Evaluation of Irrigation Water Quality by Data Envelopment Analysis and Analytic Hierarchy Process-Based Water Quality Indices: the Case of Aksaray City, Turkey

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Abstract In this study, two water quality indices (AHP-IWQI and DEA-IWQI) based on Data Envelopment Analysis and Analytic Hierarchy Process have been produced in order to evaluate the water quality of surface waters used in agricultural irrigation. Depending on the efficiency scores of indices, two different water quality classification systems, which are composed of four suitability categories, have been defined. The 10 different alternatives and a total of 13 sub-criteria classified under 3 main criteria groups were used in the establishment of a hierarchical structure. For the sub-criteria, efficiency scores for electrical conductivity and sodium adsorption ratio having the highest efficiency score were calculated as 0.214 and 0.148, respectively. The results obtained from the indexes were compared with the results of the United States Salinity Laboratory and Wilcox diagrams. The comparative results of the predictions by AHP- and DEA-based indexes show that the accuracy ratio of the DEA-IWQI is higher than of the AHP-IWQI.

1 Introduction

Today, economic growth and rapid population growth in areas such as industry and agriculture, have increased the need for clean and qualified water resources. However, very limited surface water resources gradually lose their usable properties as a result of natural and anthropogenic factors (Vörösmarty et al. 2000). The use of low-quality water can cause serious diseases in humans, permanent damage to the ecosystem and economic losses (Schwarzenbach et al. 2010). Especially for countries located in arid and semi-arid climate zone, efficient use of water resources is very important in terms of eliminating economic losses. Efficient use of water resources is directly related to water quality (Ayers and Westcot 1985). Therefore, many countries and organizations have developed many different criteria and standards on water quality for the protection of water resources and prevention of quality loss. This surplus in the number of criteria and standards may cause some disruptions and misinterpretations in water quality studies. A single water sample can be identified in different water quality classes according to different criteria.

Water quality indexes (WQI) are systems that combine all selected physical, chemical and biological parameters into a single score depending on the purpose use of the water. WQI is a simple and useful method for

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assessing the suitability of irrigation water quality (Tyagi et al. 2013). WQI is also an effective method of eliminating the confusion caused by the excess number of water quality criteria and standards in the water quality assessment process (Cude 2001). Water quality indexes make it easier to classify water resources according to their intended use (Gazzaz et al. 2015) and they are also widely used in water pollution detection studies. Today, there are various water quality indexes developed by different researchers to be used in the determination of water quality (Abbasnia et al. 2019; Lai et al. 2017; Mukate et al. 2019). Zahedi (2017) used two different water quality indices to evaluate water quality in the Karaj Plain of Iran. Similarly, Adimalla (2019) used a water quality index to evaluate water quality in south India. Many of these indexes have been developed for groundwater considering drinking water standards. There are few water quality indexes developed for the quality of surface water resources which are commonly used in agricultural irrigation. Some researchers such as Smith (1990) and Nagles et al. (2001) used water quality indexes to measure the quality of surface waters.

The main differences between water quality indexes are the selection of parameters and the methods used to calculate the index. Dissolved minerals, organic matter content, heavy metals, and physico-chemical properties of water are important factors that directly affect water quality (Fetter 2001). These parameters affect water quality in certain proportions and their importance ranking for water quality is different from each other (Ji 2017). Kavurmaci (2016) emphasized that the importance ranking of the parameters can change according to the intended use of the water. So that, even a single parameter which is determined above the limit values, can avoid the use of water completely (Chhabra 2017). The choice of parameters that control water quality is the most significant agent affecting the success of the WQI (Karakuş 2018). One of the biggest errors made in water quality index calculations is the inadequate number of criteria for evaluation and incorrect parameter selection. Another important error is the inability to determine correctly the importance of ranking the parameters and their effect rates on the water quality (Sánchez 2015).

Multi-criteria decision-making techniques (MCDM) are widely used in water quality index calculations to determine the effect rates of parameters on water quality accurately. Analytical Hierarchy Process (AHP) is the most commonly used MCDM method today (Do et al. 2013). AHP is a widely used technique to solve complex problems, based on mathematics (Forman and Gass 2001). This method, which is preferred by many researchers because it is simple and practical to use, uses a scale based on importance ranking ranging from 1 to 9 (Saaty 2008). The decision-maker uses this scale to determine the importance ranking of the parameters. There is a linear relationship between the accuracy of AHP results and decision-maker preferences. The reliability of the AHP technique depends on how the efficiency score of each parameter has been determined (Ghorbanzadeh et al. 2018a).

The most important issues to be considered in AHP applications are the decision-makers who should be selected from experts and determination of preferences with the least error rate (Golden et al. 1989). It is important to ensure the results obtained from AHP application by using a different method for the reliability of water quality indexes. The use of diverse techniques can lead to dissimilar results. This difference arises from the fact that the basic mathematical equations used to calculate the weights of the criteria are different (Tscheikner-Gratl et al. 2017). Data envelopment analysis (DEA) is an effective application for identifying risks for water quality (Zema et al. 2018) and producing water quality index. AHP performs the ranking of the parameters by taking into account the significance levels of the parameters with binary comparisons (Ghorbanzadeh et al. 2018b), while DEA examines and analyzes the relations between the parameters and alternatives (Thanassoulis and Silva 2018). Although DEA is not frequently used in WQI calculations, it is a method that can produce accurate and effective results (Kavurmaci and Apaydin 2019).

In this article, two different water quality indexes were produced by using AHP and DEA methods in order to evaluate the surface water quality of ponds used for irrigation purposes in Aksaray city province in Central Anatolia region. Thus, the values that can express the suitability of water quality as a single score were obtained. The results obtained from the new indexes suggested in this article were compared among themselves and also with water quality diagram of US Salinity Laboratory which is widely used in the literature. The main objective of this article is to develop an index that combines numerous surface water quality data under a single water quality score and produces easy to use and reliable results. Thus, the quality of surface waters

can be easily expressed with a single score and classification.

2 Material and Methods

2.1 Study Area and Sampling

Aksaray is located between North Latitudes 37°58″ and 39°11″ and East Longitudes 33°11″ and 34°30″ in the Central Anatolian region of Turkey and covers an area of approximately 4589 km² (Fig. 1). Its height above mean sea level varies between 900 to 3200 m. Semi-arid and arid climate types prevailed in Aksaray. The average annual temperature for Aksaray is 12.4 °C. The mean annual rainfall amount is below 350 mm in the region. Two or 3 months of the year are dominantly drought.

Aksaray is one of Turkey's most important agricultural areas. The planted area for grains and other plant products in Aksaray province is 2,382,962 decares. Besides, the area of vegetable gardens in Aksaray province is 98,338 decares. The contribution to the Turkey production rate of agricultural products such as zucchini, sugar beet, barley, potato, and trefoil widely produced in Aksaray province is 9.2%, 6.8%, 3.2%, 4.4% and 1.8%, respectively (ATSO 2019). Most of the water used for agricultural irrigation is supplied from ponds and aquifers. The most important surface water sources used for irrigation of agricultural areas are Ciftevi, Bogazkoy, Sarıyahsi, Helvadere, Güzelyurt, Gulagac, Bozkir, Balci, and Kepir ponds and Mamasun dam. These water resources play an important role in improving the quality and quantity of agricultural products grown in the region. All of the ponds are located in the eastern part of the study area. These lakes are located in the most easily impacted regions by human activities. The rains in summers are insufficient and agricultural product growers commonly use groundwater ve ponds in order to irrigate cultivated areas.

In recent years, researchers have identified some problems and crop losses in the agricultural products irrigated by ponds. These anomalies usually appear as staining and turning pale or yellowing of leaves and dying of the plants. The hydrogeochemical properties
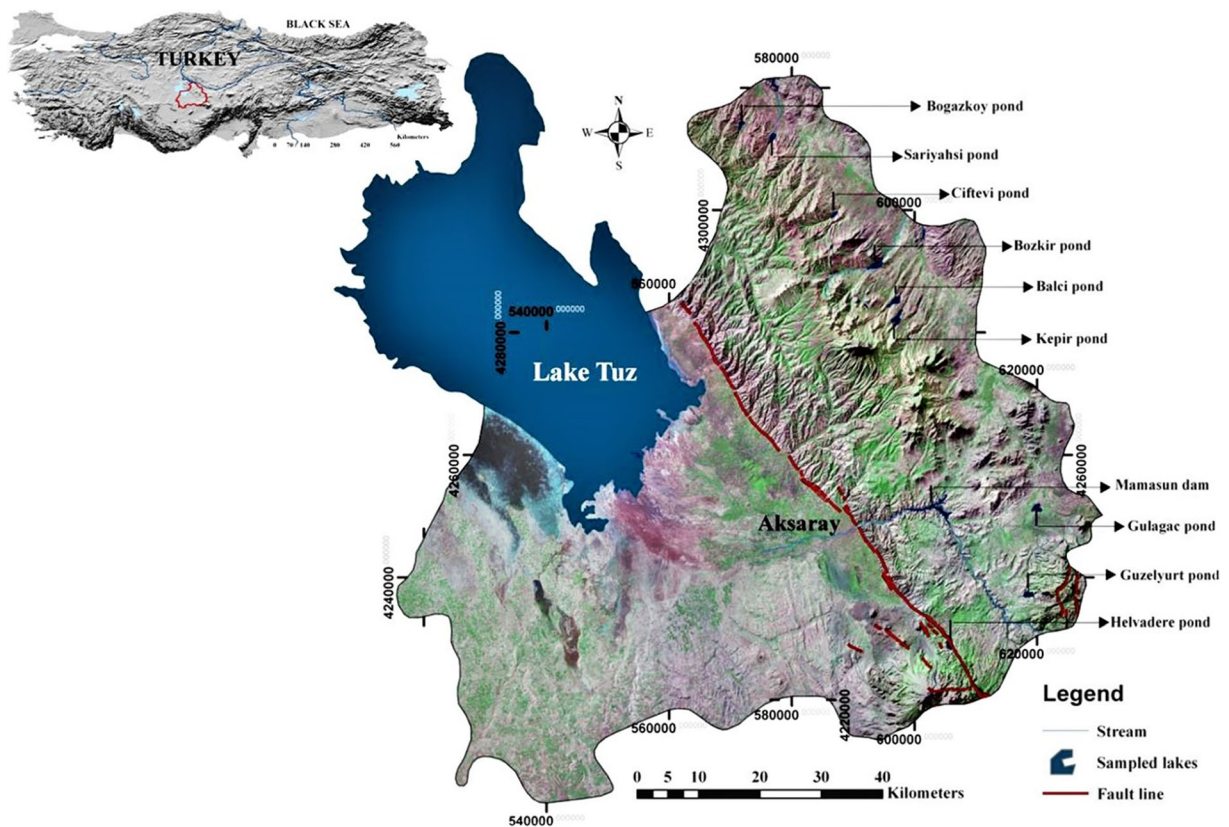

Fig. 1 General view of the study area and the sampling sites

and water quality of the ponds used for irrigation were investigated in order to determine the causes of these anomalies (Table 1). Ponds were selected taking into account water volume, depth, drainage area, irrigation characteristics, and crops irrigated. A total of 20 water samples were collected from the ponds in the study area to evaluate the water quality. Sampling was carried out in May 2018 and September 2018. The analysis of water samples was conducted at the Chemistry Laboratory of State Hydraulic Works (DSI). The water quality of the ponds was evaluated according to TSI (2009) (TSI) and the FAO (1985) (FAO) standards. For this purpose, two different models that can easily and reliably estimate water quality have been developed using the MCDM techniques such as AHP and DEA.

2.2 The Design of Hierarchical Structure

The main purpose of this study is to develop the water quality index in order to evaluate the water quality of ponds used in agricultural irrigation easier and simpler. The water quality index is a system that can display a large number of water quality parameters of any water source as a single number and was first developed by Horton (1965). In recent years, it has been widely used by many researchers in studies on water quality. Although there are various water quality indexes developed by different researchers, each region has its own hydrogeological, ecological and limnological characteristics. Therefore, the preferred methods and selected parameters in the calculation of water quality indexes may vary.

   In this scope of the study, two different water quality indexes (AHP-IQWI and DEA-IWQI) were created by using two different effective MCDM techniques such as AHP and DEA. In this way, both reliability and success rates of AHP and DEA techniques can be compared in the design of water quality indexes. The designed water quality indexes essentially consist of a three-stage hierarchy (Fig. 2). The first stage of the hierarchy consists of the aim of the study, the second stage is the selection of criteria and sub-criteria, and the final stage is the evaluation of decision alternatives. In the hierarchy, due to the large number of parameters that control the suitability of water quality, the problems experienced during the evaluation of water quality have been identified as multi-criteria decision-making problems. Therefore, it is aimed to establish water quality indexes that can produce a simple and useful value that defines the

suitability of irrigation water. When determining criteria and sub-criteria, the geometric means of the opinions, obtained from 10 different experts who have scientific studies on water quality and standards developed by institutions such as FAO and U.S. Salinity Laboratory, were used.

2.3 The Design of AHP-Based Water Quality Index

AHP developed by Saaty (2005) is one of the most widely used MCDM techniques. AHP is a decision making and estimation method that gives percentage distributions of the criteria that affect the decision hierarchy. AHP assigns values between 1 and 9 and compares the criteria within themselves and determines the effect weights of the criteria within the system. The basis of the method is based on binary comparisons between criteria, sub-criteria and the alternatives. In the first stage of the AHP-supported water quality index design, 10 different alternatives (irrigation ponds), and a total of 13 sub-criteria classified under 3 main criteria groups were identified. These criteria are (i) physico-chemical parameters, (ii) chemical parameters, and (iii) suitable parameters. Group 1 contains basic physico-chemical parameters related to the natural structure of water such as pH, electrical conductivity (EC), total dissolved solids (TDS), and total hardness (TH). Group 2 includes fundamental chemical parameters such as chloride (Cl^-), magnesium (Mg^{2+}), sodium (Na^+), calcium (Ca^{2+}), and boron (B), which significantly affect the water quality. Group 3 consists of parameters such as sodium adsorption ratio (SAR), soluble sodium percentage (Na%), magnesium hazard (MH), and residual sodium carbonate (RSC), which are used to determine the suitability of irrigation water. Each criterion is divided into four different quality classes considering FAO, U.S. Salinity Laboratory and TSI standards, in order to establish the hierarchical structure.

   In the next step, binary square comparison matrices with n x n dimensions have been designed in which diagonal elements take the value of 1. In the creation stage of the comparison matrices, binary comparisons of decision alternatives, criteria and sub-criteria were made one-to-one and mutually according to their significance values. The scale suggested by Saaty (2008) was used to make bilateral mutual comparisons. If one parameter is considered to be more important than the other, a coefficient ranging from 1 to 9 is assigned by the decision-maker according to its significance degree. In binary

Table 1 Hydrogeochemical analysis results of water samples in dry and rainy period

Id	Parameter Sample	T (°C)	pH	EC (μS/cm)	TDS (mg/L)	TH (mg/L)	Alk (mg/L)	HCO_3 (meq/L)	SO_4^{2-} (meq/L)	Cl^- (meq/L)	Ca (meq/L)	K (meq/L)	Mg (meq/L)	Na (meq/L)	B (mg/L)	Na% (meq/L)	RSC (meq/L)	MH (meq/L)	SAR (meq/L)	Water type
1	Çiftevi pond*	20.35	8.12	464.20	268.71	184.83	189.88	3.80	0.71	0.75	2.29	0.05	1.60	1.07	0.108	22.33	0.10	41.18	0.61	$Ca-HCO_3$
	Çiftevi pond**	10.00	8.31	507.73	326.51	254.01	247.72	4.95	0.58	0.72	2.86	0.05	1.89	1.17	0.090	20.43	0.20	39.75	0.60	$Ca-HCO_3$
2	Boğazköy pond*	16.06	8.73	506.72	292.47	217.09	260.07	4.87	0.82	0.61	2.59	0.08	1.75	1.35	0.131	24.79	0.54	40.33	0.73	$Ca-HCO_3$
	Boğazköy pond**	10.76	9.23	532.09	338.24	265.44	283.30	5.67	0.68	0.77	2.77	0.10	2.10	1.58	0.122	25.63	0.79	43.16	0.81	$Ca-HCO_3$
3	Sarıyahşi pond*	23.36	8.70	508.47	282.14	185.33	212.10	4.24	0.95	0.53	2.36	0.05	1.67	1.56	0.126	28.42	0.21	41.47	0.87	$Ca-HCO_3$
	Sarıyahşi pond**	11.98	9.21	612.44	382.36	284.35	298.08	5.96	1.40	0.77	3.11	0.06	2.18	2.00	0.117	28.00	0.67	41.19	0.97	$Ca-HCO_3$
4	Helvadere pond*	18.62	7.42	312.46	229.35	107.10	145.35	2.91	0.35	0.67	2.04	0.07	0.95	0.98	0.074	25.96	0.09	31.82	0.62	$Ca-HCO_3$
	Helvadere pond**	9.07	7.58	289.26	183.06	142.02	137.81	2.76	0.41	0.76	1.65	0.09	1.07	1.10	0.068	30.41	0.03	39.48	0.74	$Ca-HCO3$
5	Güzelyurt pond*	21.37	9.16	442.36	260.73	154.96	187.20	3.74	0.50	0.92	2.42	0.35	0.65	1.26	0.086	34.36	0.68	21.22	0.76	$Ca-HCO_3$
	Güzelyurt pond**	8.42	8.68	377.79	240.72	167.28	188.45	3.60	0.45	0.76	2.20	0.35	0.85	1.09	0.076	32.02	0.55	27.91	0.67	$Ca-HCO_3$
6	Gülağaç pond *	21.16	7.07	688.18	279.72	269.67	296.44	5.27	0.30	0.89	2.38	0.20	1.93	1.54	0.693	28.86	0.96	44.79	0.84	$Ca-HCO_3$
	Gülağaç pond **	11.97	7.82	831.05	439.63	313.21	376.78	7.21	0.48	1.06	2.70	0.28	2.64	2.49	0.882	34.13	1.87	49.38	1.24	$Ca-HCO_3$
7	Mamasun dam *	23.70	9.12	610.50	378.95	196.47	245.31	4.91	0.69	2.37	2.42	0.36	1.85	3.04	1661	44.36	0.63	43.30	1.66	$Na-HCO_3$
	Mamasun dam*	9.84	8.52	404.28	363.02	210.12	267.70	5.35	0.45	1.80	2.60	0.35	1.97	2.84	0.383	41.09	0.78	43.19	1.50	$Na-HCO3$
8	Bozkır pond*	21.62	8.91	1333.37	599.70	348.74	357.22	6.00	0.89	5.46	3.19	0.31	2.20	5.54	0.261	52.03	0.60	40.83	2.68	$Na-HCO_3$
	Bozkır pond**	10.85	9.23	1563.08	848.07	455.45	455.39	8.62	2.23	5.00	5.11	0.33	2.83	6.41	0.253	45.89	0.67	35.66	2.51	$Na-HCO_3$
9	Balcı pond *	20.38	9.01	210.42	153.60	84.53	116.63	2.33	0.35	0.31	2.14	0.03	0.41	0.48	0.025	16.76	0.22	16.01	0.31	$Ca-HCO_3$
	Balcı pond **	8.55	8.25	183.03	126.84	78.28	104.18	2.08	0.19	0.38	1.60	0.03	0.38	0.43	0.032	18.93	0.11	18.98	0.32	$Ca-HCO3$
10	Kepir pond *	21.01	8.25	330.09	192.76	139.38	131.30	2.63	0.83	0.23	2.27	0.04	0.65	0.63	0.048	18.57	0.29	22.25	0.39	$Ca-HCO_3$
	Kepir pond **	9.58	8.20	296.69	188.49	143.69	149.14	2.98	0.55	0.40	2.10	0.04	0.74	0.70	0.032	20.82	0.15	25.95	0.45	$Ca-HCO_3$

EC: electrical conductivity, *TDS*: total dissolved solids, *TH*: total hardness, *Alk*: alkalinity, *SAR*: sodium adsorption ratio, *Na%*: soluble sodium percentage, *RSC*: residual sodium carbonate, *B*: boron concentration, *MH*: magnesium hazard, *: dry, **: rainy
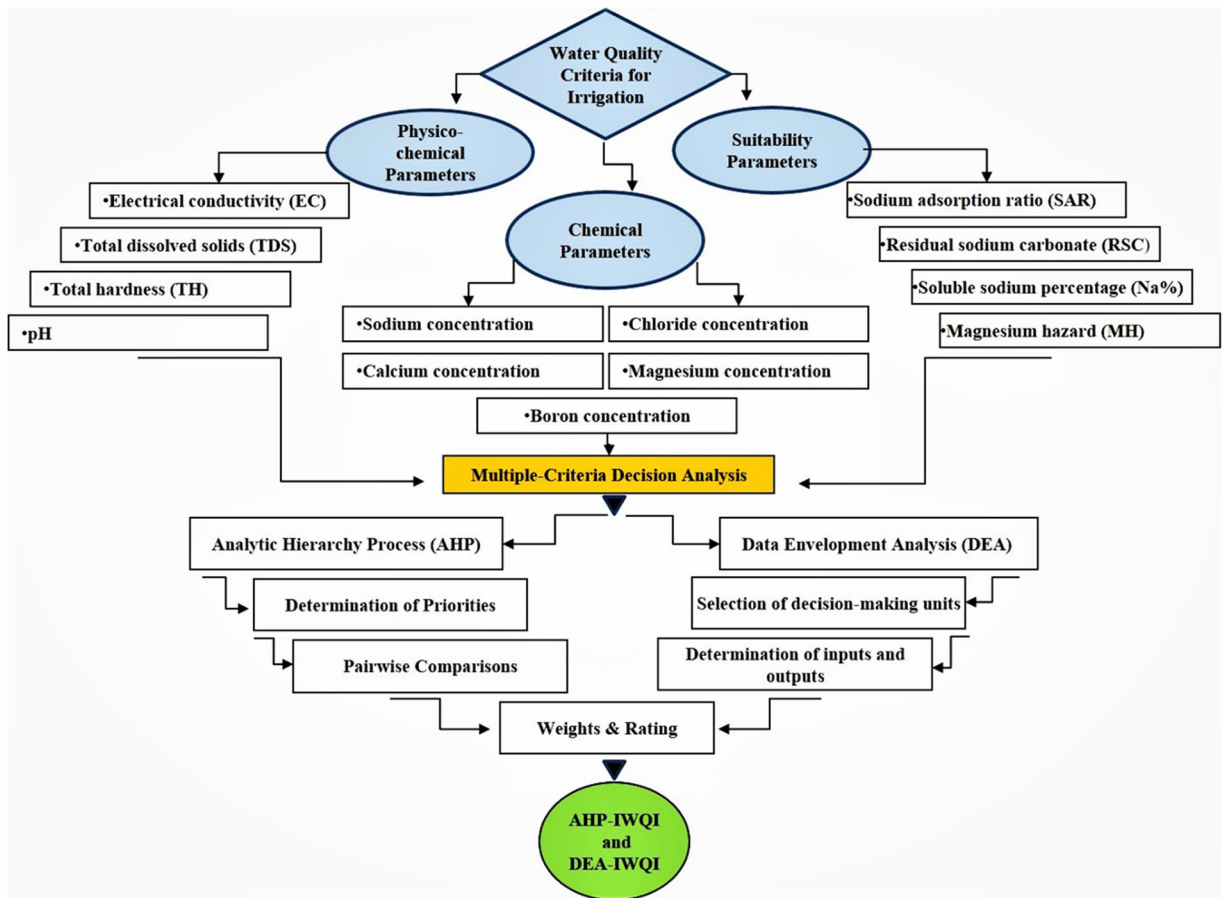
Fig. 2 Flowchart of research methodology

comparisons, a value of 1 was assigned to the parameters considered to be of equal importance. By using comparison matrices, priority and weight vectors of each parameter in the hierarchy were determined and AHP-supported Water Quality Index (AHP-IWQI) was developed. Priority order of parameters and weight vectors are given in Table 2.

According to the AHP methodology, the inconsistency ratio of the comparison matrices must be less than 0.1 in order to use the relevant data group in the study. The inconsistency ratio of the binary comparisons made at the last stage of the application was calculated as 0.012. The designed matrices and comparisons are consistent and those comparisons can be used in the evaluation process.

2.4 The Design of DEA-Based Water Quality Index

Data Envelopment Analysis (DEA) is a mathematical solution technique that aims to measure the

effectiveness degree of Decision Making Units (DMUs) using a large number of parameters having different measurement units. The units that are tried to determine the degree of effectiveness in DEA are called decision-making units (Charnes et al. 1994). In DEA, an activity surface is formed by using input and output data of the decision units and each decision unit is evaluated in terms of the distance to the activity surface. DEA developed by Charnes et al. (1978), is used to estimate the production efficiency of individuals or institutions mostly in the fields of business and economics. DEA is preferred in this study because it is possible to prefer a large number of inputs and outputs, unlike the classical effectiveness approaches, and because it allows each decision unit to be compared with other decision units (Yilmaz and Harmancioglu 2008). In this way, it can be easily determined which decision unit is more effective than the others. In this scope of study, weighted CCR model was preferred because it gives more accurate results to compare irrigation water quality of ponds.

Table 2 Ranges of suitability classes of the criteria used for AHP modeling

Parameters	Unit	W_i	Excellent	Good	Permissible	Unsuitable
pH	–	0.0180	7.5–8.5	>8.5	6.0–7.5	<6
EC	(μS/cm)	0.1480	<250	250–750	750–2250	>2250
TDS	(mg/L)	0.1480	<100	100–500	500–1000	>1000
TH	(mg/L)	0.0250	<100	100–500	500–1000	>1000
Cl⁻	(meq/L)	0.0680	<1	1.0–5.0	5.0–10.0	>10
Na⁺	(meq/L)	0.0690	<1	1.0–5.0	5.0–10.0	>10
Ca	(meq/L)	0.0130	<1	1.0–5.0	5.0–10.0	>10
% Na	(meq/L)	0.1000	<20	20–40	40–80	>80
SAR	(meq/L)	0.2140	<1	1–2	2–5	>5
RSC	(meq/L)	0.1000	<1.25	1.25–2.5	2.05–5.0	>5
B	(mg/L)	0.0480	0.0–0.5	0.5–1.2	1.2–2.0	>2
Mg	(meq/L)	0.0130	<1	1.0–5.0	5.0–10.0	>10
MH	(meq/L)	0.0350	<25	25–50	50–75	>75

EC: electrical conductivity, *TDS*: total dissolved solids, *TH*: total hardness, *SAR*: sodium adsorption ratio, *Na%*: soluble sodium percentage, *RSC*: residual sodium carbonate, *B*: boron concentration, *MH*: magnesium hazard, *Wi*: the weight score

The DEA model can be calculated by the following mathematical equations (Charnes and Cooper 1984):

$$Max_k(v, u) = Max \sum_{r=1}^{p} u_r Y_{rk} \qquad (1)$$

under the following restrictions;

$$\sum_{i=1}^{m} v_i X_{ik} = 1 \qquad (2)$$

$$\sum_{r=1}^{p} u_r Y_{rj} - \sum_{i=1}^{m} v_i X_{ij} \le 0 \quad (j = 1, \ldots, n) \qquad (3)$$

$$u_r, v_i \ge 0 \qquad (r = 1, \ldots, p), (i = 1, \ldots, m)$$

where;

x_{ik} = amount of input i utilized by DMU k, y_{rk} = amount of output r produced by DMU k, x_{ij} = amount of input i utilized by DMU j, y_{rj} = amount of output r produced by DMU j, v_i = weight given to input i by DMU k, u_r = weight given to output r by DMU k, ε = a positive number, p = number of outputs, n = number of DMUs, m = number of inputs, k = efficiency score of DMU k.

During the design phase of the model, the ponds were used as decision units of the model and hydrogeochemical data set of ponds were used as input and output parameters. The hydrogeochemical data set was obtained as a result of the measurements of values belonging to some parameters and the calculation of some other parameters. In design of the DEA-based model, important chemical parameters such as Na, Cl, Mg, B, Ca were selected as input, and Na%, SAR, RSC, MH, TH and EC values were selected as output parameters. The selection of the input and output parameters were determined in accordance with the opinions of 10 different experts in the field of water quality. In the next stage of the study, weight values were assigned to the determined inputs and outputs. In the process of assigning the weight values, the prioritization matrice used for the AHP method and the weight values of the parameters were used.

Some decision units may appear to be more effective because of high values of their less important input and outputs, while some other decision units may appear to be more ineffective because of low values of their more important input and outputs. To avoid this problem, weight restrictions are applied to all inputs and outputs. Due to the restriction conditions applied, it is ensured that the weighted output / input ratio for each decision unit does not exceed 1. In the final stage, the basic CCR model and the weight restricted model were solved and the DEA-supported Water Quality Index (DEA-IWQI) was developed. In the DEA-IWQI, the quality assessment of ponds ranges from 0 to 1. The results of the DEA-IWQI are given in Table 4. The highest value

indicates the pond with the highest irrigation water quality and the lowest value indicates the pond with the poorest water quality.

3 Results and Discussion

3.1 Hydrogeochemical Evaluation

In order to evaluate the hydrogeochemical properties of ponds, physical and chemical analysis results of samples collected from ponds during rainy and dry periods were used. The lowest and highest values of some the physical and chemical parameters measured in May 2018 and September 2018 are: pH; (7.6–9.2), (7.1–9.2) EC; (183–1563.1), (210.4–1333.4) μS/cm, Na^+; (0.4–6.4), (0.5–5.5) meq/L, Cl^-; (0.4–5.0), (0.2–5.5) meq/L, Ca^{2+}; (1.6–5.1), (2.0–3.2) Mg^{2+}; (0.4–2.8), (0.4–2.2) meq/L, B; (0.0–0.9), (0.0–1.7) mg/L, SAR; (0.3–2.5), (0.3–2.7) meq/L, Na%; (18.9–45.9), (16.8–52.0) meq/L and RSC; (0.0–1.9), (−0.3–1.0) meq/L, respectively (Table 1).

According to the Total Dissolved Solids (TDS) and EC values, 90% of ponds can be described as good for agricultural irrigation in May and September 2018. The Bozkir pond has higher sodium and chlorine values than the other ponds, so the highest TDS and EC values have been measured in the Bozkir pond. EC values within Bozkir pond ranged from 1333 to 1563 μS/cm. The value of Na^+ in Bozkir pond varies between 5.54 to 6.41 meg/L in May and September 2018 analysis periods. The Bozkir pond contains Cl^+ up to 5.46 meq/L. The Na^+ and Cl^- contents in the Bozkir pond may be increased as a result of the dissolution of sodium rich evaporitic rocks. Na^+ in surface water is derived mainly from the decomposition of feldspars and from sodium salts. The lowest EC values were measured in the Balci pond. The EC values of the Balci pond ranged from 183.0 to 210.4 μS/cm. SAR ratio of Balci pond is much smaller than in Bozkir pond (2.68 meq/L). Hydrogeochemical data indicate that chloride concentrations within ponds ranged from 0.23 to 5.46 meq/L. Cl^- and Na^+ ions in the Helvadere, Bogazkoy, Sariyahsi, Gulagac, Balci and Kepir ponds have been observed to be decreasing in dry periods. This change observed in the ion concentrations shows that these ponds are formed by waters belonging to different hydraulic systems. Also, the interaction of water with domestic and industrial wastes within the hydrological system could be another factor that explains the temporal ion exchange of the ponds.

The dominant ion type was Na^+, Ca^{2+} and HCO_3^- during the all sampling periods. The order of cations and anions for many pond are $Ca^{+2} > Mg^{+2} > Na^+ + K^+$ / $HCO_3^- > Cl^- > SO_4^{-2}$. Whereas, the ionic sequence based on relative proportions for Mamasun dam and Bozkir pond are $Na^+ + K^+ > Ca^{+2} > Mg^{+2} / HCO_3^- > Cl^- > SO_4^{-2}$. The fact that ponds have a similar ion sequence can be proof that these waters were sharing a common watershed or have a same/similar origin. According to the analysis results of ponds, two different hydrochemical facies have been identified. Mamasun dam and Bozkir pond have Na-HCO_3 water type while other ponds have Ca-HCO_3 water type. In general, Na-HCO_3 type waters are characterized as mixed waters, where no ion exceeds 50%. These waters were formed as a result of mixture of Na-Cl and Ca-$HCO3$ water types. Ca-HCO_3 water type indicates the presence of carbonate rocks in the region. The dominant water type present in ponds is the Ca-HCO_3 water type. The ponds having Na-HCO_3 water type showed SAR values between 1.5–2.68 while these values measured in the range of 0.3–1.24 in the ponds having Ca-HCO_3 water type. According to the general hydrochemical trend of the water quality during the sampling periods, the ponds are saturated with calcite, dolomite and aragonite, rather than gypsum, halite and anhydrite. The ponds have the ability to dissolve gypsum, halite, anhydrite and precipitating calcite, dolomite and aragonite.

3.2 Evaluation of Irrigation Water Quality

The most important factor in the quality of irrigation water is the existence and structure of the dissolved solid materials (salt) in the water. High salt concentrations in the irrigation water affect the capability of plants to assimilate water through their roots when a certain level is exceeded (Zaman et al. 2018). This limit value depends on the factors such as soil structure and texture, drainage conditions of the site, the salt tolerance of the raised plant and climate (Bauder et al. 2011).

SAR, EC, Na%, Na, Cl and B concentrations are the most commonly used parameters in the literature to evaluate irrigation water quality. The SAR values of ponds in May 2018, and September 2018 range from 0.3 to 2.7 and 0.3 to 2.5 meq/L, respectively. The water having SAR values greater than 9 meq/L is threat for irrigation (FAO 1985). According to the SAR values,

the water samples have been classified as "good water" for the Gulagac pond and Mamasun dam, "permissible water" for the Bozkir pond and the rest as excellent water. The irrigation water quality especially in view of the SAR value in the Bozkir pond is worse than the other water sources. The EC values of ponds in May 2018 and September 2018 range from 183.0 to 1563.1 μS/cm and 210.4 to 1333.4 μS/cm, respectively. According to EC values, the quality of irrigation water has been divided into four categories i.e., excellent (EC < 250 μS/cm), good (EC: 250 to 750 μS/cm), permissible (EC: 750 to 2250 μS/cm) and unsuitable (EC > 2250 μS/cm). The irrigation water quality of the Gulagac and Bozkir ponds were described as permissible in sampling periods, while Balci pond was categorized as excellent. The irrigation water quality of other ponds was defined as good.

The evaluation of USSL (1954) diagram showed that the Bozkir pond fall in the area of C_3S_1 category (high salinity and low sodium waters) (Fig. 3). The Bozkir pond is inconvenient for irrigation of plants sensitive to salt due to having high EC. The irrigation class of the Gulagac pond was described as C_3S_1 in May 2018, while it was categorized as C_2S_1 in September 2018. The main reason for the changes occurring in the irrigation class may be due to the change of ion content of water because of water-rock interaction or ion exchanges. The Mamasun dam categorized in the C_2S_1 area (medium salinity and low sodium waters) which may be used for crops having low salt tolerance. The most of water samples fall in the area of C_2S_1 category which can be used for all crops without the hazard of salinity and sodium. According to Na, Cl and B concentrations, the most of the samples classified in excellent or good category which can be used for all plants without the danger of salinity and sodium. The evaluation of Wilcox (1948) Diagram showed that the irrigation class of the Bozkir pond was described as "permissible to doubtful" in September 2018, while it was categorized as "good to permissible" in May 2018 (Fig. 4). The irrigation class of the Gulagac pond was described as "good to permissible" in May 2018, while it was categorized as "excellent to permissible" in September 2018. During all sampling periods, other ponds were categorized as "excellent to permissible."

Bozkir pond is classified as having moderate irrigation risk while the other ponds and Mamasun dam are classified as having low irrigation risk. Cabbage, spinach and tomato can be produced with a small efficiency loss in the areas irrigated by Bozkir Ponds having medium concentrated salty waters. Besides, salt resistant agriculture plants such as sugar beet, wheat, barley, soya bean and sorghum can be produced without any efficiency loss in these areas.

3.3 Evaluation of AHP-Based Water Quality Index Results

In a decision hierarchy, AHP calculates the importance values of both the factors affecting the decision and the decision points in terms of these factors by making one-to-one comparisons, using a predefined comparison scale (Saaty and Vargas 2012). As a result, differences in importance turn into percentage distribution over decision points (Vargas 1990).

In this scope of study, a hierarchical model designed to determine the suitability of irrigation water quality was constructed using a total of 13 sub-criteria under 3 main criteria groups. By using binary comparison matrices, the percent importance distributions showing the importance values of the 3 main criterion groups and criterions relative to each other, were obtained in the hierarchy. Calculation of inconsistency rates of all comparison matrices less than 0.1, indicates that the designed hierarchical model is reliable and successful. The efficiency scores for the physico-chemical parameters, chemical parameters and suitability parameters that constitute the three main criterion groups were calculated as 0.2604, 0.1061 and 0.6333, respectively. The main group of suitability parameters has a weight ratio of 63% in the hierarchy. For the sub-criteria, efficiency scores for EC and SAR having the highest efficiency scores, were calculated as 0.214 and 0.148, respectively and efficiency scores for Ca and Mg having the lowest efficiency scores were calculated as 0.013. A model at an acceptable level, was produced by using the importance values of the main criteria and sub-criteria which we defined for the decision problem. By means of this model, efficiency scores showing the irrigation water quality of alternatives (ponds) were obtained. The efficiency scores of the ponds ranged from 0.0312 to 0.234 for September 2018 sampling period, while these values were calculated from 0.0379 to 0.2209 for the May 2018 sampling period (Table 3).

During all sampling periods, the pond with the lowest irrigation water quality is Bozkir pond. Bozkir pond has 0.2340 and 0.2209 efficiency scores for dry and rainy periods, respectively. The pond with the highest
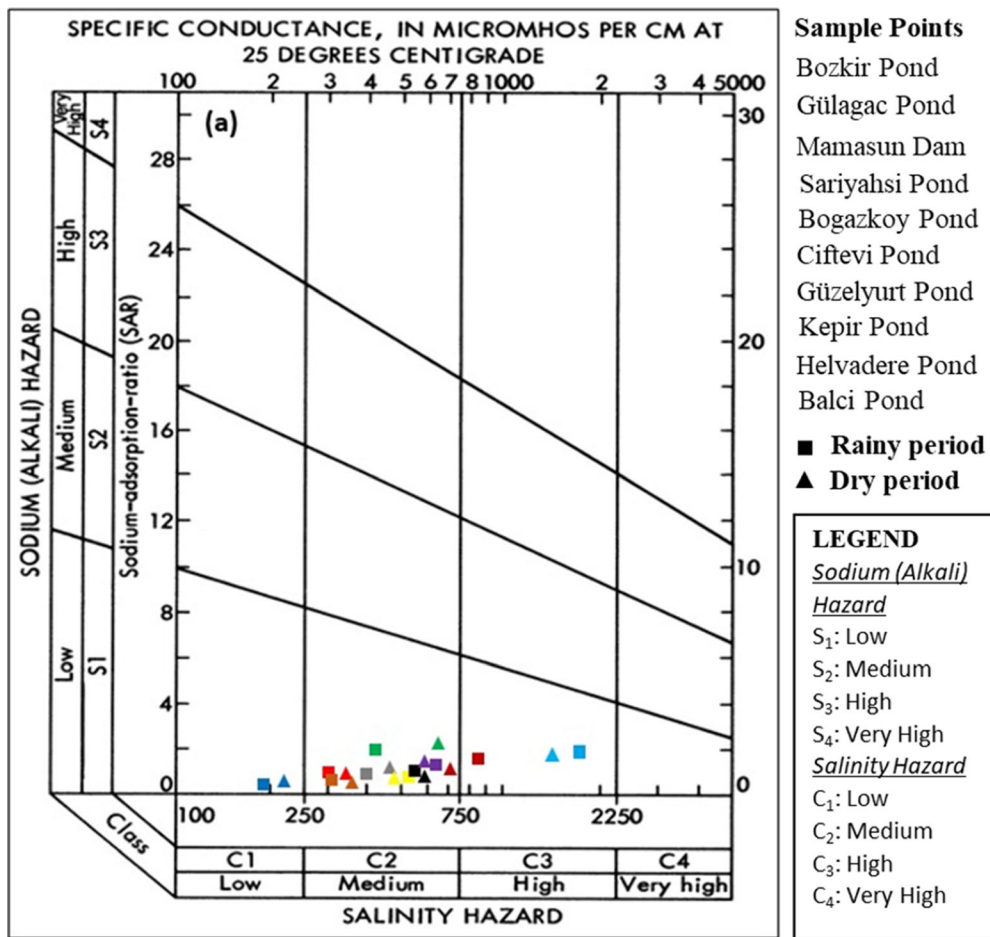
Fig. 3 USSL diagram showing the suitability of water samples for irrigation

irrigation water quality is Balci pond. Efficiency scores of Balci pond for dry and rainy periods are 0.0312 and 0.0379 respectively. The water quality of Ciftevi, Sariyahsi, Helvadere, Gulagac, Balci and Kepir ponds increased during the dry period, whereas the water quality of the other water resources decreased. This is because of interaction with different water sources, point or spatial contamination or ion exchange between ions. A decrease in the SAR values were determined at all of the ponds which indicated increase at water quality during the dry period except Ciftevi pond. This result is an indication that SAR is an effective parameter on seasonal water quality differences of ponds.

When the functional correlation of the AHP-IWQI and parameters having high efficiency values such as EC and SAR was analyzed, a significant proportional relationship was found between these parametrers and AHP-IWQI (Fig. 5). The correlation coefficient obtained from the linear regression between SAR and AHP-IWQI values in the arid period is 0.93 while this value for EC and AHP-IWQI is 0.89. According to the results of the correlation coefficient, AHP-IWQI can be defined as a function of EC and SAR values. These linear functions have been tested using the AHP-IWQI values calculated for the rainy period. The correlation coefficients of the estimated and calculated AHP-IWQI values for EC and SAR parameters are 0.86 and 0.95, respectively. Linear regression results showed that the calculated and estimated AHP-IWQI values for the rainy period are in good agreement.

The water quality of the ponds is divided into four different groups in terms of efficiency scores (Table 4). The first group of water quality was used for ponds with efficiency scores of less than 0.1 and the water quality of ponds with this range was classified as "excellent." The second group of water quality class has efficiency scores
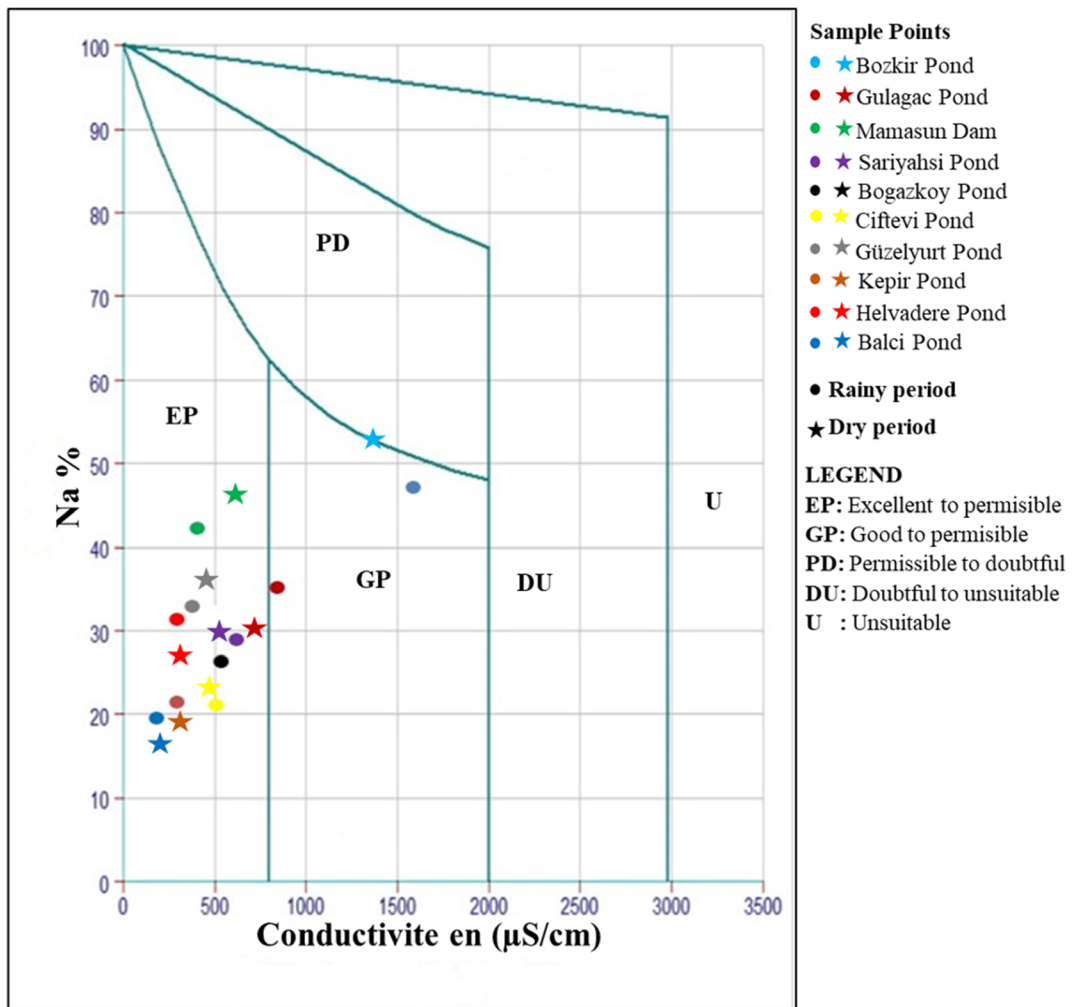
Fig. 4 Wilcox diagram showing the suitability of water samples for irrigation

between 0.1 and 0.2 and is defined as "good" quality water class. The efficiency scores of the third group of water quality class ranges from 0.2 to 0.3 and the quality of the waters in this group was described as "permissible." The fourth group of water quality class has efficiency score greater than 0.3 and the water quality of this group is classified as "unsuitable." It is unfavorable to use waters having the fourth group irrigation water quality.

According to AHP-IWQI results, Gulagac pond and Mamasun dam have "good" water quality, Bozkir pond has "permissible" water quality and the other ponds have "excellent" water quality. Water quality classes of the other ponds except Sariyahsi pond did not change during dry and rainy periods. The water quality class of Sariyahsi pond changed from "good" in the rainy period

to "excellent" in the dry period. However, this difference in water quality class happened with a very small change rate. So that, Sariyahsi pond can be classified as "excellent" in both sampling periods. It is seen that the results of AHP-IWQI classification are quite similar when compared with diagrams showing the quality of irrigation waters developed by the U.S. Salinity Laboratory and Wilcox (1948). According to these diagrams, Bozkir pond can be classified as suspicious irrigation water with low sodium and high salinity hazard. The other ponds are classified as very good–good quality irrigation waters. These results are proof that the developed AHP-IWQI can produce accurate and reliable results. The AHP-IWQI is more useable and practical than the U.S. Salinity Laboratory and Wilcox (1948) diagrams. One of the major advantages of AHP-IWQI is

Table 3 The efficiency scores of water resources in dry and rainy period

Sample	AHP-WQI		DEA-WQI	
ID	Dry period	Rainy period	Dry period	Rainy period
Ciftevi pond	0.066734	0.071542	0.93853	0.84485
Bogazkoy pond	0.094634	0.093662	0.81692	0.82023
Sariyahsi pond	0.091472	0.102740	0.82123	0.78431
Helvadere pond	0.060316	0.067999	0.95419	0.93253
Guzelyurt pond	0.097679	0.076378	0.79145	0.82023
Gülağaç pond	0.122862	0.148133	0.64874	0.60247
Mamasun dam	0.161116	0.128870	0.71439	0.74638
Bozkir pond	0.234077	0.220948	0.57786	0.58299
Balci pond	0.031288	0.037929	1.00000	0.97159
Kepir pond	0.038959	0.050936	1.00000	1.00000

Table 4 Irrigation water quality ranking criteria

AHP-WQI-range	DEA-WQI-range	Category-rank	Interpretation
0–0.1	0.85–1	Excellent	Can be used safely to irrigate all kinds of plants and crops
0.1–0.2	0.70–0.85	Good	Generally safe to use as irrigation water
0.2–0.3	0.55–0.70	Permissible	Suitable for irrigation of plants with high salt tolerance, however may be harmful to plants having low salt tolerance
> 0.3	< 0.55	Unsuitable	Not suitable for use as irrigation water

the inclusion of the effect rates of many parameters in the determination of water quality. Furthermore, the distances of the samples to the limit values of the quality

class ranges can be determined more clearly by means of the water quality scores produced.

In the irrigation field of Bozkir pond, the preference for cultivation of plants and agricultural products with higher salt tolerance may reduce economic losses due to product loss. Agricultural risks related to irrigation water in this region may also vary depending on the type of plant, irrigation method applied, the amount of water, and exposure time. Other ponds and the Mamasun dam
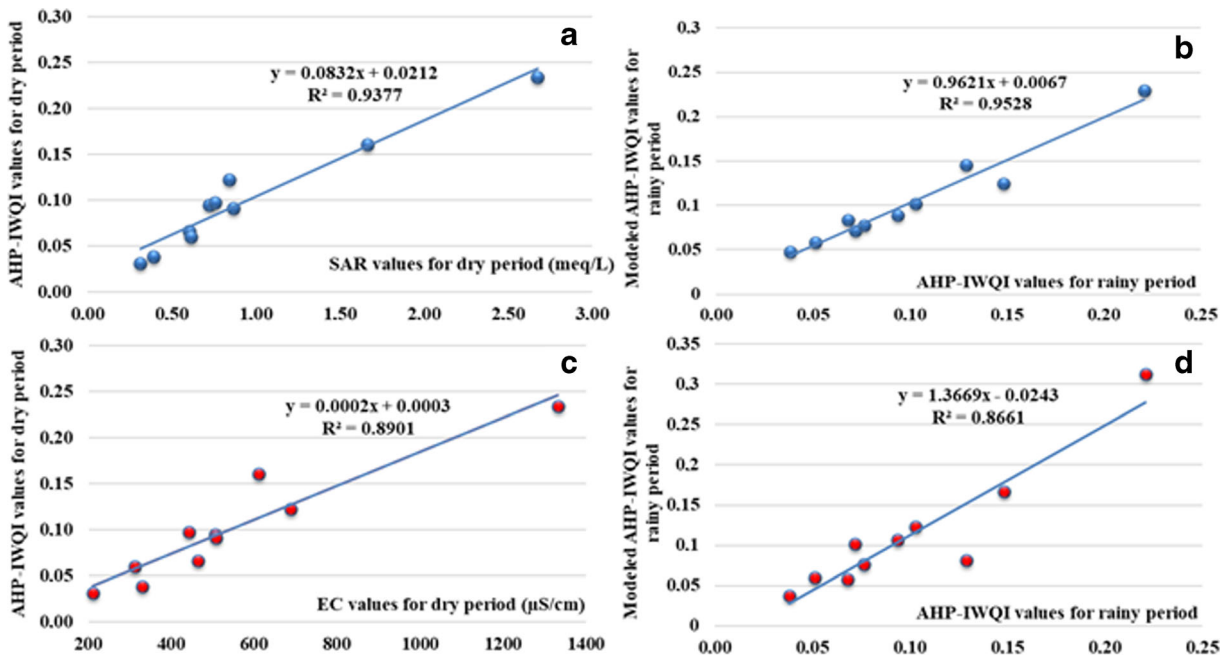
Fig. 5 The linear correlation between SAR and AHP-IWQI for dry period (**a**), the linear correlation between estimated AHP-IWQI and AHP-IWQI for rainy period (**b**), the linear correlation between EC and AHP-IWQI for dry period (**c**), and the linear correlation between estimated AHP-IWQI and AHP-IWQI for rainy period (**d**)

can be used safely for irrigation of all kinds of plants and agricultural products.

3.4 Evaluation of DEA-Based Water Quality Index Results

Within the scope of this model, ponds to be examined for water quality were selected as decision-making units (DMUs). Efficiency scores of DMUs were calculated to have values between 0 and 1. While the highest water quality is indicated by an efficiency score of 1, the irrigation water quality will decrease as the efficiency score approaches 0. The efficiency scores of DMUs range from 0.5778 to 1 and 0.5829 to 1 for the September and May 2018 sampling periods, respectively. In the dry period, the highest efficiency score was determined as 1 in Balci and Kepir ponds. The lowest efficiency scores were calculated as 0.5778 and 0.6487 in the Bozkir and Gulagac ponds, respectively. In the rainy period, the highest efficiency scores were calculated as 0.9715 and 1 for Balci and Kepir ponds, and the lowest efficiency scores were 0.5829 and 0.6024 for Bozkir and Gulagac ponds, respectively. When the temporal changes of water quality were examined, it was determined that Ciftevi, Sariyahsi, Helvadere, Gulagac, and Balci ponds had lower efficiency scores in the rainy period. The water quality of these ponds increased during the dry period. These results are consistent with AHP-IWQI.

The water quality of DMUs is divided into four different classes in terms of efficiency scores. The first group of water quality class was used for DMUs with efficiency scores between 1 and 0.85, and the water quality of DMUs with this range was classified as "excellent." The efficiency scores range of the second group water quality class was determined between 0.85 and 0.70 and was defined as "good" quality water class. The efficiency scores of the third group of water quality class range from 0.70 to 0.55 and the water quality of the DMUs in this group is classified as "permissible." The fourth group of water quality class has an efficiency score less than 0.55 and the water quality of this group is classified as "unsuitable." According to the DEA-IWQI, it is unfavorable to use waters having the fourth group irrigation water quality.

According to the results of DEA-IWQI, Gulagac and Bozkir ponds have "permissible," Balci, Kepir, Helvadere and Ciftevi ponds have "excellent" and the other ponds and Mamasun dam have "good" water

quality. Except for Ciftevi pond, the water quality classes of the ponds did not change during dry and rainy periods. The water quality class of Ciftevi pond changed from "good" in the rainy period to "excellent" in the dry period. The results of DEA-supported water quality index classification are determined to be similar when compared with the diagrams showing the quality of irrigation waters developed by the U.S. Salinity Laboratory and Wilcox (1948) and when compared with AHP-WOI.

3.5 Comparison of AHP-IWQI and DEA-IWQI Results

In recent years, different water quality indexes have been developed by the researchers to indicate water quality as a single score. The main differences in these studies are the selection of criteria used in the development of the index and the determination of the impact values of these criteria on water quality. In the selection of criteria, in addition to globally accepted standards, regional standards have also been used. While some researchers prefer to use several criteria taking place in the standards, some others use a much larger number of criteria to generate their indexes. The main differences between the indexes, result from the weight values assigned to the selected criteria. The most important reason for the difference between the indices is the importance ranking and impact values of the criteria, which are determined according to the common opinion of the decision-makers. One of the challenges faced by the model developer is the mistakes that decision-makers make in the process of assigning efficiency values to the criteria. This error can even cause the water quality class to change. The main purpose of this study is to obtain an accurate and reliable index and to determine the most compatible method for this purpose. Therefore, the results obtained from AHP-IWQI and DEA-IWQI were compared among themselves and with different irrigation water quality assessment methods.

According to the comparison results of AHP-IWQI and DEA-IWQI efficiency values and water quality classes, the biggest differences at water classes were observed in Bogazkoy, Güzelyurt, and Gulagac ponds and Mamasun dam. The water quality of Gulagac pond is classified as "good" in AHP-IWQI classification system and as "permissible" in DEA-IWQI classification system (Table 5). Similarly, while Bogazkoy and Güzelyurt ponds were classified as "excellent" in AHP-IWQI classification system, the water quality class

Table 5 Category-distribution for water samples

Irrigation water index	Sampling date	Category-rank for surface waters			
		Excellent	Good	Permissible	Unsuitable
AHP-IWQI	May 2018	Ciftevi, Bogazkoy, Helvadere, Guzelyurt, Balci, and Kepir ponds	Sariyahsi and Gülagac ponds and Mamasun dam	Bozkir pond	–
	September 2018	Ciftevi, Bogazkoy, Sariyahsi, Helvadere, Guzelyurt, Balci, and Kepir ponds	Gülagac pond and Mamasun dam	Bozkir pond	–
DEA-IWQI	May 2018	Helvadere, Balci and Kepir ponds	Ciftevi, Bogazkoy, Sariyahsi, and Guzelyurt ponds and Mamasun dam	Gülagac and Bozkir ponds	–
	September 2018	Ciftevi, Helvadere, Balci, and Kepir ponds	Bogazkoy, Sariyahsi, and Guzelyurt ponds and Mamasun dam	Gülagac and Bozkir ponds	–
United States Salinity Laboratory (USSL) salinity diagram	Classification	C1S1	C2S1	C3S1	C4S1
	May 2018	Balci pond	Ciftevi, Bogazkoy, Sariyahsi, Helvadere, Guzelyurt, and Kepir ponds and Mamasun dam	Gülagac and Bozkir ponds	–
	September 2018	Balci pond	Ciftevi, Bogazkoy, Sariyahsi, Helvadere, Guzelyurt, Kepir, and Gulagac ponds and Mamasun dam	Bozkir pond	–

of these ponds was defined as "good" in DEA-IWQI classification system during both sampling periods. Balci, Kepir and Helvadere ponds were classified as "excellent" in both indexes during all sampling periods, while Bozkir pond was categorized as "permissible" ve and water quality classes of the ponds had not changed.

In AHP-IWQI, it is seen that the weight of the criteria having a high efficiency score increases and the weight of the criteria having a low efficiency score decreases. Thus, while AHP-IWQI brought ponds into one top category towards "good" class, DEA-IWQI pushed ponds further down and classified them into one subcategory. Making a separate comparison of each DMU in the DEA-IWQI index with the other DMUs may also be the cause of the difference between the indexes. Another reason for this difference may be the selection of input and output parameters used in the production of DEA-IWQI.

When the water quality classes of the ponds were evaluated by the United States Salinity Laboratory (USSL) salinity diagram, it was observed that Balci pond with low sodium and low salt content had very good quality irrigation water, whereas Bozkir pond having high salt was classified as suspicious-usable water.

The other ponds were classified as good irrigation waters with medium salt and low sodium content. When the irrigation water quality classes of the ponds were evaluated with the Wilcox (1948) diagram, it was determined that all of the waters were classified as very good-good and good-usable. The results obtained from the USSL salinity diagram seem to be more compatible with DEA-IWQI index results.

In the DEA-IWQI index, the major factor in the classification of Gulagac pond as "permissible" is that the Gulagac pond has higher EC values than the other ponds. Considering that the efficiency scores of SAR and EC parameters are the highest efficiency scores affecting water quality, it can be concluded that; the DEA-IWQI index has produced more accurate and reliable results than the AHP-IWQI index.

3.6 Discussion of Conceptual AHP and DEA Models

AHP has a structure that simplifies complex problems and allows the decision-maker to measure the degree of consistency of their judgements. However, AHP does not take into account the uncertainties that may exist about the decision, criteria, and options in the

assessments made; this judgment may have a significant effect on the decision to be made (Cheng 1996). Decision-makers' preferences in AHP are generally not linearly related to data (Sánchez 2015). Another weakness in AHP is the differences of opinion among experts on the priority values assigned to the criteria for establishing binary comparison matrices (Ghorbanzadeh et al. 2018b). The biggest difference between AHP and DEA is that DEA compares and evaluates not only criteria but also the alternatives among themselves.

DEA is a type of modeling that achieves a certain result based on a particular mathematical calculation method. It is not based on estimation or probability and is a deterministic model since it does not contain uncertainty (Yun et al. 2004). In the DEA method, when measuring the efficiency of decision-making units by using input and output values, the production function does not need to be known (Boussofiane et al. 1991). DEA is a nonparametric model that does not rely on the assumption that there is any functional relationship between inputs and outputs (Cheng et al. 2007). However, water quality data and evaluations are parametric, because the increase in Na^+ value causes an increase in values such as EC, TDS, and SAR. There is a linear function between EC and TDS values. Cl^- values are another parameter that affects TDS and EC values linearly. Although the DEA-IWQI produced in this scope of study differs from the basic theoretical characteristics of the DEA method, the success rate of the results obtained from the DEA-IWQI is quite high.

One of the main characteristics of DEA is that, the decision units are wanted to be more than the number of inputs and outputs in order for the model's ability to decompose effectively and reliably. However, the selected input and output elements must be used for each decision unit. Within the scope of this study, the number of decision units evaluated was selected as 10 and the total number of inputs and outputs were selected as 11. At the same time, positive values are used for inputs and outputs in DEA models. It is generally accepted that inputs and outputs have positive values in DEA applications (Bowlin 1998). In this study, some RSC data being negative, used in the calculation of efficiency scores, did not affect the success rate of the model.

Although some of the fundamental features of DEA which were developed in theory have been ignored, the results from DEA-IWQI are quite successful. This may be due to the use of completely numerical data as input and output values. Since DEA is specifically developed

for administration and economic studies, these limitations identified for DEA can be ignored in the numerical data analysis used in water quality studies. The results obtained from this study are proof of this. This study also showed that successful results can be obtained from a theoretically nonparametric model by using parametric data.

4 Conclusions

In this study, water qualities of important dams and ponds used for irrigation purposes in Aksaray province were investigated with the help of multi-criteria decision-making techniques. For this purpose, two different irrigation water quality indexes (AHP-IWQI and DEA-IWQI) and two different classification systems were produced by using AHP and DEA techniques. The hierarchical structures of the indexes are based on the selection of important criteria affecting the irrigation water quality, determination of the quality ranges of the criteria and calculation of the efficiency scores of the criteria. The hierarchical structure was established by using hydrogeochemical data of 10 different water resources by taking the opinions of 15 different scientists who are experts in water quality about irrigation water standards developed by organizations such as FAO, TSI, and U.S. Salinity Laboratory. Electrical conductivity and sodium adsorption ratio with the highest efficiency scores have been determined as the most important criteria affecting irrigation water.

In order to determine the irrigation water quality, irrigation water classification systems developed by using efficiency scores obtained from AHP-IWQI and DEA-IWQI were divided into four different water quality classes. These quality classes were defined as excellent, good, permissible, and unsuitable. In the classification system of both indexes, Balci, Kepir, and Helvadere ponds were classified as "excellent" and Bozkir pond was classified as "permissible." The results were found to be largely compatible with world-accepted and widely used diagrams developed by United States Salinity Laboratory (USSL) and Wilcox (1948) and hydrogeochemical data. As a result, AHP-IWQI and DEA-IWQI are easy-to-use indexes that can produce reliable results for assessing irrigation water quality.

In this study, although some limitations of basic methodology of DEA were ignored, the DEA technique

has gained more successful results than the AHP technique in determining the quality of irrigation water. The DEA technique is a technique that can produce more useful and reliable results than the AHP technique when the right parameters are selected in terms of determining irrigation water quality and producing water quality index.

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