Managing Water Supply and Demand to Achieve Economic and Environmental Objectives: Application of Mathematical Programming and ANFIS Models

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Abstract

The integrated management of water supply and demand has been considered by many policymakers; due to its complexity the decision makers have faced many challenges so far. In this study, we proposed an efficient framework for managing water supply and demand in line with the economic and environmental objectives of the basin. To design this framework, a combination of ANFIS and multi-objective augmented ε-constraint programming models and TOPSIS were used. First, using hydrological data from 2001 to 2017, the rate of water release from the dam reservoir was estimated with the ANFIS model; afterwards, its allocation to agricultural areas was performed by combining multi-objective augmented ε-constraint models and TOPSIS. To prove the reliability of the proposed model, the southern Karkheh basin in Khuzestan province, Iran, was considered as a case study. The results have showed that this model is able to reduce irrigation water consumption and to improve its economic productivity in the basin.

Keywords Water integrated management · Water supply · Water demand

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1 Introduction

Water resource management is one of the most important challenges of the present century and has caused major global concerns. In recent years, the demand for surface and groundwater resources has increased significantly as a consequence of the extensive agricultural activities. Thus, the scarcity of water resources has been exacerbated (Flach et al. 2020).

Water scarcity has posed several challenges for the achievement of food security. These obstacles have become far more severe in the developing countries (FAO 2015); In fact, increased water demand due to population growth, economic development, pollution of water resources, and reduced groundwater and surface water quality on one hand, and decreasing water supply due to unsustainable management of these resources on the other hand, have become prominent issues in many countries (La Jeunesse et al. 2016); Therefore, the sustainable use of water resources is critical for the maintenance of food security, environmental quality, and the necessary resources for appropriate economic growth and development.

Decision makers encounter many challenges in water resources management and have to decide on the allocation of scarce water supply. This allocation shall be such that the economic objectives of agricultural activities get achieved along with the environmental sustainabilities (Forni et al. 2016). All the mentioned factors have led to an imbalance in water supply and demand. In other words, since the economic supply of water is always limited and its demand is continuously increasing, it would be difficult to plan for the optimal use of water resources. Competent management of the utilization of the existing water resources and facilities, called water supply and demand management approach, can make it possible (Allawi et al. 2019).

Iran is located in one of the water-scarce regions of the world and has experienced severe droughts during thousands of years. Numerous studies have shown that due to the recent population growth, urbanization, industrialization, agricultural expansion and climate change, the country is currently facing a serious water crisis (Madani 2014; Zamani et al. 2019); As a result, comprehensive water management has become the main concern of community members, experts, and managers.

Rivers and surface waters are raised as the main sources of water supply and transfer for various uses. Reservoir dams are highly important sources of storage and regulation of surface water, runoff, and floods; however, due to fluctuations in river discharge and reservoir capacity limit, the time distribution between the inflow to reservoirs and downstream water requirements have posed some difficulties (Sabouni and Mardani 2013). Accordingly, extracting the operation rules of dams is one of the essential issues in water supply management, especially surface water resources. Lack of planning for the amount of water released from the reservoir would lead to problems such as water shortage during drought, instability of agricultural production downstream of dams, urban water rationing in dry seasons, and environmental problems; In this regard, the extraction of optimal exploitation rules has received more attention from researchers (Hadiyan et al. 2020).

In Iran, surface water resources play a major role in meeting the water needs of urban, agricultural, and industrial sectors; nonetheless, owing to irregular rainfall, continuous droughts, and uncertainty in water supply, thus management of existing water resources and facilities has become all more important in the recent years. Many studies have shown that the water resources crisis in this country is increasingly growing (Madani 2014), as a consequence of mismanagement and lack of comprehensive planning; therefore, reforming the existing management policies is necessary for dealing
with this crisis; besides, optimizing the outflow of reservoirs is an important step in decision making regarding water resources management (Rahimi et al. 2020; Sabouni and Mardani 2013; Zarei et al. 2019).

Due to the uncertainty concerning the variables of reservoir operation, in many studies, the theory of fuzzy sets has been used to extract the operation rules of these reservoirs. Based on the results of these studies, the Fuzzy Inference System (FIS) is more in line with the real world as it deals with the uncertainty conditions in reservoir operation models (Kambalimath and Deka 2020; Ranković et al. 2012). Some researchers have proposed the Artificial Neural Networks (ANNs) method in relation to water resources management due to the wide changes in input variables and structures and learning algorithms (Farzaneh-Gord et al. 2020; Nasirzadehroshenin et al. 2020). High accuracy of forecasting, suitable generalizability, and low computational costs are among the advantages of this method (Kambalimath and Deka 2020).

Accordingly, the combination of FIS with ANNs as Adaptive Neuro-Fuzzy Inference System (ANFIS), has been used in various studies to extract the optimal rules of reservoir operation (Safavi et al. 2013; Sedighkia and Abdoli 2022).

The ANFIS model uses a neural network learning algorithm and fuzzy logic for non-linear mapping between input and output space. This model has the advantages of FIS and the ability to learn neural networks; therefore, being compared to ANNs or FIS separately, it would have a higher capability (Ashrafi et al. 2017; Safavi et al. 2013; Yaseen et al. 2017); moreover, the uncertainty related to major water supply sources in agricultural production systems would have a significant effect on the cropping pattern and farmers’ income (Guerrero-Baena et al. 2019). In this regard, due to the growing concerns about the uncertainty of water supply farmers might opt to produce crops with low gross profit and capital accumulation in the cropping pattern. Farmers’ withdrawal from long-term investment in agriculture would reduce the productivity of the existing production resources (Guerrero-Baena et al. 2019).

Meanwhile, the agricultural sector with a potentiality of consuming about 90% of the available water there, is the largest consumer of water in Iran. On the other hand, the conflict of water consumption among the users of the agricultural sector and environmental services has increased the competition for using water resources, particularly in the developing countries (Allan 2003); accordingly, the establishment of a policy is recommended for the protection and storage of water and the use of storage water for environmental purposes (Sisto 2009). In this regard, determining the optimal cropping pattern in order to optimally allocate water resources, meet environmental needs, and maximize the gross profit of farmers, can be considered as one of the appropriate solutions to this problem (Smith et al. 2020).

There are several studies concerned on determining the optimal cropping pattern that in addition to the economic objective, have considered other objectives such as protection of water resources, reduction of the environmental pollution caused by fertilizer and pesticide consumption, and reduction of production risk (Bajany et al. 2021; Mirzaei and Zibaee 2021). Providing maximum gross profit and optimal water allocation in optimizing cropping patterns are two clear objectives of many studies, including the study of Galán-Martín et al. (2015) and Najafabadi et al. (2019).

Due to the existence of conflicting objectives in the agricultural production system, many researchers have proposed multi-objective programming to determine the optimal cultivation pattern (Najafabadi et al. 2019; Mirzaei and Zibaee 2021). However, in this approach, instead of an optimal solution, a set of solutions is often obtained.
The methods used for solving the multi-objective optimization model are very different and the most important are weighted, constrained, and multi-criteria simplex methods. The constrained method is more acceptable than other multi-objective programming solver methods (Fathipour and Saidi-Mehrabad 2018). In this method, each objective is optimized separately and others are added to the model as constraints. Through changing the values of the right-hand side of the constrained objectives, a set of Pareto optimal solutions can be achieved. Several versions of the constrained method have been used to solve linear multi-objective programming problems, one of which is the augmented ε-constraint method. One of the advantages of this method, as opposed to the older versions of the constrained method, is that it extracts a set of strong efficient solutions and eliminates weak efficient ones (Vahid Pakdel et al. 2020).

2 Study Area

In 1998, Iran began building the largest dam on the Karkheh River. This dam, with a storage capacity of 7.5 billion cubic meters and an active storage capacity of 4.7 billion cubic meters, is located northwest of Khuzestan province and has been put into operation since August 2002 (Marjanizadeh et al. 2010; Masih et al. 2010). Presently, this dam provides about 8.1 billion cubic meters of water requirement for 320,000 hectares of downstream agricultural land, and also it helps in controlling floods in these lands (Fereidoon and Koch 2018). Hoveyzeh Wetlands is one of the largest wetlands in West Asia and the Mesopotamian plain (the land between the Euphrates and Tigris Rivers); these wetlands are located jointly between Iran and Iraq. The eastern part of Hoveyzeh wetlands is known as Hoorolazim, located at the end of Karkheh River in Khuzestan province, Iran.

South Karkheh is an important sub-basin of Karkheh River, which includes the agricultural areas of Paypol, Kowsar-Quds, Hamidiyeh, Azadegan, and Karkheh Noor (Fig. 1). Rainfall in this sub-basin has been reported to be less than 150 mm over many years. On the other hand, most of the rainfall in winter and summer is close to zero. In other words, due to drought and irregular rainfall patterns, this sub-basin has faced severe water shortages in recent decades. Irrigation of agricultural lands has also reduced water inflow to Hoorolazim wetland (Choubin et al. 2019).

In general, this wetland has undergone many changes over the recent decades. For example, in the war between Iran-Iraq from 1981 to 1989, the construction of roads in wetlands by warring parties caused the wetland to dry up. The construction of several diversion dams in the Karkheh and Tigris basins have also caused a severe reduction in the inflow of water into the wetland. Exploitation of Karkheh Dam and the drilling related to oil extraction in recent years has increased the hydrological and environmental stresses on the Hoorolazim Wetland, which has led to the drying up of a large part of the wetland. According to the aforementioned points, meeting the water needs of this wetland can be very effective in restoring ecological conditions and improvement of its environmental performance (Ghobadi et al. 2015).

A review of the literature shows that in order to optimize the performance of the reservoir (Sedighkia et al. 2022) and to manage the downstream water demand (Mirzaei and Zibaei 2021), water demand is considered as an exogenous parameter. However, the relationship between reservoir performance and water demand is a two-way relationship; therefore, by optimizing reservoir performance and cropping pattern, simultaneous management of water supply and demand can improve the weakness of previous studies in
resolving the conflict of water consumption between economic and environmental sectors. In the present study, the combination of ANFIS tool and augmented ε-constraint method for simultaneous management of water supply and water demand has been used, which has led to the creation of a new structure for resolving the conflict between economic and environmental objectives.

In general, the aim of the present study has been the simultaneous management of water supply and demand in agricultural lands of Karkheh Dam sub-basin with an emphasis on economic and environmental objectives.

3 Materials and Methods

Figure 2 presents the relationship among the three phases of the study for comprehensive management of water supply and demand under the Karkheh Dam (South Karkheh) basin (conceptual framework). In the first phase, the optimum and most efficient operation rules of the Karkheh dam reservoir have been extracted and the volume of the water released from this reservoir has been estimated with the ANFIS model. In the second phase, using a multi-objective augmented ε-constraint programming model for economic and environmental objectives, an efficient set of solutions were extracted. In the third phase, the best efficient solution was determined using the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), and the appropriate cropping pattern was extracted for achieving the optimal solution of the objectives. In what follows, the details of these three phases will be discussed.
Adaptive Neural Network Based on Fuzzy Inference System

These types of networks, created by combining artificial neural networks and fuzzy logic, categorize and learn fuzzy rules, and fuzzy logic inferred uncertain parameters of artificial neural networks (Ebtehaj and Bonakdari 2014; Yaseen et al. 2017); Therefore, ANFIS model, compared to the separate application of artificial neural networks and fuzzy logic, has a higher capability (Ashrafi et al. 2017). Three major types of ANFIS models are Mamdani, Sugeno, and Tsumoto, among which the Sugeno system is the most widely used; In fact, ANFIS system is the implementation of this system as a feed-forward network structure. Figure 3 shows a Sugeno fuzzy system with two inputs, one output, and two rules (Kisi 2013).

The two inputs of the system are $x$ and $y$, its output is denoted by $f$, and the two rules of this system can be expressed as Eqs. (1) and (2) (Takagi and Sugeno 1983).

\[
\text{If } x \text{ is } A_1 \& y \text{ is } B_1 \text{ then } f = p_1 x + q_1 y + r_1 \tag{1}
\]

\[
\text{If } x \text{ is } A_2 \& y \text{ is } B_2 \text{ then } f = p_2 x + q_2 y + r_2 \tag{2}
\]

According to the figure, the structure of ANFIS network consists of five layers. The first layer is the input layer and each node in that is equivalent to a fuzzy set; the output of each
node is equal to the membership degree of the input variable in the fuzzy set. The parameters of each node determine the shape of the membership function of the fuzzy set of that node. Various functions, such as triangular, trapezoidal, and bell-shaped features are used in the design of neural-fuzzy networks (Tarazkar et al. 2018).

In the second layer, the input values of each node are multiplied and the result, which is the weight of the rules, is obtained. Each node in the second layer calculates the activity degree of a rule and is represented by Eq. (3).

\[ Q_i^2 = w_i = \mu_{A_i}(x) \times \mu_{B_i}(y) \]  

where \( \mu_{A_i}(x) \) is the degree of membership of \( x \) in set \( A_i \) and \( \mu_{B_i}(y) \) is the degree of membership of \( y \) in set \( B_i \). In the third layer, nodes play an important role and determine the relative weight of the rules. Using Eq. (4), the relative weight of node \( i \) can be calculated in relation to the total weight of this layer.

\[ Q_i^3 = \bar{w}_i = \frac{w_i}{w_1 + w_2} \quad i = 1, 2 \]  

where \( \bar{w}_i \) is the degree of the weight activity of the \( i^{th} \) rules. In the fourth layer, the output of each node is in the form of Eq. (5).

\[ Q_i^4 = \bar{w}_i f_i = \bar{w}_i (p_i x + q_i y + r_i), \quad i = 1, 2 \]  

where \( p_i, q_i, \) and \( r_i \) are the adaptive parameters of this layer, also called consequence parameters. The fifth layer is the ANFIS output, and each node in it calculates the final output value using Eq. (6).

In this layer, the number of nodes is equal to that of the outputs, hence equal to one in most studies. Two types of linear and constant membership functions can be used to calculate the output.

\[ Q_i^5 = \sum \bar{w}_i f_i = \frac{\sum w_i f_i}{\sum w_i} \]  

Finally, according to Eq. (7) the total output can be expressed as a linear combination of the consequence parameters.

\[ f = \sum \bar{w}_i f_i = (\bar{w}_1 x) p_1 + (\bar{w}_1 y) q_1 + (\bar{w}_1) r_1 + (\bar{w}_2 x) p_2 + (\bar{w}_2 y) q_2 + (\bar{w}_2) r_2 \]  

Two learning algorithms are usually used for training an ANFIS network: the error back-propagation and hybrid method. In this study, both algorithms were used and the results were compared.

### 3.2 Multi-objective Programming Model

The model used in the present study is a multi-objective planning model used to maximize the gross profit of farmers and minimize water consumption to store it for wetland environmental services. In this model, the optimal combination of land allocation \( (X_{c,a}) \) to crops \( (c) \) and different areas \( (a) \) is obtained from objective functions and technical, structural, and political constraints.
Objective functions are defined as Eqs. (8) and (9).

\[
\begin{align*}
\text{max} \quad & Z_1 = \sum_c \sum_a p_c y_{c,a} X_{c,a} - \sum_c \sum_a t_{c,a} X_{c,a} \\
\text{min} \quad & Z_2 = \sum_c \sum_a t_{c,a} X_{c,a}
\end{align*}
\] (8) (9)

These equations show the total gross profit and the amount of water used in the basin, respectively.

Where the parameters are \( p_c \): price per unit of crop (c); \( y_{c,a} \): crop yield in area (a); \( t_{c,a} \): cost of production without water cost per crop (c) and area (a); \( w_p \): price per unit of consumption irrigation water; \( n w_{c,t} \): net water requirement per crop (c) and month (t); and \( e f_{c,a} \): efficiency of irrigation technology per crop (c) and area (a), and the model variables are \( X_{c,a} \): decision variable of area under cultivation per crop (c) and area (a); \( Z_1 \): free variable of total gross profit, and \( Z_2 \): total amount of water consumption.

The constraints of the amount of available arable land and the amount of available irrigation water are considered in Eqs. (10) and (11), respectively.

\[
\begin{align*}
\sum_c X_{c,a} & \leq \text{land}_a \\
\sum_c (n w_{c,t} / e f_{c,a}) X_{c,a} & \leq \text{Water}_t
\end{align*}
\] (10) (11)

The general form of the multi-objective programming model for optimizing the cropping pattern can be expressed as Eq. (12) (Francisco and Ali 2006).

\[
\begin{align*}
\text{max} \quad & Z_1(X_j), Z_2(X_j), ..., Z_h(X_j), ..., Z_k(X_j) \\
Z_1(x) & = Z_1(x_1, x_2, ..., x_n) \\
Z_2(x) & = Z_2(x_1, x_2, ..., x_n) \\
Z_h(x) & = Z_h(x_1, x_2, ..., x_n) \\
& \vdots \\
Z_k(x) & = Z_k(x_1, x_2, ..., x_n)
\end{align*}
\] (12)

where \( Z \) is the vector of the objective function and \( Z_i \) is the individual objective function, \( n \) is the number of agricultural products and \( X_j \) is the area under cultivation allocated to the crop \( j \).

The general form of a multi-objective model in which the \( h \) objective of the total existing objectives \( k \) is optimized and the remaining \( k-1 \) is considered as a constraint can be considered as Eq. (13) (Hwang and Masud 1979):

\[
\begin{align*}
\text{max} \quad & Z_h(x_1, x_2, ..., x_n) \\
Z_1(x_1, x_2, ..., x_n) & \geq e_1 \\
Z_2(x_1, x_2, ..., x_n) & \geq e_2 \\
& \vdots \\
Z_{h-1}(x_1, x_2, ..., x_n) & \geq e_{h-1} \\
Z_{h+1}(x_1, x_2, ..., x_n) & \geq e_{h+1} \\
& \vdots \\
Z_k(x_1, x_2, ..., x_n) & \geq e_k
\end{align*}
\] (13)
By changing the parametric values of \( e \) on the right-hand side, a set of efficient solutions is obtained. Using the multi-objective augmented \( \varepsilon \)-constraint programming method, strongly efficient solutions are extracted and weak efficient ones are eliminated. For this purpose, the surplus or deficit variables are used to convert the constraints of Eq. (13) from unequal to equal (Eq. (14)).

\[
\begin{align*}
max &\left( Z_h(x_1, x_2, ..., x_n) \\ + &\text{eps}(s_1 + s_2 + ... + s_{h-1} + s_{h+1} + ... + s_k) \right) \\
Z_1(x_1, x_2, ..., x_n) - s_1 &= e_1 \\
Z_2(x_1, x_2, ..., x_n) - s_2 &= e_2 \\
&\vdots \\
Z_{h-1}(x_1, x_2, ..., x_n) - s_{h-1} &= e_{h-1} \\
Z_{h+1}(x_1, x_2, ..., x_n) - s_{h+1} &= e_{h+1} \\
&\vdots \\
Z_k(x_1, x_2, ..., x_n) - s_k &= e_k
\end{align*}
\]

\( \text{eps} \) is a very small value (usually between 10–3 and 10–6).

It is worth noting that in this method, to avoid the problem of measurement scale, instead of \( s_j \) variables in the objective function, \( \frac{s_j}{r_i} \) is used, where \( r_i \) is the range of the i-th objective function (the distance between the worst and the best target value). Therefore, the objective function can be considered as Eq. (15).

\[
\begin{align*}
max &\left( Z_h(x_1, x_2, ..., x_n) \\ + &\text{eps}\left( \frac{s_1}{r_1} + \frac{s_2}{r_2} + ... + \frac{s_{h-1}}{r_{h-1}} + \frac{s_{h+1}}{r_{h+1}} + ... + \frac{s_k}{r_k} \right) \right)
\end{align*}
\]

This new version of the constrained method is called the augmented \( \varepsilon \)-constraint method.

### 3.3 Selecting the Final Cropping Pattern Using TOPSIS

From Pareto’s efficient answers, it is possible to choose the best one according to the different opinions and views between decision makers and stakeholders, for which the TOPSIS has been used. In this method, the shortest distance from the ideal solution is selected as the optimum option, which includes the following steps:

1. Initially, for the best maximum and minimum criteria, the highest and lowest values are known as ideal solutions, respectively.
2. In this step, for the best maximum and minimum criteria, the lowest and highest values are known as anti-ideal solutions, respectively.
3. In the last step, the relative closeness to the ideal solution index (CI) is calculated for each alternative using Eq. (16).

\[
CI = \frac{(R)^-}{(R)^+ + (R)^-}
\]
where $R^-$ and $R^+$ are the distances of each solution from the anti-ideal and ideal solution, respectively. This method is classified as a compromise method.

4 Results and Discussion

In the present study, river inflow and reservoir water storage were considered as the input of the fuzzy inference system; besides, the model results were considered as the water released from the reservoir (Safavi et al. 2013; Tarazkar et al. 2018). For this purpose, the monthly data of input and output variables from 2001 to 2017 were used.

Fig. 4 shows the trend of changes in inflow, storage, and release volume from the reservoir. An investigation of the trend of changes in input and output variables shows that during the years 2008 to 2015, inflow, storage, and release volume from the reservoir severely decreased; therefore, it can be concluded that drought was prevailed in this basin during these years.

According to the data used, the membership functions of the fuzzy inference system were defined for the input and output variables, including five Gaussian membership functions and seven linear membership functions, for different months. For instance, Fig. 5 shows the Gaussian membership functions of the April input variables.

The maximum and minimum data of the variables were considered as the upper and lower bounds of the membership functions. Thus, for input variables including inflow and storage volume from the reservoir, five Gaussian membership functions including "Very Low", "Low", "Medium", "High", and "Very High", and for the output variable (release volume), seven linear membership functions including "Very Low", "Low", "Relatively Low", "Medium", "Relatively High", "High", and "Very High" were considered. Also, the Center of Gravity (COG) and Equal Frequency Discretization (EFD) methods were used for the defuzzification and classification of the mentioned functions, respectively (Jiang et al. 2009; Yang and Webb 2002).

The best combination of the reservoir operation rules was obtained in the training and test parts for each month based on the minimum mean square error. Next, the three-dimensional solution space was obtained according to the extraction rules of reservoir operation for different
months. Figure 6 shows an example of this space for the months of June, September, December, and March.

Finally, according to the obtained solution space, the amount of water released from the reservoir was simulated (predicted) separately for different months. After that, the amount of observed and simulated annual release water was obtained from the sum of these values in different months of each year (Fig. 7). According to the results, based on the rules of proper operation compared to the observed values, the percentage of change in the predicted released water volume was about 14.8%. The results showed that the predicted volume for water release in most years was less than the observed volume, except for the years 2002, 2016, and 2017. Also, the analysis of input variable data showed that the inflow to the reservoir and the reservoir storage volume were high during 2002, 2016, and 2017. Therefore, it can be concluded that more water can be released in wet years. In dry years, however, the volume of the released water obtained through ANFIS method was less than the observed values, proving that the water supply was not properly managed in drought conditions. This

Fig. 5 Membership functions of ANFIS model input variables
means that less water should be released on dry days and better supply management should be done, but this result shows that this has not happened. The reason for this could be meeting the water requirements for agriculture and wetlands downstream of the dam.

**Fig. 6** ANFIS model three-dimensional solution space, **a** June, **b** September, **c** December and **d** March

**Fig. 7** Comparison of observed and predicted release water volume
The results obtained from ANFIS method had a high validity owing to the effective input variables, logical and appropriate operation rules, application of uncertainty conditions, and the use of neural network methods in predicting the output variable, which has been proven in other studies (Ashrafi et al. 2017; Khadr and Schlenkhoff 2018; Yaseen et al. 2017).

In order to manage the demand for irrigation water in the southern Karkheh basin, which includes the agricultural regions of Payepol, Kowsar-Quds, Hamidiyeh, Azadegan, and Karkheh Noor in Khuzestan province, an optimal cropping pattern model was extracted with the aim of maximizing the gross profit and minimizing the farmers’ water consumption.

The irrigation schedule of cultivated crops for different months of the year is presented in Table 1, which shows crops such as wheat, barley, canola, tomatoes, onions, and sugar beets were grown in autumn and winter. Furthermore, crops such as mung bean, cucumber, watermelon, corn, rice, sesame, and beans were grown in spring and summer.

Figure 8 shows that in 2017, the amount of predicted release water in spring, especially in April, was much higher than the observed release water. The reason for this finding was the amount of heavy rainfall in the spring, followed by the high rate of input flow and reservoir storage variables.

Given the water consumption of these areas compared to the water released from Kowsar Dam in 2017, about 30% of the monthly released water in this year, predicted via ANFIS and the use of appropriate operation rules, was considered as available water (Fig. 8).

| Crops         | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Wheat         |     |     |     |     |     |     |     |     |     |     |     |     |
| Barley        |     |     |     |     |     |     |     |     |     |     |     |     |
| Rapeseed      |     |     |     |     |     |     |     |     |     |     |     |     |
| Tomato        |     |     |     |     |     |     |     |     |     |     |     |     |
| Onion         |     |     |     |     |     |     |     |     |     |     |     |     |
| Sugar beet    |     |     |     |     |     |     |     |     |     |     |     |     |
| Mung bean     |     |     |     |     |     |     |     |     |     |     |     |     |
| Cucumber      |     |     |     |     |     |     |     |     |     |     |     |     |
| Watermelon    |     |     |     |     |     |     |     |     |     |     |     |     |
| Maize         |     |     |     |     |     |     |     |     |     |     |     |     |
| Rice          |     |     |     |     |     |     |     |     |     |     |     |     |
| Sesame        |     |     |     |     |     |     |     |     |     |     |     |     |
| Bean          |     |     |     |     |     |     |     |     |     |     |     |     |
The two-objective model introduced according to the 2017 data was solved through the augmented ε-constraint method and the Payoff matrix for the basin was extracted (Table 2). The elements of each row of this matrix were determined through optimizing the respective objective regardless of the other. Therefore, there is an optimal objective in each row and the value of the other is calculated parametrically.

The results of the payoff matrix showed that the maximum gross profit, regardless of the other objective, was equal to $1667.06, in which case, the amount of water consumption would be 14,733.27 cubic meters per hectare. On the other hand, the minimum amount of water consumption, regardless of the other objective, was equal to 7555.59 cubic meters per hectare, in which case, the profit rate would be $ 404.09 per hectare. Therefore, the results of the payoff matrix clearly demonstrate the contrast between the studied objectives.

Afterwards, using the TOPSIS method and with the same weight of objectives, the best answer was obtained from the set of efficient solutions (Fig. 9). The results showed that the optimal amount of gross profit and water consumption in the basin was equivalent to $1554 and 13,323 cubic meters per hectare, respectively.

Table 3 reports the optimal cropping pattern for achieving the best solution of objectives by regions. It is observed that of all regions in optimal conditions, the total area under cultivation has decreased compared to the existing cropping pattern (base). This finding is supported by the findings of Najafabadi et al. (2019). Hamidiyeh and Karkheh Noor

![Fig. 8 Comparison of the amount of available water observed and predicted through ANFIS for the South Karkheh sub-basin](image-url)
regions (-70%) had the highest and Azadegan (-19%) and Kowsar-Quds (-18%) had the lowest reduction in cultivation area.

Compared to the basic conditions, the optimal gross profit of Kowsar-Quds and Azadegan regions were more than double. Meanwhile, this parameter is decreased by 70% in Hamidiyeh and Karkheh Noor regions. Water consumption of all regions is decreased in the optimal pattern due to the reduction in cultivated areas; As a result, the most severe decrease in this parameter was about 70% and related to Hamidiyeh and Karkheh Noor regions.

Based on the results of Table (3), by implementing the optimal cropping pattern in the regions of Payepol, Kowsar-Quds, and Azadegan, water economic efficiency can be significantly improved. The composition of cultivation in different regions showed that this increase was due to the change in cropping patterns from low gross profit crops (wheat) to high gross profit crops (onion and watermelon). Accordingly, in Payepol region, about 46% of the total optimal cropping pattern in the region was allocated to onion cultivation; whereas, in the basic conditions this crop was not cultivated in this area.

In Kowsar-Quds region, watermelon had similar conditions and a large share of the optimal cropping pattern (about 64%) was related to this crop. Onion and watermelon were included in the optimal cropping pattern of Azadegan region, and in total they comprised about 63% of the cultivated area. Different results for different regions indicate the dynamic and multilevel nature of changes in available water resources in terms of vulnerability and adaptation, which has been proven in other studies (Esteve et al. 2015; Westerhoff and Smit 2008).

Figure 10 compares the total cultivation of different crops, gross profit, water consumption, and economic efficiency of water in the whole basin area under optimal and basic conditions. As observed, according to the amount of water available from the ANFIS method, in order to achieve economic and environmental objectives in the whole area of the basin, it would be necessary to reduce wheat cultivation by about 30% and increase onion and watermelon cultivation instead. These changes at the basin level would increase the total gross profit by more than $10 million, reduce water consumption by more than 600 million cubic meters, and increase water economic efficiency from $0.06 to $0.12.
Table 3  Optimal and basic cropping pattern of different regions

|                 | Payepol Base (%) | Payepol Optimal (%) | Kosar-Ghods Base (%) | Kosar-Ghods Optimal (%) | Hamidiyeh Base (%) | Hamidiyeh Optimal (%) | Azadegan Base (%) | Azadegan Optimal (%) | Karkheh Noor Base (%) | Karkheh Noor Optimal (%) |
|-----------------|------------------|---------------------|-----------------------|-------------------------|--------------------|-----------------------|--------------------|-----------------------|-------------------------|-------------------------|
| Wheat           | 31               | 57                  | 24                    | 67                      | 69                 | 69                    | 27                 | 73                    | 67                      | 67                      |
| Barley          | 8                | 14                  | 2                     | 5                       | 3                  | 3                     | 4                  | 12                    | 17                      | 17                      |
| Rapeseed        | 0                | 0                   | 0                     | 1                       | 0                  | 0                     | 0                  | 0                     | 0                       | 0                       |
| Tomato          | 2                | 3                   | 2                     | 6                       | 1                  | 1                     | 0                  | 0                     | 0                       | 0                       |
| Onion           | 46               | 0                   | 0                     | 0                       | 0                  | 0                     | 26                 | 0                     | 0                       | 0                       |
| Sugar beet      | 1                | 1                   | 0                     | 0                       | 0                  | 0                     | 0                  | 0                     | 0                       | 0                       |
| Mung bean       | 1                | 2                   | 0                     | 0                       | 0                  | 0                     | 0                  | 0                     | 0                       | 0                       |
| Cucumber        | 0                | 0                   | 0                     | 1                       | 1                  | 1                     | 0                  | 0                     | 0                       | 0                       |
| Watermelon      | 7                | 12                  | 0                     | 0                       | 0                  | 0                     | 0                  | 0                     | 0                       | 0                       |
| Maize           | 1                | 3                   | 7                     | 19                      | 25                 | 25                    | 5                  | 14                    | 13                      | 13                      |
| Rice            | 1                | 2                   | 0                     | 0                       | 1                  | 1                     | 0                  | 0                     | 1                       | 1                       |
| Sesame          | 0                | 0                   | 0                     | 0                       | 0                  | 0                     | 0                  | 0                     | 1                       | 1                       |
| Bean            | 12,965.2         | 23,178              | 10,866                | 13,200                  | 4225.5             | 14,085                | 18,096             | 22,367                | 6878.4                  | 22,928                  |
| Aggregate (hectares) | 16,919.8       | 17,012.7            | 23,530.7              | 11,004.3                | 3417.2             | 11,390.6              | 33,937.6           | 16,683.1              | 4601.9                  | 15,339.5                |
| Gross margin (thousand dollar) | 143.201        | 288.522             | 159.929               | 178.587                 | 69.344             | 231.147               | 227.852            | 282.110               | 106.565                 | 355.218                 |
| Water consumption (MCM) | 0.118          | 0.059               | 0.147                 | 0.062                   | 0.049              | 0.049                 | 0.149              | 0.059                 | 0.043                   | 0.043                   |
| Water economic productivity (dollar per m3) | 0.118           | 0.059               | 0.147                 | 0.062                   | 0.049              | 0.049                 | 0.149              | 0.059                 | 0.043                   | 0.043                   |
The model used in the current study was able to improve the farmers’ profit, reduce water consumption, and significantly increase water economic productivity by optimal water supply and demand management, and provide a suitable cropping pattern. Comparison of the results of this study with results of others (for example Esteve et al. 2015; Galán-Martín et al. 2015; Najafabadi et al. 2019) have shown that the various planning models in different basins have not been able to achieve such an improvement in water economic efficiency.

On the other hand, contrary to popular belief, the adoption of some of these strategies, while improving hydrological performance, can increase the gross margin of farmers; so, while reducing their water consumption, which has been corroborated by other studies, increasing farmers’ profit is possible either (Esteve et al. 2015; Mirzaei and Zibaei 2021; Laskookalayeh et al. 2022; Tarazkar et al. 2018).

5 Conclusion

The purpose of this study was to provide a framework for simultaneous management of water supply and demand with economic and environmental objectives under uncertainty. For this purpose, the southern Karkheh basin of Khuzestan province was selected as the case study. Operation rules of Karkheh dam were extracted as a water supplier under the southern Karkheh basin, and the volume of water released from the reservoir was estimated using the ANFIS model. Then, using the multi-objective programming model and applying the augmented ε-constraint method, the available water resources were allocated to different agricultural areas in the basin.

In addition to increasing gross profit, the proposed conceptual framework can reduce farmers’ water consumption to meet the environmental needs of the basin and consequently improve the economic productivity of water; nevertheless, in this catchment area,
another study has been conducted to resolve the conflict of water consumption, which has not resulted in a significant increase in water economic productivity (Nikmehr and Zibaei 2020). Also, a comparison of the study results that have used augmented ε-constraint method with the present study shows that this method although increasing the economic productivity of farmers (Mirzaei et al. 2021; Mirzaei and Zibaei 2021), has been able to greatly reduce water consumption; Therefore, the present model has been effective in resolving the consumption conflict between the economic and environmental sectors, and can be used for other regions as well. in addition to considering economic and environmental objectives in managing water demand, this model has paid attention to optimizing the performance of the reservoir and has managed water demand according to the amount of optimal outlet water from the reservoir.

Based on the results, proper operation rules and the ANFIS model were able to manage water release in different months of the year according to inflows and reservoir storage volume. Thus, in wet years more water volume was released; unlike in drought years less water volume was released. So, as the rate of release from the reservoir of Karkheh Dam is not optimal in the current situation, it is recommended that to decide on the release of water from this dam, water resource planners and policy makers use the proposed model.

From the results of the study, it can be seen that reducing the total area under cultivation and modifying the cropping pattern to increase onion and watermelon cultivation plays an effective role in managing water demand for the study areas. The proposed conceptual framework was able to increase the gross profit, improve the economic efficiency of water, and reduce farmers’ water consumption to meet the environmental needs of the basin.

Finally, it is suggested that according to the capabilities of the current model for comprehensive management of water resources, this model get used for creating an initiative for the relevant managers of other basins in Iran.

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Availability of Data and Materials Data and model estimation output are available from the corresponding author upon reasonable request.

Declarations

Conflict of Interest The authors state that they have no conflict of interest.

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