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ORIGINAL ARTICLE

Proposing a novel method for the irrigation water quality assessment, using entropy weighted method, entitled: "EIWQI"

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Abstract

In the pursuit of advancing water quality assessment methodologies, particularly for the purposes of irrigation, it is of utmost importance to enhance our understanding of water quality to effectively manage water resources. Recognizing this necessity, our study introduces the application of the Entropy method, for the first time, in the assessment of irrigation water quality in the Urmia plain groundwater resources. The approach coined as entropy weighted irrigation water quality index (EIWQI) has been devised. Key indicators of irrigation water quality, namely, Sodium Absorption Ratio (SAR), Residual Sodium Carbonate (RSC), Sodium percentage (Na%), Total Hardness (TH), and Electrical Conductivity (EC), were calculated for 69 groundwater samples, alongside the determination of major ions present in the groundwater, including Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, $So4_2^{-}$, Cl^{-}, HCo_3^{-}, and CO_3^{2-}. Subsequently, the water quality index was quantified through the implementation of the entropy weighted method. The proposed EIWQI enables the classification of irrigation water quality into four categories: excellent, good, doubtful, and unsuitable. Following the application of the EIWQI to the aforementioned data points, the groundwater of the study area was categorized as good (42.02%), doubtful (52.17%), and unsuitable (5.79%). To assess the accuracy of the proposed methodology, the EIWQI calculation results were compared with the SAR, Na%, and RSC values obtained from the sample points, as well as their fuzzy overlay outputs. Performance criteria such as Mean Absolute Deviation (MAD), Mean Absolute Percentage Error (MAPE), Mean Square Error (MSE), and Root Mean Square Error (RMSE) were utilized, all of which substantiated the accuracy of the model, yielding values of 0.217, 8.574, 0.217, and 0.466, respectively. These results underscore the precision and applicability of the proposed methodology.

Keywords Entropy method · Irrigation · Water quality index · EIWQI · Fuzzy Overlay

Introduction

The sustainable development of nations relies crucially on the availability of natural resources, particularly water resources encompassing both surface and groundwater. Amongst various water consumers, drinking and irrigation represent the foremost demands, globally depleting groundwater reserves, especially within arid and semi-arid regions (Siebert et al. 2010). However, groundwater resources face multiple challenges, imperiling their ongoing viability, including the pervasive influences of climate change and anthropogenic activities (Burri et al. 2019; El Asri et al. 2019; Hou´em´enou et al. 2020; Azzirgue et al. 2022; Docheshmeh Gorgij et al. 2023). These aforementioned factors commonly exacerbate water quality degradation, rendering it unsuitable for drinking and/or irrigation purposes, consequently hindering socio-economic progress.

Given the significance of monitoring and assessing water quality for contamination control and reduction (Chowdury et al. 2019; Zhu et al. 2019; Rahman et al. 2020; Chidambaram et al. 2022), the adoption of cutting-edge methodologies becomes essential. Consequently, numerous approaches have been employed, yielding favorable outcomes in evaluating groundwater quality. Notably, index-based, statistical, and geographic-based approaches have emerged as prominent methodologies for assessing and visualizing groundwater quality (Das et al. 2020; El Mountassir et al. 2020; Gao

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et al. 2020; Jahin et al. 2020; Wu et al. 2020; Chidambaram et al. 2022; Docheshmeh Gorgij et al. 2023).

The Water Quality Index (WQI) stands as an extensively employed approach in the field, illustrating the degree of water quality suited for various applications. Numerous investigations have incorporated the use of WQI in conjunction with multivariate statistical methods to assess the quality of both surface and groundwater. This practice has been observed in several notable studies, including those conducted by Lee et al. (2022), Multu and Kurnaz (2018), Multu and Uncumusaoglu (2018), Multu and Uncumusaoglu (2022), Maity et al. (2022), Uncumusaoglu and Multu (2021), and Uncumusaoglu and Multu (2022). Within the realm of WQI, Meireles et al. (2010) introduced an innovative variant known as the Irrigation Water Quality Index (IWQI), employed specifically for the assessment of water used in irrigation, adhering to various guidelines established by international organizations, such as Ayers and Westcot (1985).

Multiple studies have examined the integration of the conjugated form of the Improved Water Quality Index (IWQI) method with various approaches, thereby reducing the inherent subjectivity of IWQI performance. Notably, Simsek and Gunduz (2007) devised an IWQI framework for the Simav Plain in Turkey, in which the irrigation water quality was classified into three distinct categories: low, medium, and high quality. Furthermore, Singh et al. (2018) incorporated Saaty's Analytic Hierarchy Process (SAHP) into IWQI, thereby augmenting the evaluation process. Exploiting the capabilities of Geographic Information System (GIS), coalesced with IWQI, numerous scholars such as Batarseh et al. (2021), Çadraku (2021), Passos et al. (2019), Akter et al. (2016), and Al-Hadithi et al. (2019) studied water quality specifically with regard to irrigation purposes. In addition to conventional methods used in Water Quality Index (WQI) assessment, there has been a surge in the utilization of artificial intelligence techniques to enhance WQI accuracy. Recent studies by Docheshmeh Gorgij et al. (2023), Chidambaram et al. (2022), Valentini et al. (2021), Bui et al. (2020), and Ahmed et al. (2019) exemplify this growing trend.

The calculation of the Irrigation Water Quality Index (IWQI) has been conducted for numerous regions, primarily focusing on specific individual parameters, such as the major ions of water, electrical conductivity (EC), sodium adsorption ratio (SAR), and others. However, there has yet to be a comprehensive incorporation of all relevant parameters into the IWQI assessment. This present study concentrates on the integration of pertinent and widely applicable parameters in the evaluation of IWQI, surpassing their heterogeneous dimensions and units through the utilization of Entropy weighted calculations. Initially introduced by Shannon in 1948, the concept of entropy (Li et al. 2010) has since been extensively employed in various research endeavors (Li et al. 2010; Amiri et al. 2014; Docheshmeh Gorgij et al. 2019). However, its application in water quality assessment has primarily been limited to drinking water quality evaluations. For the very first time, this study employs the Entropy method in the assessment of irrigation water quality, thereby proposing the Entropy Weighted Irrigation Water Quality Index (EIWQI).

Materials and methods

The evaluation of water suitability for irrigation purposes relies on several parameters and indices put forth by diverse organizations and agencies. In this investigation, our emphasis lies on the quantification of parameters such as Electrical Conductivity (EC), Total Hardness (TH), Sodium Absorption Ratio (SAR), Residual Sodium Carbonate (RSC), and Na^+ percentage (Na%) through the following determinations:

Electrical conductivity (EC)

Electrical conductivity (EC) denotes the extent to which water is capable of transmitting an electrical current. This property is contingent upon the abundance and intensity of dissolved ions, alongside the water's temperature profile.

Sodium adsorption ratio (SAR)

SAR for the first time was computed by Richards (1954), Its explanation can be found below:

$$\mathrm{SAR} = \frac{\mathrm{Na}^+}{\sqrt{\frac{\mathrm{Ca}^{2+}+\mathrm{Mg}^{2+}}{2}}}. \tag{1}$$

As the Specific Absorption Rate (SAR) value increases, there is a noticeable reduction in the hydraulic conductivity of the soil, leading to a subsequent decline in irrigation effectiveness. Adhering to the guidelines set forth by the World Health Organization (WHO 2011) and the Food and Agriculture Organization (FAO 2017), it is considered unsuitable for irrigation purposes when the SAR value exceeds 10.

Sodium percentage (Na%)

Since the high quantity of sodium percentage disrupts the soil texture same as SAR, it could be assumed as a key factor in irrigation water quality evaluation, and can be computed as follows:

$$\mathrm{Na}\% = \frac{(\mathrm{Na}^{+} + \mathrm{K}^{+}) \times 100}{(\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+} + \mathrm{Na}^{+} + \mathrm{K}^{+})}. \tag{2}$$

Residual sodium carbonate (RSC)

When the summation of $\mathrm{HCO}^{-}{}_{3}$ and $\mathrm{CO}^{2-}{}_{3}$ concentration exceeds the of Ca^{2+} and Mg^{2+} concentration, Ca^{2+} and Mg^{2+} will precipitate in soil. Richards (1954) calculated the RSC index which can be expressed as below:

$$\mathrm{RSC} = (\mathrm{HCo}_3^{-} + \mathrm{Co}_3^{-2}) - (\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+}). \tag{3}$$

Total hardness (TH)

TH is stated as the molar concentrations of entire multivalent cations in water:

$$\mathrm{TH} = \sum \text{multivalent cations}. \tag{4}$$

However, the summation of calcium and magnesium concentration is used instead of that, practically:

$$\mathrm{TH} \approx \mathrm{Ca}^{2+} + \mathrm{Mg}^{2+}. \tag{5}$$

Table 1 summarizes the abovementioned parameters and their criteria for the groundwater quality.

Entropy method

Entropy is a fundamental concept that quantifies the degree of stochasticity inherent in a given occurrence. In this study, we adopt a method proposed by Guey-Shin et al. (2011) to assess the mathematical randomness of an event. The EIWQI measurement consists of several distinct phases as outlined below:

First, we consider a matrix denoted as the eigenvalue matrix, X, which captures the irrigation water quality data for m samples and n parameters. The specific formulation of this matrix is elaborated upon in the subsequent formula:

$$X = \begin{bmatrix} X_{11} & \cdots & X_{1n} \\ \vdots & \cdots & \vdots \\ X_{m1} & \cdots & X_{mn} \end{bmatrix}. \tag{6}$$

Since the parameters for irrigation water quality have different units, they should be normalized, to eliminate the existed error, the normalized matrix, hence, is as below:

$$Y = \begin{bmatrix} Y_{11} & \cdots & Y_{1n} \\ \vdots & \vdots & \vdots \\ Y_{m1} & \cdots & Y_{mn} \end{bmatrix}. \tag{7}$$

The value of each parameter, i.e., P_j, in each sample, i.e., i, could be calculated as follows:

$$P_{ij} = Y_{ij} \Big/ \sum_{i=1}^{m} Y_{ij}. \tag{8}$$

The information entropy, e_j, then, can be calculated as below:

$$e_j = -\frac{1}{\ln m} \sum_{i=1}^{m} P_{ij} \ln P_{ij}. \tag{9}$$

The higher the quantity of entropy, the lesser is the effectiveness of P_j. for each parameter there is a weigh in entropy form, ω_j, afterwards, which can be calculated as follows:

$$\omega_j = \frac{1 - e_j}{\sum_{j=1}^{n} (1 - e_j)}. \tag{10}$$

The qualitative rating scale q_j for each parameter can be determined as below:

$$q_j = \frac{C_j}{S_j} \times 100 \tag{11}$$

where C_j and S_j are the concentration of parameter and standard value of that, respectively, based on irrigation water quality guidelines. In the present study, the standards, introduced by scholars in Table 1 has been used. The final step of EIWQI calculation will be as follows:

Table 1 Classification of the effective parameters in irrigation water quality

	Excellent	Good	Doubtful	Unsuitable
TH (Sawyer and McCarty 1978)	< 75	75–150	150–300	> 300
EC (Wilcox 1955)	< 250	250–750	750–5000	> 5000
SAR (Richards 1954)	< 10	10–18	18–26	> 26
Na% (Wilcox 1955)	0–20	20–40	40–80	> 80
RSC (Richards 1954)	< 1.25		1.25–2.5	> 2.5

Table 2 Entropy weighted irrigation water quality ranking

EIWQI	Rank	Index
Excellent	1	< 50
Good	2	50–100
Doubtful	3	100–200
Unsuitable	4	> 200

$$\mathrm{EIWQI} = \sum_{j=1}^{n} \omega_j q_j. \tag{12}$$

The groundwater quality, considering the derived EIWQI can be categorized in four levels, which can be seen in Table 2.

Study area

The study site encompasses a portion of Urmia plain, situated on the western side of Urmia Lake (Fig. 1). A significant proportion, exceeding 60 percent, of the groundwater reservoirs in this region are currently allocated for irrigation purposes (Amiri et al. 2016). In terms of climate, Urmia plain exhibits Mediterranean characteristics, characterized by an average annual temperature of 17 °C and an annual precipitation of 346mm (Amiri et al. 2017). Urmia city, serving as the capital of West Azerbaijan, along with its surrounding residential areas, accommodates a substantial population that is predominantly engaged in the field of agriculture. This locale holds utmost agricultural significance within Iran, thus resulting in an immense demand for groundwater usage specifically for irrigation. Therefore, it remains imperative to effectively monitor and assess the water resources within this area, considering the extensive extraction of groundwater and the potential alterations in its quantity and quality.

Performance evaluation of proposed method

To evaluate the efficacy of the presented methodology in examining the quality of irrigation water, a comprehensive analysis was carried out utilizing established statistical parameters. These parameters, namely, the Mean Absolute Deviation (MAD), Mean Absolute Percentage Error (MAPE), Mean Square Error (MSE), and Root Mean Square Error (RMSE), were employed to gauge the performance of the proposed approach. These statistical indicators can be described mathematically as follows:

$$\mathrm{MAD} = \frac{\sum_{i=1}^{n} \left| X_{o,i} - X_{p,i} \right|}{n} \tag{13}$$

$$\mathrm{MSE} = \frac{\sum_{i=1}^{n} \left(X_{o.i} - X_{p,i} \right)^2}{n} \tag{14}$$

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} (X_{o,i} - X_{p,i})^2}{n}} \tag{15}$$

$$\mathrm{MAPE} = \left(\frac{\sum_{i=1}^{n} \left| \frac{X_{o,i} - X_{p,i}}{X_{o,i}} \right|}{n} \right) * 100 \tag{16}$$

where $X_{o,i}$ and $X_{p,i}$ are the observational and predicted parameter which is EIWQI here, while n is the number of samples.

Results and discussion

Understanding the quality of groundwater is of utmost importance, as it serves as a primary determinant for various purposes, including drinking water and agricultural applications (Ghalib 2017). Although water resources can be contaminated due to anthropogenic activities, natural processes also have the potential to alter its quality (Ismail et al. 2015). To assess the quality of water, a comprehensive investigation can be conducted, focusing on the major ions present in the water (Ismail et al. 2020). To gain a holistic understanding of groundwater and its hydrochemistry for diverse applications, sophisticated graphical representations such as the US salinity diagram, Wilcox diagram, and Piper diagram can be employed (Ghalib 2017).

The trilinear diagram devised by Piper (1944) serves as a valuable tool for providing explicit insights into water quality conditions. Accordingly, the present study adopts this diagram to comprehensively discern the hydro-chemical classification and facies of groundwater samples within the designated area. As illustrated in Fig. 2, the piper diagram effectively represents the hydro-chemical attributes of the study region. Analysis of the piper diagram elucidates that the principal composition of groundwater in the study area is characterized by Ca^{2+}–Mg^{2+}–$\mathrm{HCO}^{-}{}_{3}$. Specifically, the dominant cations comprise Ca^{2+} and Mg^{2+}, while $\mathrm{HCO}^{-}{}_{3}$ emerges as the prevailing anion. Remarkably, the concentrations of Ca^{2+} and Mg^{2+} in the groundwater considerably outweigh those of Na^{+} and K^{+}. Furthermore, the $\mathrm{HCO}^{-}{}_{3}$ concentration in the groundwater surpasses that of Cl^{-} and $\mathrm{SO}_4{}^{2-}$ to a significant extent.

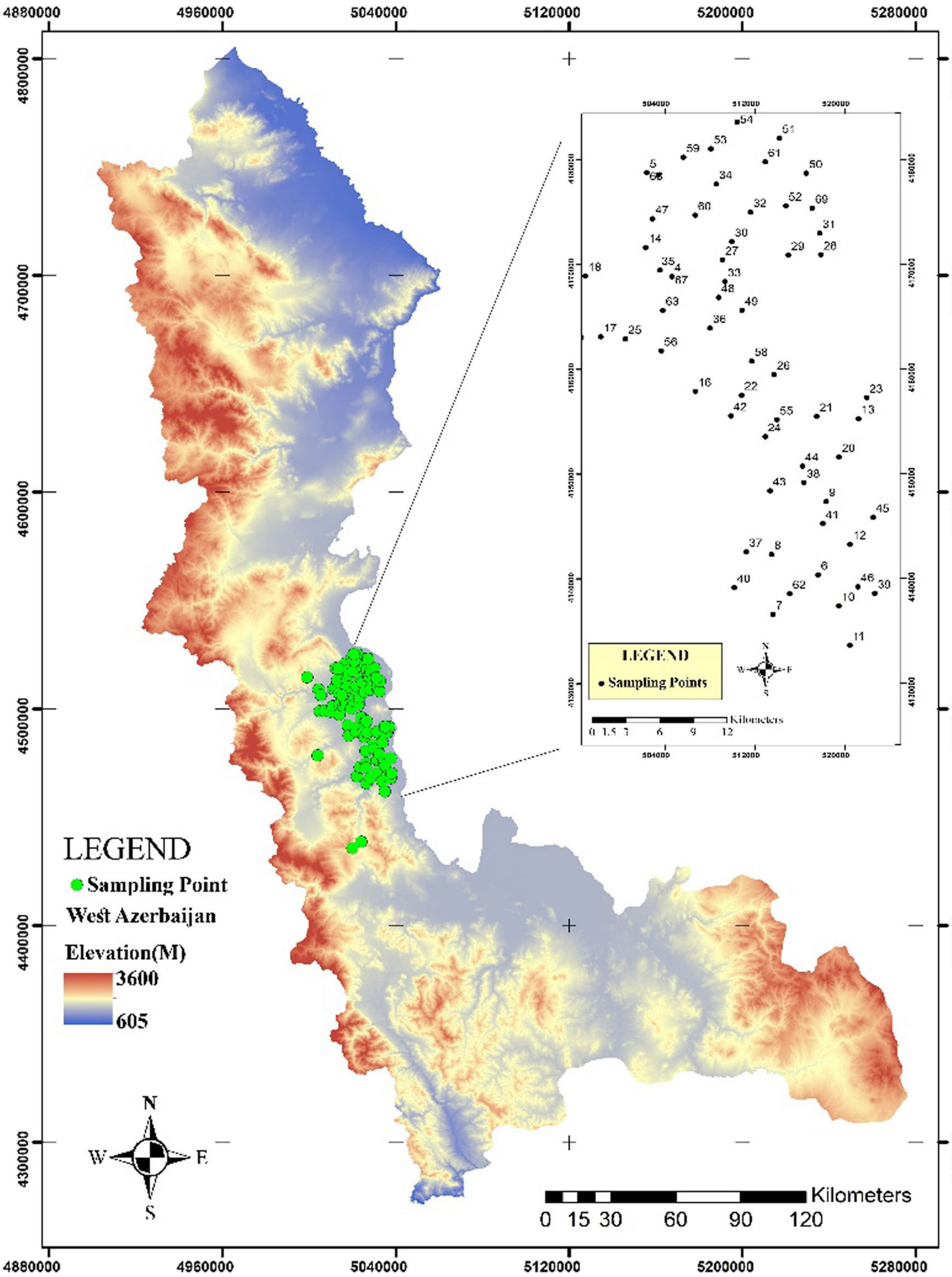


Fig. 1 Location of the study area and sampling points

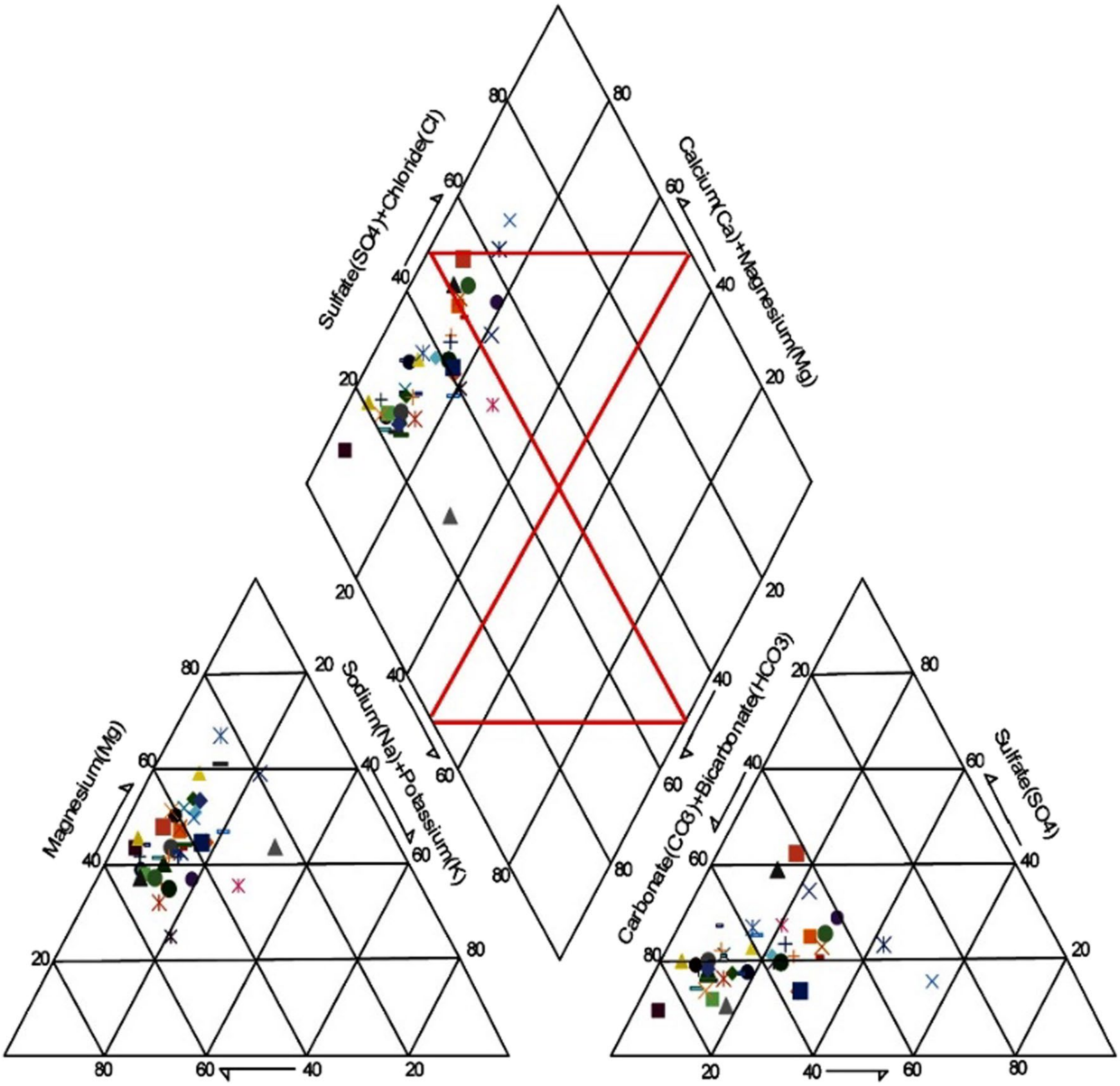


Fig. 2 Piper diagram of the groundwater samples in the study area

Table 3 Statistics of major ions and irrigation water quality parameters in the study area

	EC	K^+	Na^+	Mg^{2+}	Ca^{2+}	Co^{2-}_3	HCO^-_3	Cl^-	So^{2-}_4	SAR	Na%	RSC	TH
Average	939.1	9.08	181.42	357	462	0.006	656.85	136.42	218.57	12.41	17.66	162.1	409.5
Maximum	2230	20	770	1160	1030	0.23	1350	650	870	57.97	54.54	170	950
Minimum	370	1	20	110	150	0	340	10	30	2	4.9	– 970	155
Std	388.8	5.395	149.4	211.7	160.1	0.032	203.8	126.4	167.7	9.314	8.699	175.3	163.7

To have a better insight about the major ion distribution of the study area in addition to irrigation water quality parameters, i.e., SAR, Na%, RSC, TH and EC, Table 3 shows the statistics of major ions and irrigation water quality parameters.

Based on the data presented in Table 3, it can be observed that the most influential ions in the study area are calcium (Ca^{2+}), magnesium (Mg^{2+}), and bicarbonate (HCO^-_3) with average concentrations of 462 mg/l, 357 mg/l, and 657 mg/l, respectively. The elevated levels of

Ca^{2+} and Mg^{2+} contribute to water hardness, rendering it practically ineffective. The order of cations, arranged according to their concentration from greatest to least, is as follows: $Ca^{2+} > Mg^{2+} > Na^{+} > K^{+}$.

Regarding the anions in the groundwater samples, the abundance order in the study area is as follows: $HCO^{-}_{3} > SO_{4}{}^{2-} > Cl^{-}$, taking into consideration the average concentration. The substantial fluctuations in standard deviation for the anions indicate significant spatial variations among them. This sizable variability might be indicative of a considerable presence of anthropogenic activities within the study area (Wu et al. 2020). Moreover, HCO^{-}_{3} can react with Ca^{2+} or Mg^{2+} to form calcium carbonate ($CaCO_3$) or magnesium carbonate ($MgCO_3$), respectively. As a result, these two byproducts precipitate in water and soil, thus reducing the porosity of the soil texture. Furthermore, electrical conductivity (EC) exhibits a notable range, spanning from 370 to 2230, along with a high degree of standard deviation. This suggests a wide spectrum of water quality. The average EC measures approximately 939, which signifies good suitability for irrigation purposes. In contrast, the total hardness (TH) considerably exceeds the standard limits, varying between 155 and 950, whereas excellent and good quality thresholds for TH are lower than 150. Consequently, the water quality beyond this range becomes questionable or inadequate. Moreover, the sodium adsorption ratio (SAR), a crucial parameter in assessing water quality for irrigation, ranges from 2 (excellent) to 57.97 (unsuitable). The sodium percentage (Na%) in the study area varies from excellent to doubtful, ranging from 4.9 to 54.54 while exhibiting a relatively normal standard deviation. The residual sodium carbonate (RSC) parameter undergoes dramatic fluctuations, ranging from -970 to 170, primarily due to varying concentrations of HCO^{-}_{3} and the combination of Ca^{2+} and Mg^{2+}. Notably, the water samples display an elevated concentration of Ca^{2+} and Mg^{2+}. The distribution of SAR, Na%, RSC, EC, and TH in the study area is depicted in Fig. 3.

Given the plethora of variations observed in the SAR, Na%, RSC, EC, and TH values, each with its distinct distribution, a decision has been made to combine these variables using the fuzzy method. This approach aims to mitigate uncertainties and minimize errors encountered when generalizing different parameters across the entire study area. As demonstrated in Table 4, the evaluation of individual parameter generalizations in the study area depicts a pronounced degree of error. As a consequence, the resulting uncertainty becomes considerably elevated.

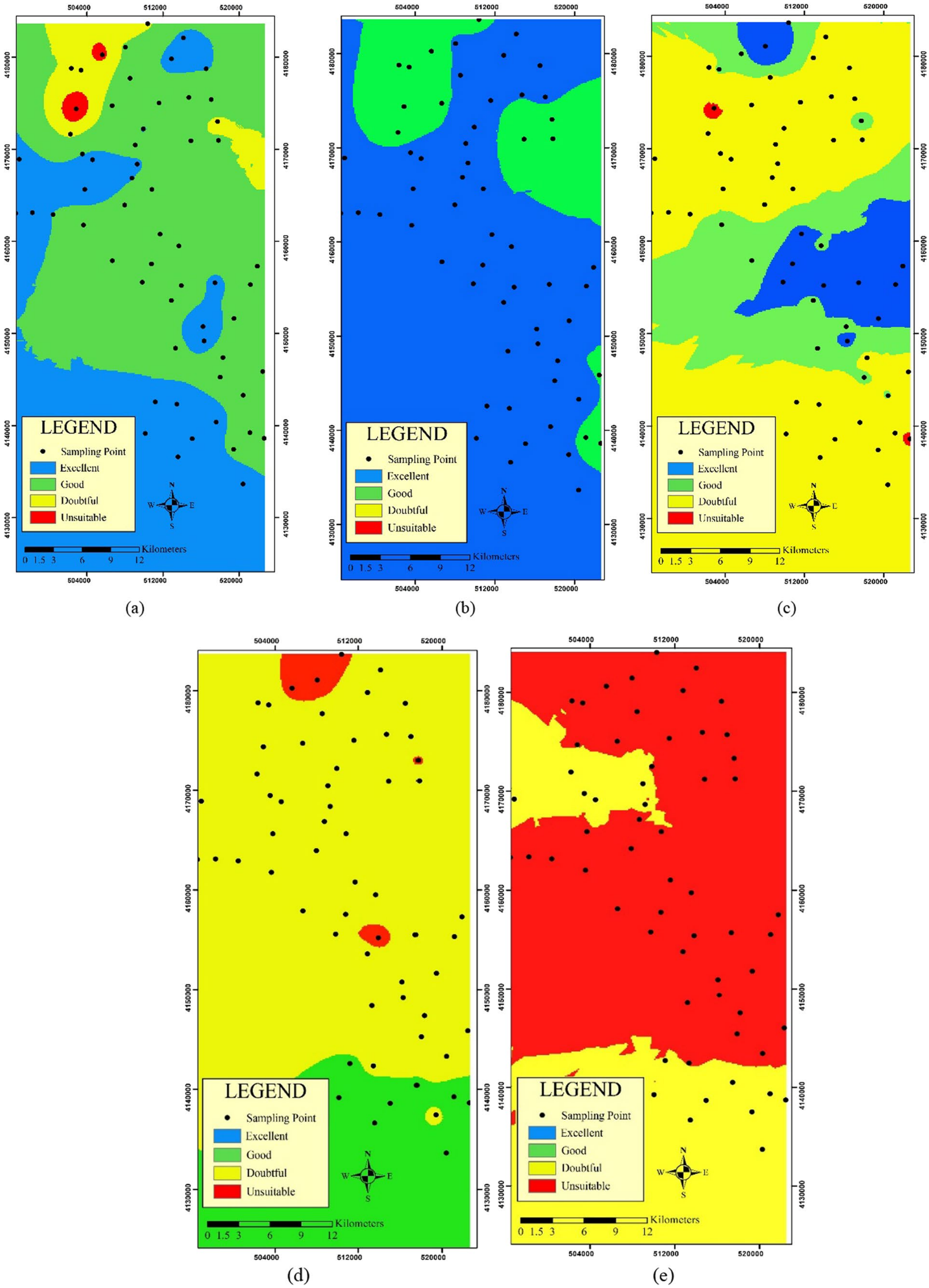
Figure 4 shows the deriving map of overlayed EC, TH, SAR, Na% and RSC maps (Fig. 4a) besides the resulted map of entropy weighted method (Fig. 4b), proposed in present study.

As illustrated in Fig. 4, a notable resemblance in the results can be observed between the conventional fuzzy overlay method and the proposed method, namely, the Entropy-based Integrated Water Quality Index (EIWQI). Consequently, it can be inferred that the EIWQI approach can be astutely employed to expedite the process and reduce associated costs, rather than independently plotting numerous parameters and constructing a fuzzy overlayed map for quality assessment across the study area. Of noteworthy significance is the fact that if any water quality parameter for irrigation in a given water sample surpasses the defined thresholds, the groundwater from the same sample is deemed unsuitable for irrigation, even if other parameters conform to the limits. This implies that while certain groundwater samples may appear suitable for irrigation based on a specific parameter (such as the Sodium Adsorption Ratio or SAR), they may be unsuitable based on other parameters (such as Electrical Conductivity or EC). Consequently, the groundwater overall is generally rendered unsuitable for irrigation. Nevertheless, it should be acknowledged that the entropy method, by assigning weightage to each parameter accordingly, engenders normality and nullifies discrepancies among them while concurrently reducing uncertainties.

Figure 5 illustrates a comparison of the water quality levels across 69 water samples within the study area. The *X*-axis denotes the sample numbers, ranging from 1 to 69, while the *Y*-axis represents the quality grades assigned to each water sample. Here, a grade of 1 signifies excellent quality, grades 2, 3, and 4 represent good, doubtful, and unsuitable water quality for irrigation purposes, respectively.

Table 5 shows the performance evaluation of EIWQI method, in comparison with fuzzy overlay method of irrigation water quality parameters.

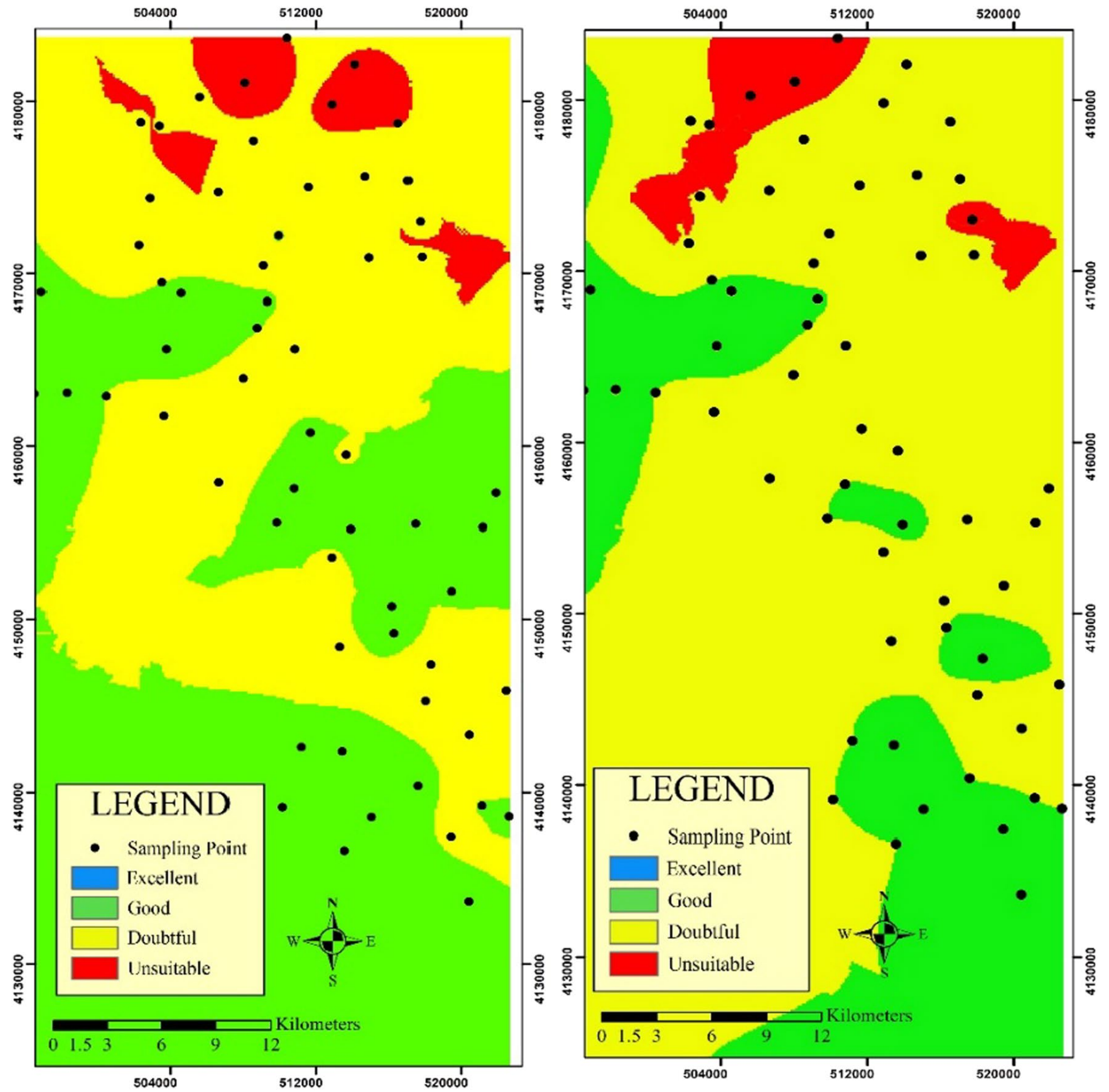
Based on the results of the performance assessment, the present study makes a conclusive observation that the EIWQI method is a viable approach. This method has demonstrated the potential to minimize the uncertainty associated with calculating various parameters by undertaking the normalization and amalgamation of all relevant factors. Notably, the overall uncertainty presented by this method is shown to be lower than the individual uncertainties associated with each parameter.



(a) (b) (c)

(d) (e)

Fig. 3 SAR (**a**), Na% (**b**), RSC (**c**), EC (**d**) and TH (**e**) distribution in the study area



(a) (b)

Fig. 4 Fuzzy overlayed map (**a**) and proposed EIWQI map (**b**)

Conclusion

Determining the quality of water for various purposes, particularly for irrigation, is imperative, particularly in arid and semi-arid regions, such as Iran. Therefore, it is crucial to explore innovative and practical approaches to accomplish this objective. The present investigation has revealed that the effectiveness of the Water Quality Index (WQI) model can be enhanced through the inclusion of an entropy assessment, resulting in an improved ranking system for water quality. Furthermore, this study has demonstrated that the application of the entropy method is a valuable technique for augmenting comprehension of water quality concerns.

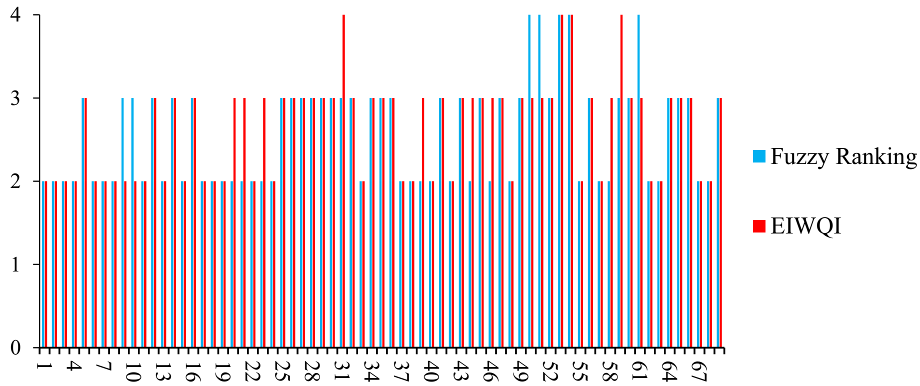


Fig. 5 Comparison between the EIWQI and Fuzzy ranking

Table 4 Performance evaluation criteria

	MAD	MSE	RMSE	MAPE
SAR	1.014493	1.362319	1.167184	79.95169
Na%	1.362319	2.26087	1.503619	126.57
RSC	1.594203	2.898551	8.401596	156.1594

Table 5 Performance evaluation criteria for the proposed method

	MAD	MSE	RMSE	MAPE
EIWQI	0.217391	0.217391	0.466252	8.574879

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Data availability Not available.

Declarations

Competing interests The authors declare no competing interests.

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