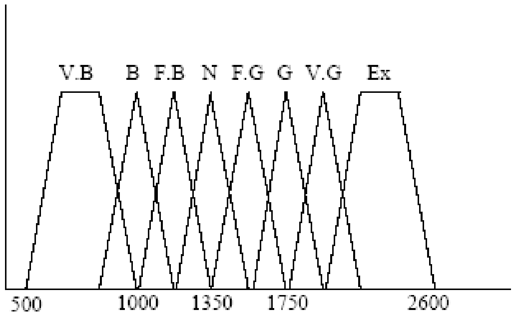


Fig. 4 Dividing of climate conditions in linguistic numbers with base of estimated yearly release from Zayandehrood Dam (MCM).

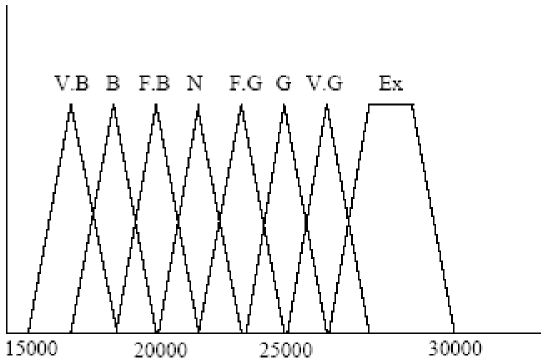
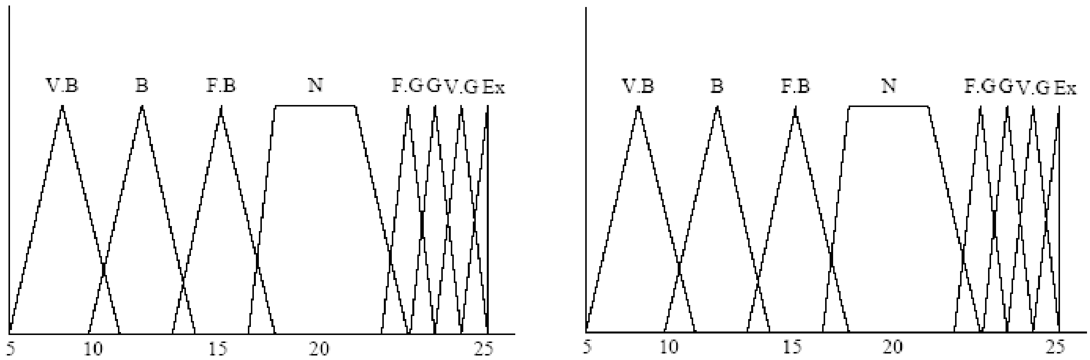


Fig. 5 Dividing of cropping area in linguistic numbers (Ha).



a) Cropping percent of Wheat b) Cropping percent of Rice

Fig. 6 Dividing of cropping percent of each crop in linguistic numbers.

Table 5. The cropping percent of each crop

Crop	Wheat	Barely	Corn	Rice	Potato	Onion	Green	Provender	Orchards
Percent	Fuzzy	8	4	Fuzzy	7	4	6	12	Fuzzy

With use of FIS we can improve some rules for prediction of total cropping area and the affection of farmers for each crop based on climate conditions. The results of this prediction are variable for different release from Zayandehrood dam. Table 6 shows the results for three different yearly release from dam, 850 (MCM), 1550 (MCM) and 2150 (MCM), which are defined as bad, normal and excellent yearly water conditions respectively.

Table 6. Results of FIS for prediction of cropping area and percent of each crop for different water conditions.

Yearly Release (MCM)	Cropping Area (ha)	Cropping percent of Rice	Cropping percent of Wheat	percent of Orchards
850	17578	21	18.5	29.8
1550	24061	29	16.9	18.3
2150	27615	31.2	14.3	19.2

With attention to these results it can be understood that if the water conditions get better, the cropping area is enlarger, the affections of rice and wheat are increased too, but the affection of orchards is decreased. Because the area of orchards is nearly constant, the affection of orchards enlarges with enlarging the total cropping area.

At the end we can calculate the net demand of each crop in each month for irrigation. These values are calculated by FAO-CROPWAT method in a ten yearly average database and with attention to usual crop growing periods. The growing period of each crop is illustrated in Figure 7.

Ultimately the total net demand of water for irrigation of all of the crops can be calculated with this formula:

$$ND_i = \sum_c A * Per_c * dc_i \qquad (7)$$

Where ND_i is the total monthly net demand, A is the total annual cropping area which is obtained by Fuzzy Inference Systems, Per_c is the lean of farmers on each crop and dc_i is the net demand of each crop in each month which is calculated by FAO-CROPWAT.

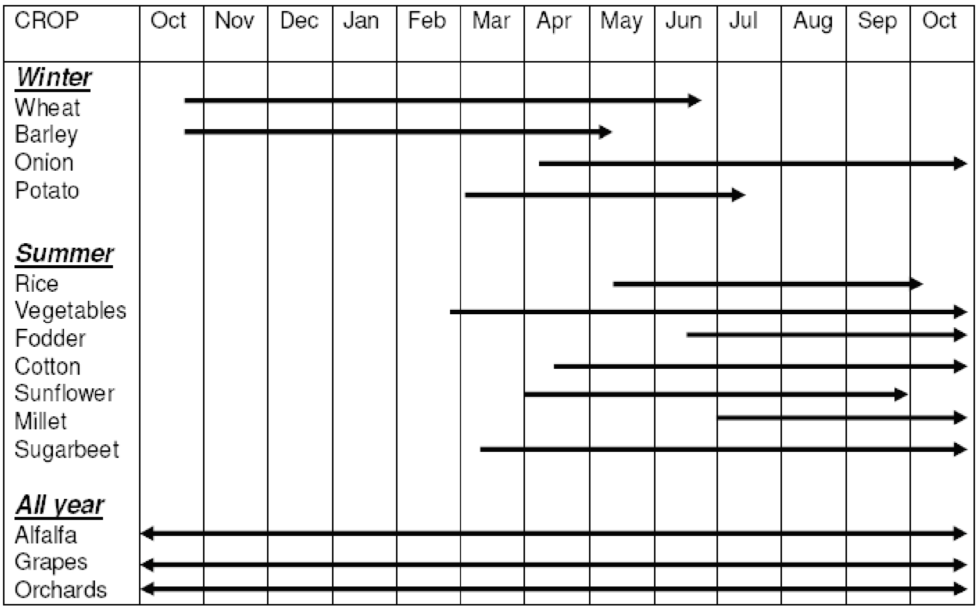


Fig. 7 Typical basic calendar in Zayandehrood basin.

CONCLUSION

In this paper, we follow two goals; in one hand we can simulate the operation of the reservoir of Zayandehrood dam in a two step process. In the first step the amount of input water into the reservoir at the last month of the year is predicted by using the amount of water in the previous months and the SOI parameter of the last month of each year as inputs of an ANFIS model. The second step is developed another ANFIS model which its inputs are the amount of input water into the reservoir, the output of the first step's model, and the amount of snow of the last month. The output of the second step is the yearly release of the next year which is the first goal of this model. The second goal is got through the third step. The third step result is a preparation of a cropping schedule with consideration to different climate conditions and their influence on water conditions with use of experiences and knowledge of experts. This goal is obtained by fuzzy Inference Systems method. The other thing which is also obtained is calculation of net monthly demand of water with consideration to developed cropping schedule by FIS.

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