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# Application of Entropy Weighted Water Quality Index and Physicochemical Indices to Evaluate Groundwater Quality in Damghan Plain

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In this study, the Entropy Weighted Water Quality Index (EWQI) was used to assess the groundwater suitability for drinking purposes in Damghan Plain, Iran. This index has been known as the most unbiased model for assessing drinking water quality. Additionally, physicochemical indices including Sodium Adsorption Ratio (SAR), Magnesium Hazard (MH), Kelley's Ratio (KR), Salinity Hazard (SH), Synthetic Harmful Coefficient (K), Potential Salinity (PS), Total Dissolved Solids (TDS), Chloride ($Cl^-$), Permeability Index (PI) and Soluble Sodium Percentage (SSP) were used to evaluate the suitability of groundwater for irrigation purposes at August 2018 (dry season) and February 2019 (wet season). The results indicated that sodium ($Na^+$) and chloride ($Cl^-$) are exceeding the permissible limits based on WHO standards and $Cl^-$ has the highest entropy weight. EWQI maps illustrated that the groundwater has moderate quality in the western parts and poor quality in the eastern parts of the study area. The mean value of this index has decreased from 149.47 in August 2018, to 147.26 in February 2019, which reflects that the groundwater quality has been improved for drinking purposes. The values of SAR, KR, PI and SSP indices slightly increased, which indicated that the quality of groundwater has more deteriorated in terms of these indices. The mean value of MH, SH, K, PS, TDS and $Cl^-$ indices have slightly decreased during the study period. Finally, Land Use-Land Cover (LULC) map was used to show which groundwater consumption is appropriate with its quality. Groundwater in the urban areas has moderate and poor quality for drinking purpose and suitable quality in terms of SAR, K and PI and unsuitable in terms of MH, KR, SH, PS, TDS, $Cl^-$ and SPP in agricultural lands. The suitable condition in terms of SAR, K and PI is because of the high concentration of $Mg^{2+}$ and $Ca^{2+}$. Thus, groundwater is not suitable for irrigation in the agriculture sector.

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## 1. Introduction

Today, water resources play a vital role in economic, social developments and quality of life across the world. Human activities such as urbanization, and agricultural and industrial development are deteriorating the quality of these resources (Oki and Akana, 2016). However, decreasing water quality is one of the most important problems in recent century (Nair *et al*., 2015; Li *et al*., 2017).

In arid and semi-arid regions, groundwater resource is the most important source of fresh water for various requirements such as human consumption, agricultural and industrial purposes, due to lacking rainfall and surface water. Population growth and increasing use of these resources have caused depletion in groundwater levels and decreased its quality for various agricultural purposes (Asghari Moghaddam and Vadiati, 2016). Additionally, groundwater and its effects on humans' health and development are closely related in these regions. Therefore, if its quality is poor, caused by excessive application of fertilizers for instance, humans' health will be in danger (Pei-Yue *et al*., 2010) and this dependency has increased in the recent decades (Adimalla, 2020). Thus, this is the reason for a comprehensive assessment of the quality of groundwater for proper management of this important resource.

The groundwater quality is determined by some parameters from physical, chemical and biological aspects (Schriks *et al*., 2010). The concentration of some physicochemical parameters can affect its suitability for drinking, irrigation and industrial purposes. Therefore, it is necessary to be aware of the physical and chemical composition of groundwater to evaluate its usefulness for various purposes (Venkateswaran *et al*., 2011). Analyzing groundwater is important to employ a groundwater resource management strategy. Mapping spatial variation of various physicochemical compositions is essential to correctly develop the groundwater schemes and management, consequently (Manoj *et al*., 2017).

Various methods have been used to evaluate the quality of water over time. Traditional methods are often qualitative and cannot accurately describe its quality (Asghari Moghaddam and Vadiati, 2016). However, new water quality assessment methods have been increased, recently. One of the common methods for drinking purposes is Water Quality Index (WQI). This index is a numerical way to determine the suitability of water (Amiri et al., 2014) and considered in many parts of the world, due to its high capability in expressing water quality information and application of important and effective parameters in the evaluation of water quality (dos Santos Simões et al., 2008). A necessary step in this method is to assign a weight of each parameter which is determined by experts based on their experience, knowledge and discretion (Amiri et al., 2013). Therefore, assigning a correct weight for each parameter is required to take the maximum advantage of this index. There are various ways to determine the weight of the parameters, such as the entropy method. In this method, the weight of parameters determine based on their concentration and shows the relative importance of parameters in groundwater quality. This method provides the most unbiased, justifiable, accurate, and reliable analysis of groundwater quality. Combining WQI with the entropy method is a way to reduce the subjectivity errors while assigning the weight of water quality parameters (Peiyue et al., 2010). Entropy Water Quality Index (EWQI) is a model which provides unbiased, accurate and reliable analysis of groundwater quality by determining a suitable weight for each water quality parameter (Feng et al., 2019; Singh et al., 2019; Wang et al., 2019; Maskooni et al., 2020; Ukah et al., 2020;).

In terms of irrigation purposes, the water quality is supposing a significant necessity with the rising pressure on agriculture (Wijnen *et al*., 2012). For adopting a suitable plan for agricultural lands, an adequately understand the properties of water is needed and measurement of physicochemical parameters in water reservoir is necessary to achieve this aim. There are various indices to evaluate the quality of water, such as Sodium Adsorption Ratio (SAR), Magnesium Hazard (MH), Kelley's Ratio (KR), Salinity Hazard (SH), Potential Salinity (PS), Sodium Percentage (Na%) and Permeability Index (PI) which are widely used over the world (Sharma *et al*., 2017; Ememu and Nwankwoala, 2018; Jain and Vaid, 2018; Ghazaryan *et al*., 2019; He *et al*., 2019; Kahsay *et al*., 2019; Kumari and Rai, 2020; Singh *et al*., 2020).

Damghan Plain, Iran, is located in an arid region and surface water is limited, so the major source of fresh water is groundwater. Therefore, groundwater, as the only source of clean water, needs to be well-used. Thus, in the present study, the suitability of groundwater quality in Damghan Plain for drinking uses has been assessed by EWQI, as well as for the agricultural purposes using physicochemical characteristics and indices through GIS. Combining the groundwater data with GIS can provide suitable and effective results of groundwater conditions. As Damghan Plain has limited surface water resources, groundwater is the main freshwater resource, and it is essential to investigate the groundwater quality for proper management, thus in the present study the groundwater in this plain has been evaluated.

## 2. Materials and methods

### *2.1. Case Study*

Damghan Plain is located in Semnan province between 35° 51' and 36° 09' latitude and 54° 04' and 54° 26' longitude, with an area of 732.51 km$^2$. It is located in the south of the Alborz mountain range and north of the Kavir desert with an arid and semi-arid climate (Arabameri *et al*., 2019). The average temperature is 15.8 °C and the long-term annual average of precipitation is about 151 mm (Ashtiani *et al*., 2016). The elevation varies from 1309 meters (a.s.l.[1]) in the northwest to 1047 meters (a.s.l.) in the southeast. This plain, like other arid and semi-arid regions, is facing with water problem. The water supply is mostly through the groundwater resources (Parhizkar *et al*., 2015) which are mainly used for the agricultural purposes. Fig 1 shows the study area and location of piezometers and quality monitoring wells in Iran.

### *2.2. Methodology*

In this study, nine physicochemical parameters, including Sodium ($Na^+$), Calcium ($Ca^{2+}$), Magnesium ($Mg^{2+}$), Sulfate ($SO_4^{2-}$), Chlorine ($Cl^-$), Bicarbonate ($HCO_3^-$), Potential of Hydrogen (pH), Total dissolved solids (TDS), Electrical Conductivity (EC), and were used from 21 groundwater samples in Damghan Plain in August 2018 and February 2019. The data of groundwater quality were obtained from the Iran Water Resources Management Company. In Damghan Plain agricultural activities are started in February (wet season) and finished in August (dry season) and the groundwater is used during these activities and charged during the autumn season.

The quality of groundwater assessed for suitability in drinking adopting EWQI and agricultural purposes using physicochemical indices namely Sodium Adsorption Ratio (SAR), Magnesium Hazard (MH), Kelley's Ratio (KR), Salinity Hazard (SH), Synthetic Harmful Coefficient (K), Potential Salinity (PS), Total Dissolved Solids (TDS), Chloride ($Cl^-$), Permeability Index (PI) and Soluble Sodium Percentage (SSP) based on groundwater data.

In order to generate the maps of adopted indices, Inverse Distance Weighted (IDW) interpolation technique was employed in ArcMap 10.7. This technique is widely used by many researchers to assess the spatial distribution of groundwater physicochemical parameters (Kawo and Karuppannan, 2018; Rostami *et al*., 2019; Gnanachandrasamy *et al*., 2020; Verma *et al*., 2020; Zolekar *et al*., 2020). In this interpolation technique, the value of un-sampled cells is calculated using surrounding points (Prasanth *et al*., 2012).

[1] Above sea level

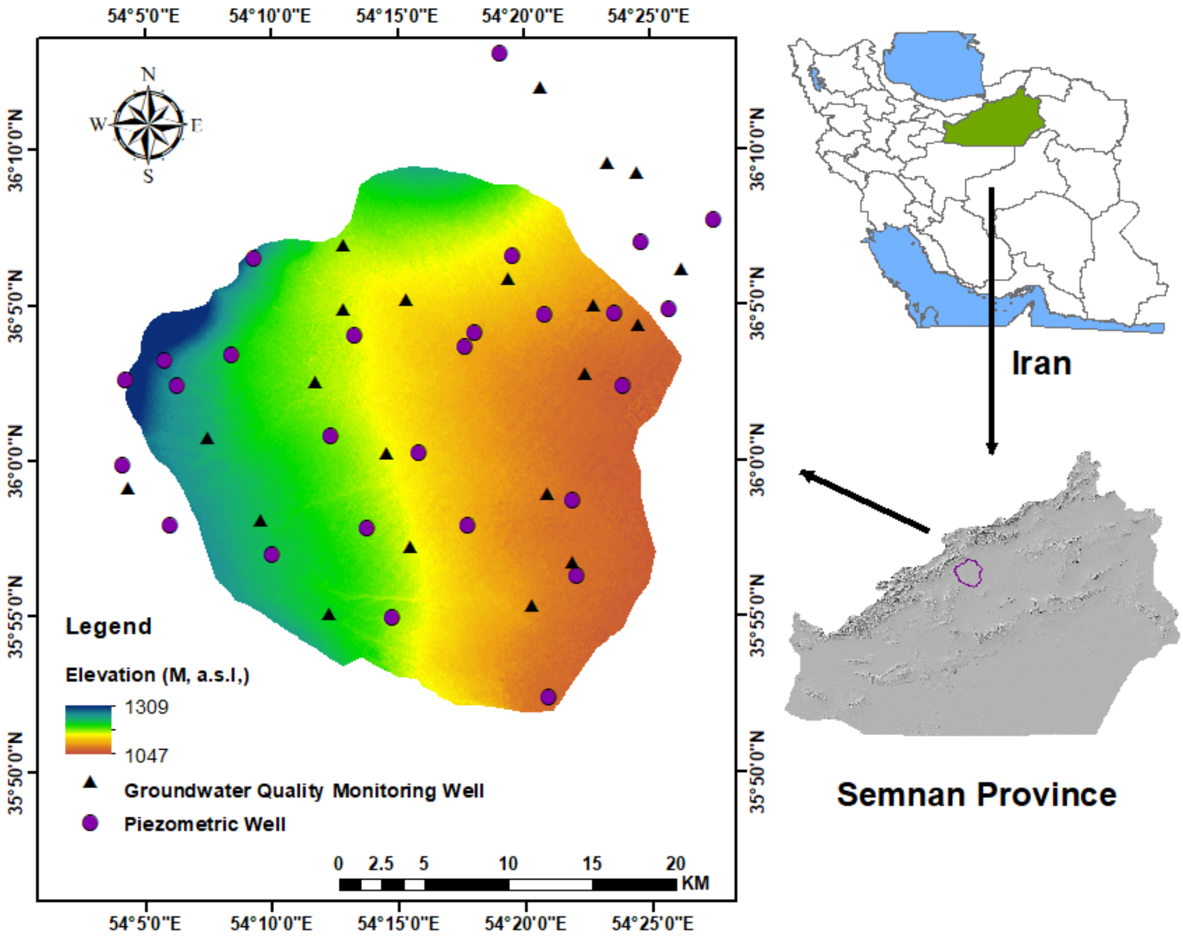


**Fig. 1.** Study area and location of piezometers and quality monitoring wells

*2.2.1. Entropy Weighted Water Quality Index*

WQI is widely used for evaluating groundwater suitability for drinking purposes, which its quality depends on physicochemical parameters (Liu *et al*., 2020). In calculation of WQI, the weights of each parameter are usually determined based on expert opinion, but recently, entropy theory has been used to compute the weight of water quality parameters (Egbueri *et al*., 2020; Maskooni *et al*., 2020; Ukah *et al*., 2020; Adimalla, 2021;). In this study, EWQI, which is presented by Pei-Yue *et al*. (2010), was used to assess the groundwater quality for drinking purposes. The concept of entropy was initially proposed by Shannon (1948) which expresses the uncertainty degree of a stochastic event (Amiri *et al*., 2014), or in other words, it shows how much an event can be stochastic (Gorgij *et al*., 2017).

EWQI provides an unbiased assessment of water quality considering all the measured parameters (Ukah *et al*., 2020) and its calculation is done in three steps including: calculating entropy weight, quality rating scale for each parameter and classification of the groundwater quality. In the first step, the performance matrix is constructed. The matrix ($X$) indicates a summary of physicochemical analysis data, as $m$ ($i = 1, 2, \dots, m$) denotes the number of wells that are monitored to assess groundwater quality based on $n$ ($j = 1, 2, \dots, n$) measured parameters. Thus, $x_{ij}$ is the value of $j^{th}$ parameter in the $i$th well.

Then, according to the analyzed data, matrix $X$ can be constructed as follows:

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \quad (1)$$

Since the groundwater quality parameters have different units, the normalized matrix will be computed using the efficiency type normalizing function as (Pei-Yue *et al.*, 2010);

$$y_{ij} = \frac{x_{ij}-(x_{ij})_{min}}{(x_{ij})_{max}-(x_{ij})_{min}} \quad (2)$$

Where $x$ is the value of $j$th parameter in the $i$th well and $(x_{ij})_{max}$ and $(x_{ij})_{min}$ are the maximum and minimum values of $j$th parameter, respectively.

Then, the $Y$ (normalized) matrix will be constructed as:

$$Y = \begin{bmatrix} y_{11} & y_{12} & \cdots & y_{1n} \\ y_{21} & y_{22} & & y_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ y_{m1} & y_{m2} & \cdots & y_{mn} \end{bmatrix} \quad (3)$$

The $j$th parameter index amount, in $i^{th}$ sample is calculated as;

$$P_{ij} = \frac{y_{ij}}{\sum_{i=1}^{m} y_{ij}} \quad (4)$$

Where $m$ represents the number of wells. In the next step, the entropy value of parameter $j$ is computed as follows;

$$e_j = -\frac{1}{\ln(m)} \sum_{i=1}^{m} P_{ij} \,.\ln P_{ij} \quad (5)$$

The less the value of $e_j$ is, the more effect the $j$ index will have (Pei-Yue *et al.*, 2010). The following step is to calculate the entropy weight for each parameter as;

$$w_i = \frac{1-e_j}{\sum_{j=1}^{n}(1-e_j)} \quad (6)$$

The second step to determine EWQI value is to compute the quality rating scale ($q_i$) for each parameter in every sample as;

$$q_i = \left(\frac{C_i}{S_i}\right) \times 100 \quad (7)$$

Where $C_i$ is the concentration of each physicochemical parameter in each groundwater sample in *mg/L* except for pH which is defenseless and $S_j$ is the standard of each parameter based on World Health Organization (WHO) Standards (Table 1).

The third step is to calculate EWQI as following formula;

$$EWQI = \sum_{j=1}^{n} w_i \,.\, q_i \quad (8)$$

Where $n$ is the number of groundwater quality parameters.

**Table 1.** Groundwater quality limitation for drinking purposes based on World Health Organization Standards (WHO, 2011)

| Parameter | Unit | WHO Standard |
|---|---|---|
| $Na^+$ | mg/L | 200 |
| $Mg^{2+}$ | mg/L | 50 |
| $Ca^{2+}$ | mg/L | 75 |
| $SO_4^{2-}$ | mg/L | 250 |
| $Cl^-$ | mg/L | 250 |
| $HCO_3^-$ | mg/L | 120 |
| pH | - | 6.5 – 8.5 |
| TDS | mg/L | 500 |

According to Pei-Yue *et al*. (2010), the groundwater quality based on EWQI is classified in five ranks for drinking purposes (Table 2).

**Table 2.** Groundwater quality ranking based on EWQI for drinking purposes

| Groundwater quality | Rank | EWQI |
|---|---|---|
| Excellent drinking quality | 1 | < 50 |
| Good drinking quality | 2 | 50 - 100 |
| Moderate drinking quality | 3 | 100 – 150 |
| Poor drinking quality | 4 | 150 – 200 |
| Extremely Poor drinking quality | 5 | 200 |

*2.2.2. Evaluation of Groundwater Quality for Irrigation Purposes*

There are several parameters and indices for assessing the groundwater status for agricultural purposes, which provide comprehensive results to recognize the groundwater suitability for irrigation. In the present study, Sodium Adsorption Ratio (SAR), Magnesium Hazard (MH), Kelly's ratio (KR), Salinity Hazard (SH), Synthetic Harmful Coefficient (K), Potential Salinity (PS), Total Dissolved Solids (TDS), Chloride ($Cl^-$), Permeability Index (PI) and Soluble Sodium Percentage (SSP) were adopted in order to assess the suitability of quality of groundwater for agricultural activities (Table 3). All the cations and anions are in *meq/L* to calculate these indices.

After determining the groundwater quality, Land Use-Land Cover (LULC) using Landsat OLI 8 images and groundwater level fluctuations map during the study period were generated for the study area to better understanding of the groundwater uses for various purposes. The methodology applied in this research is summarized in Fig 2.

## 3. Result

For assessing the groundwater suitability for drinking and irrigation purposes, physicochemical compounds of groundwater samples were measured. The statistical summary of the physicochemical of groundwater samples parameters are presented in Table 4.

**Table 3.** Groundwater quality indices for irrigation purposes

| Index | Equation | References |
| --- | --- | --- |
| Sodium Adsorption Ratio | $SAR = \frac{Na^+}{\sqrt{\frac{(Ca^{2+}+Mg^{2+})}{2}}}$ | Ravikumar *et al.* (2011) |
| Magnesium Hazard | $MH = \frac{Mg^{2+}}{(Ca^{2+}+Mg^{2+})} \times 100$ | Szabolcs (1964) |
| Kelley's Ratio | $KR = \frac{Na^+}{(Ca^{2+}+Mg^{2+})}$ | Kelley (1963) |
| Salinity Hazard | $SH = EC\ (\mu S/cm)$ | Tahmasebi *et al.* (2018) |
| Synthetic Harmful Coefficient | $K = 12.4 \times TDS + SAR$ | Zhou *et al.* (2009) |
| Potential Salinity | $PS = Cl^- + \frac{SO_4^{2-}}{2}$ | Doneen (1962) |
| Total Dissolved Solids | $TDS\ (mg/L)$ | Davis and DeWiest (1966) |
| Chloride | $Cl^-\ (meq/L)$ | Stuyfzand (1989) |
| Permeability Index | $PI = \frac{(Na^+ + \sqrt{HCO_3^-})}{(Na^+ + K^+ + Ca^{2+} + Mg^{2+})} \times 100$ | Doneen (1964) |
| Soluble Sodium Percentage | $SSP = \frac{Na^+}{Na^+ + Mg^{2+} + Ca^{2+}}$ | Wani *et al.* (2014) |

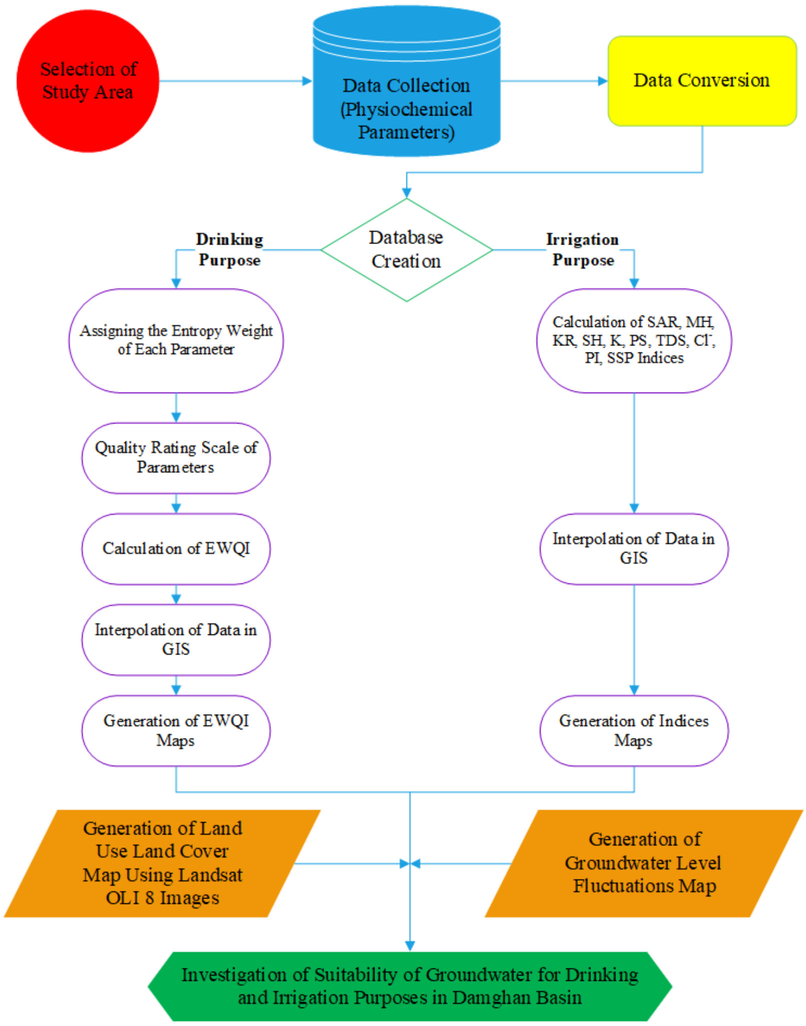


**Fig. 2.** Flowchart of the adopted methodology

**Table 4.** Statistical summary of physicochemical parameters

| Parameter | Unit | Minimum | Maximum | Mean | Standard Deviation |
|---|---|---|---|---|---|
| $Na^+$ | mg/L | 168.29 | 533.37 | 301.48 | 73.32 |
| $Mg^{2+}$ | mg/L | 35.24 | 125.15 | 57.60 | 16.08 |
| $Ca^{2+}$ | mg/L | 48.10 | 166.33 | 80.83 | 23.13 |
| $SO_4^{2-}$ | mg/L | 109.99 | 403.93 | 232.41 | 85.26 |
| $Cl^-$ | mg/L | 328.98 | 917.45 | 451.68 | 113.24 |
| $HCO_3^-$ | mg/L | 125.10 | 326.46 | 226.28 | 62.08 |
| pH | - | 7.14 | 7.95 | 7.61 | 0.22 |
| TDS | mg/L | 1022.00 | 2600.00 | 1379.05 | 282.86 |
| EC | µmhos/L | 1532.00 | 3930.00 | 2070.57 | 428.36 |

### *3.1. Geochemical Characterization of Groundwater*

#### *3.1.1. Ions Concentration*

Statistically investigation of the ions results in each sample is necessary to realize groundwater conditions. Based on mean value of cations and anions, the order of cations is followed by $Na^+ > Ca^{2+} > Mg^{2+}$ and the anions are ordered as $Cl^- > HCO_3^- > SO_4^{2-}$. $Na^+$ and $Cl^-$ have the most concentrations, compared to other cations and anions. So high concentration of these ions increases the salinity of groundwater, so that gives salty taste to it and has the greatest effect on the high values EC. Also, high concentration of sodium can cause high blood pressure in humans as well as kidney and heart disease. It has been reported by Ehteshami (*et al*., 2015) as well. Parhizkar (*et al*., 2015) reported that the main agricultural product in the region is pistachios, which can be due to the high concentration of these ions and high salinity in groundwater. The standard deviation of pH was 0.22 which indicates that its value does not change too much all over the plain. Maximum and minimum values of TDS exceeded standard value (Table 1), which its high value could be due to water-rock interaction (mineral dissolution) and evaporation (Xu *et al*., 2019).

Correlation analysis of physicochemical parameters was applied to present the degree of relation of them. The results showed the highest correlation was between all cations and all anions, while, in terms of individual ions, $Na^+$ and $Cl^-$ had the strongest correlation with a correlation coefficient of 0.629, and there were the least correlation between $Ca^{2+}$ and $SO_4^{2-}$ with a correlation coefficient of 0.001, approximately (Fig 3). The relationship between $Ca^{2+}$ and $SO_4^{2-}$ indicates that gypsum is not a primary processes of groundwater chemistry (Chen *et al*., 2019) as well as, the weak relationship of $Ca^{2+} + Mg^{2+}$ and $HCO_3^- + SO_4^{2-}$ reflects that carbonates and sulfate cannot be dissolved in groundwater (Li *et al*., 2018). Totally, it can be said that, the hydrochemical process in the Damghan Plain are not influenced by one process and it is mainly influenced by several items including ions exchange, ions concentration and evaporation.

#### *3.1.2. Durov Diagram*

Durov diagram is employed in order to display a useful relationship for groundwater samples having similar physicochemical parameters compound. Durov diagram disclosed that cations were dominated by $Na^+$, while anions were dominated by $Cl^-$ and there are not significant differences between the concentration of ions, TDS and pH values in both months August, 2018, and February, 2019. In the middle square, it is clearly observed that $Na^+$-$Cl^-$ type is more dominant than other types. The values of pH, raged from 7.14 to 7.95 with an average of 7.61 which indicates that the groundwater has slightly alkaline nature and there are slight changes in the plain. TDS varied between 1022 and 2600 mg/L, with a mean value of 1379.05 (Table 4).

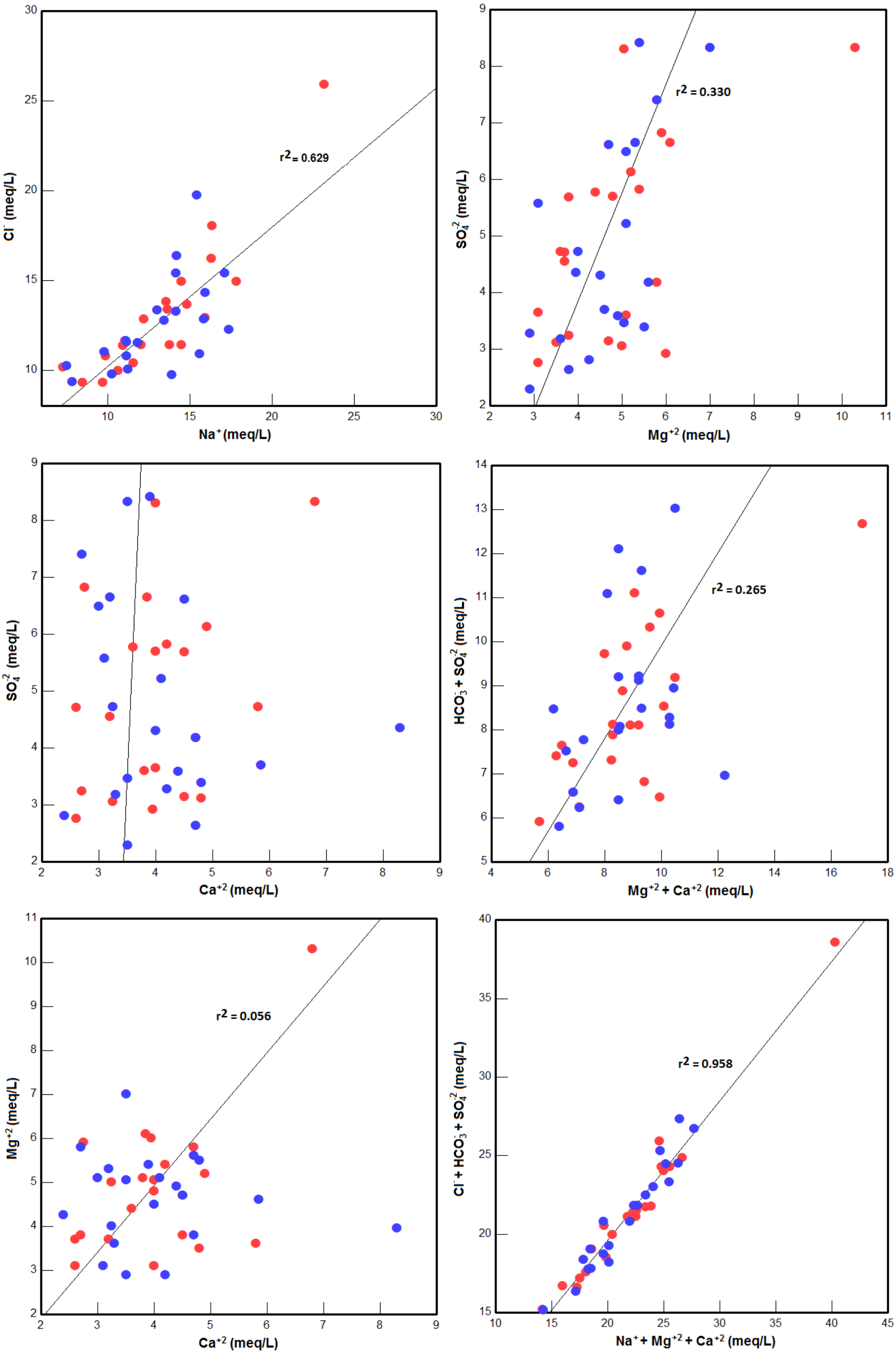


**Fig. 3.** Bivariate diagrams of ionic concentrations in groundwater samples (Red: August; Blue: February)

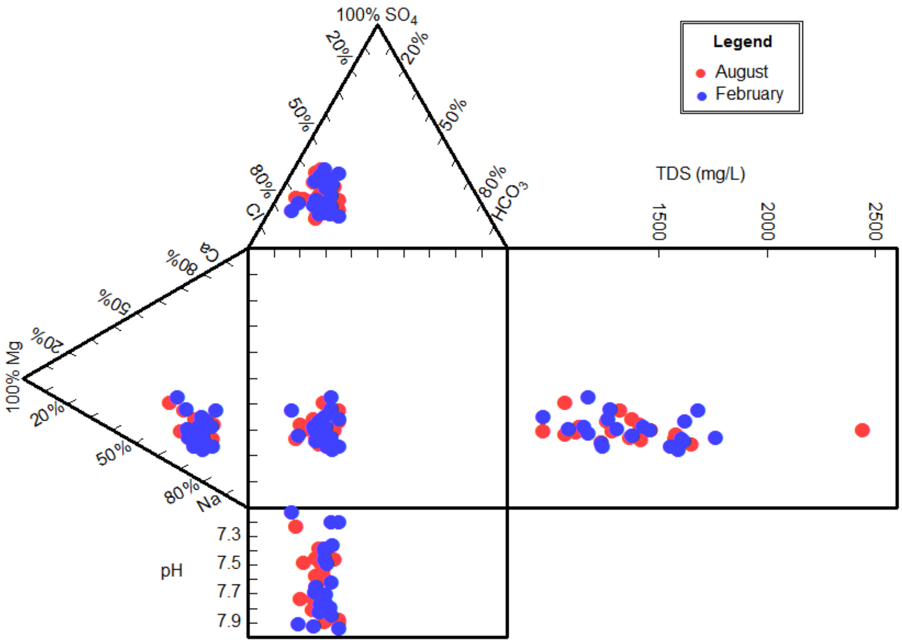


**Fig. 4.** Classification of groundwater samples based on Durov diagram

*3.2. Entropy Weighted Water Quality Index*

The most important step in computing EWQI is to determine the entropy weight, which is considered as a coefficient for calculating the WQI. Entropy weight of each parameter reflects the relative importance of that parameter in groundwater quality. A parameter with high entropy weight has little change in groundwater quality and has reached stability in the aquifer environment. Conversely, if the entropy weight of a parameter is low, its quality changes are high and it plays the major role in affecting groundwater quality.

After initial investigations, entropy weight was computed for each parameter. The higher the entropy weight of a parameter is, the greater the effectiveness of that parameter is. The results of parameters' entropy weight revealed that the effectiveness of the parameters follows $Cl^-$ > $Mg^{2+}$ > $SO_4^{2-}$ > TDS > $Ca^{2+}$ > $HCO_3^-$ > $Na^+$ > pH order, in August, 2018, while, in February, 2019, the order is as $Cl^-$ > $SO_4^{2-}$ > $Ca^{2+}$ > TDS > $Mg^{2+}$ > $HCO_3^-$ > pH > $Na^+$. As it is shown in Fig 5, $Cl^-$ has the highest entropy weight among the parameters and there is no significant difference between them (with value of 0.176 in August and 0.173 in February). Therefore $Cl^-$ has the most effect on groundwater quality in the study area.

After computing the entropy weight of parameters and water quality rating scale, based on the standards of the World Health Organization (WHO, 2011), the groundwater quality for drinking purposes was estimated in study area for both months. The values of EWQI map ranged from 111.74 to 175.47, with mean value of 149.47 in August, 2018, while, in February, 2019, they were found between 113.02 and 189.08, with mean value of 147.26. The results revealed that groundwater quality is classified as moderate to poor.

According to the spatial distribution maps of EWQI, the value of this index was lower in eastern parts than western parts and the classified maps clearly depicted two moderate and poor zones in August, 2018, and February, 2019 (Fig 6). These maps represented that the groundwater quality changes from Moderate class in the west to "Poor" class in the east. The comparison of the classified EWQI maps of two months showed that the quality of groundwater for drinking purpose become a little bit better in south parts, while in the north parts it was a little deteriorated. This is also consisting with the hydraulic slope of the area as groundwater moves from northwest to southeast. Groundwater in 275.57 $Km^2$ area (37.62 %) in August and 358.65 $Km^2$ area (48.96 %) in February had moderate quality, while 456.94 $Km^2$ area (62.38 %) in August and 373.86 $Km^2$ area (51.04%) in February had poor quality.

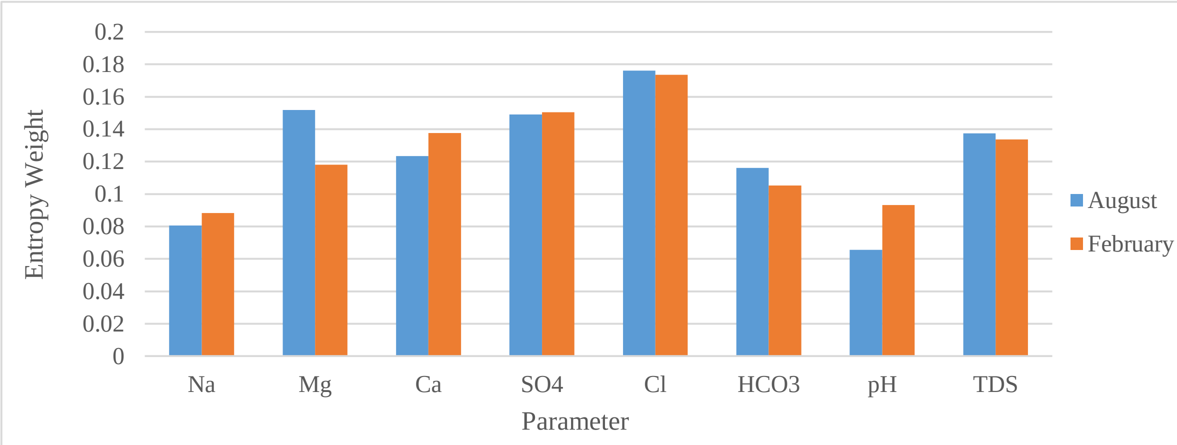


**Fig. 5.** The entropy weight of physicochemical parameters

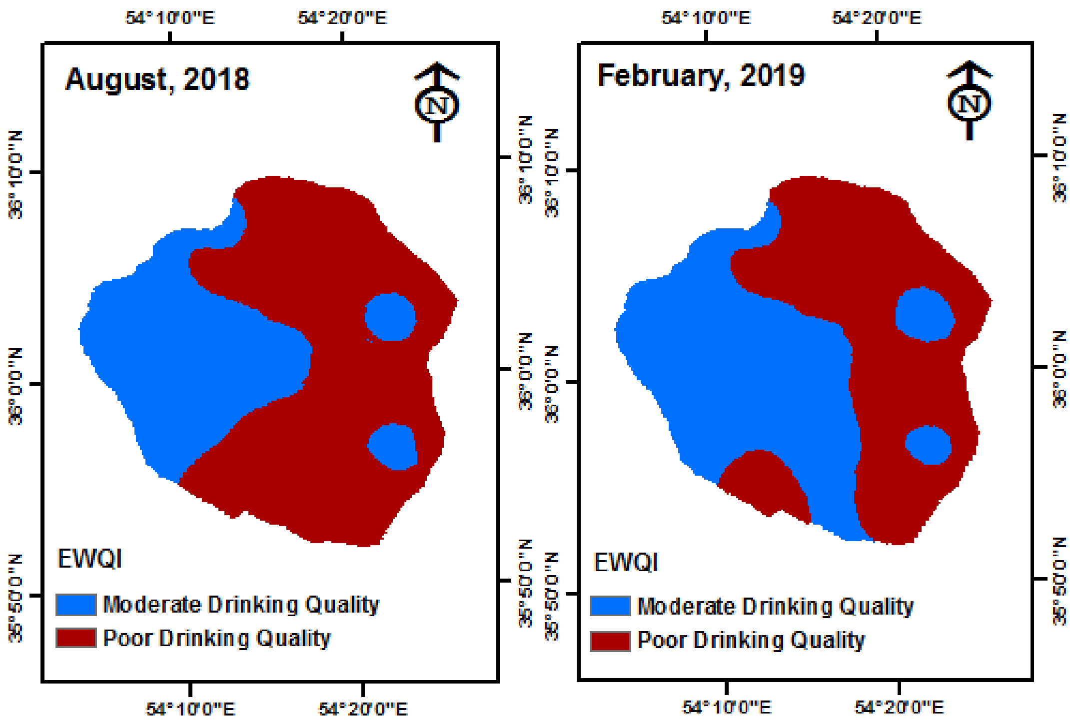


**Fig. 6.** Spatial distribution maps of drinking water quality based on EWQI

*3.3. Groundwater Quality for Irrigation Purposes*

The suitability of groundwater quality for irrigation purpose in the region was assessed using SAR, MH, KR, SH, K, PS, TDS, $Cl^-$, PI, SSP indices. Physicochemical parameters of groundwater were adopted to calculate these indices and the spatial distribution maps of indices developed by Geographic Information System (GIS) based on IDW spatial analysis technique (Fig 7).

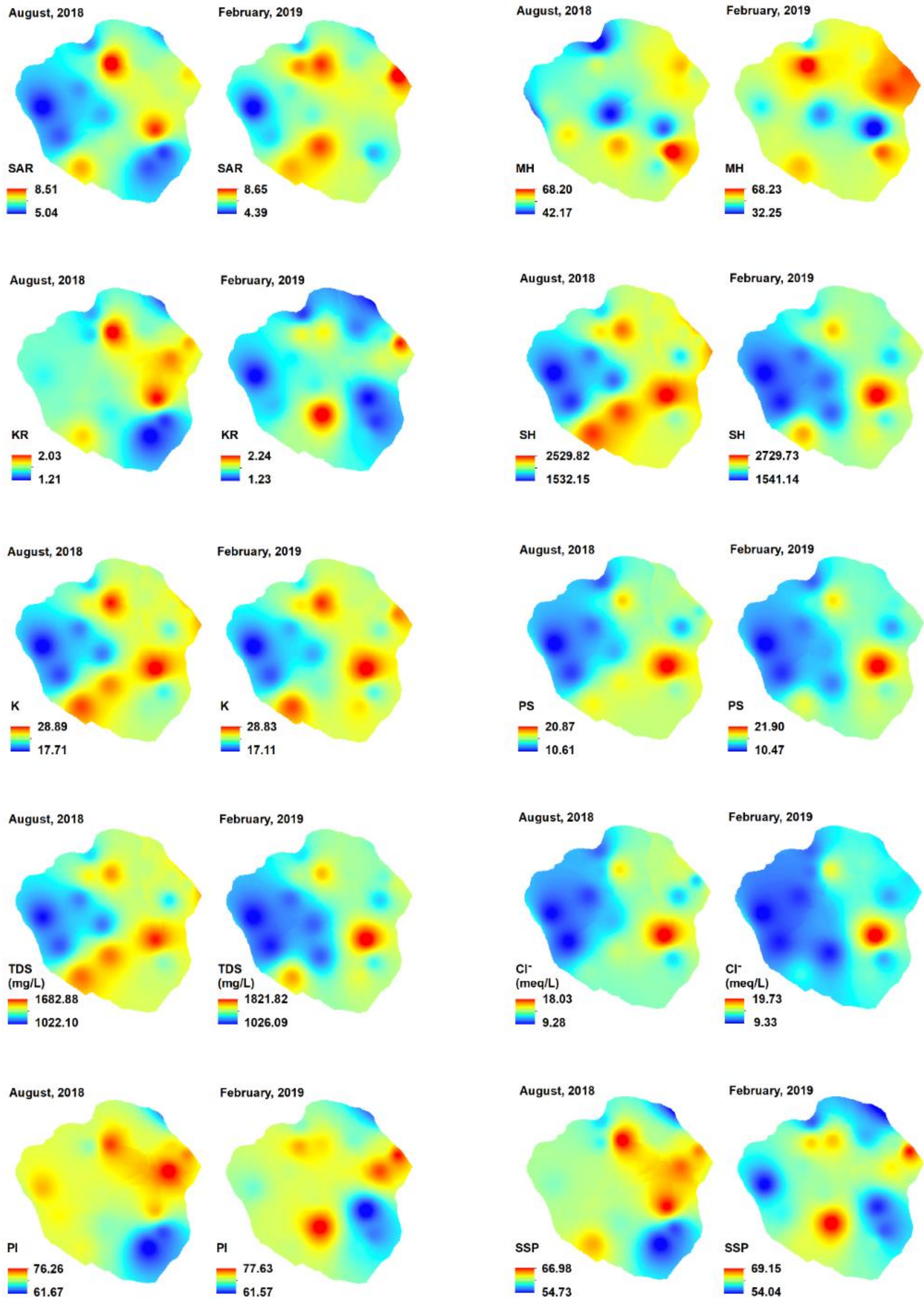


**Fig. 7.** Maps of groundwater quality indices for irrigation purpose

*Sodium Adsorption Ratio*

SAR shows the sodicity hazard and if water has high concentration of sodium and calcium, it may change the structure of the soil (Adimalla, 2020). According to the results, SAR values ranged from 5.04 to 8.51 in August, 2018, and from 4.39 to 8.65 in February, 2019. Groundwater in all samples was categorized into "Excellent" class in both months (Table 5). The average of SAR values in these months are 6.37 and 6.41. These maps represented that SAR values totally are higher in eastern parts of the study area than western parts in both month (Fig 7).

**Table 5.** Groundwater quality classification based on SAR (Ravikumar et al., 2011)

| SAR | Groundwater Quality | Number of Samples (%) | |
|---|---|---|---|
| | | August | February |
| < 10 | Excellent | 21 (100.00%) | 21 (100.00%) |
| 10 - 18 | Good | 0 (0.00%) | 0 (0.00%) |
| 15 - 26 | Injurious | 0 (0.00%) | 0 (0.00%) |
| 26 < | Unsuitable | 0 (0.00%) | 0 (0.00%) |

*Magnesium Hazard*

Magnesium normally exchanges with sodium in the irrigated soil (Keesari *et al.*, 2016) and its high concentration increases the soil aggregation (Zhou *et al.*, 2020). The results showed that 4 samples in August and 5 sample in February had groundwater which were classified into suitable class and groundwater in the rest of the samples were classified into unsuitable status (Table 6). The maps of MH presented that the groundwater in central parts of the plain had better conditions than northern and southern parts in terms of this index. The mean value of MH during the study period decreased from 54.43 to 52.61.

**Table 6.** Groundwater quality classification based on Magnesium Hazard (Szabolcs, 1964)

| MH (%) | Groundwater Quality | Number of Samples (Percent) | |
|---|---|---|---|
| | | August | February |
| < 50 | Suitable | 4 (19.00%) | 5 (24.00%) |
| 50 < | Unsuitable | 17 (81.00%) | 16 (76.00%) |

*Kelley's Ratio*

KR is defined to determine the concentration of sodium against the concentration of magnesium and calcium (Gaikwad *et al.*, 2020). The results indicated that the most of the groundwater samples (90.50%) were categorized into unsuitable class in both months and only 2 groundwater samples (9.50%) had suitable condition (Table 7). The maps of this index represented KR value in August is higher in west and in February in south and its value a little increased from 1.58 to 1.59 from August, 2018, to February, 2019.

**Table 7.** Groundwater quality classification based on Kelley's Ratio (Kelley, 1963)

| KR | Groundwater Quality | Number of Samples (Percent) | |
|---|---|---|---|
| | | August | February |
| < 1 | Suitable | 2 (9.50%) | 2 (9.50%) |
| 1 < | Unsuitable | 19 (90.50%) | 19 (90.50%) |

*Salinity Hazard (SH)*

Salinity is one of the most crucial parameter which uses to distinguish the groundwater quality for irrigation and determines the existence of salt in groundwater, which its high concentration can affect on osmotic process of plants (Subramani *et al.*, 2005). SH index value ranged between 1532.15 and 2529.82 in August, and between 1541.14 and 2729.73 in February. In August, groundwater was classified into "Doubtful" class in 15 samples, while in 6 samples was classified into "Unsuitable" class and in February, groundwater was classified into

"Doubtful" class in 15 samples and "Unsuitable" class in 5 samples (Table 8). The average values of SH in August and February were 2036.99 and 1996.70, respectively. These maps indicated that the SH values were lower in western parts of the study area than eastern parts in both month (Fig 7).

**Table 8.** Groundwater quality classification based on Salinity Hazard (Tahmasebi *et al*., 2018)

| EC(*μ*mohs/cm) | Groundwater Quality | SH Class | Number of Samples (Percent) | |
|---|---|---|---|---|
| | | | August | February |
| < 250 | Excellent | C1 | 0 (0.00%) | 0 (0.00%) |
| 250–750 | Good | C2 | 0 (0.00%) | 0 (0.00%) |
| 750–2250 | Doubtful | C3 | 15 (71.00%) | 16 (76.00%) |
| 2250 < | Unsuitable | C4 | 6 (29.00%) | 5 (24.00%) |

*Synthetic Harmful Coefficient*

Synthetic Harmful Coefficient mainly indicates the salt and alkalis hazards (Xu *et al*., 2019). Based on the results, the groundwater in the most samples had excellent condition (15 samples in both months). The maps of this index showed that the value of K was higher in eastern parts than western parts, with average value of 23.20 in August and 22.91 in February (Fig 7).

**Table 9.** Groundwater quality classification based on Synthetic Harmful Coefficient (Zhou *et al*., 2009)

| K | Groundwater Quality | Number of Samples (Percent) | |
|---|---|---|---|
| | | August | February |
| < 25 | Excellent | 15 (71.00%) | 15 (71.00%) |
| 25 - 36 | Good | 5 (24.00%) | 6 (29.00%) |
| 36 - 44 | Injurious | 1 (5.00%) | 0 (0.00%) |
| 44 < | Unsuitable | 0 (0.00%) | 0 (0.00%) |

*Potential Salinity*

PS index is primarily related to the content of chloride and sulfate. The total groundwater samples were within injurious to unsatisfactory class in both month based on PS values, which ranged from 10.61 to 20.87 (with an average of 14.93) in August and from 10.47 to 20.90 (with an average of 14.65) in February. In both months the values were higher in southeastern than other parts (Fig 7).

*Total Dissolved Solids*

TDS estimates the total organic and inorganic substances which are dissolved in water (Pan *et al*., 2019). That the groundwater in all samples was classified within slightly saline class in both months and the maps illustrated that TDS value were found from 1022.10 1682.88 mg/L in August and from 1026.09 to 1821.82 mg/L in February. The TDS value was totally higher in eastern parts than other parts in both months (Fig 7).

*Chloride*

Chloride may originate from various sources such as weathering, seawater infiltration and leaching of sedimentary rocks (Rout and Sharma, 2011). High concentration of this anion can be a sign of excessive organic pollution (Yogendra and Puttaiah, 2008). The results indicated the groundwater in all samples was categorized into brackish class in both months (Table 12). The western parts had lower value of $Cl^-$ than eastern parts in both months (Fig 7) and mean value of $Cl^-$ was 12.42 meq/L and 12.26 meq/L in August and February, respectively.

**Table 10.** Groundwater quality classification based on Potential Salinity (Doneen, 1962)

| PS (meq/L) | Groundwater Quality | Number of Samples (Percent) | |
|---|---|---|---|
| | | August | February |
| < 3 | Excellent to Good | 0 (0.00%) | 0 (0.00%) |
| 3 – 5 | Good to Injurious | 0 (0.00%) | 0 (0.00%) |
| 5 < | Injurious to Unsatisfactory | 21 (100.00%) | 21 (100.00%) |

**Table 11.** Groundwater classification based on Total Dissolved Solids (Davis and DeWiest, 1966)

| TDS (mg/L) | Groundwater Class | Number of Samples (Percent) | |
|---|---|---|---|
| | | August | February |
| < 1000 | Non Saline | 0 (0.00%) | 0 (0.00%) |
| 1000 – 3000 | Slightly Saline | 21 (100.00%) | 21 (100.00%) |
| 3000 – 10000 | Moderately Saline | 0 (0.00%) | 0 (0.00%) |
| 10000 < | Very Saline | 0 (0.00%) | 0 (0.00%) |

**Table 12.** Classification of groundwater based on Chloride (Stuyfzand, 1989)

| Ranges (meq/L) | Categories | Number of Samples (Percent) | |
|---|---|---|---|
| | | August | February |
| < 0.14 | Extremely Fresh | 0 (0.00%) | 0 (0.00%) |
| 0.14 – 0.85 | Very Fresh | 0 (0.00%) | 0 (0.00%) |
| 0.85 – 4.23 | Fresh | 0 (0.00%) | 0 (0.00%) |
| 4.23 – 8.46 | Fresh Brackish | 0 (0.00%) | 0 (0.00%) |
| 8.46 – 28.21 | Brackish | 21 (100.00%) | 21 (100.00%) |
| 28.21 – 282.06 | Brackish - Salt | 0 (0.00%) | 0 (0.00%) |
| 282.06 – 564.13 | Salt | 0 (0.00%) | 0 (0.00%) |
| 564.13 < | Hypersaline | 0 (0.00%) | 0 (0.00%) |

*Permeability Index*

Irrigation water can affect the soil permeability in long term (Ramesh and Elango, 2012). The results of PI showed that groundwater in most samples ranged between 25 and 75 (class II) (Table 13). In both months, PI value was lower in southeastern than other parts (Fig 7) and its mean value increased from 69.61 to 70.02 during the study period.

**Table 13.** Groundwater quality classification based on Permeability Index (Doneen, 1964)

| PI (%) | Groundwater Quality | Class | Number of Samples (Percent) | |
|---|---|---|---|---|
| | | | August | February |
| 75 < | Suitable | Class I | 1 (5.00%) | 3 (14.00%) |
| 25 – 75 | Suitable | Class II | 20 (95.00%) | 18 (86.00%) |
| < 25 | Unsuitable | Class III | 0 (0.00%) | 0 (0.00%) |

*Soluble Sodium Percentage*

SSP is an important index for assessing the sodium hazard and shows the dominant of sodium to the total cations (Peiyue *et al*., 2011). 19 groundwater samples were classified into unsuitable class (Table 14) and its value was totally higher in central parts than other parts in both months (Fig 7) and its mean value increased from 60.83 to 60.93 from August, 2018, to February, 2019.

**Table 14.** Groundwater quality classification based on Soluble Sodium Percentage (Wani *et al*., 2014)

| SSP | Groundwater Quality | Number of Samples (Percent) | |
|---|---|---|---|
| | | August | February |
| < 50 | Suitable | 2 (9.50) | 2 (9.50) |
| 50 < | Unsuitable | 19 (90.50) | 19 90.50) |

*3.4. Groundwater table changes and Land Use Land Cover*

Groundwater table changes map was produced to show the changes in groundwater table during study period and its effect on groundwater quality using groundwater table data. Changes of groundwater table during the study period were investigated using groundwater table data for two studied month. The map of groundwater level fluctuations (Fig 8, Left) illustrated that groundwater table decreased in the northern parts of the region, while in the southern parts has increased from August, 2018, to February, 2019. The changes of groundwater table range from -0.69 to +0.32 meter, with the average of -0.19 meter, which generally indicates the groundwater table depletion in south of the plain during study period.

For better understanding the suitability of groundwater, which provides the required water for different types of land use, the Land Use/Land Cover (LULC) map was generated by LULC map of Natural Resources and Watershed Management Organization of Iran (Fig 8, Right). According to this map, the most part of plain is bareland (56.8%) and followed by agricultural lands (15.85%), poor range (12.29%), urban area (9.02%), saltland (3.99%), and agriculture-fallow (2.05%) (Table 15). Saltland area is located in the east side of the plain and rangeland is in the north and west side and bareland is between them, which indicate that natural vegetation is decreasing from west to east. Due to the presence of saltland in the east side the amount of salinity is higher in this area, and value of EC, SAR KR and PS indices is higher.

## 4. Discussion

In the present study, EWQI, as a novel method, and various physicochemical indices were employed through GIS to determine the groundwater suitability for drinking and irrigation purposes, respectively.

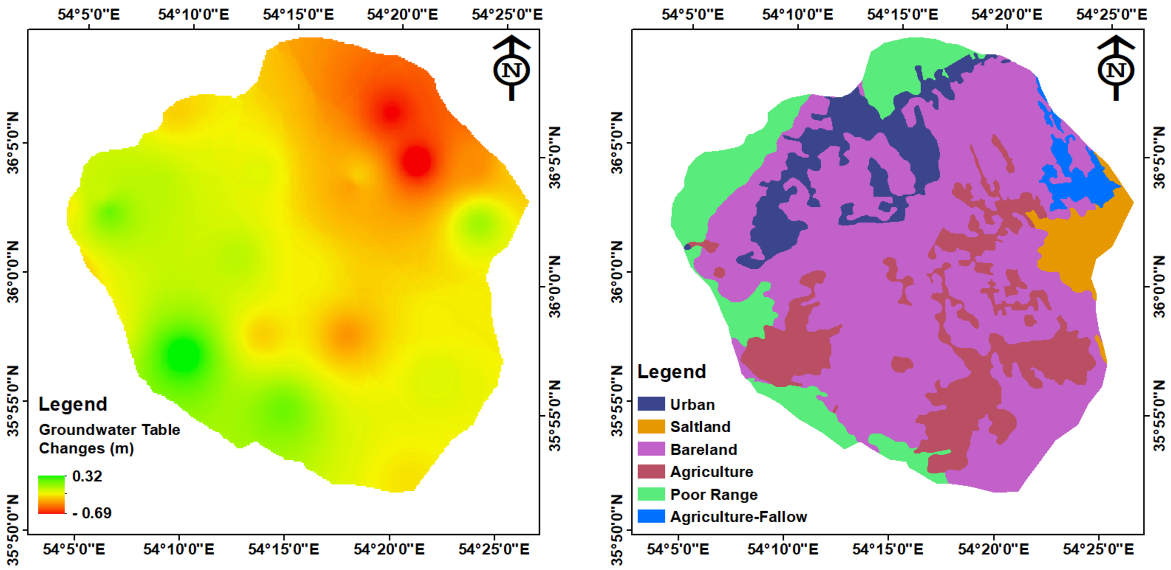


**Fig. 8.** The maps of groundwater table changes from August, 2018 to February, 2019 (Left) and LULC for Damghan Plain (Right)

**Table 15.** Area of LULC types in Damghan Plain

| LULC Type | Area ($Km^2$) | Area (%) |
|---|---|---|
| Urban | 66.05 | 9.02 |
| Saltland | 29.23 | 3.99 |
| Bareland | 416.06 | 56.8 |
| Agriculture | 116.14 | 15.85 |
| Poor Range | 90.01 | 12.29 |
| Agriculture-Fallow | 15.02 | 2.05 |
| Sum | 732.51 | 100.00 |

The initial study of groundwater characteristics represented that $Na^+$ and $Cl^-$ have the highest concentrations in groundwater among cations and anions, respectively, and are exceeding the permissible limits of WHO standards in both months August, 2018, and February, 2019. Moreover, the strong relationship between these two ions based on bivariate diagram reflected salinity status of groundwater. On the other hand, the relationship between other cations and anions are weaker than their relationship. Despite this issue along with high levels of TDS, precautions should be taken for drinking. Additionally, groundwater quality for salinity-sensitive crops is poor and plants which are more resistant to salinity should be cultivated in the studied plain.

The results of evaluation of groundwater quality using the EWQI highlighted that among the all parameters, $Cl^-$ has the highest entropy weight in both months which indicated this ion has the highest effect on groundwater quality and less changes. EWQI maps implied groundwater totally had moderate status in west and poor status in east of the area. The mean value of this index become a little lower from 149.47 in August to 147.26 in February, which reflected that the groundwater quality has not changed much and has just slightly improved for drinking purpose. The reason of this decreasing can be increasing the groundwater level in the southern parts of the area, which shows that with the decrease of groundwater level, its quality decreased and in the southern parts, with the increase of groundwater level (increase of groundwater quantity), its quality slightly increased.

The assessment of groundwater quality for irrigation showed that although SAR, KR, PI and SSP indices had slightly increased in their mean value, but groundwater is suitable in terms of SAR, K and PI in both months and has not limitation for using in agricultural sectors. This result indicates that the concentration of $Na^{+}$ was more appropriate than other ions used in these indices. Conversely the groundwater has not good status in terms of SSP, MH, SH, K, PS, TDS and $Cl^{-}$ indicating groundwater has high concentration of solid materials and other ions.

The evaluation of groundwater suitability for irrigation purposes revealed that SAR, KR, PI and SSP indices had slightly increased in their mean value, which indicated the groundwater quality become worse in terms of these indices. On the other hand, the mean value of MH, SH, K, PS, TDS and $Cl^{-}$ indices have slight decrease during the study period. SH, PS and $Cl^{-}$ values in the southern parts have been increased from August to February. This can be due to rising groundwater table.

LULC map was employed to show which groundwater consumption is appropriate with its quality. This map indicated that the most urban areas were located in the north parts, in which groundwater has both moderate and poor quality, in west side has moderate quality while in east side has poor quality. Agricultural lands are located in the middle and south of the plain, in which the groundwater has mainly suitable quality in terms of SAR, K and PI and unsuitable in terms of MH, KR, SH, PS, TDS, $Cl^{-}$ and SPP. The suitable condition in terms of SAR, K and PI is due to the high concentration of $Mg^{2+}$ and $Ca^{2+}$ (Table 4). Thus, groundwater is not suitable for irrigation in agriculture sector.

## 5. Conclusion

The results of groundwater quality for drinking purpose showed that Cl- has the most effect on its quality and has less change among all used physicochemical parameters. Base on EWQI, the quality of groundwater is totally moderate in western parts of Damghan Plain, while in the eastern parts it has poor status. The evaluation of groundwater suitability for irrigation purposes revealed that SAR, KR, PI and SSP indices had slightly increased in their mean value, which indicated the groundwater quality become worse in terms of these indices. On the other hand, the mean value of MH, SH, K, PS, TDS and Cl- indices have slight decrease during the study period. SH, PS and Cl- values in the southern parts have been increased from August to February. This can be due to rising groundwater table.

The results of the present study provide guidance to decide for appropriate management. It is recommended that relevant organizations adopt the suitable strategies to save by sustainable use and to enhance the quality of groundwater in Damghan Plain to make more usable the groundwater and which is mainly used for agricultural purposes.

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## Appendix

**Table 616: Data table of physicochemical parameters**

| Row | Month | UTM (X) | UTM (Y) | $Na^{+}$ (mg/lit) | $Mg^{2+}$ (mg/lit) | $Ca^{2+}$ (mg/lit) | $SO_4^{2-}$ (mg/lit) | $Cl^{-}$ (mg/lit) | $HCO_3^{-}$ (mg/lit) | pH | TDS (mg/lit) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Aughust, 2018 | 236000 | 3986300 | 333.355 | 43.74 | 116.232 | 226.7016 | 529.2685 | 128.142 | 7.74 | 1341 |
| 2 | | 240800 | 3989200 | 195.415 | 37.665 | 52.104 | 132.5628 | 328.976 | 192.213 | 7.9 | 1022 |
| 3 | | 243800 | 3984200 | 223.2329 | 44.955 | 52.104 | 225.741 | 328.976 | 164.754 | 7.6 | 1088 |
| 4 | | 247300 | 3992300 | 244.8435 | 44.955 | 64.128 | 218.0562 | 352.0185 | 164.754 | 7.46 | 1131 |
| 5 | | 247700 | 3978500 | 366.4606 | 61.3575 | 80.16 | 398.649 | 456.596 | 170.856 | 7.59 | 1614 |
| 6 | | 249100 | 3996600 | 317.262 | 65.61 | 84.168 | 279.5346 | 403.421 | 274.59 | 7.47 | 1467 |
| 7 | | 249200 | 4000400 | 266.684 | 42.525 | 96.192 | 149.3733 | 367.971 | 305.1 | 7.89 | 1213 |
| 8 | | 251400 | 3987900 | 251.9704 | 37.665 | 80.16 | 174.8292 | 401.6485 | 158.652 | 7.82 | 1121 |
| 9 | | 252700 | 3982300 | 340.9417 | 74.115 | 77.154 | 318.9192 | 483.1835 | 244.08 | 7.41 | 1607 |
| 10 | | 252900 | 3997000 | 410.3715 | 58.32 | 80.16 | 273.2907 | 529.2685 | 256.284 | 7.39 | 1575 |
| 11 | | 259000 | 3998100 | 314.5032 | 61.965 | 76.152 | 172.4277 | 474.321 | 274.59 | 7.5 | 1369 |
| 12 | | 259800 | 3978600 | 280.7079 | 63.18 | 98.196 | 294.4239 | 454.8235 | 146.448 | 7.74 | 1387 |
| 13 | | 260900 | 3985200 | 375.8865 | 46.17 | 90.18 | 272.8104 | 639.1635 | 134.244 | 7.24 | 1683 |
| 14 | | 261200 | 4009400 | 375.6566 | 57.105 | 90.18 | 150.8142 | 573.581 | 302.049 | 7.58 | 1592 |
| 15 | | 262300 | 3981100 | 254.2694 | 71.685 | 55.11 | 327.5646 | 412.2835 | 125.091 | 7.46 | 1310 |
| 16 | | 263400 | 3992300 | 277.0295 | 46.17 | 54.108 | 155.6172 | 403.421 | 268.488 | 7.86 | 1226 |
| 17 | | 264000 | 3996400 | 311.7444 | 60.75 | 65.13 | 146.4915 | 488.501 | 259.335 | 7.65 | 1382 |
| 18 | | 265100 | 4004800 | 168.2868 | 72.9 | 79.158 | 139.7673 | 359.1085 | 216.621 | 7.54 | 1082 |
| 19 | | 266600 | 3995100 | 333.355 | 53.46 | 72.144 | 277.1331 | 403.421 | 241.029 | 7.46 | 1375 |
| 20 | | 266800 | 4004200 | 227.8309 | 70.47 | 94.188 | 200.7654 | 382.151 | 305.1 | 7.91 | 1305 |
| 21 | | 269300 | 3998400 | 533.368 | 125.145 | 136.272 | 399.6096 | 917.446 | 265.437 | 7.49 | 2600 |
| 22 | February, 2019 | 236000 | 3986300 | 325.7683 | 54.675 | 80.16 | 206.529 | 545.221 | 128.142 | 7.92 | 1392 |
| 23 | | 240800 | 3989200 | 180.4715 | 35.235 | 70.14 | 109.9887 | 330.7485 | 213.57 | 7.41 | 1026 |
| 24 | | 243800 | 3984200 | 235.8774 | 43.74 | 66.132 | 152.7354 | 345.6375 | 207.468 | 7.47 | 1060 |
| 25 | | 247300 | 3992300 | 258.4076 | 48.6 | 65.13 | 226.7016 | 355.5635 | 186.111 | 7.78 | 1137 |
| 26 | | 247700 | 3978500 | 364.6214 | 65.61 | 78.156 | 403.9323 | 454.8235 | 195.264 | 7.39 | 1614 |
| 27 | | 249100 | 3996600 | 358.644 | 70.47 | 54.108 | 355.422 | 385.696 | 286.794 | 7.21 | 1395 |
| 28 | | 249200 | 4000400 | 256.3385 | 46.17 | 94.188 | 126.3189 | 381.0875 | 326.457 | 7.95 | 1261 |
| 29 | | 251400 | 3987900 | 256.7983 | 35.235 | 84.168 | 157.5384 | 408.7385 | 180.009 | 7.93 | 1130 |
| 30 | | 252700 | 3982300 | 319.561 | 37.665 | 62.124 | 267.5271 | 344.9285 | 176.958 | 7.5 | 1126 |
| 31 | | 252900 | 3997000 | 393.5888 | 61.965 | 82.164 | 250.2363 | 545.221 | 237.978 | 7.66 | 1590 |
| 32 | | 259000 | 3998100 | 299.7896 | 59.535 | 88.176 | 171.9474 | 472.5485 | 298.998 | 7.71 | 1381 |
| 33 | | 259800 | 3978600 | 325.7683 | 57.105 | 90.18 | 317.4783 | 469.7125 | 158.652 | 7.7 | 1479 |
| 34 | | 260900 | 3985200 | 354.7357 | 47.9925 | 166.332 | 208.9305 | 699.4285 | 158.652 | 7.14 | 1822 |
| 35 | | 261200 | 4009400 | 326.6879 | 55.89 | 117.234 | 177.2307 | 579.6075 | 320.355 | 7.83 | 1608 |
| 36 | | 262300 | 3981100 | 255.8787 | 64.395 | 64.128 | 318.9192 | 411.22 | 155.601 | 7.78 | 1290 |
| 37 | | 263400 | 3992300 | 271.9717 | 51.6375 | 48.096 | 134.9643 | 407.675 | 286.794 | 7.8 | 1235 |
| 38 | | 264000 | 3996400 | 308.9856 | 61.3575 | 70.14 | 166.1838 | 451.2785 | 280.692 | 7.77 | 1320 |
| 39 | | 265100 | 4004800 | 172.8848 | 68.04 | 94.188 | 200.2851 | 362.6535 | 241.029 | 7.63 | 1095 |
| 40 | | 266600 | 3995100 | 400.026 | 61.965 | 60.12 | 311.2344 | 433.5535 | 280.692 | 7.37 | 1449 |
| 41 | | 266800 | 4004200 | 225.7618 | 66.825 | 96.192 | 162.3414 | 389.241 | 298.998 | 7.21 | 1321 |
| 42 | | 269300 | 3998400 | 366.2307 | 85.05 | 70.14 | 399.6096 | 506.226 | 286.794 | 7.86 | 1699 |