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Groundwater quality status based on a modification of water quality index in an arid area, Iran

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ABSTRACT

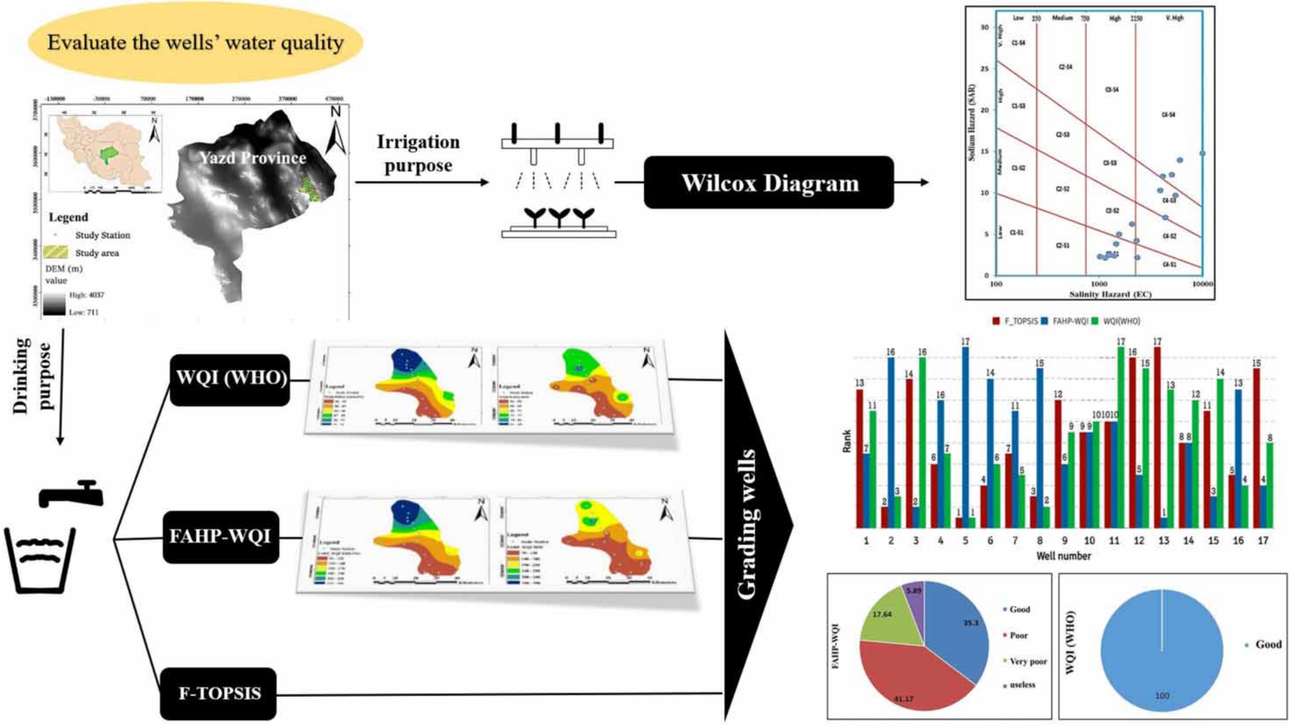
Increasing population, high demand for food, and uncontrolled abstraction of aquifers have severely affected the water quality. This study aimed to evaluate the water quality of 17 deep agricultural wells in Bahabad plain from the perspective of irrigation and drinking. In order to determine the water quality of wells and analyze the water quality index (WQI), a set of statistical methods such as a fuzzy analytic hierarchy process (FAHP) and TOPSIS were used. WQI is considered one of the primary methods for assessing drinking water quality. Still, due to the discrepancy between the results and the WQI (WHO), it was decided to modify the WQI method. The integrated use of FAHP-WQI and the TOPSIS method led to significant changes in the grading and the classification of water wells. The results showed that these two methods combined could be used as a good and complementary technique to eliminate ranking inconsistencies by WQI. Combining WQI results with GIS also allows for a deeper analysis of drinking water quality. The results showed that most of the water quality problems are due to wells in the northern region of the plain, and more than 41% of wells in this region are not in good condition.

Key words: fuzzy-AHP, groundwater, Wilcox diagram, WQI

HIGHLIGHTS

- This study aims to evaluate groundwater quality of the Bahabad plain.
- TDS, pH, EC, and HCO_3^- are the most important parameters of the project.
- FAHP was used to identify parameter weights in the Bahabad plain WQI.
- The use of TOPSIS method leads to many changes in the ranking and classification of water wells.

GRAPHICAL ABSTRACT



INTRODUCTION

Nowadays, increasing population, rising living standards, and social welfare in many countries have increased the demand for water for various agricultural, industrial, and urban uses. Groundwater is considered an important water source due to its potential for less pollution and higher storage capacity than surface water (Faithful & Finlayson 2005; Khosravi *et al.* 2017). In arid and semi-arid regions such as Iran, groundwater has a significant share in drinking water supply and agriculture. On the one hand, overuse of groundwater resources and, on the other hand, pollution of these waters due to environmental changes and activities of agriculture and industry have created a challenge in water resources management (Khan *et al.* 2003; Sargaonkar & Deshpande 2003; Chang 2004). These factors have led to various strategies for quality and quantity control of surface and groundwater resources to be the headline of many scientific studies. Many indicators have been presented for water quality analysis to convert the values of different parameters into a general and complete index, one of which is the water quality index (WQI) (Mohebbi *et al.* 2013; Krishan *et al.* 2016). The WQI model is one of the most common numerical methods for summarizing pollution status and quality of water resources intended for domestic and drinking purposes (Egbueri *et al.* 2020). The concept of WQI was first developed and proposed by Horton in the middle of the past century; he was the first researcher to suggest the use of WQI (Rubio-Arias *et al.* 2012). Since then, many studies have been reported in different countries on water indicators, such as the United States, Britain, Canada, India, etc. (Egbueri *et al.* 2019).

One way to classify water quality in agriculture is to use the Wilcox or USSL diagram. The USSL diagram is created by plotting the sodium and salinity line, leading to 16 different classes that evaluate water suitability for irrigation (Egbueri *et al.* 2021). In this diagram, water quality groups are classified into four categories (high, medium, poor, and very poor) (Wilcox 1948). In the past two decades, the use of fuzzy logic has been the most prominent innovation, and its use is appropriate for WQI. This approach makes it possible to evaluate the impact of each variable on the final WQI (Minh *et al.* 2019). Researchers and decision-makers have readily accepted it because of its ability to control uncertainty in various sciences, including water quality management. For long-term water quality assessment, fuzzy logic can be used in conjunction with extensive data analysis.

Since the fairness of judgments in hierarchical analysis is high but uncertain, it could not reflect human thinking styles (Kahraman *et al.* 2003). To overcome this shortcoming and make a powerful decision, Van Laarhoven and Pedrycz proposed the fuzzy analytic hierarchy process (FAHP: Van Laarhoven & Pedrycz 1983).

The TOPSIS model is one of the decision making models that could solve many of the problems faced by planners and decision makers. This model was first proposed by Hwang & Yoon (1981) and then paved its way as one of the best and most accurate models of multi-index decision making among planners (Akbari & Mahdi Zahedi 2008). This technique is based on the concept that the selected option has to be as close to the most ideal positive solution (the best possible choice) and as far from the most negative solution (the worst possible choice) as possible (Momeni 2006).

In recent decades, WQI has drawn attention from several scholars throughout the world. For instance, Dahiya *et al.* (2007) investigated water quality in 16 villages in the south of India based on 10 qualitative parameters of drinking water. The fuzzy set theories were used to determine water quality in their study. This study demonstrated that from among 42 samples taken, the quality of four samples was desirable, 23 samples were acceptable, and the remaining 15 samples were of unacceptable quality. In another study, Lermontov *et al.* (2009) investigated the development of quality index and assessed the water quality of a river in Brazil and revealed that this novel index could be a proper tool to monitor the quality of the river under study. In their study, a novel fuzzy water quality index (FWQI) was proposed, which was logically close to other indices and had a close coordination with classic WQI traditionally calculated in Brazil. Another study on the quality of ground aquifer water in northern Ethiopia based on WQI conducted by Hosseini-Moghari *et al.* (2015) demonstrated that GWQI changes for ground water samples was between 54.41% and 86.24% and all ground water samples were of a good quality for drinking purposes. This study developed seven FWQI models with various water quality parameters based on triangular and trapezoidal membership functions.

Also, hydrogeochemical processes and the quality of water resources in the Ojuto region were studied by Egbueri *et al.* (2019). In this study, the WQI showed that only 17.86% of the samples analyzed are of good quality for drinking, while the quality of other samples is poor, very poor, and unusable, respectively.

Another study assessed the quality of drinking water in a rural area of Nigeria based on chemometrics and multiple index methods (Egbueri *et al.* 2020). In this study, the use of pollution load index, WQI, and entropy-weighted WQI (EWQI) showed that some wells (about 8–12%) in the study area were slightly polluted.

In the case of applying Wilcox model, several studies have been conducted as well. Irrigation water quality assessment through Wilcox model was conducted in Darussalam, Tanzania by Sappa *et al.* (2015). This study revealed that the samples collected were in the C3-S2, C3-S1, C2-S1, and C4-S2 classes and were in the range of average to poor water quality. Scholars attributed this downward trend to increase in salinity and decrease in the ground water levels.

The USSL diagram was also used to assess multi-criteria water quality for human, irrigation, and industrial purposes in the Omonia region, as examined by Egbueri *et al.* (2021). In this study, 73.33% of the samples were drawn below the C1S1 zone (risks of low salinity and low sodium), while 13.33% were drawn below the zone C1S2 (risks of low salinity and moderate sodium). This result indicates that these samples will carry little risk when used for irrigation and agricultural purposes and can therefore be used on almost all types of soils.

The main concern behind the present study is to determine the quality of groundwater in the Bahabad region of Yazd Province in Iran so that a realistic perspective and understanding could be presented of the overall quality of water resources in this area. The results of water quality analysis using the WQI method have always been associated with some uncertainty. In addition, the weight and importance of qualitative parameters in each region can be different and affect the zoning maps results and the numerical value of WQI. For this reason, in this study, the FAHP-WQI method was used to weigh the quality parameters and correct the results of the water quality index. Also, the TOPSIS method was used to rank the water quality index of wells. Therefore, the first purpose of the present study was to use the WQI (WHO) method to analyze and rank water samples in wells in the Bahabad plain. In the next step, using the TOPSIS and FAHP-WQI methods in an integrated manner, the validity of the classes and possible discrepancies in the WQI (WHO) method were investigated. Finally, each well was examined for agriculture by the Wilcox diagram.

MATERIALS AND METHODS

Study area

The Bahabad plain with an estimated area of 1,090 km^2 is located in the river zone of the Iranian Plateau and groundwater is the only source it has for water (Kherad *et al.* 2014). This plain is located in Yazd Province in the river zone of the Iranian

Plateau. Geographical coordinates of this plain are between 55 °50′ and 56 °12′ East longitude and 31 °36′ and 32 °01′ of North latitude. Its central district is Bahabad, located 85 kilometers away in the northeast of Bafgh. The area of the city is 8 km^2 and is located 1,398 m above the sea (Figure 1). The city's average maximum and minimum temperatures are 26 and 10 °C, respectively. Industrial and agricultural activities in the region have recently threatened the quality of water in this area and scholars have started to pay attention to its quality in the region (Kherad *et al.* 2014). The bedrock in the area is of dolomite and dolomite lime. The evaporation rate in Yazd is 3,000 mm annually, the average temperature is 18.9 °C and the average relative humidity is 35.3%. According to De Martonne's classification, this region's climate is arid and based on Emberger, it is in the mild and hot desert area. Groundwater is harvested through deep and semi-deep wells, aqueducts and springs. Overall annual discharge of water resources is about 617 million m^3 from which 92% goes to agriculture, 5% goes to sanitation and drinking, and the remaind goes to industry and animal husbandry. The direction of groundwater is from the southwest toward the northeast (Yazd Regional Organization 1992).

To study the climate of the study area, 22-year statistics of Bahabad meteorological station (1999–2021) have been used. In this statistical period, the highest rainfall is in January, and the maximum temperature is in July. Also, the least amount of rainfall occurs in September, and the minimum temperature occurs in February. The average annual rainfall is about 65.7 mm. More than half of the annual rainfall (about 60%) is in winter and then autumn is the rainiest season in the region.

Bahabad plain is geologically part of the Central Iran zone and the Lut desert basin. The geological classes in the Bahabad Basin are very diverse and have different facies. According to the data and information received from the Geological Survey & Mineral Explorations of Iran (GSI) and the Regional Water Company of Yazd Province, a geological map of the Bahabad plain was prepared, which shows the different geological classifications of this region (Figure 2).

Also, human activities in the study area include agricultural activities and urban regions. According to Figure 3, it can be seen that poor rangelands cover most areas of this plain, and parts of the north and south of the plain include areas with urban and agricultural use.

Sample collection and analysis

The purpose of the fieldwork for this study was to identify and sample 17 wells in this area. Sampling points can be seen in Figure 1. All samples were collected using pre-washed and sterilized 1-liter plastic bottles and also pH and EC parameters were measured at the sampling site. The samples were stored in polyethylene containers and transferred to the laboratory

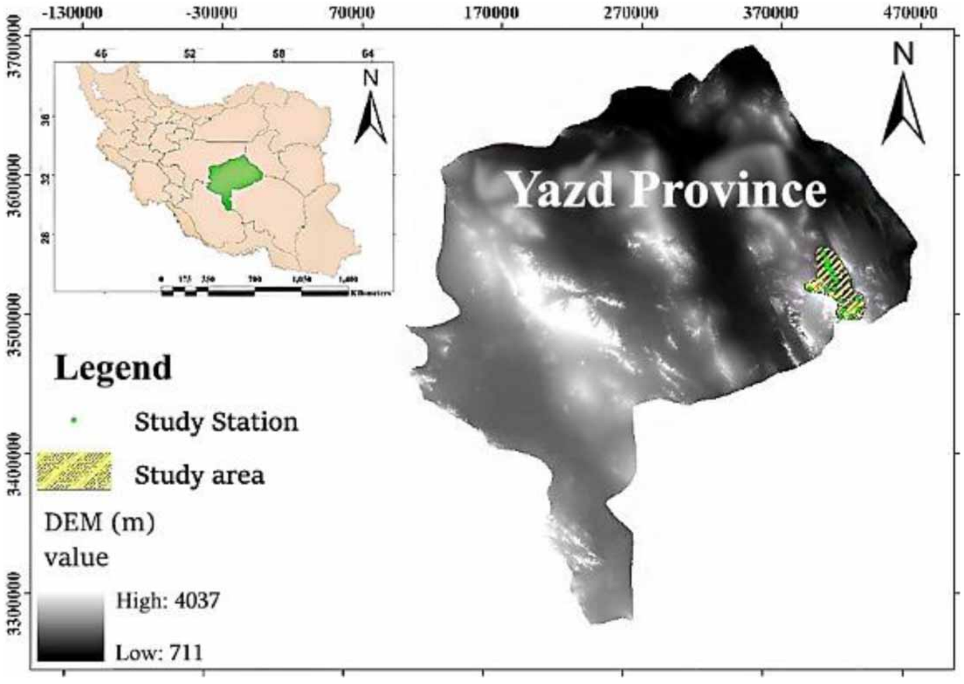


Figure 1 | The study area and the respective sampling points.

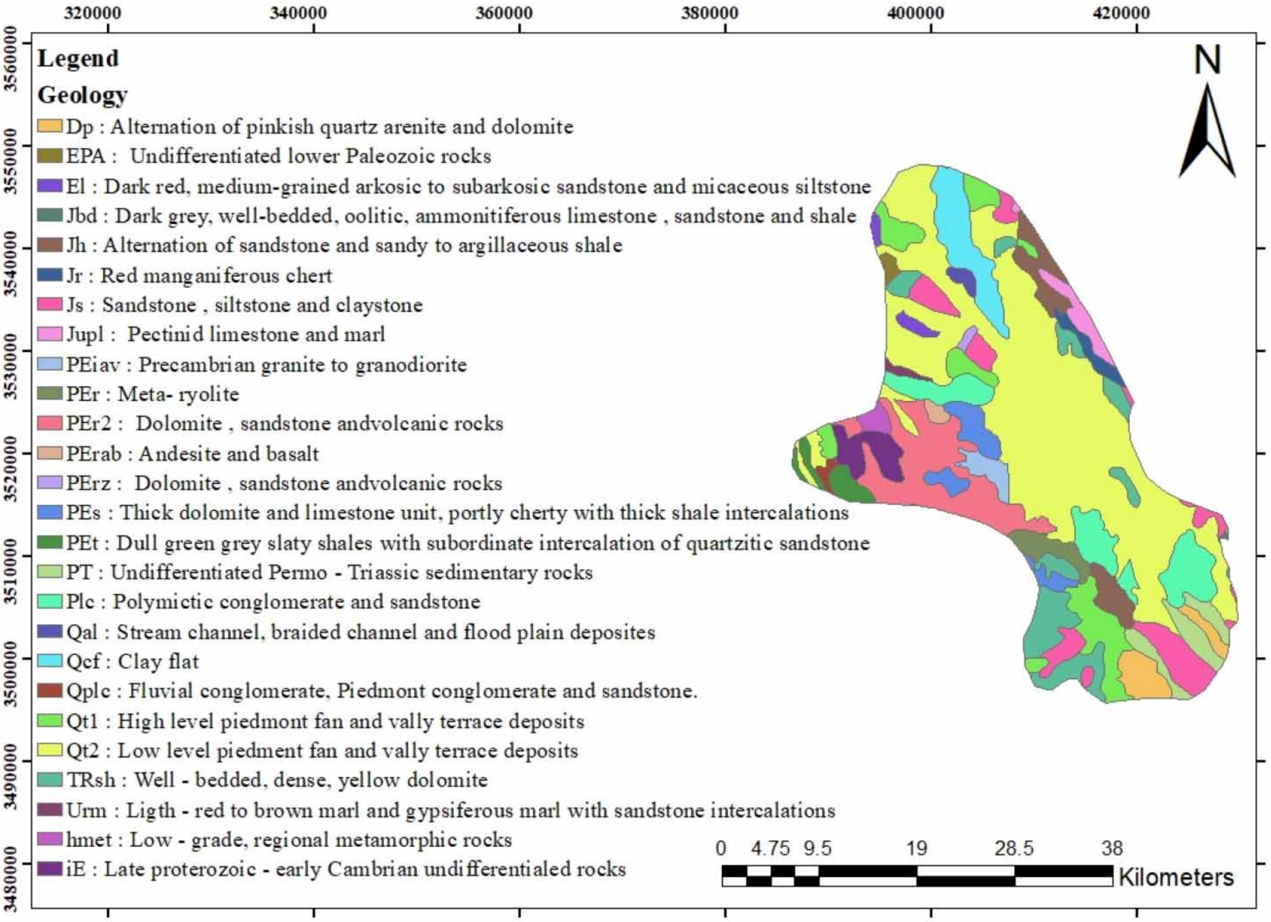


Figure 2 | Geological map of Bahabad plain.

for chemical analysis. A conductivity meter was used to measure the TDS and EC values of water samples and ion chromatography was used to measure the values of anions and cations.

The pH parameter was measured with a pH meter and the amount of K^+ cation was measured using a flame photometer in milligrams per liter using calibration curves. In order to determine chloride, the silver nitrate titration method was used. Other parameters such as sodium (Na^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), bicarbonate (HCO_3^-), and sulfate (SO_4^{2-}) in the laboratory using standard methods for anions and cations according to Recommendations of the American Public Health Association (APHA 2005) were measured.

WQI (WHO)

The WQI can measure changes in water quality in a particular source over time or compare the quality of a water source with other water sources (Rajankar *et al.* 2009). The WQI method is calculated based on standards dictated by the World Health Organization (WHO 2011). In the present study, chemical parameters such as TDS, Na^+, Mg^{2+}, Ca^{2+}, Cl^-, pH, HCO_3^-, and SO_4^{2-} were used.

Therefore, one weighting factor has to be assigned for each chemical parameter. The weighting factor of each parameter is acquired using Equation (1).

Calculating water quality grading

Water quality grading is calculated through the following equation (Brown *et al.* 1970):

$$q_n = 100\left(\frac{V_n - V_i}{S_n - V_i}\right) \tag{1}$$

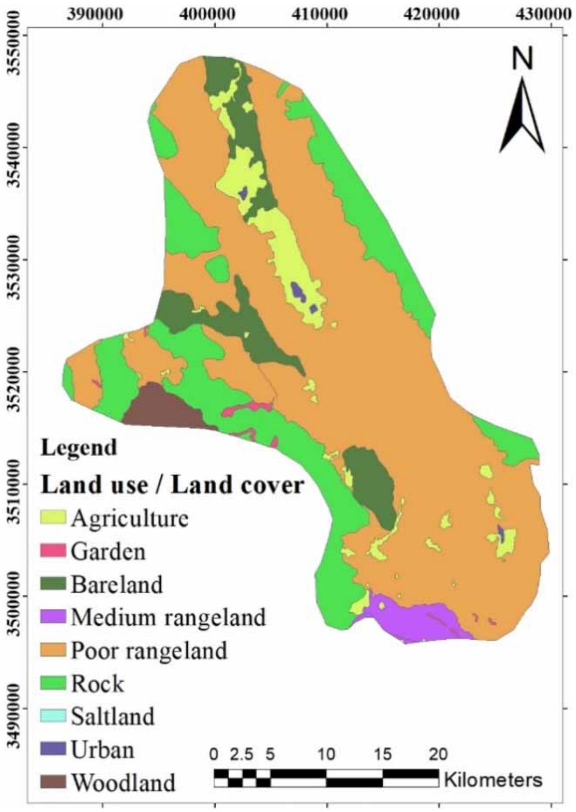


Figure 3 | Land use map of Bahabad plain.

where q_n is the water quality grading for parameter n, v_n is the observed value for parameter n, S_n is the permissible standard rate and V_i is the ideal value of the parameter.

Calculating unit weight (W_n)

Unit weight of the parameter related to an appropriate value is reversed with the proposed standardized value S_n:

$$W_n = K/S_n \tag{2}$$

where W_n is the unit weight for the parameter n, K is the standard value for parameter n and S_n is the constant for the proportion.

The constant for the proportion is calculated through the following equation:

$$K = 1/\sum(1/S_n) \tag{3}$$

and finally overall WQI is linearly calculated by adding quality grading to the unit weight:

$$WQI = \sum q_n W_n / \sum W_n \tag{4}$$

The values calculated for WQI are generally categorized into five classes: excellent, good, poor, very poor, and inappropriate. Classification of water quality based on WQI is represented in Table 1.

Wilcox diagram

The Wilcox diagram, which can classify water into different classes for agricultural use, is based on the values of electrical conductivity (EC) and sodium adsorption ratio (SAR). EC and SAR parameters are each classified into four groups (C1 to

Table 1 | Categorization of water quality based on WQI

Class	WQI value	Water quality status
A	<50	Excellent water
B	51-100	Good water
C	101-200	Poor water
D	201-300	Very poor water
E	>300	Water unsuitable for Drinking

C4) and (S1 to S4, respectively) (Miller *et al.* 1984). In the Wilcox diagram, agricultural water is divided into 16 categories from C1S1 to C4S4 (Table 2), and the EC and SAR interval is also shown in Table 3 (Wilcox 1955).

Calculation of parameter's weight using FAHP (FAHP-WQI)

To overcome the problem of uncertainty in judgments and make more important decisions, Van Laarhoven & Pedrycz (1983) proposed the FAHP. The FAHP is a more advanced analytical technique developed from the traditional AHP model. It is assumed that FAHP determines the weight of criteria firstly through pairwise comparison conducted by experts in the field, where subjective judgments are the key to determining weight ratio. In 1996, FAHP was developed based on triangular fuzzy numbers (TFNs) and pairwise comparison through multi-criteria analysis models by Chang (Chang 1996). In this approach, after formation of decision making hierarchy, a triangular fuzzy number is assigned for each parameter according to their significance (Table 4) and pairwise comparison matrices for each level of hierarchy tree are created (Tseng *et al.* 2008; Şener & Şener 2015; Goodarzi *et al.* 2022). Numbers 2/3, 1, 3/2, 2, 5/2, 3, 7/2, 4, 9/2 are the ratios of fuzzy scaling related to preference power of an element over other ones with various distances.

A fuzzy number could be expressed in a triangular or trapezoidal way. In a TFN, the number relevant to the numerator is expressed as $M = (l\ m\ u)$ where l, m, and u stand for the least possible value, the most probable value and the maximum rate considered for each number respectively and number considered could range between a and c. FAHP stages developed by Chang are as follows (Chang 1996):

Stage 1: Formation of pairwise comparison matrix using fuzzy numbers

Stage 2: Calculation of matrix S for each of the lines of pairwise comparison matrix

$$S_i = \sum_{j=1}^{m} M_{gi}^{j} \otimes \left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{gi}^{j} \right]^{-1} \tag{5}$$

Table 2 | Classification of agricultural irrigation water based on Wilcox diagram

Type of water quality for agriculture	Water category
Freshwater, completely harmless to agriculture	C1S1
Slightly salty, almost suitable for agriculture	C2S1, C2S2, C1S2
Saltwater, for agriculture with the necessary preparations	C3S3, C3S2, C3S1, C2S3, C1S3
Very salty, harmful to agriculture	C1S4, C2S4, C3S4, C4S4, C4S2, C4S1

Table 3 | EC and SAR ranges in Wilcox diagram

Class	EC (μS/cm)	Class	SAR
C1	100–250	S1	0–10
C2	250–750	S2	10–18
C3	750–2,250	S3	18–26
C4	>2,250	S4	>26

Table 4 | Fuzzy numbers of pairwise comparison of one parameter with another parameter

Linguistic scale for importance	Triangular	Triangular fuzzy reciprocal scale
Just equal	(1, 1, 1)	(1, 1, 1)
Equally important	(1/2, 1, 3/2)	(2/3, 1, 2)
Weakly more important	(1, 3/2, 2)	(1/2, 2/3, 1)
Weakly more important	(3/2, 2, 5/2)	(2/5, 1/2, 2/3)
Strongly more important	(2, 5/2, 3)	(1/3, 2/5, 1/2)
Absolutely more important	(5/2, 3, 7/2)	(2/7, 1/3, 2/5)

where M is the TFNs inside pairwise comparison matrices. In fact, while calculating matrix S each one part of fuzzy numbers is added peer to peer and is multiplied by the overall sum in reverse fuzzy (Equations (6)–(8)).

$$\sum_{j=1}^{m} M_{g^i}^{j} = \left(\sum_{j=1}^{m} l_j . \sum_{j=1}^{m} m_j . \sum_{j=1}^{m} u_j\right). \qquad j = 1.2. \;\dots\; .m \tag{6}$$

$$\sum_{i=1}^{n}\sum_{j=1}^{m} M_{g^i}^{j} = \left(\sum_{i=1}^{n} l_i . \sum_{i=1}^{n} m_i . \sum_{i=1}^{n} u_i\right). \qquad i = 1.2. \;\dots .n \tag{7}$$

$$\left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{g^i}^{i}\right] = \left(\frac{1}{\sum\limits_{i=1}^{n} u_1}, \frac{1}{\sum\limits_{i=1}^{n} m_1}, \frac{1}{\sum\limits_{i=1}^{n} l_1}\right) \tag{8}$$

Stage 3: Calculation of magnitude of S compared to each other. At this stage, $S_i s$ are compared to each other from the point of view of the degree of their magnitude using Equation (9).

$$V(M_2 \geq M_1) = sup_{y \geq x}[min(\mu_{M1}(x).\mu_{M2}(y))] \tag{9}$$

Equation (9) could also be expressed as Equation (10):

$$V(M_2 \geq M_1) = hgt(M1 \cap M2) = \mu_{M2}(d) \\ = \begin{cases} 1 & if\ m_2 \geq m_1 \\ 0 & if\ l_1 \geq u_2 \\ \dfrac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)} & otherwise \end{cases} \tag{10}$$

where $M_1 = (l_1, m_1, u_1)$ and $M_2 = (l_2, m_2, u_2)$ are two TFNs and d is the maximum point of intersection between M_1 and M_2 (Figure 4).

Stage 4: At this stage, non-standardized weight vector is acquired by calculating minimum $V_{(min)}$ values calculated in the previous stage.

$$\min V = (M \geq M_i). \quad i = 1.2. \;\dots .k \tag{11}$$

$$d'(A_i) = \min V(S_i \geq S_k) \qquad k = 1.2. \dots . n; k \neq i \tag{12}$$

$$W' = (d'(A_1).d'(A_2). \dots . d'(A_n))^T \quad A_i(i = 1.2. \dots .n) \tag{13}$$

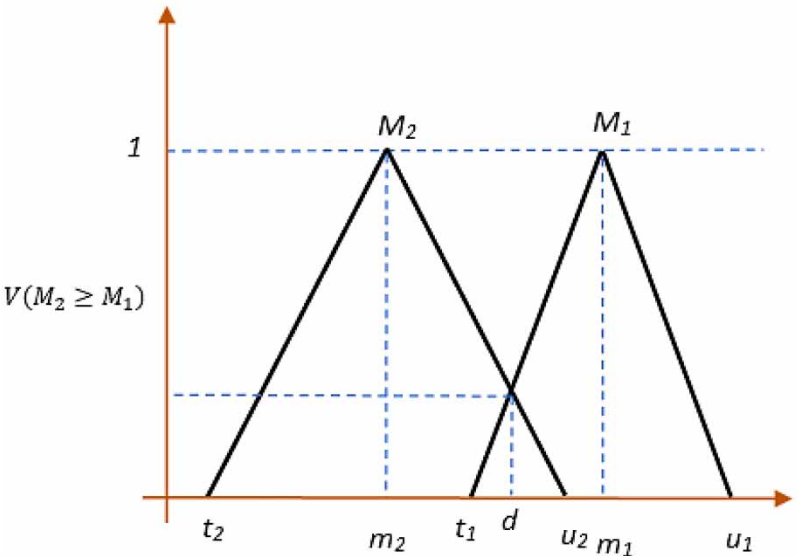


Figure 4 | Degree of magnitude of two fuzzy numbers compared to each other (Şener & Şener 2015).

Stage 5: The non-standardized weight vector acquired previously was normalized so that the final weight vector which was the ultimate goal of fuzzy calculations was produced. The value of W acquired at this stage is a non-fuzzy number.

$$W = (d(A_1).d(A_2).\dots.d(A_n))^T \tag{14}$$

TOPSIS model

Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) was first developed by Hwang & Yoon (1981) and as time passed, modifications were made to make it one of the best and most accurate multivariate decision-making methods available (Akbari & Mahdi Zahedi 2008). In this study, TOPSIS was used as a classic multivariate decision-making approach along with the F-AHP weighting model to validate grading of WQI. TOPSIS is a classic MCDM model developed by Hwang & Yoon (1981). The main stages of TOPSIS in assessing water quality are as follows (Guo *et al.* 2008; Sadi-Nezhad & Damghani 2010)

Stage 1: Making initial decision matrix:

At this stage, if there are m samples from n parameters, the data could be expressed in the form of the following matrix (Equation (15)):

$$\mathrm{c} = \begin{bmatrix} C_{11} & C_{22}\cdots & C_{1n} \\ C_{21} & C_{22}\dots & C_{2n} \\ \vdots & \vdots\ddots & \vdots \\ C_{m_1} & C_{m_2}\dots & C_{mn} \end{bmatrix} \tag{15}$$

where C expresses the initial decision and cij shows the observed values for $i = 1, 2, \dots, m$ and $j = 1, 2, \dots, n$.

Stage 2: Normalization of initial decision matrix:

Since there could be some complex equations in the initial decision matrix, this matrix has to be standardized so that abnormalities related to units of measurement and scale are eliminated. The standard decision matrix (R) is represented in the form of Equation (16) and its standardization is conducted through Equation (17):

$$c = \begin{bmatrix} r_{11} & r_{22}\cdots & r_{1n} \\ r_{21} & r_{22}\dots & r_{2n} \\ \vdots & \vdots\ddots & \vdots \\ r_{m_1} & r_{m_2}\dots & r_{mn} \end{bmatrix} \tag{16}$$

$$marix.r_{ij} = c_{ij} / \left[\sum_{i=1}^{m} c_{ij}^{2} \right]^{\frac{1}{2}} \tag{17}$$

Stage 3: Determining the weight of each parameter:

Since each parameter is of different significance in qualitative assessment, the weight of each index is determined using F-AHP theory. Standard weighting matrix F could be calculated through following equations:

$$f_{ij} = r_{ij} \times \omega_j \tag{18}$$

$$F = (f_{ij})_{m \times n} \tag{19}$$

Stage 4: Determining positive (G) and negative (B) ideal reference points:

$$f_j^{+} = max\{f_{1j}.f_{2j}.\dots.f_{mj}\} \tag{20}$$

$$f_j^{-} = min\{f_{1j}.f_{2j}.\dots.f_{mj}\} \tag{21}$$

$$G = \{f_1^{+}.f_2^{+}.\dots.f_n^{+}\} \tag{22}$$

$$B = \{f_1^{-}.f_2^{-}.\dots.f_n^{-}\} \tag{23}$$

Stage 5: Calculating the distance to positive and negative ideal reference points:

$$\begin{aligned} d^{+} &= \sqrt{\sum_{j=1}^{n} [f_{ij} - (f_{ij})_G]^2} \\ d^{-} &= \sqrt{\sum_{j=1}^{n} [f_{ij} - (f_{ij})_B]^2} \end{aligned} \tag{24}$$

where $(f_{ij})_G$ and $(f_{ij})_B$ are the values in positive and negative ideal reference points respectively and d^{+} and d^{-} are the distances to positive and negative ideal reference points.

Stage 6: Calculating TC coefficient of each sample and assessment of water quality

$$TC = \frac{d^{-}}{d^{-} + d^{+}} \tag{25}$$

After determining TC, the grade of groundwater quality is determined based on the grade of proximity coefficient. The larger the value of TC and the closer it is to one, the higher the quality of water will be.

RESULTS AND DISCUSSION

Examining WQI (WHO), FAHP-WQI, and F_TOPSIS approaches

The present study assessed the quality of drinking water in the Bahabad region using WQI (WHO). Moreover, FAHP-WQI was utilized to eliminate contradictions existing in the WQI (WHO) and F_TOPSIS approaches. In Figure 5, it could be observed that based on the analysis of WQI (WHO), almost all the area of Bahabad is located in the grading of good from the point of view of the state of its wells. This figure shows the assessment of state of wells through Kriging interpolation and IDW models. It could be concluded that the southwestern and central regions of the study area had a better quality of drinking water compared to its northern and southeastern regions. The location of reference wells used to assess the quality of water in the study area is marked blue.

As it was discussed earlier, utilizing WQI (WHO) had some contradictions; however, comparisons made with the previous approach reveal that considering FAHP-WQI, more than 35% of the study area is in the grading of good. Results from relative weights assigned for each of the qualitative parameters show that parameters higher than the standard mean the quality of

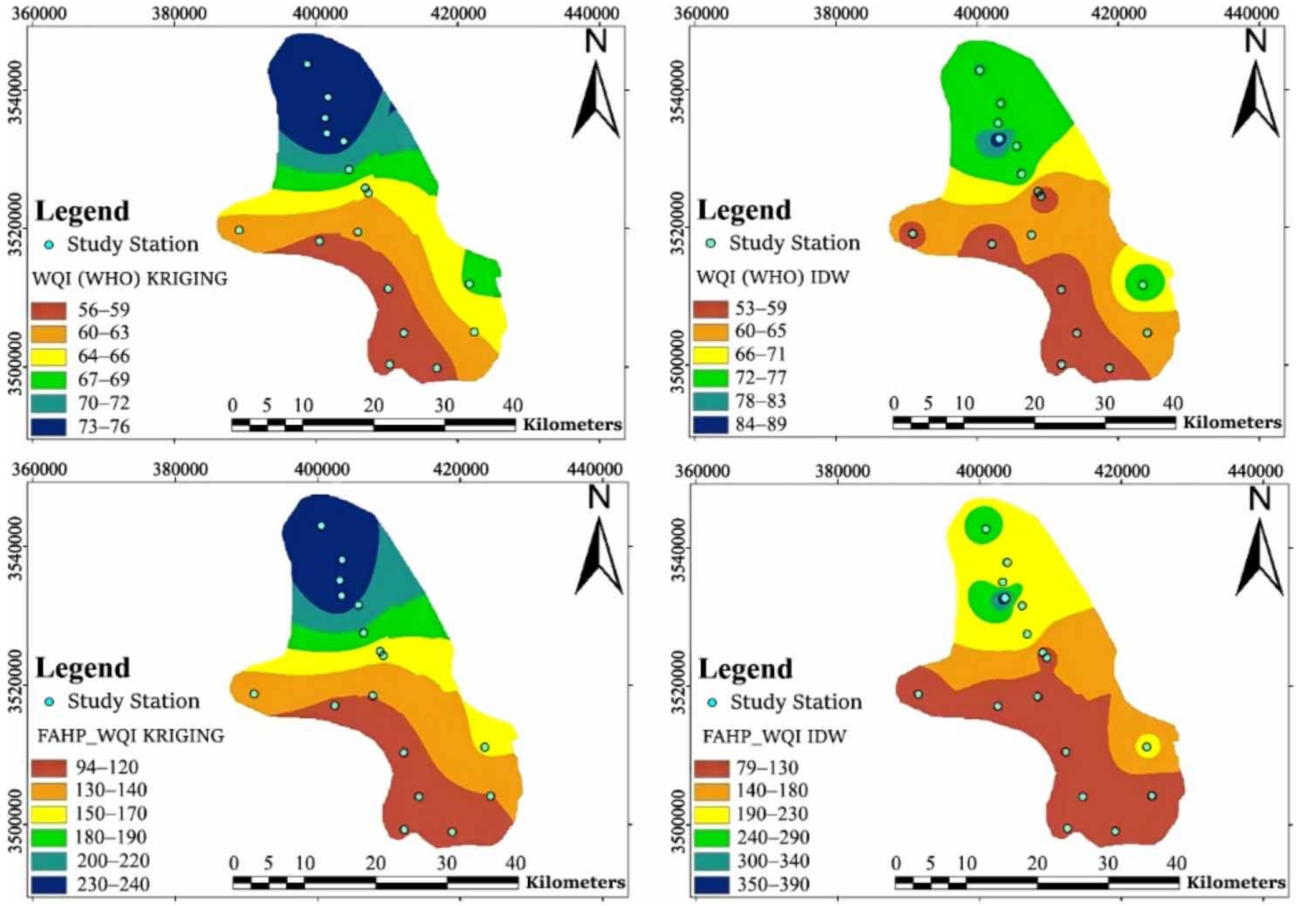


Figure 5 | Evaluation of drinking water wells using Kriging Interpolation and IDW models for WQI (WHO) and FAHP-WQI.

drinking water decreases and this in turn affects the quality grade of the well. Spatial cohesion of the data was examined using Kriging interpolation and IDW methods. Interpolation grading for each index revealed that IDW to the power of two and Kriging are the best ways to estimate and zone the components. Thus, to draw water quality of wells under study, IDW zoning and Kriging in ARC GIS environment were utilized. According to Figure 5, and based on FAHP-WQI analysis, it could be observed that six out of 17 wells are qualitatively classified as good; seven wells out of 17 are classified as poor, three wells are classified as very poor and the remaining one was unusable.

Results for grading the wells under study using WQI (WHO) and FAHP-WQI into good, poor, very poor, and useless are presented in Figure 6. According to the results of grading based on WQI after applying FAHP-WQI, these findings could vary extensively. Such changes could normally be seen in wells with WQI levels close to each other. However, using the multivariate TOPSIS approach and F-AHP weighting, the observed wells could be classified based on good quality prioritization.

Regarding WQI (WHO) calculations, it should be noted that, in spite of using index, lower quality of each parameter in WQI grading coupled with its relative weight is not comprehensible. Nevertheless, using normalized weight for all parameters in FAHP-WQI calculations could increase their effect on WQI grading. For instance, results for the well No. 5 calculated by WQI (WHO) put it in the good class of water quality; however, FAHP-WQI results puts the same well into the unusable category of water quality. On the other hand, this well was in the tenth grade according to TOPSIS model, which could be a proof of convergence of these results with those of WQI (WHO). Some of the most important samples for changes in the grading of wells based on their grades are represented in Table 6.

Water quality grading of wells based on F_TOPSIS

As discussed earlier, one of the main goals of this study was to compile methods to calculate WQI and TOPSIS for quality assessment and grading of water wells. Due to various and experimental weight for each chemical parameter, using the WQI method decreases the effect of parameters with values more than standard values on quality of drinking water and errors in

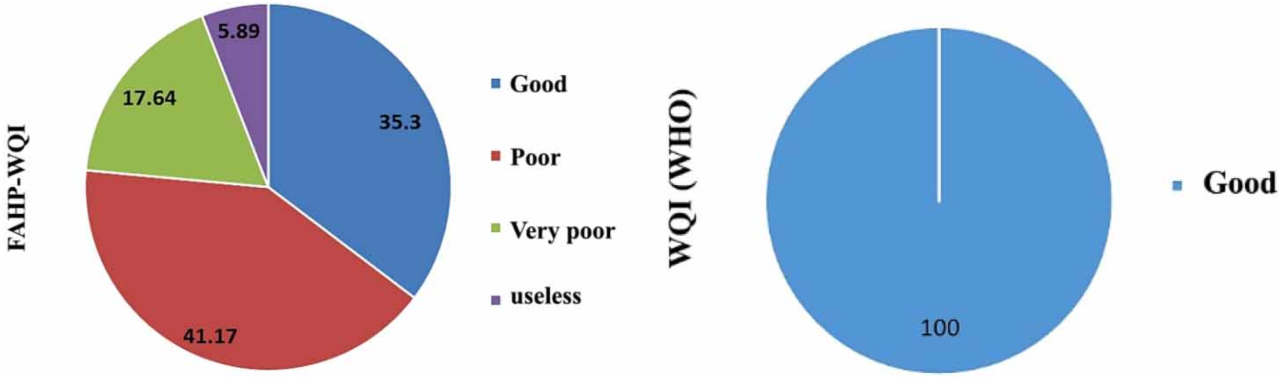


Figure 6 | Grading of water quality in study area using WQI (WHO) and FAHP-WQI.

the quality grading of wells. Thus, the present study used the multivariate TOPSIS decision-making model combined with FAHP to calculate and compare the quality grading of wells with WQI. Moreover, in WQI, weights of each qualitative parameter are considered experimentally and according to expert views; however, in the F_TOPSIS, weights are the outcomes of data standardization. Results for weight values of each qualitative parameter and quality grading of wells through F_TOPSIS methods are presented in Tables 5 and 6 respectively. Parameters with maximum fuzzy weights had the highest impact on water quality grading. Therefore, it seems as if TDS and pH parameters with respective weights of

Table 5 | Final weight factor using WQI (WHO) and Fuzzy-AHP

Parameters	pH	TDS	TH	EC	SO_4^{2-}	Cl^-	HCO_3^-	K^+	Na^+	Mg^{2+}	Ca^{2+}
Weight factor of WQI(WHO)	0.50	0.002	0.008	0.002	0.017	0.007	0.035	0.35	0.021	0.028	0.021
Weight factor of fuzzy-AHP	0.169	0.178	0.052	0.156	0.067	0.003	0.136	0.021	0.112	0.097	0.008

Table 6 | Study area's wells grading based on three methods of WQI (WHO), F_TOPSIS, FAHP-WQI

WQI (WHO)		FAHP-WQI		F_TOPSIS		
Value	Rank	Value	Rank	Value	Rank	Well number
58.2	11	101.86	7	0.085	13	1
77.4	3	245.17	16	0.442	2	2
53.6	16	85.774	2	0.079	14	3
71.2	7	194.37	12	0.306	6	4
89.3	1	389.37	17	0.708	1	5
74.1	6	212.71	14	0.37	4	6
74.9	5	176.63	11	0.274	7	7
78.6	2	233.62	15	0.426	3	8
60.6	9	95.63	6	0.09	12	9
59.5	10	122.53	9	0.133	9	10
52.9	17	122.83	10	0.123	10	11
53.7	15	95.74	5	0.058	16	12
55.7	13	79.443	1	0.027	17	13
56.2	12	121.46	8	0.136	8	14
54.6	14	92.282	3	0.095	11	15
76.4	4	196.89	13	0.313	5	16
61.9	8	94.577	4	0.069	15	17

0.178 and 0.169 had the highest impact and CA parameter with 0.008 weight had the lowest impact based on F_TOPSIS grading.

Using the F_TOPSIS method, the quality rating of wells relative to WQI (WHO) changed, and such a change is particularly noticeable in the ranking of wells with close WQI values. For instance, well No. 17 with a WQI value of 61.9 is in the good grading, while that same well is in the 15th rank based on F_TOPSIS grading. In Figure 7, the difference in qualitative grading of the wells under study is reported based on the three methods used in this study. It could be seen that results from F_TOPSIS and WQI (WHO) had a better convergence compared to the FAHP-WQI method. The clearest example of this difference in qualitative grading of the wells through methods under study could be observed in the case of wells No. 5 and 13.

Wilcox diagram

As mentioned earlier, the Wilcox diagram is used to classify water quality for irrigation. Figure 8 represents the Wilcox diagram for the plain under study. According to this figure, some 58.5% of wells are in C4S4 and C3S1 classes, which are classes with poor water quality that could only be used with coerced-textured soils and proper drainage systems particular for specific products. Furthermore, some 23.5% of wells are in the C4S4 class, which is very poor. However, none of the wells could be classified as good or even average.

DISCUSSION

The study aimed to assess the quality of water from 17 deep agriculture wells in Bahabad plain from the points of view of irrigation and drinking. To determine the quality of water from these wells, WQI was utilized along with the FAHP and the results from both of them were compared. In the FAHP method, experts were used to prepare pairwise comparison matrices between model parameters to determine the weight and importance of each parameter more accurately. Table 7 shows the criteria results with respect to the goal. Also, to ensure the accuracy of each matrix, its inconsistency ratio was calculated by Gogus & Boucher (1997) method. To calculate the consistency ratio (CR), we divide each matrix's consistency index (CI) by its random index. If the value is less than 0.1, the matrices are considered compatible, and the results can be trusted.

Using the TOPSIS ranking method can confirm the results of WQI(WHO). But the FAHP-WQI method is different from the results of the previous two methods. The results show that using them together can be used as a good and complementary technique to eliminate ranking inconsistencies by WQI. According to the results of this study, the average WQI(WHO) of Bahabad plain is 65.22 and based on this index, 100% of resources are in the good range. According to FAHP-WQI, 35.3% of resources are in the good range and 64.7% are in the poor to useless range. The results of weight analysis of 11 groundwater quality parameters determined based on FAHP showed that TDS, pH, EC, and HCO_3^- parameters with weights

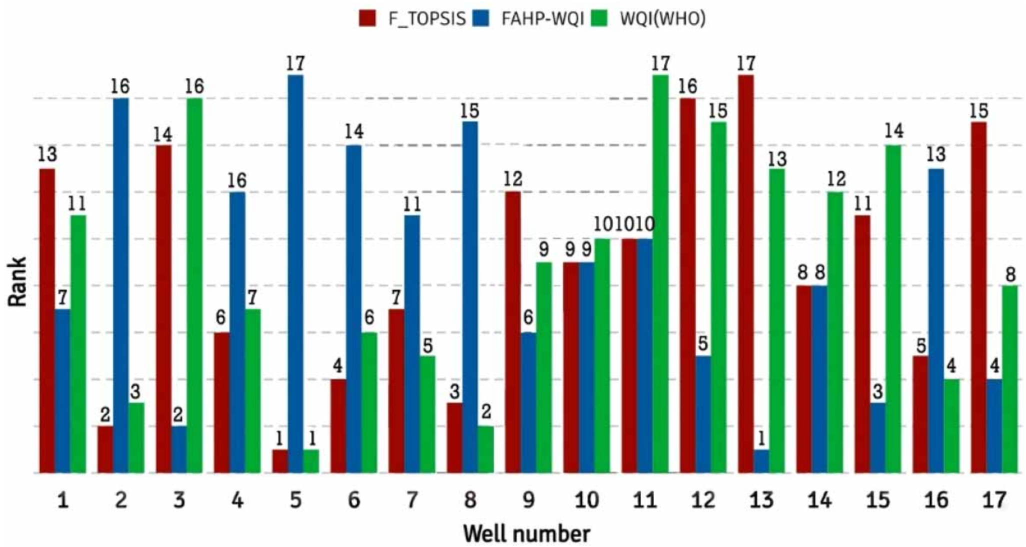


Figure 7 | Grading 17 wells under study through F_TOPSIS, FAHP-WQI and WQI (WHO).

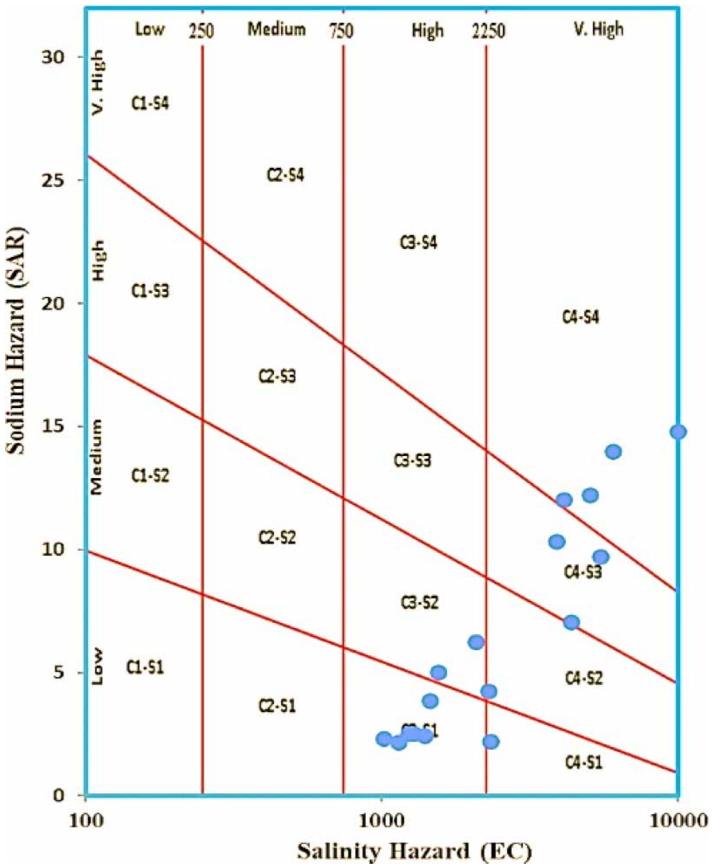


Figure 8 | Wilcox diagram to determine irrigation water quality.

Table 7 | The criteria results with respect to the goal

Criteria	**Abbreviation**	**Weight**	**Rank**
Total dissolved solids	TDS	0.178	1
pH	pH	0.169	2
Electrical conductivity	EC	0.156	3
Bicarbonate	HCO_3^-	0.136	4
Sodium	Na^+	0.112	5
Magnesium	Mg^{2+}	0.096	6
Sulfate	SO_4^{2-}	0.066	7
Total hardness	Th	0.052	8
Potassium	K^+	0.021	9
Calcium	Ca^{2+}	0.008	10
Chloride	Cl^-	0.003	11

of 0.178, 0.169, 0.156, and 0.136, respectively, are the most influential elements on WQI. According to the land use/land cover (LULC) map, various factors affect groundwater quality. In some areas of this plain, agricultural activities and urban areas can be seen that these uses have been more in the central to northern parts. Also, the grading of sediments in the southern part of the plain is relatively coarse to medium, and in the central and northern regions, finer granulation consisting of clay and sand is observed.

In a study by Atashi Yazdi *et al.* (2022) in the aquifer of Bahabad plain, the results of WQI were as follows: 23.53% of the samples have good quality, 35.29% have low quality, 17.65% have inferior quality, and 23.53% have non-drinkable quality. These results are very close to the results of the FAHP-WQI method in the present study and show the good accuracy of this model. Mahammad & Islam (2021) also used the FAHP method along with the groundwater quality index in a study entitled evaluating the groundwater quality of Damodar Fan Delta (India) using F-AHP MCDM technique. Weight was assigned to the GWQI model parameters using the FAHP method, and the four most important parameters were TDS, F^-, Fe^-, and Cl^-, respectively. In another study, Minh *et al.* (2019) assessed spatial and temporal changes in groundwater quality over ten years from 2009 to 2018 in An Giang. As in the present study, GWQI was created based on the F-AHP process for assigning weight parameters. After calculating the groundwater quality index, As and total iron parameters were introduced as the most influential parameters. In this study, the water quality of different samples in Bahabad plain based on WQI (WHO) and using TOPSIS ranking is appropriate and almost inappropriate based on FAHP-WQI. However, this index does not include all water parameters, such as heavy metals, and it cannot be said with certainty that water quality is appropriate in all respects. Therefore, it is suggested that other parameters such as the concentration of heavy metals be included in the index and evaluated in future studies.

CONCLUSION

In this research, an approach based on ranking and weighting methods based on fuzzy logic was proposed to evaluate groundwater quality in terms of drinking and agriculture compared with definitive methods. In definitive methods, the quality of each parameter measured is divided into three categories based on existing standards: desirable, acceptable, and unauthorized. Due to the significant number of measurable parameters in each sample, it is not possible to decide what rank one sample is qualitatively compared to other samples. WQI is considered one of the main factors in evaluating drinking water quality. However, due to the resulting discrepancies with WQI (WHO), the FAHP-WQI model and the TOPSIS method with fuzzy-AHP weighting have led to significant changes not only in the ranking but also in the classification of water wells. In the proposed approach, the inaccuracies caused by sampling and measurement were reduced by considering the fuzzy method in the ranking, and experts evaluated the importance of each qualitative parameter in the degradation of aquifer quality. In this study, the water quality index rank of 17 quality samples taken from wells in the Bahabad plain and their spatial distribution in the ArcGIS environment were determined. The results showed that using the FAHP-WQI model and TOPSIS method can show good performance as appropriate techniques to eliminate ranking inconsistencies by WQI. The use of the TOPSIS method led to a more reliable analysis of the weight sensitivity of various chemical parameters in water. FAHP-WQI showed that in 35.3% of Bahabad plain areas, water quality was suitable for proper irrigation, 41.17% water quality was poor, and 23.35% water quality was unsuitable. According to the Wilcox diagram, about 47% of the wells were in the C3S2 and C3S1 classes, and about 23.5% of the well water was in the C4S4 class. The results of the Wilcox diagram showed that most of the wells for irrigation use were in moderate to poor condition. This plain is currently among the endangered lands from the point of view of harvesting groundwater and if the drought continues in it, irreparable damage will be caused and the costs induced for farmers and the people living there will be tremendous.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST STATEMENT

The authors declare there is no conflict.

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