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ORIGINAL ARTICLE

Evaluation of groundwater quality using a GIS-MCDA-based model: a case study in Aksaray, Turkey

Murat Kavurmaci[1]

Abstract Evaluation of water resources and the protection of these resources from environmental pollutants is a difficult and complex process. In this study, a development of model to estimate the water quality and identify the most suitable regions based on good water quality was aimed. For this purpose, 40 water samples were taken through water wells in Aksaray region of Turkey. A groundwater quality index (AWQI) based on water chemistry data has been developed to assessment the groundwater quality using the techniques of the multi-criteria decision analysis. Based on this index, four suitability classes were defined as excellent, good, permissible and unsuitable. Kriging method was used to determine the spatial distribution of groundwater quality parameters in the study area. For each map, different semivariogram models were tested by cross-validation and the best model was selected. The exponential model having a minimum standard error was selected the most suitable model for deriving water quality maps. The areas that are excellent for groundwater quality are concentrated in the northeastern and southeastern parts of the region where the AWQI-II scores were greater than 0.9. This study provides general information on how to determine the spatial distribution of the groundwater quality and identify the performance scores of criteria affecting water quality in inland aquifers.

Keywords Groundwater quality · Water quality index · Multi-criteria decision analysis · Geostatistics · Turkey

✉ Murat Kavurmaci
muratkavurmaci@yahoo.com

[1] Geological Engineering Department, Aksaray University, 68100 Aksaray, Turkey

Introduction

Due to the rising population and growing economy in agriculture, industry and other sectors, the demand for water that has a high water quality is increasing rapidly. Water quality can be described as a measure of the suitability of water for a particular use based on selected physical, chemical and biological characteristics (Cordy 2001). Understanding the processes and factors that control the quality of water is important for the protection of ecosystems (Marjani and Jamali 2014). When water quality is poor, it affects not only life but the surrounding ecosystem as well. The injudicious use of poor quality water can lead to serious health problems and may even cause economic losses (Bardalo et al. 2001). The temporal and spatial variations of the water quality are a result of changes in the normal functioning of an ecosystem (Germolec et al. 1989). Several factors have a direct effect on the water quality. These factors include dissolved minerals, the concentration of microscopic algae, quantities of pesticides, herbicides, heavy metals and other contaminants. Some parameters can affect the taste, smell or clarity of water (Cordy 2001).

Before using water for any purpose, the quality parameters must be determined according to the intended use. The measurement of water quality parameters at every location is not always feasible in view of the time and the cost involved in data collection (Gorai and Kumar 2013). Therefore, prediction of values at other locations based upon selectively measured values could be one of the alternatives. The monitoring of the parameters that affect water quality in the environment is very important for water resource planning and management (Banerjee and Srivastava 2009). Many problems were observed during water quality monitoring because of the complexity

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associated with analyzing a large number of measured parameters (CCME 2001). The large number of water quality parameters has caused to the emergence of various water quality classifications for a single water source (Ojha et al. 2003). One possible solution to this problem is to reduce the multivariate nature of water quality data by employing an water quality index (WQI) that will mathematically combine all water quality measures and provide a general and readily understood description of water (CCME 2001).

A WQI is a dimensionless number that combines multiple water quality variables into a single number by normalizing values to subjective rating curves (Miller et al. 1986). Since 1965, when Horton (1965) proposed the first water quality index, WQI has been extensively used or proposed by many researchers for describing the water quality (Harkins 1974; Walski and Parker 1974; Dinius 1987; Ball and Church 1980; Egborge and Coker 1986; Giljanovic 1999; Prasad and Bose 2001; Cude 2001; Liou et al. 2004; Nasiri et al. 2007; Boyacioglu 2007; Ramakrishnaiah et al. 2009; Sadat-Noori et al. 2014; Selvam et al. 2014; Abtahi et al. 2015). Water quality index reflects the composite influence of different water quality parameters on the overall quality of water (Horton 1965; Pesce and Wunderlin 2000). It is a very useful tool for communicating the information on the overall quality of water (Gorai and Kumar 2013). Although basic methodologies have been developed by different researchers to assess the water quality, the geological and hydrogeological characteristics of each region mostly vary (Hem 1985). The quality of water can change with the dissolution of minerals (Kesler 1994).

Analytic hierarchy process (AHP) and data envelopment analysis (DEA), complex decision analysis techniques, have been used for assessing water quality and to determine the WQI in previous years (Banai-Kashani 1989; Jha et al. 2010; Pourghasemi et al. 2012; Do et al. 2013; Jeihouni et al. 2014; Kavurmaci and Üstün 2016). A method was developed by Agarwal et al. (2013) for the purpose of delineation of the potential groundwater zone in India, and they used AHP. Sener and Davraz (2013) also used the AHP and GIS (geographical information system) for the purpose of identifying the groundwater quality. A resemble technique which includes AHP utilized by Shabbir and Ahmad (2015) was applied for estimating the vulnerability of water reserve in Islamabad and Rawalpindi. Kumar et al. (2014) used multiple-criteria decision analysis for mapping groundwater areas.

In this paper, the water quality of the Aksaray region was determined by using hydrogeological data and statistical techniques. The primary aim of this research was to improve a model to estimate the quality of the groundwater and find the convenient areas based on the high water quality. The 40 water samples from various wells in the region were collected in order to evaluation of the groundwater quality using MCDA. Furthermore, Aksaray water quality index (AWQI) was improved using a combination of factors affecting the quality of water. Two new groundwater quality indexes (AWQI-I and AWQI-II) were proposed based on AHP and AHP-DEA results. The groundwater vulnerability maps of the Aksaray were conducted based on these indexes. This study provides general information on how to evaluate the groundwater quality. The results in this research can help to understand the groundwater evolution and the pollution processes of other inland aquifers. Also, these data can be used in health sector strategies, particularly in the agricultural activities and the calculation of risks associated with water quality. Economic losses in the agricultural sector will be reduced due to the use of water quality maps in the study area.

Materials and methods

The study area and sampling

The study area comprises the city of Aksaray and surrounding areas in the Central Anatolian region of Turkey, with the location of $33°12'$ and $34°26'E$ longitude and $37°58'$ and $39°01'N$ latitude (Fig. 1). According to the 2011 census, the population of the district is 278,171 of whom 195,990 live in the city of Aksaray. The average altitude of the region is 980 m. The mean temperature is 12.06 °C, and the mean annual rainfall is 339.8 kg/m². For the period between 1970 and 2015, the annual average number of days with snow-covered ground is 25, the annual average wind speed is 2 m/s, and the annual average rate of moisture is 65 %. It is also one of the most important agricultural areas in the Anatolia with groundwater irrigation being widely used. More than 2000 water wells supply irrigation and drinking water. The depth of these wells ranges from 40 to 160 m, and the flow in these wells ranges between 1.5 and 45 L/s.

Sampling was performed from 40 wells in March 2015, May 2015, September 2015, and December 2015. The annual statistical summary of the water samples is given in Table 1. Two types of bottle were used: high-density polyethylene double-capped for major ions (Na, Mg, K, Ca, Cl, SO₄), and acid-washed polyethylene double-capped to minimize the interaction of minor metals. Samples were transported in cool polyethylene bags to prevent contamination. Water chemistry analyses for all samples were performed at the Chemistry Laboratory in the Environmental Engineering Department of Aksaray University. The anion values were measured by ion chromatography machine. Analysis of cation was carried out with an ICP
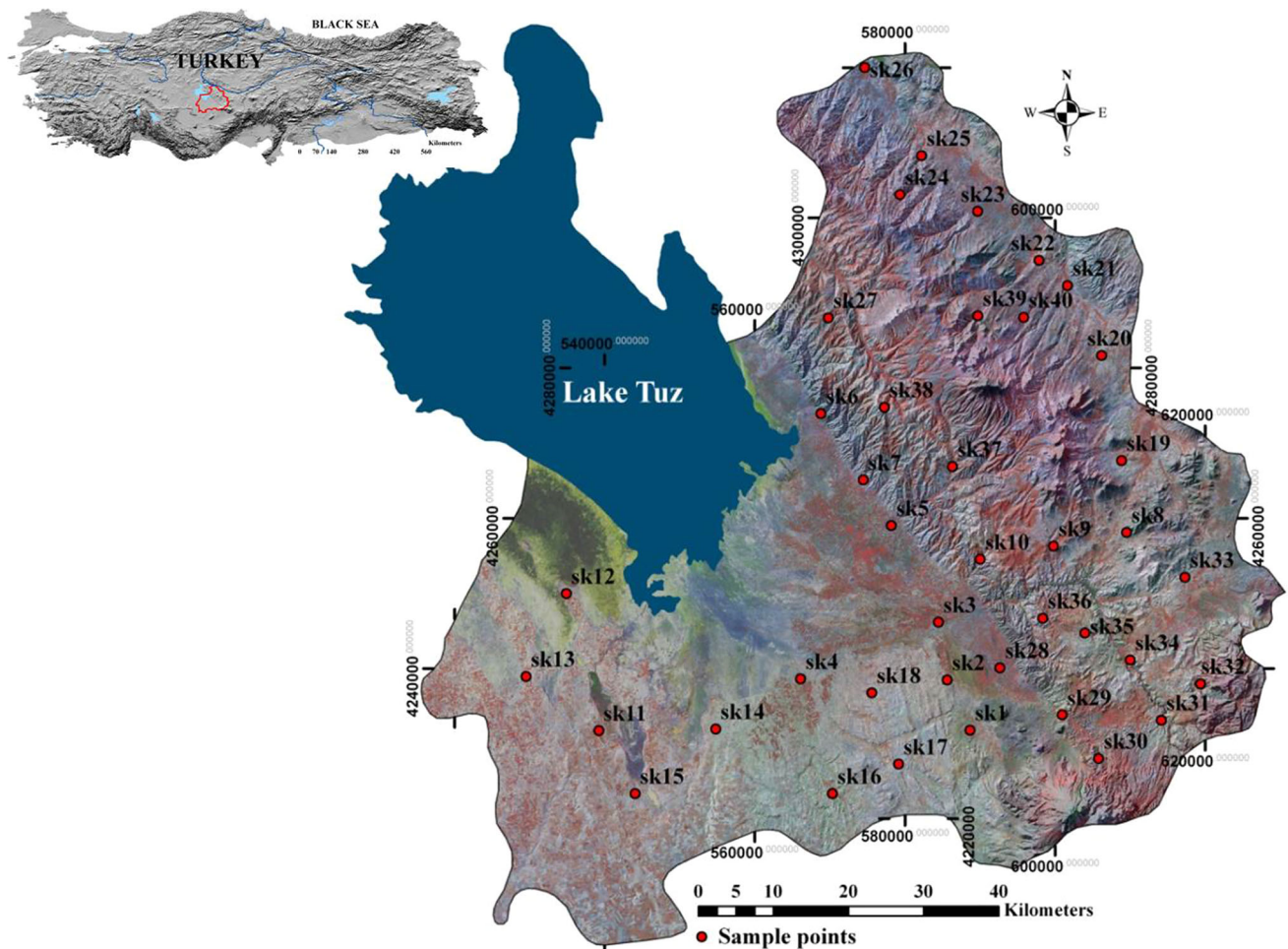
Fig. 1 Location of the sampling points and general view of the study area on Landsat-5 TM image data

MS device. The physicochemical properties such as groundwater depth, temperature, EC, TDS were measured at the sampling site every month in 1-year term. For measuring physicochemical parameters, a portable conductivity meter, pH meter and oxygen meter were used. The water analysis results were evaluated in line with the European Union (2014) (EU) and World Health Organization (2012) (WHO) standards which have provided a framework for safe drinking water. Water quality maps were conducted using ordinary Kriging interpolation technique to evaluate the quality of groundwater.

Geological and hydrogeological system

The Central Anatolian Crystalline Complex rock unit is located on the base of the study area. This complex contains crystalline rocks, which consist of Central Anatolian Metamorphics, Central Anatolia Ophiolites which provide a regular stratification, and the Central Anatolia Granitoids which discontinuously divide the aforementioned units (Goncuoglu et al. 1996).

The most important units that created the aquifers in the study area are marbles belonging to Central Anatolia Metamorphites of Paleozoic Age (Altas et al. 2011). Faulted, fractured and karstic-hollowed sections, which developed vertically in this unit, created a high permeability in terms of hydrogeology. Although the Central Anatolia Granitoids of the Upper Cretaceous period are impermeable, they became fragile due to alterations. These units are permeable in the faulted and fractured upper belts and forms weak aquifer systems in the region (Kavurmaci et al. 2010). The hydrogeologic framework of fine-grained sedimentary rock is includes shallow, intermediate and deep intervals having variable hydraulic properties. The Tertiary Conglomerate and sandstone sedimentary layers are permeable. These permeable units are an important aquifer feature for groundwater sources with a shallow circulatory system and low flow rates in the study area.

Groundwater flow in aquifers typically shows directional inequality or anisotropic behavior because rock features and tectonic structures impart local heterogeneity

Table 1 Annual statistical summary of the criteria used for modeling

Year/2015			March			May			September			December		
P	Unit	n	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean
T	(°C)	40	10.0	18.1	13.7	11.8	24.0	17.6	14.3	26.9	18.7	7.4	19.9	13.7
pH	–	40	6.4	8.0	7.4	6.1	7.9	7.2	6.2	7.9	7.3	6.2	8.1	7.3
EC	(µS/cm)	40	265.0	2452.5	696.1	180.5	2596.0	735.5	194.0	3300.0	825.1	282.0	2320.0	739.0
Th	(mg/L)	40	218.0	836.0	408.1	93.3	796.7	330.3	108.0	912.0	331.1	134.0	860.0	353.6
Tu	(NTU)	40	0.2	16.6	2.3	0.1	18.6	3.1	0.0	29.2	5.0	0.0	36.6	3.6
Cl^-	(mg/L)	40	11.3	319.5	77.9	5.3	340.7	81.3	9.8	354.6	89.0	10.0	370.0	84.6
Na^+	(mg/L)	40	11.3	641.2	81.8	8.6	489.1	71.2	4.8	642.3	93.5	11.3	531.1	79.3
SO_4^{2-}	(mg/L)	40	3.0	416.4	76.9	8.8	306.8	60.1	9.5	394.5	84.5	3.6	405.6	77.3
Alk	(mg/L)	40	149.1	873.0	267.4	101.2	971.3	291.2	130.0	843.0	283.6	152.0	958.0	278.0
As	(mg/L)	40	0.00	0.10	0.02	0.00	0.07	0.01	0.00	0.09	0.03	0.00	0.07	0.01
B	(mg/L)	40	0.04	3.12	0.56	0.02	3.06	0.49	0.04	3.42	0.62	0.03	3.97	0.67
Mn	(mg/L)	40	0.01	0.13	0.02	0.01	0.11	0.02	0.01	0.21	0.02	0.01	0.01	0.01
Li	(mg/L)	40	0.00	0.37	0.06	0.00	0.34	0.05	0.00	0.41	0.07	0.00	0.42	0.05
Ba	(mg/L)	40	0.03	0.45	0.10	0.02	0.36	0.07	0.01	0.41	0.10	0.01	0.41	0.11
TOC	(mg/L)	40	1.4	9.7	3.7	1.6	23.3	3.9	0.6	64.5	4.5	1.2	9.5	3.5
TN	(mg/L)	40	1.1	27.6	9.3	1.5	26.7	9.2	1.7	25.3	8.8	1.0	26.8	9.9
Nt	(mg/L)	40	0.0	24.9	9.0	0.8	25.2	8.3	0.7	22.8	8.7	0.9	22.7	8.6
Amn	(mg/L)	40	0.0	0.1	0.0	0.0	0.4	0.1	0.0	0.8	0.1	0.0	0.1	0.0

P parameters, *T* temperature, *EC* electrical conductivity, *Th* total hardness, *Tu* turbidity, *Alk* alkalinity, *TOC* total organic carbon, *TN* total nitrogen, *Amn* ammonium, *Nt* nitrate, *n* the number of samples

to the aquifer framework. Conductive features at intermediate depths include tectonic fractures and bed-parallel mechanical layering. Tectonic systems provide wide pathways for groundwater flowing. Groundwater is stored and circulates in fractured-bedrock aquifers. Groundwater flow in the deep bedrock aquifer generally reflects confined-flow conditions, principally related to tectonic control.

Conceptual framework for AWQI

One of the aims of this study was to develop a convenient method for the assessment of groundwater quality for the Aksaray City in Turkey using the MCDA techniques. AHP is one of the most commonly used MCDA techniques that was first developed by Saaty (2005) to determine the rank of alternative decisions and to find the best decision based on certain criteria. The AWQI is calculated to reduce the large number of data, so a numerical value which obtained from the AWQI expresses the complete water quality at a specific location. A large number of evaluation criteria can be expressed as a single value with this index. This index creates a value related to quality conditions of water. This created value is the key value for experts to determine the usage of water body in order to quality and identification.

The 18 parameters classified under four groups were used in establishment of the AWQI. These parameters and groups were explained as follows: (1) group 1 (pH, turbidity, hardness, electrical conductivity and temperature), (2) group 2 (alkalinity, sodium, chloride, sulfate) (3) group 3 (arsenic, manganese, boron, lithium and barium) and (4) group 4 (nitrate, total nitrogen, total organic carbon and ammonium) (Fig. 2). These 18 parameters were selected according to the hydrological conditions of the research area and problem complexity. The selected parameters can vary according to regional conditions. Water quality is also related with the regional geology and environmental system. For example, the dissolution of the surrounding rock causes an increase in the dissolved mineral content of the groundwater. The range values of each index are given in Table 2.

Each parameter was separated into the four different classes using assigning numerical values in the quality rating process. Assigned numerical values from excellent to unsuitable classes were determined according to standards developed by EU, WHO and Turkish Water Pollution Control Regulation (WPCR). These values have to be suitable for national, regional and local conditions. The spatial distribution maps of the parameters such as boron, arsenic, chlorine and sodium having high weight value are given in Fig. 3 to give an idea to the decision makers.
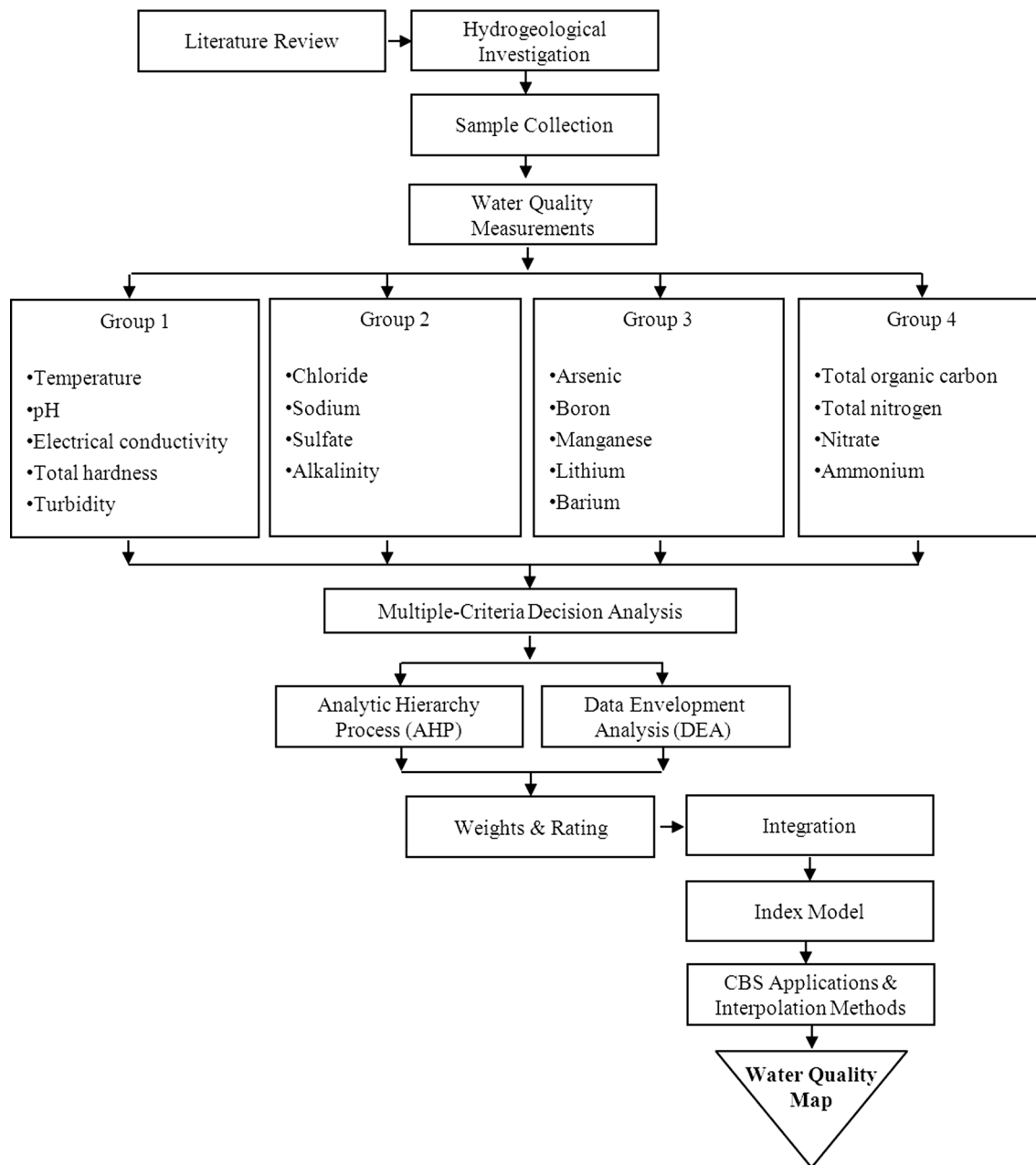
Fig. 2 Flowchart of the methodology

Pairwise comparisons and determination of priorities

Once the hierarchy is established, a pairwise comparison matrix is constructed for each criterion at each level. The experts can choose to weigh each criterion against each other at each level, which refers to the levels above and below it, and mathematically combine the entire scheme together (Wang et al. 2009; Mohammadi and Limaei 2014). In the current study, a pairwise comparison was performed on all related attributes to establish the relative importance of the hierarchy criteria. Criteria

weight (W_i) was calculated by normalizing the criteria weight (W_i) of each factor. Experts evaluated the importance of pairs of grouped elements in terms of their contribution to the higher hierarchy (Eastman 2003; Wang et al. 2009). Finally, all the values for a given attribute were pairwise compared.

The pairwise comparisons were made by the experts. The main criteria were compared to each other, and then sub-criteria were evaluated against to each other criterion. Finally, 40 wells were compared by these sub-criteria. Experts determined the order of importance of the criteria by Tables 2 and 3. Each pair of criteria was compared in

Table 2 Ranges of suitability classes for AHP

Parameters	W_i	Unit	Excellent	Good	Permissible	Unsuitable
T	0.001	(°C)	0–10			
pH	0.006	–	6.5–8.5	>8.5	<6.5	–
EC	0.023	(µS/cm)	<250	250–1000	1000–2250	>2250
Th	0.012	(mg/L)	<150	150–500	500–1000	>1000
Tu	0.003	(NTU)	<5	5–25	25–50	>50
Cl^-	0.015	(mg/L)	<30	30–250	250–600	>600
Na^+	0.029	(mg/L)	<125	125–250	250–1000	>1000
SO_4^{2-}	0.007	(mg/L)	<200	200–400	400–1000	>1000
Alk	0.004	(mg/L)	<250	250–500	500–1000	>1000
As	0.284	(mg/L)	<0.01	0.01–0.02	0.02–0.05	>0.05
B	0.247	(mg/L)	<0.1	0.1–0.5	0.5–1	>1
Mn	0.076	(mg/L)	<0.05	0.05–0.5	0.5–3	>3
Li	0.038	(mg/L)	<0.01	0.01–0.05	0.05–0.1	>0.1
Ba	0.019	(mg/L)	<0.5	0.5–1	1–2	>2
TOC	0.033	(mg/L)	<5	5–8	8–12	>12
TN	0.015	(mg/L)	<0.5	0.5–2	2–5	>5
Nt	0.133	(mg/L)	<5	5–10	10–20	5–20
Amn	0.072	(mg/L)	<0.02	0.02–0.1	0.1–1	>1

T temperature, *EC* electrical conductivity, *Th* total hardness, *Tu* turbidity, *Alk* alkalinity, *TOC* total organic carbon, *TN* total nitrogen, *Amn* ammonium, *Nt* nitrate

terms of its relative importance using 9 points system from 1 to 9. A score of 1 demonstrated equally importance a score of 9 refers to strong importance. In this study, the AHP system was formed from 40 alternatives (wells), 4 main criteria and 18 sub-criteria.

For each pairwise comparison, mean judgment was determined by geometric average of experts' judgments. In the matrix diagonal entries equal to one for all criteria and their sub-criteria evaluations. The corresponding comparison of one criterion to another, applying the geometric mean of each expert's query, is entered into the matrix. Table 3 is used for each comparison. For instance, if factor A is selected to factor B with the power of favorite of "5", after that the assessment of factor B with factor A is "1/5" (Üstün and Barbarosoglu 2015). The characteristic vector of matrix is founded, and the priorities of factors are defined. The discrepancy rate of the matrix is calculated. The discrepancy rate shows that the experts' decisions are convenient in the decision-making process. The discrepancy rate has to be lower than 0.1.

The AHP-DEA model

The performance analysis of decision-making units (DMU) is carried out with DEA linear programming model. This model is widely used in performance analysis and comparison in most systems (Berg 2010).

Charnes et al. (1994) proposed a model for determining the performance score of the DMU according to number of inputs and outputs. In this study, the DMUs were 40 wells in the study area. In addition to this, inputs of this study were the four groups determined for establishment of the AWQI.

$$\text{Max } \theta_0(v, u) = \sum_{r=1}^{s} u_r y_{ro}, \qquad (1)$$

s.t.

$$\sum_{i=1}^{m} v_i x_{io} = 1, \qquad (2)$$

$$\sum_{r=1}^{s} u_r y_{rj} - \sum_{i=1}^{m} v_i x_{ij} \geq 0, \quad (j = 1, 2, \ldots, n) \qquad (3)$$

$$u_r, v_i \geq 0, \qquad (4)$$

where θ_o = performance score of DMU "o", m = number of inputs, s = number of outputs, n = number of DMUs, x_{ij} = number of the ith input used by DMU j, y_{rj} = amount of the rth output from DMU j, v_i = weight given to the ith input, and u_r = weight given to the rth output.

The performance scores of the DMUs were determined by 10 times running of the AHP and AHP-DEA models. Each DMU is weighted as input and output with these models, and the aim of this weighting is optimization of performance score. If the performance score of a DMU is equal to one, this DMU can be effectively used in the establishment of the AWQI. On the other hand, the DMU can not be used in the establishment of the AWQI.
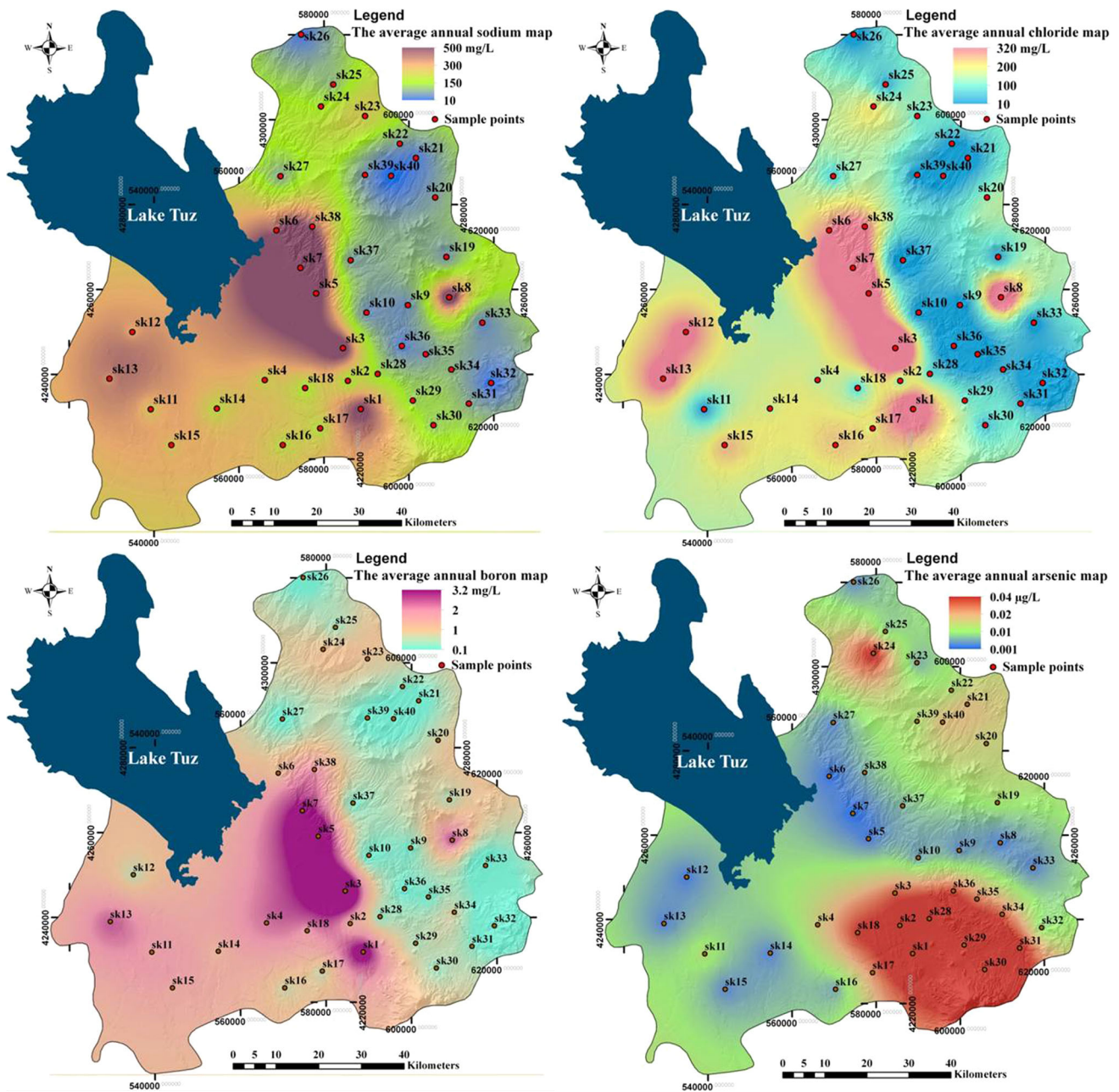
Fig. 3 Spatial distribution maps of important parameters such as arsenic, boron, sodium and chloride

Table 3 Saaty's 1–9 scale for AHP preference index

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one over another
5	Strong importance	Experience and judgment strongly favor one over another
7	Very strong importance	Activity is strongly favored, and its dominance is demonstrated in practice
9	Absolute importance	Importance of one over another affirmed on the highest possible order

Geostatistical method

The maps of groundwater quality were constructed using results of proposed models and the Kriging method. A Geostatistical Analyst tool was used in construction of the groundwater quality maps. This tool correlated the attribute values at sampled regions and estimated these values at unsampled regions (Stein 1999). The geostatistical evaluation was carried out on the hydrogeological data of the 40 wells.

The Kriging method is an optimal interpolation based on regression against observed z values of measured surrounding data points, weighted according to spatial covariance values. The Kriging method is a commonly used method for the water quality problems (Goovaerts et al. 2005; Chica-Olmo et al. 2014). Kriging is expressed below (Esri 2015);

$$Z(x_o) = \sum_{i=1}^{N} \lambda_i Z(x_i), \tag{5}$$

where x_0 is kriged or estimated value at point x_0, λ_i is Kriging weights which are solution of the Kriging system, $Z(x_i)$ is the known value that used for estimating value at the location (x_o), and N is the number of measurements (Goovaerts et al. 2005).

In this method, the spatial variation is explained by variogram models. This stage is an important for spatial characterization and estimation (Aldworth 1998). The variogram (γ) for lag distance h is expressed as follows (Oliver 1990),

$$\gamma(h) = \frac{1}{2n} \sum_{i=1}^{n} [Z(x_i) - Z(x_i + h)]^2, \tag{6}$$

where $\gamma(h)$ is the predicted value of the variogram for lag distance h; $n(h)$ is the number of pairs of data points at lag h; $z(x_i)$ is the value of Z sample at point x_i and $z(x_i + h)$ is the value of Z sample at a distance h from point x_i.

Firstly, semivariogram models were derived according to exponential, spherical, gaussian or linear models for accurate predictions on unsampled regions. Different lag distance values were applied for spatial autocorrelation in quality maps. The exponential model having a minimum standard error was selected the most suitable model for deriving water quality maps.

Relations between the predicted and measured data were determined using the cross-validation statistics. The coefficient of determination (R^2) was used as performance criteria for the prediction in cross-validation. R^2 should be close to 1 (Esri 2015).

Results and discussion

Hydrogeochemical evaluation

Ion abundances for many sampling points have remained the same during the whole sampling season. However, the ion sequencing of some waters has changed due to climate conditions. However, there was no change in the types of water during the sampling period. The characteristics of water samples in May 2015 are given in Table 4. The some parameters of the water samples are: temperature (T) 12.1–26.9 °C, pH 6.1–7.8, electrical conductivity (EC) 186–3300 µS/cm, total dissolved solids (TDS) 154–2475 mg/L. The some water samples (sk1, sk3, sk5, sk6, sk7, sk12, sk13 and sk37) have TDS concentrations over 1000 mg/L. According to the TDS classification developed by Fetter (1988), sk3 and sk7 can be defined as brackish water. The groundwaters located relatively closer to Lake Tuz have the highest TDS values. Also, this type of water can be formed as result of dissolving large amounts of Na^+ and Cl^- minerals, from the salt deposits and evaporite rocks during the water–rock interactions occurring in the study area. According to the pH values, some of these water samples are slightly acidic and others are slightly alkaline. The EC values of the most water samples exceeded the drinking water standards set by WHO (2012).

The major ions are as follows: Cl^-, Na^+, SO_4^{2-}, HCO_3^-, Ca^{2+} and Mg^{2+} in May sampling period between (9.8–324.6), (4.8–642.3), (9.5–283.1), (115.4–1638.4), (20.3–183.1) and (7.9–110.3) mg/L, respectively. The dominant water type present in groundwater is the $CaHCO_3$ type. Ca^{2+} and HCO_3^- are dominant ions in groundwater. The order of relative abundance of major ions is $Ca^{2+} > Mg^{2+} > (Na^+ + K^+)/HCO_3^- > Cl^- > SO_4^{-2}$. The high Ca^{2+} and HCO_3^- and low concentrations of TDS in the groundwater are referred to the water resources having shallow and short-term cycle systems. The water samples have $CaHCO_3$, $NaHCO_3$ and $NaCl$ water facies feature. Water samples (sk1 and sk6) contain $NaCl$ water types with noncarbonate alkalinity, and greater than 50 % of $NaCl$ content. Whereas other water samples showed $CaHCO_3$ and $NaHCO_3$ water types with high carbonate hardness. The high content of $CaHCO_3$ indicates that the main origin of this water facies is due to the recharge from a carbonate aquifer. The water type of aquifers changed from $NaCl$ to $NaHCO_3$ and $CaHCO_3$ type depending on the distance from the LT. Also, the interaction of water in different aquifers within the hydrological system could be another factor that explains the different facies type of the groundwater.

Table 4 Physical and chemical analysis results of sampling points in the May 2015

Sample Id	T (°C)	pH	EC (µS/cm)	Th (mg/L)	Tu (NTU)	Cl⁻ mg/L	Na⁺	SO₄²⁻	Alk	As	B	Mn	Li	Ba	TOC	TN	Nt	Amn	SAR
sk1	19.8	6.70	1200	305	4.94	263.467	190.658	10.1044	330.77	0.049	1.537	0.014	0.209	0.226	2.7	4.4	3.9	0.01	22.24
sk2	17.9	7.47	579	256	2.69	68.7667	48.3755	44.894	202.03	0.016	0.618	0.015	0.036	0.053	3.2	11.5	11.2	0.01	5.73
sk3	17.2	6.09	2221	763	9.70	340.7	325.562	73.5823	819.27	0.065	3.060	0.111	0.341	0.358	4.3	2.8	1.7	0.31	26.90
sk4	18.1	7.69	647	256	1.89	92.5	63.3503	58.8667	162.7	0.016	0.882	0.015	0.024	0.041	8.2	12.7	12.4	0.14	8.10
sk5	21.0	7.03	1182	391	2.23	167.167	162.248	45.9465	479	0.006	1.934	0.013	0.078	0.095	2.9	2.7	2.5	0.01	16.67
sk6	20.1	7.49	1467	507	0.09	300.367	180.141	123.441	367.73	0.005	0.977	0.019	0.050	0.067	3.5	8.9	8.2	0.03	17.47
sk7	21.7	6.35	2596	797	0.86	319.933	489.081	306.821	971.33	0.008	1.314	0.024	0.169	0.186	3.3	24.2	19.0	0.02	42.42
sk8	17.1	7.58	367	223	0.14	24.95	21.3324	13.2795	208.33	0.002	0.157	0.014	0.002	0.019	3.5	9.5	9.0	0.05	2.69
sk9	16.6	7.45	411	245	0.24	23.4	20.0784	17.4595	204.27	0.006	0.141	0.014	0.004	0.021	3.5	12.8	12.0	0.40	2.38
sk10	19.5	7.42	664	289	0.30	30.1333	73.7941	94.0174	293.2	0.018	0.781	0.015	0.023	0.040	5.1	8.9	8.4	0.03	8.48
sk11	17.0	7.02	911	398	2.28	136.267	80.1895	58.4787	326.9	0.002	0.347	0.014	0.052	0.069	3.4	3.1	1.9	0.29	7.76
sk12	15.6	6.78	1006	485	2.12	102.867	67.7825	71.8031	417.43	0.005	0.627	0.014	0.120	0.137	3.8	2.2	1.8	0.26	5.99
sk13	16.3	6.84	1025	488	1.36	119.1	73.2903	74.8595	392.77	0.004	0.619	0.014	0.119	0.136	3.8	2.9	2.6	0.35	6.46
sk14	17.9	7.12	852	343	2.12	105.567	70.8305	66.1833	337.07	0.002	0.405	0.015	0.071	0.088	3.7	1.5	0.8	0.30	6.97
sk15	17.3	7.15	775	337	6.20	99.8	65.8833	51.2415	330.93	0.005	0.340	0.014	0.043	0.060	4.6	2.9	2.4	0.21	6.83
sk16	17.8	7.74	544	225	2.70	55.3667	60.5819	73.5754	190.23	0.026	0.826	0.014	0.034	0.051	3.6	13.8	12.8	0.24	7.67
sk17	16.3	7.87	372	207	9.82	31.3667	22.4616	20.9588	179.37	0.013	0.282	0.014	0.019	0.036	2.6	11.5	11.0	0.25	3.03
sk18	16.8	7.66	553	295	8.89	65.6333	29.3265	75.5361	160.4	0.010	0.373	0.014	0.025	0.042	2.6	16.6	16.0	0.24	3.34
sk19	16.1	7.23	373	226	18.59	18.8333	15.1931	22.6404	190.73	0.010	0.082	0.011	0.019	0.036	3.7	8.7	8.3	0.01	1.90
sk20	17.8	7.57	412	208	0.06	23.4333	27.2689	23.0099	181.6	0.003	0.171	0.015	0.001	0.018	2.8	15.1	14.1	0.16	3.54
sk21	21.2	7.25	894	404	0.14	55.8667	79.7489	190.127	284.67	0.002	0.399	0.015	0.019	0.036	3.1	6.2	5.7	0.17	7.82
sk22	17.8	7.13	944	505	1.24	102.5	68.2856	41.1085	341.37	0.039	0.526	0.017	0.031	0.048	3.6	8.6	6.8	0.04	6.40
sk23	16.6	7.21	625	365	0.40	35.3	35.1357	59.8743	265.7	0.002	0.194	0.015	0.006	0.023	3.4	8.3	7.9	0.03	3.66
sk24	17.5	7.45	310	189	2.21	17.7333	11.8407	11.5131	180.4	0.001	0.042	0.014	0.010	0.027	2.8	7.9	7.6	0.01	1.54
sk25	15.0	7.09	580	370	0.48	42.7	26.8358	52.2	262.27	0.001	0.105	0.015	0.018	0.035	2.9	4.4	3.4	0.01	2.70
sk26	18.6	7.31	753	391	0.05	59.3	46.9621	92.1785	266.2	0.005	0.170	0.018	0.023	0.040	2.3	16.9	16.7	0.01	4.73
sk27	20.6	7.77	800	414	0.49	62.6333	45.8362	75.2617	368.33	0.013	0.244	0.014	0.054	0.071	4.5	7.7	6.5	0.06	4.79
sk28	18.2	6.76	688	383	0.96	42.5	42.457	70.4134	260.87	0.041	0.177	0.015	0.060	0.077	2.5	2.2	1.1	0.01	4.23
sk29	13.9	6.55	573	311	14.88	50.6333	41.1659	33.4431	267.8	0.026	0.171	0.015	0.059	0.076	2.3	16.6	15.8	0.01	4.48
sk30	11.8	7.18	181	93	0.57	33.7667	19.2412	14.7256	101.2	0.009	0.046	0.014	0.024	0.041	4.2	1.9	0.9	0.03	3.10
sk31	16.6	7.30	189	95	1.05	5.3	10.921	8.8226	132.67	0.003	0.019	0.014	0.007	0.024	2.1	3.5	2.7	0.02	1.65
sk32	19.0	7.04	337	152	2.26	24.3333	18.7472	19.2771	138.7	0.001	0.025	0.015	0.002	0.019	1.6	12.4	10.4	0.07	2.54
sk33	17.3	7.43	707	400	1.49	48.9333	48.4093	41.745	339.23	0.004	0.437	0.014	0.025	0.042	3.2	9.7	9.5	0.04	5.10
sk34	24.0	7.16	344	137	0.69	18.5	26.4568	15.9436	175.4	0.011	0.132	0.014	0.060	0.077	3.3	3.9	3.4	0.01	3.78
sk35	18.0	7.67	344	200	0.14	18.7667	16.9965	33.5406	174.1	0.005	0.125	0.014	0.015	0.032	2.0	11.3	10.4	0.03	2.21

Table 4 continued

Sample Id	T (°C)	pH	EC (µS/cm)	Th (mg/L)	Tu (NTU)	Cl⁻ mg/L	Na⁺	SO₄²⁻	Alk	As	B	Mn	Li	Ba	TOC	TN	Nt	Amm	SAR
sk36	16.3	7.12	464	281	0.24	15.5667	22.5739	28.5293	257.8	0.009	0.177	0.014	0.021	0.038	23.3	11.3	10.0	0.09	2.58
sk37	15.9	7.33	1061	468	0.23	125.667	138.162	172.813	428.37	0.010	0.888	0.014	0.027	0.044	5.7	6.8	6.1	0.01	13.60
sk38	15.0	7.58	369	174	18.30	27.1333	8.66828	21.4991	164.17	0.025	0.116	0.015	0.021	0.038	3.1	26.6	25.2	0.21	1.12
sk39	15.9	7.40	335	215	0.15	16.7667	8.56195	11.723	173.23	0.049	0.039	0.015	0.002	0.019	2.3	3.9	3.2	0.02	1.08
sk40	16.2	6.99	763	419	0.35	59.4667	42.3017	80.9226	320.8	0.033	0.154	0.015	0.012	0.029	2.9	21.9	20.5	0.04	4.26

T temperature, *EC* electrical conductivity, *Th* total hardness, *Tu* turbidity, *Alk* alkalinity, *SAR* sodium adsorption ratio, *TOC* total organic carbon, *TN* total nitrogen, *Amm* ammonium, *Nt* nitrate

According to the general hydrochemical trend of the groundwater quality during the sampling period, the groundwater is saturated with calcite, dolomite and aragonite, rather than gypsum, halite and anhydrite. The groundwater has the ability to dissolve gypsum, halite, anhydrite and precipitating calcite, dolomite and aragonite. All of the water samples are suitable for agricultural irrigation. Besides, some of the water samples (sk1, sk2, sk3, sk4, sk10, sk16, sk17, sk18, sk19, sk22, sk27, sk28, sk29, sk37, sk38, sk39 and sk40) are not suitable drinking water because of having high arsenic concentration.

Evaluation of groundwater quality

The evaluation of groundwater quality was carried out in three steps. The first involved the standard implementation of AHP, in which the researchers and 10 experts used a well-designed questionnaire to rank the 40 samples obtained from the study area through wells. The experts evaluated these wells (alternatives) based on the four groups and 18 sub-factors given in Table 2. Obtained pairwise comparisons and their reviews were decided by the experts. Then, the weights of 18 sub-factors were determined using the pairwise comparison matrix. The discrepancy rate of all pairwise comparisons was less than 0.1; therefore, this study results were valid.

The results of AHP model are given in Table 5. The first column in Table 5 represents alternatives or DMUs. The weights of each well according to studied four groups are given in the next four columns and the fifth column demonstrated the final weights of alternatives in terms of AHP model. The final weights of alternatives are called as the AWQI-I index generated using AHP model.

The groundwater quality map was derived using the AWQI-I index in Fig. 3. According to the results of AHP, the most water quality in the study area was found in the sk31 with an AWQI-I index of 0.032323, and the least water quality was obtained from sk7 with an AWQI-I index of 0.007372. The water quality index of other samples is given in Table 5.

The second step was the application of the AHP-DEA model. A different AWQI and a different map were obtained from this step. The AHP-DEA model used in this study is a hybrid model which construct with combined using of the AHP and DEA methodologies. The AHP values obtained in the previous step were selected as the input parameters of the AHP-DEA model in terms of the four groups (θ, β, γ and μ) (Table 4). The AHP-DEA model assigns performance score in the range of 0–1 for each DMU. The input parameters were explained as follows:

θ 1/(first group weights)
γ 1/(second group weights)

Table 5 Weights values of the sub-criteria and AWQI generated using AHP and AHP-DEA models for each well in May 2015

Well Id	Group 1	Group 2	Group 3	Group 4	AWQI-1	AWQI-2
sk1	0.016	0.009	0.013	0.048	0.022	1.000
sk2	0.025	0.027	0.015	0.020	0.018	0.867
sk3	0.009	0.006	0.008	0.037	0.016	0.781
sk4	0.025	0.027	0.015	0.007	0.015	0.867
sk5	0.016	0.012	0.025	0.048	0.029	1.000
sk6	0.012	0.011	0.027	0.018	0.022	0.620
sk7	0.008	0.005	0.025	0.020	0.020	0.571
sk8	0.025	0.031	0.032	0.018	0.028	1.000
sk9	0.025	0.031	0.032	0.010	0.025	1.000
sk10	0.025	0.026	0.015	0.016	0.017	0.837
sk11	0.025	0.026	0.028	0.037	0.030	0.837
sk12	0.018	0.026	0.026	0.037	0.028	0.837
sk13	0.017	0.026	0.026	0.037	0.028	0.837
sk14	0.025	0.026	0.028	0.039	0.031	0.837
sk15	0.024	0.026	0.029	0.037	0.031	0.837
sk16	0.025	0.027	0.015	0.010	0.015	0.867
sk17	0.024	0.027	0.017	0.010	0.017	0.867
sk18	0.024	0.027	0.017	0.010	0.017	0.867
sk19	0.024	0.031	0.029	0.027	0.028	1.000
sk20	0.025	0.031	0.032	0.010	0.025	1.000
sk21	0.025	0.026	0.029	0.016	0.025	0.837
sk22	0.022	0.026	0.015	0.018	0.017	0.837
sk23	0.025	0.026	0.032	0.018	0.027	0.837
sk24	0.025	0.031	0.043	0.027	0.036	1.000
sk25	0.027	0.026	0.029	0.048	0.034	1.000
sk26	0.025	0.026	0.029	0.020	0.026	0.837
sk27	0.025	0.026	0.016	0.018	0.018	0.837
sk28	0.025	0.026	0.016	0.048	0.026	1.000
sk29	0.025	0.026	0.016	0.020	0.019	0.837
sk30	0.061	0.027	0.040	0.041	0.040	1.000
sk31	0.059	0.031	0.043	0.048	0.044	1.000
sk32	0.025	0.031	0.043	0.012	0.032	1.000
sk33	0.025	0.026	0.029	0.018	0.025	0.837
sk34	0.036	0.031	0.016	0.048	0.027	1.000
sk35	0.025	0.031	0.029	0.012	0.024	1.000
sk36	0.025	0.030	0.029	0.009	0.023	0.970
sk37	0.018	0.012	0.027	0.025	0.024	0.620
sk38	0.025	0.031	0.017	0.009	0.017	1.000
sk39	0.027	0.031	0.031	0.039	0.033	1.000
sk40	0.025	0.026	0.017	0.010	0.017	0.837

β 1/(third group weights)

μ 1/(fourth group weights)

The Deafrontier software was used in calculations of weights. The performance score of each DMU was determined with using the AHP-DEA model. If the performance score of a DMU is equal to 1, this DMU can be effectively used. On the other hand, if the performance score of a DMU is less than 1, the DMU can not be effectively used (Cooper et al. 2000; Üstün 2015). The final weights of alternatives were called as the AWQI-II index generated using AHP-DEA model. The results of the AHP-DEA model are given in Table 4. According to Table 4, 12 efficient DMUs were found with respect to AWQI-II index. The AWQI-II index of the rest wells was lower than 1, and these wells had lower water quality. The lowest score was obtained from sk7 with an AWQI-II index of 0.59664.
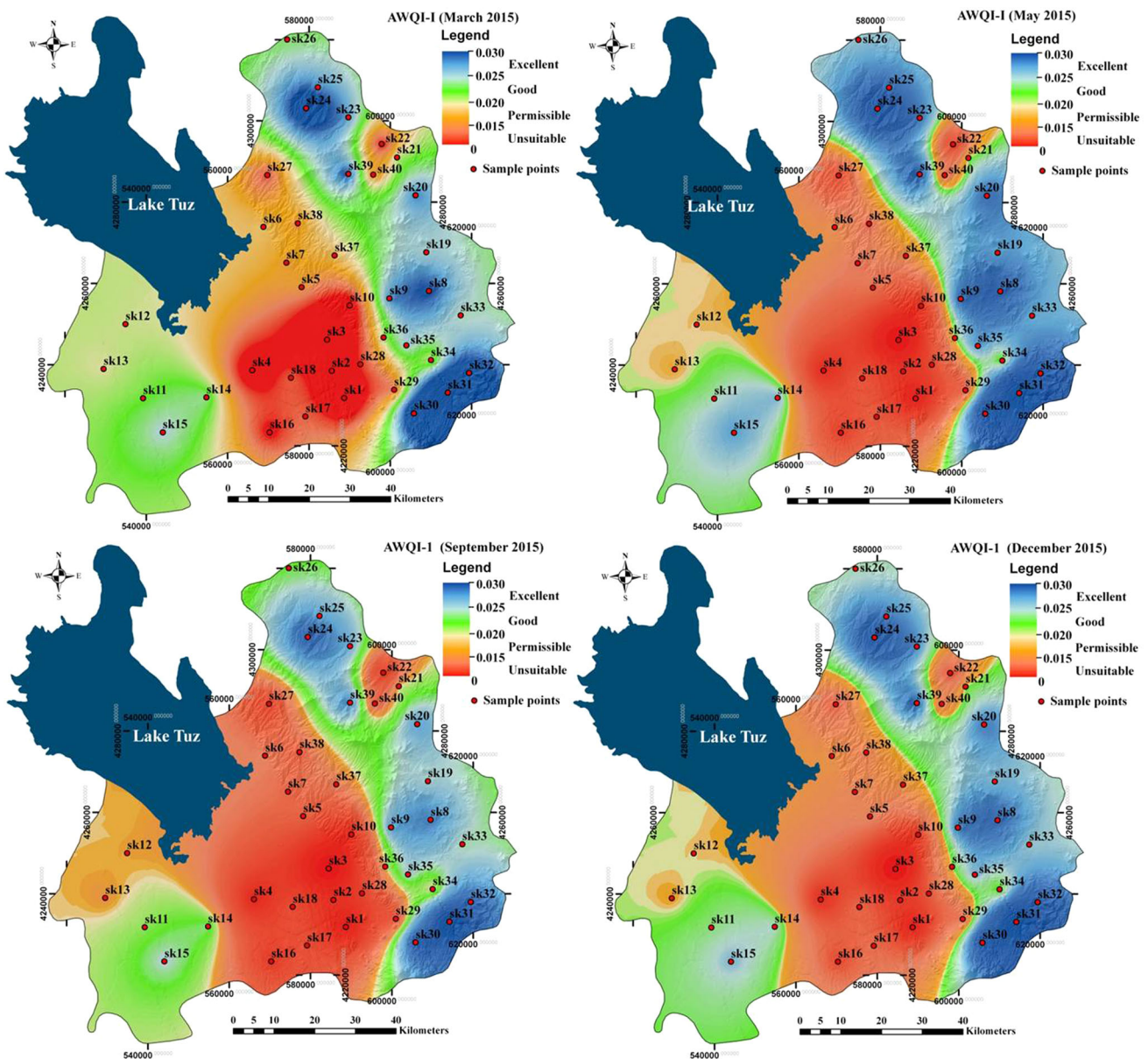
Fig. 4 Spatial distribution maps of the groundwater quality based on AHP index (AWQI-I)

In the AHP-based evaluation model, group weight of each criterion group is as follows: third group (57 %), fourth group (27 %), second group (11 %) and first group (5 %). According to the AHP-based analysis, the most important factors are "nitrate" from fourth group and "arsenic" from third group.

Spatial estimation of groundwater quality based on the AWQI

The data obtained from MCDA-based models were used in construction of groundwater quality maps in the last step of the study. The R^2 of these maps were 0.94 and 0.96,

respectively. It is found from cross-validation test that the selected model and factors are significant. The groundwater quality maps of the region are given in Figs. 4 and 5. These maps show a similar distribution. Based on these values, groundwater quality in different zones of the study area is classified as (1) excellent, (2) good, (3) permissible and (4) unsuitable. The detailed descriptions of these classes are given in Table 6.

Groundwater quality maps are effective for identifying locations that involve the threat of contamination. The AWQI-I values range between 0.007 and 0.032. The groundwater quality is considered unsuitable in the regions where AWQI-I < 0.01 and excellent in the northeastern,
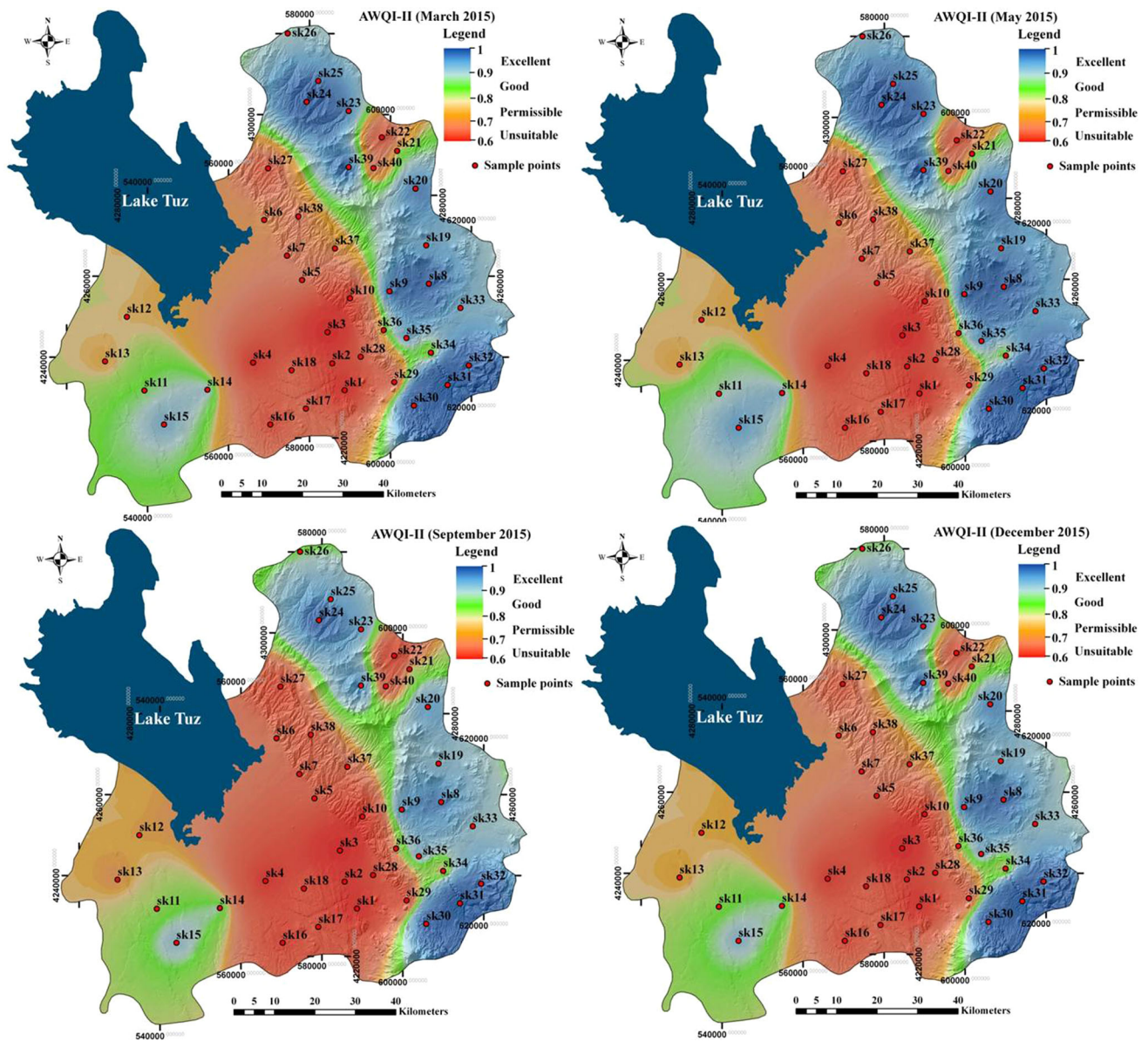
Fig. 5 Spatial distribution maps of the groundwater quality based on DEA index (AWQI-II)

Table 6 Groundwater quality ranking criteria

A-GWQI-range	D-GWQI-range	Category-rank	Interpretation
0.025–0.030	0.9–1	Excellent	Safe to use as drinking water
0.020–0.025	0.8–0.9	Good	Generally safe to use as drinking water
0.015–0.020	0.7–0.8	Permissible	Inconvenient to use as drinking water; however, for some pollutants there may be health concern
0–0.015	0.6–0.7	Unsuitable	Should not be used as drinking water

eastern and southeastern where AWQI-I > 0.25. Lower groundwater quality is observed, especially toward the LT. The areas that have high water quality were concentrated in the northeastern and southeastern portions of the region, which represent approximately 24.2 % of the total area.

Rock in this region is generally developed from The Tertiary Conglomerate and sandstone sedimentary layers, and it has a good texture and high porosity content. Unsuitable areas represent approximately 26.6 % of the study area and are mostly located in the central part of the region.

Fig. 6 AWQI-I and AWQI-II values of some wells according to the results of other researchers in the study area
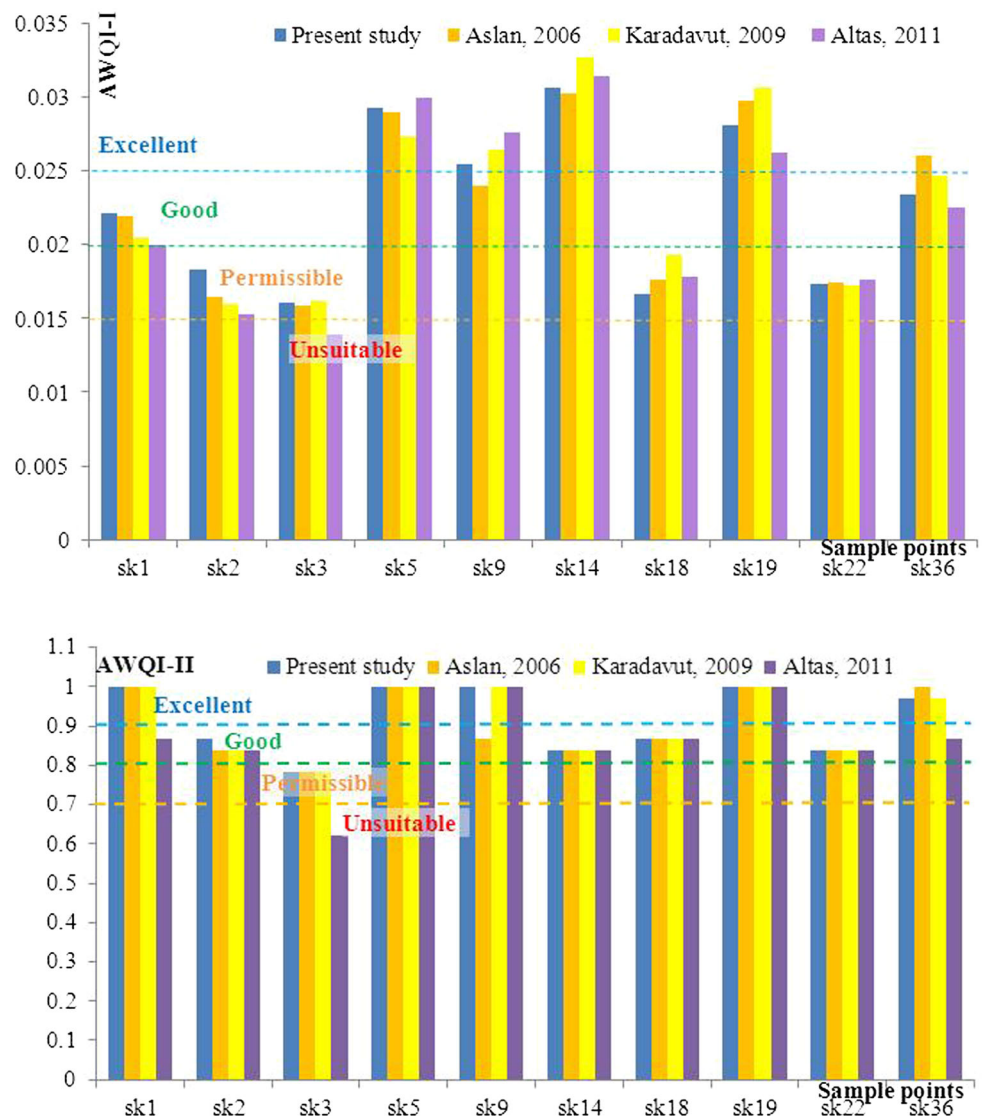
Especially in these regions, the level of contamination was found to be too high depending on intensive agricultural activities and heavy metal concentrations. The principal sources of groundwater pollution from agriculture include inorganic fertiliser, pesticides and heavy metal content. The quality of the 18 water samples exceeded the limit given in the WHO (2012) standards in terms of arsenic concentration.

The AWQI-II values range between 0.59 and 1. As shown in Figs. 3 and 4, the groundwater quality in the middle zones was found to be unsuitable (AWQI-II < 0.7) whereas in the east and western parts, it was highly suitable (AWQI-II > 0.7). The difference between the maps produced using the AWQI-I and AWQI-II can be expressed attributed to the interdependencies and feedbacks between the factors and unassociated parameters such as NO_3^-, turbidity and Cl^- values.

In compliance with the groundwater level, water quality values in the wells increased in the western and eastern sections of the region and decreased in the central section. Water quality values decrease in the wells during the dry season, while these values increase in the rainy season. The water quality of sk11 was good during the March period, but changed to excellent in the May period due to increased rainfall. Similarly, the water quality of sk26 changed from good to excellent in the May period. The water quality shows seasonal variations depending on irrigation in agricultural areas. For example, water quality of the sk5, sk6, sk7, sk37 and sk38 was permissible during the March period, while these values changed to unsuitable in the May and September periods. Similarly, the water quality of sk12 and sk13 was good in the March period, but changed to permissible in the May and September periods. Water quality of these wells decreased

depending on the rise of irrigation in the region during May and September periods.

To prove the accuracy and reliability of the obtained results, AWQI-I and AWQI-II were tested by comparative analysis with the results of other researchers (Fig. 6). In this analysis, only 10 wells commonly used with other researchers (Aslan 2006; Karadavut 2009; Altas et al. 2011) were selected. These commonly used wells are sk1, sk2, sk3, sk5, sk9, sk14, sk18, sk19, sk22, sk36. The water quality index of these wells has remained at about the same index value during the different sampling periods. The analysis results showed that AWQI-I and AWQI-II values are consistent with the results of other researchers. According to the field observations and the results of the research, the map produced with using DEA model was considered to be more successful. Thus, this method can be particularly preferred as a more efficient method for water quality mapping.

Conclusions

In this paper, the groundwater quality of Aksaray was evaluated using MCDA-based methods, AHP and the hybrid AHP-DEA. The water quality criteria were determined according to the expert opinion and international literature. For the analysis of water quality, each criterion was scored based on the given criteria. This is mostly an indirect approach based on the linear combination of the suitability score of each criterion. In this way, an index showing the suitability rate of water quality was obtained. Based on the water quality assessment results obtained from AHP and the hybrid AHP-DEA, water quality indexes (AWQI-I and AWQI-II) were suggested. Based on these indexes, four classes were defined as excellent, good, permissible and unsuitable.

Based on AWQI-II, the groundwater quality was determined as excellent (24.2 %), good (12.2 %), permissible (37.0 %) and unsuitable (26.6 %). Furthermore, using the developed indexes and the Kriging method, the water quality maps of Aksaray were created. These maps showed that the northeastern and southeastern zones of the region had high groundwater quality with AWQI-II values of more than 0.8. Poor water quality was observed in 4975 km^2 of the region, while 2842 km^2 was suitable for good water quality. All of the wells can be used for irrigation applications. Furthermore, 18 wells are not suitable for drinking due to their high salinity and the arsenic concentration.

The groundwaters were contaminated by As element as a result of the interaction with mafic–ultramafic rocks or volcanic rocks. Arsenic concentration in groundwater can be released due to dissolution of volcanic rocks, and may be contaminated in groundwater as result of the rapid alteration of minerals that have high crystallization temperature characteristic. It has created various problems in Aksaray Province and will continue to do so owing to the geological structure of the region. Some of the short-term and medium-term ways of dealing with the problems caused by natural arsenic are as follows: steady monitoring of natural As, finding alternate groundwater sources and abandoning present sources or diluting prior to use, creating awareness among local people on this subject, modifying the present treatment plants for arsenic removal.

The dominant facies type in aquifers was $CaHCO_3$. The mixing at various rates of $CaHCO_3$ and $NaCl$ water types in the study area has caused to the formation of $NaHCO_3$ water type. Generally, Ca^+ and HCO_3^- ions were more dominant.

The results of the study indicate that the proposed methods are useful and reliable in determining the optimal areas that have high water quality. Thus, the hybrid AHP-DEA model can be used as an efficient method for establishing AWQI. In addition, the water quality maps of the study can be used as early-warning tools by urban and regional planners, environmental planners and agricultural engineers.

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