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GIS-based assessment of spatial variability of Marvdasht groundwater quality for drinking

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Abstract

With increasing population and freshwater shortages worldwide, it is necessary to protect vital groundwater resources using innovative methods, particularly in arid and semi-arid regions of the world such as Iran. The main objective of this study is to use a GIS-based approach with the Groundwater Quality Index (GWQI) to analyze groundwater quality in Marvdasht, an area of 550 Km^2 and is found in the semi-arid region of Fars Province, Iran. For this purpose, we used groundwater quality data that were collected in a 5 year period (2010-2015). Maps of water quality parameters in the study area were visualized using inverse distance weighting in a GIS. The most influential water quality parameters were determined by performing map removal sensitivity analysis among the groundwater quality parameters. Mean maps of the groundwater parameters showed that total dissolved solid (TDS), electrical conductivity (EC) and total hardness (TH) were the most important parameters that exceed the maximum permissible limits for drinking water. The groundwater quality of the study area is generally desirable for drinking (GWQI = 71). The GWQI map indicated that groundwater was higher quality in northern regions of the study area. The GWQI also revealed that only 2% of the study area (11 Km^2) was below the low quality class. According to map removal sensitivity analysis, Mg^{2+}, TH and Na^+ were identified as the most sensitive water quality parameters. Therefore, these parameters need to be monitored regularly and with increased precision.

Key words: Groundwater quality, GIS, Semi-arid region, Sensitivity analysis

Introduction

Iran has been facing increasingly severe water scarcity in many parts of the country, especially in arid and semi-arid regions. Long-term droughts also have had a profound influence on the quantity and quality of groundwater in arid/semi-arid regions of Iran (Khodapanah et al. 2009; Heshmati et al. 2011; Ostovari et al. 2016). In recent decades, with increasing population growth and rising living standards, demand for groundwater resources for drinking purposes has increased significantly, resulting in a reduction in water quality and quantity, particularly in southern parts of Iran such as provinces of Fars, Bushehr and Hormozgan. Therefore, an assessment of groundwater quality for drinking is necessary (Sandra et al., 2010; Ostovari et al. 2016). In evaluating the quality of groundwater, the use of appropriate tools and techniques for the processing of qualitative data needs to be efficient, since water quality assessment is difficult due to the large amounts data that need to be analyzed (Saidi et al. 2009; Ramakrishna et al. 2009; Sharma and Patel, 2010; Tiwari et al. 2017).

One of the most useful methods for assessing water quality is the water quality index (WQI) (Babick et al., 2007). Water quality indicators are defined and calculated in a variety of ways. However, in all methods, the effect of various water quality parameters is presented in the form of a single dimensionless number indicating the quality of water (Hashtati, 2011). The ground water quality index (GWQI) is an indicator of water quality and suitability drinking. One of the advantages of GWQI is the flexibility that it allows in choosing the number of parameters in the calculation. To calculate the GWQI, WHO standards for drinking water are commonly used (Babicker, 2007; Heshmati, 2011; Tiwari et al. 2017). First, a number of groundwater chemical parameters are measured. After performing spatial processing, a map of each parameter is provided. In the last step, by computing maps obtained from the qualitative water parameters, the GWQI index map is extracted (Machiwal et al., 2011). Sandra Kumar et al. (2010) evaluated the groundwater quality assessment of West-End (India) using the GWQI. In this study, the parameters of pH, EC, turbidity, chloride and total hardness were measured and the GWQI index was calculated. According to GWQI, groundwater quality for drinking was found to be inadequate. Reza and Singh (2010) used GWQI for Orissa groundwater assessment in India. They collected water samples from 24 wells in summer and winter and they used TDS, pH, TH, turbidity, Cl^-, Ca^{2+} and Mg^{2+} to calculate the GWQI index. The GWQI ranged from 14 to 57 and 19 to 67 in the summer and winter, respectively.

Geographic information systems (GIS) have emerged as a powerful tool for storing, analyzing, and visualizing spatial data to assist the decision making process in many fields of study. GIS provide an efficient environment for fast organization, quantification, and interpretation of large volumes of spatial data (Saidi et al. 2009; Lata and Rao 2010). There have been some GIS-based studies which have been carried out for evaluating groundwater quality. Babicker et al. (2007) assessed the suitability of groundwater for human consumption in the Nassano Basin (Japan) using a GWQI GIS-based approach. The study focused on chemical parameters such as Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, SO_4^{2-} and TDS which were measured in 50 wells. The parameters of TDS and SO_4^{2-} had a higher mean rank than other parameters. In the sensitivity analysis, it was found that removal of Mg^{2+} leads to a greater change in GWQI compared to the removal of other factors which indicates that the GWSI was more sensitive to Mg^{2+} than other parameters.

Kumar et al. (2010) evaluated the groundwater water quality of Andhra Pradesh, India using a GWQI GIS-based approach. They collected samples from 170 wells and measured pH, turbidity, total alkalinity and nitrates. The inverse distance weighing method was used for zoning the qualitative parameter indices and showed that the opacity and pH parameters had a higher average weight than the other parameters. They show that the calculation of the GWQI index using qualitative maps in a GIS environment gives better results than computational methods for helping decision makers. Pandian and Kumar (2013) carried out a groundwater quality assessment in Tuticorin District, Tamil Nadu State, India using a GIS-based index. Based on the GWQI map, the groundwater quality in the Northern part of the study area is in the moderate- and poor-quality range while the Southern side of the study area, the groundwater quality is classed as good for drinking. Ostovari et al. (2016) evaluated the Lordegan aquifer in Iran using a GIS-based groundwater quality assessment. Their results showed that the Lordegan aquifer had good drinking water quality with a mean GWQI of 83. The GWQI map indicates that drinking water quality decreases moving north from the southwest, this may be attributed to the existence of agricultural activities, municipal effluent and gypsum formations present in north of the plain.

Currently, there are no GIS-based studies that look at groundwater quality assessment using the GWQI in Southern Iran. Therefore, the aim of this study is to the assess groundwater quality and its spatial variations in the Marvdasht Plain. Marvdasht groundwater, which is one of the most important aquifers in the province of Fars, because it provides drinking water for more than

200,000 people. The objectives of this study are to (1) evaluate the Marvdasht groundwater for drinking using GWQI in a GIS, (2) estimate the optimal parameters for GWQI calculation, and (3) analyze GWQI parameter sensitivity in Marvdasht groundwater by the map removal sensitivity method.

Materials and Method

Study Area

The Marvdasht plain with an area of 550 Km^2 is located in the north of Fars Province, Iran (between 29°19'-30°20' N and 52°15'-53°27' E) (Fig 1). The Marvdasht plain is situated in the Basin of the Kor River, where alluvial and colluvial soils are suitable for agriculture and pasturelands. The climate is semi-arid with cold weather in the hilly areas and a moderate climate in other regions. The average annual rainfall is about 350 mm, mainly during December to January. The Marvdasht plain includes several lithological units from Cretaceous period. The most important geological formation is chalky–salty marl material of Hormuz formation and chalky-red marl of Cachon formation in the south-east and argillaceous limestone formation of Asmari-Jahrome in the northwest and centre of the plain (Ostovari et al. 2015).

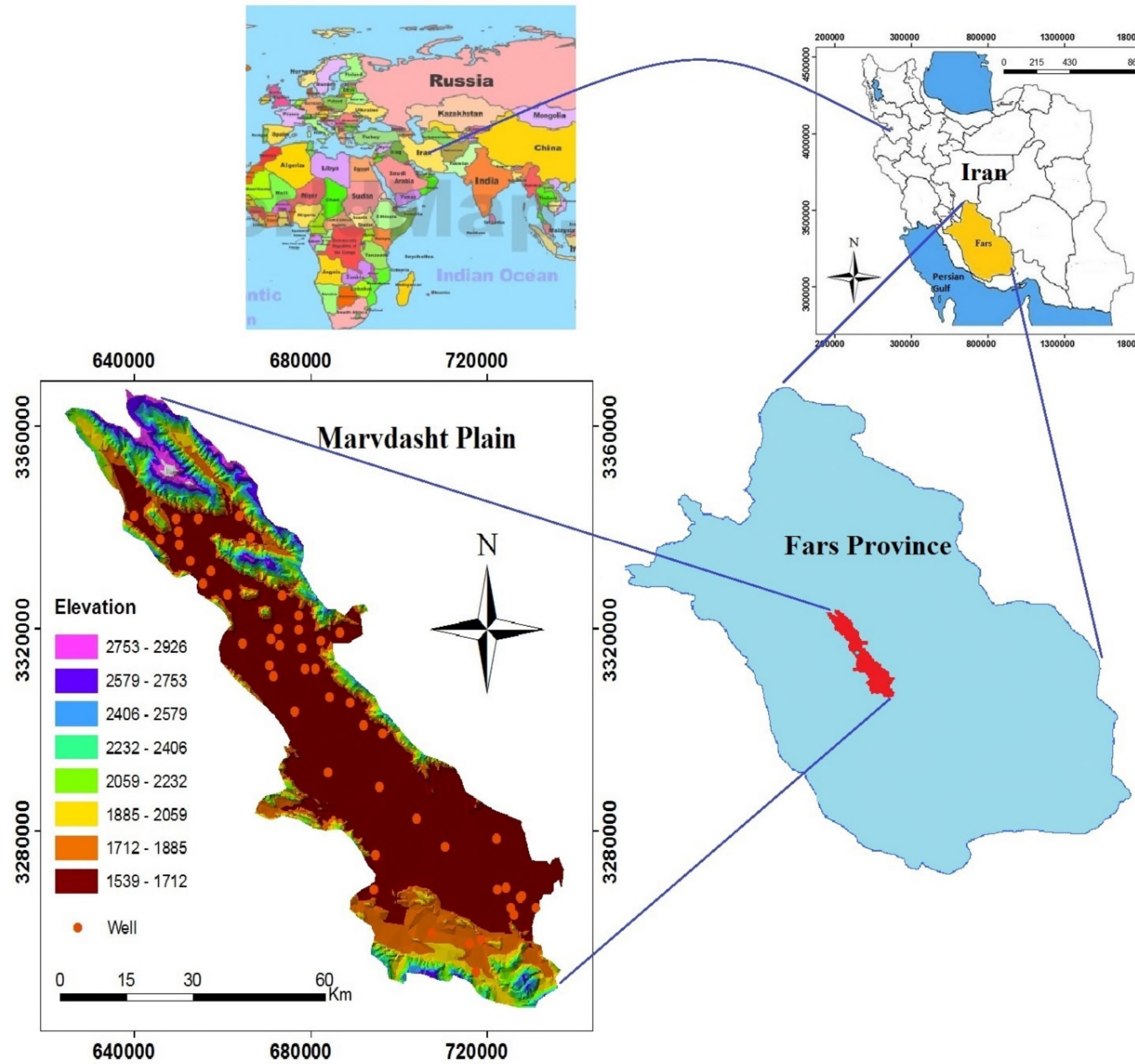

Fig 1. Study area in Fars Province, Iran and the locations of sample sites

Sampling and analysis

To assess the water quality, data from 49 agricultural wells were collected over the study area (Fig. 1) during the period 2010 -2015. Geographical locations of the sample sites, which are distributed across the entire plain, were obtained using a hand-held GPS. The average water table over the experimental area was approximately 35 meters (Ostovari et al. 2015). Groundwater samples were analyzed for 11 chemical parameters following the APHA (1998) standard. EC and pH were measured by EC and pH meters. The total dissolved solids (TDS) was obtained by the evaporation of about 100 mL of water and the residue weighed. Chloride (Cl^-) was measured immediately after transfer to the laboratory by titration with silver nitrate. Sodium (Na^+) and potassium (K^+) were determined by flame photometry. Calcium (Ca^{2+}) and magnesium (Mg^{2+}) were measured by titration with EDTA. Bicarbonate (HCO_3^-) was measured by titration with sulfuric acid and sulfate (SO_4^{2-}) was measured by spectrophotometry. Ca^{2+} and Mg^{2+} were then used to calculate total hardness (TH) as followz (Boyd, 2000):

$$TH\ (mg\ \text{of}\ CaCO_3) = (Ca^{2+} + Mg^{2+}) \times 50 \quad (1)$$

Where Ca^{2+} and Mg^{2+} are calcium and magnesium (meq/L).

Groundwater Quality Index (GWQI)

The development of Groundwater Quality Index (GWQI) involved the following steps, which are illustrated in Fig. 2.

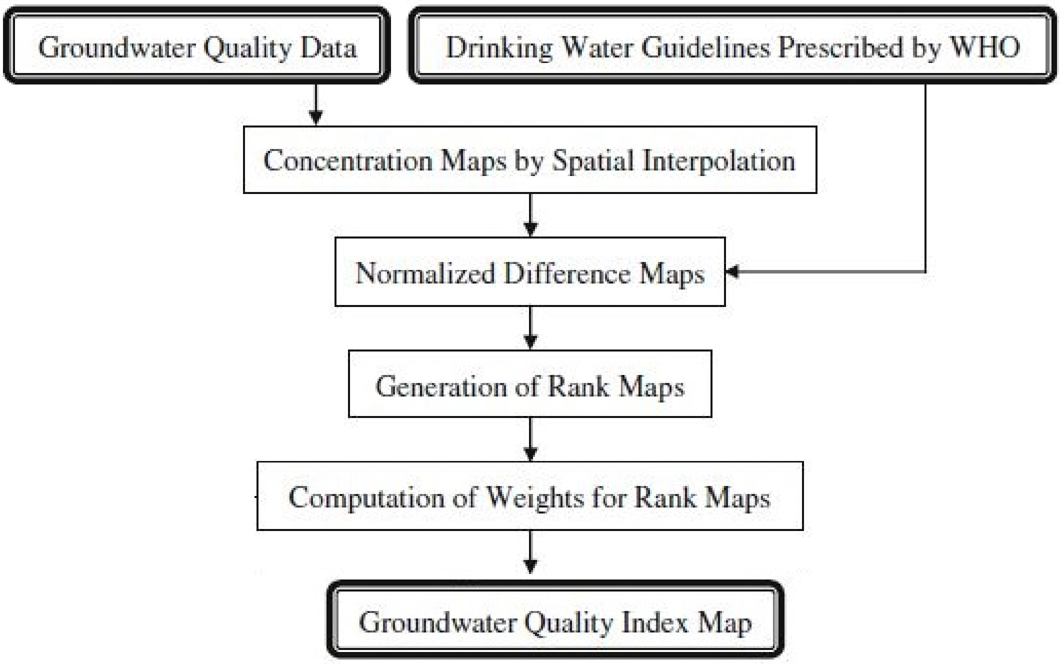

Fig. 2. Flowchart for developing Groundwater Quality Index maps (Machiwal et al. 2011)

Step 1: Concentration maps

Maps of all 11 chemical parameters were created using the inverse distance weighting (IDW) method in ArcGIS 9.3 software (ESRI Inc., 2008).

Step 2: Generation of normalized difference maps

The normalized difference maps of each parameter (NI) were constructed using the following equation:

$$NI = (C - C_m) / (C + C_m) \quad (2)$$

where C is the value of each pixel in the concentration map of each parameter and C_m is the highest desired value of each parameter, according to WHO (2001) (Machiwal et al., 2011). In the resulting maps, the pixel value of each map is between -1 and +1.

Step 3: **Generation of rank maps**

Each NI map was converted to a rank map. The following polynomial equation was used to rank the NI of every pixel between 1 and 10 (Babick et al., 2007):

$$R = 0.5 \times (NI)^2 + 4.5\ (NI) + 5 \quad (3)$$

Where R is rank value that corresponds to its NI value, and NI is the normalized map of each parameter. Each pixel in the rank map has a value between 1 and 10. Ranks 1 and 10 indicate the lowest and highest impact on water quality, respectively. The average of the pixels for each parameter were extracted from the ranking map and used as the weight of the parameter.

Step 4: Preparation of Groundwater Quality Index map

Finally, in last step, the GWQI map was obtained from the following equation:

$$GWQI = 100 - [(W_1R_1 + W_2R_2 + \ldots + W_nR_n) /n] \quad (4)$$

Where R is calculated using Eq. 3 for each parameter, W is a relative weight of the parameter which is calculated from the mean value (R) of each rank map (1–10), and N is the total number of parameters used in the analysis. The values of the pixels in the GWQI map vary between 0 and 100. Values close to 100 indicate high quality groundwater and values close to 0 indicate low quality groundwater. The weight (W) allocated to each parameter indicates its relative importance to groundwater quality and corresponds to the mean value of the associated rank map. Parameters which have a higher impact on groundwater quality (high mean) can be interpreted as being more important in assessing overall groundwater quality. The total number of parameters (N) used in the expression for the GWQI map and limits the index to values between 1 and 100. In this way, the impact of individual parameters is greatly decreased and the index calculation is never limited to a certain number of chemical parameters (Machiwal et al., 2011). The GWQI map was then classified in ten categories from 0 to 100 based on a fixed interval. So areas with the score index closer to 100 indicate high water quality and the areas with the score index closer to zero reflect low water quality. In addition, the percentage of coverage and area of water quality scores were extracted.

GWQI sensitivity analysis

Sensitivity analysis is the identification of the parameters that have the highest (or least) effect on the groundwater quality of an aquifer. In this study, the map removal sensitivity measure (Lodwick et al. 1990) was applied to examine the impact of removing any of the 11 parameters used for the calculation of GWQI and was then subsequently visualized in a GIS. The map removal sensitivity examines the sensitivity of the GWQI map to the removal of one or more of the rank maps from the analyses and is expressed in terms of a variation index as given below:

$$V_{wi} = [(GWQI - GWQI_{wi}) / GWQI]100 \quad (5)$$

Where *V*wi=variation index (%) without *i*th rank map, GWQI=Groundwater Quality Index with all the 11 rank maps, and GWQIwi=Groundwater Quality Index without *i*th rank map.

Results and discussion

Concentration maps

Summary statistics of physico-chemical parameters are given in Table 1 which also shows the maximum allowable limits of various parameters according to WHO (2011). Spatial variation of groundwater quality parameters of the Marvdasht aquifer based on the WHO standards for drinking water are mapped in Fig. 3. The pH value of groundwater varied from 7.30 to 8.25 with an average value of 7.70 (Table 1). This shows that the groundwater of the study area is mainly alkaline. Fig.3a shows that the majority of the study area (396 Km^2) are within the desirable limit of pH (7–8.5) and 28 % of the area (154 Km^2) are beyond the permissible limit.

The EC values ranged from 35.9 µS/cm to 14697.0 µS/cm with an average value of 4001.2 µS/cm (Table 1). It was found that EC in 57.1 % of samples were within the desirable-limit (0-1500 µS/cm), 8.1% of the samples fall in the not-permissible range (1500-3000 µS/cm) and 34.6% of samples are within the not-permissible limit, which are classified as hazardous according to the WHO standard. Only 19% of the study area (107.0 Km^2), located in a small portion of the northern part of the study area has an EC of less than 750 µS/cm, and hence is suitable for drinking. In the remaining area of study (81 % of the area from center to south), the groundwater is not suitable for drinking (Fig. 3b). The mean of TDS in Marvdasht groundwater is 2400 mg/L (Table 1) and based on this value, groundwater is not suitable for drinking (WHO, 2011). The results shows that only 28.5 % of the samples are below 600 mg/L of TDS which are generally considered as desirable for drinking water without any risk (WHO, 2011). Twenty six percent of the samples are within the permissible limit (600-1000 mg/L) and 44.8% of samples fall in the not permissible limit (>10000 mg/L) of TDS. Similar to EC, TDS in 67.3 % of the study area (370 Km^2) located in south is more than permissible level (1000 mg/L) for drinking (Fig. 3c).

Results showed that the majority of the groundwater samples are below the allowable limit of TH (500 mg/L) for drinking water. Only 27.0% of the samples are in the suitable for drinking limit of TH (<300 mg/L). As shown in Fig. 3d, TH in almost half of the study area is below the desirable limit (<300 mg/L). Table 1 shows Ca^{2+} concentration varied from 52.0 to 838.6 mg/L with an average of 217.1 mg/L. Sixty seven percent of the samples are within the not permissible limit (>75 mg/L) and only 32% of the samples fall in the desirable limit (<75 mg/L). Fig. 3e shows that Ca^{2+} remains below the maximum desirable limit (<75 mg/L) of WHO (2011) which covers 74% of the study area, the remaining 26% is within the maximum permissible limit (75–200 mg/L). The concentration of Mg^{2+} ranged from 12.2 to 840.5 mg/L (Table 1). Only 16% of the samples are within permissible limit of Mg^{2+} (<35 mg/L) and 84% of groundwater samples are within the permissible limit of Mg^{2+} (>30 mg/L). Similar to TH and Ca^{2+}, Fig. 3f shows that in the south of the study area, Mg^{2+} levels lead to water that is not desirable for drinking. More than 78% (432 Km^2) of the study area are above permissible limit (>30 mg/L) (Fig. 3f).

The concentration of Na^+ varied from 6.0 to 2200.4 mg/L (Table 1). Sixty one percent of the samples are below the maximum desirable limit (<200 mg/L) of WHO (2011) in 56% of the study area (309 Km^2). The remaining area is beyond the permissible limit (>200 mg/L) (Fig. 3j). The concentration of K^+ ranged between 0.5 to 32.0 mg/L (Table 1). Fig. 3h illustrates that the majority of the area (67%) has K^+ concentrations within its maximum desirable limit (<12 mg/L), whereas 33% of the area in southern areas have K concentration levels above the permissible limit (>12 mg/L).

Minimum, maximum and mean of bicarbonate concentration was 100.0, 552.1 and 309.1 mg/L, respectively (Table 1). Almost half the samples are within the maximum permissible limit of HCO_3^- (300 mg/L). The map of HCO_3^- (Fig. 3m) shows that 61% of the area in the central study area has high concentrations of HCO_3^-exceeding the maximum desirable limit (>300 mg/L). The mean sulfate concentration in Marvdasht groundwater was 301.5 mg/L (Table 1). Sixty percent of the samples in 43% of the study area (238 Km^2) are below the desirable limit of SO_4^{2-} in the north of the study area (Fig. 3m). The Cl^- varied between 13.5 and 5117.7 mg/L with an average value of 941.6 mg/l (Table 1). According to WHO (2011), 28.5% of groundwater samples exceed the maximum allowable limit of Cl^- (600 mg/L). Fig. 3n revealed that near 50% of the study area are in permissible limit of Cl^- (600 mg/L).

Table 1. Summary statistics of physico-chemical parameters of Marvdasht groundwater

Chemical parameter	unit	Mean	Min	Max	SD	CV	WHO (2011)*
pH	—	7.53	6.9	8.0	0.2	2.8	7.5-8.5
EC	µS/cm	4001.2	35.9	14697.0	2635.1	127.1	1500
TDS	mg/L	2400.7	347.2	10270.5	2823.0	117.1	1000
TH	mg/L	1123.2	199.6	5470.4	1364.5	121.1	500
HCO_3^-	mg/L	309.1	100.0	552.1	89.6	29.4	300
SO_4^{2-}	mg/L	301.5	13.2	1501.6	377.3	125.2	200
Cl^-	mg/L	941.6	13.5	5117.7	1418.1	150.5	200
Ca^{2+}	mg/L	217.1	52.0	838.6	235.1	108.2	75
Mg^{2+}	mg/L	146.1	12.2	840.5	187.4	128.2	30
K	mg/L	7.4	0.5	32.0	0.8	51	12
Na^+	mg/L	398.6	6.0	2200.4	548.8	137.7	200

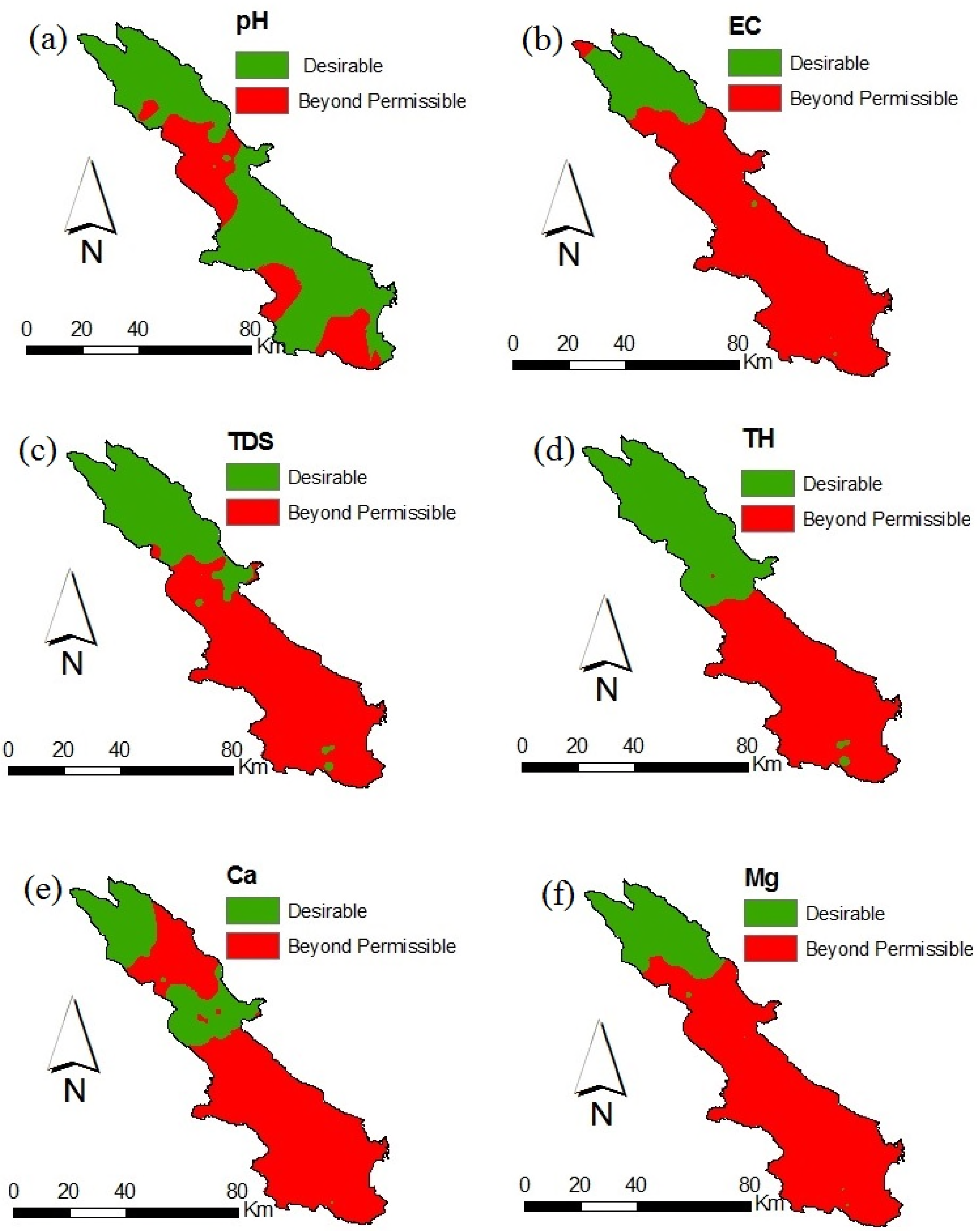

Fig. 3. Spatial variation of groundwater quality parameters of Marvdasht aquifer

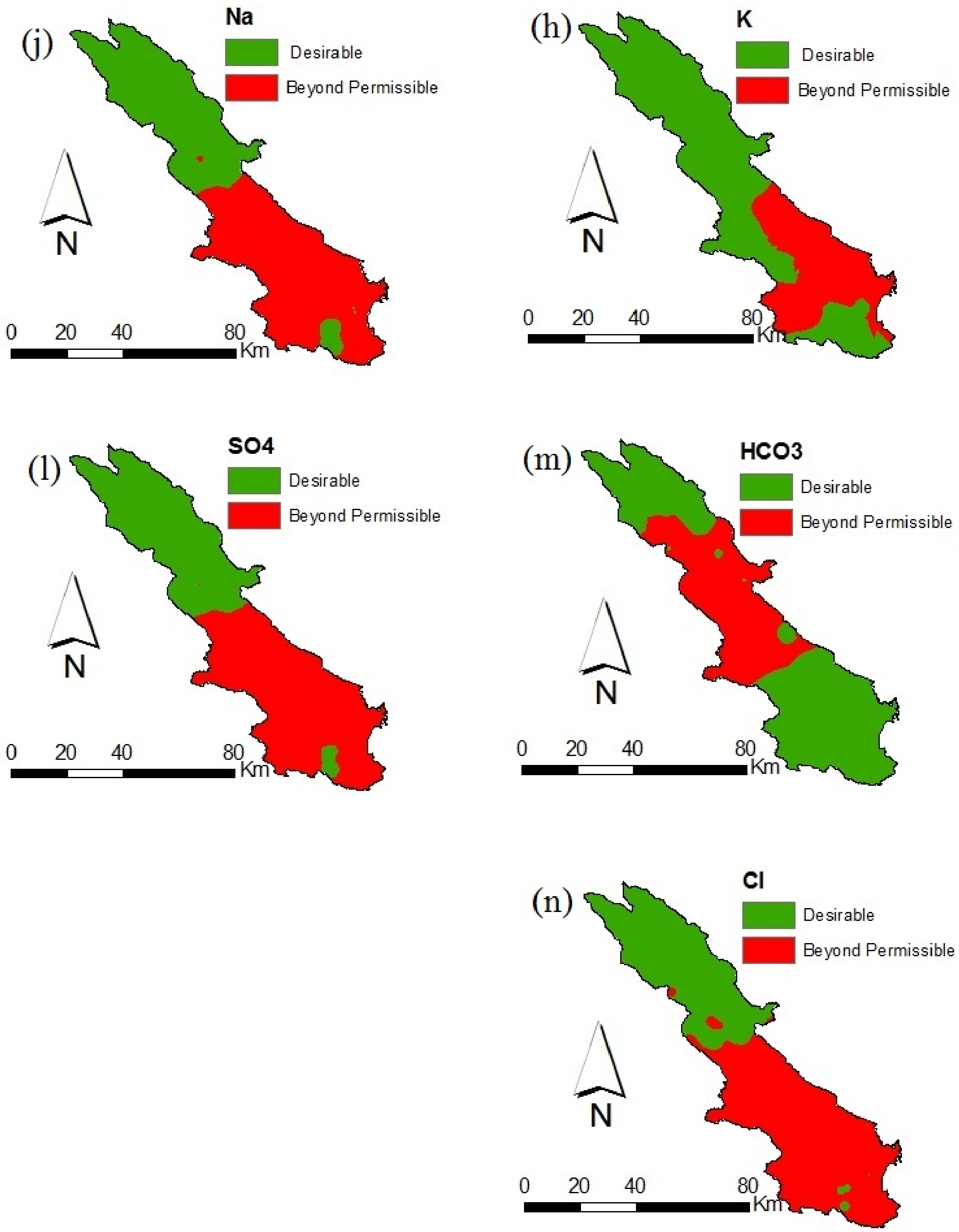

Fig. 3. (continued)

GWQI map

The mean Groundwater Quality Index (GWQI) map of Marvdasht aquifer is shown in Fig. 4. As revealed in Fig. 4, the groundwater quality of Marvdasht is generally good (mean GWQI =29 and maximum GWQI =100). The GWQI are classified in 10 classes at 10% intervals (Fig. 4). The first three classes (GWQI from 80 to 100) which cover 47% of the study area (267 Km^2) are classified as High-quality. The next four classes (GWQI from 40 to 70) are considered as Moderate-quality, and cover 44% of the study area (242 Km^2). The last and smallest three classes (GWQI from 0 to 30) cover just 2% of the study area (11 Km^2) and are assigned a Low-quality class (Fig. 4).

Fig.3 shows that high-quality groundwater exists in the northern region of the study area, while the quality of groundwater decreases from central to southern regions of the study area. According to the GWQI map (Fig. 4), from central to northern regions of the study area, groundwater shows the best quality for drinking, irrigation, and other domestic purposes. High groundwater quality is related to the greater capacity of the vadose zone to attenuate contaminant percolation in north parts of the area. At north of the plain, the aquifer is recharged with the seepage from the Droudzan dam which leads to higher quality groundwater in this area. At the southern region of the plain, groundwater quality was decreased by recharging of the aquifer with saline water coming from the Kor River and also urban wastewater of Marvdasht city. Furthermore, in this part of the aquifer, dissolution of saline and chalky formations has increased salinity, TDS and TH levels. Ostovari et al. (2015) reported that southern parts of the Marvdasht groundwater with high levels of EC and sodium absorption ratio (SAR) were not suitable for irrigation. The GWQI map presented in this study is based on 5 years of groundwater quality data, and therefore the results can be used for long-term management planning of groundwater resources in the Marvdasht aquifer. It is worth mentioning that due to the lack of data of biological, nitrate, or radioactive indicators in the water quality, the developed GWQI represents only physico-chemical groundwater quality of the Marvdasht aquifer.

Statistics of the 11 rank maps (parameters) used to calculate GWQI are illustrated in Table 2. It can be seen in Table 2, the parameter of Mg^{2+} with the highest mean rank value (5.48) has the biggest impact on spatial patterns of groundwater quality as shown in Fig. 4. Following Mg^{2+}, EC with a mean rank of 5.01 and TDS with a mean rank of 4.57 are the second and third most influential parameters on the map of GWQI, respectively. Parameters of Na^+ and K^+ have the lowest effect on the spatial patterns visible in the GWQI map. Due to existence of carbonate geological formations with lots of dolomite, Mg^{2+} is the predominate ion in the Marvdasht aquifer, this finding is contrary to the results presented by Ostovari et al. (2016) in Lordegan groundwater. Turbidity and total suspended solid were the parameters with the biggest impact on the Lordegan aquifer due to existence lots of suspended clay in groundwater (Ostovari et al. 2016).

Table 2- Summary statistics of the 11 mean rank maps used to generate GWQI

Parameter	Unit	Minimum	Maximum	Mean	Standard deviation
pH	—	3.2	4.0	3.7	0.02
EC	µS/cm	3.92	5.15	5.01	0.28
TDS	mg/L	3.71	5.26	4.57	0.25
TH	mg/L	2.76	3.66	3.32	0.16
HCO_3^-	mg/L	3.12	4.43	3.73	0.13
SO_4^{2-}	mg/L	1.93	5.93	3.41	0.25
Cl^-	mg/L	2.33	3.92	3.14	0.26
Ca^{2+}	mg/L	2.22	3.95	2.93	0.12
Mg^{2+}	mg/L	4.04	6.15	5.48	0.34
K	mg/L	1.45	2.65	1.97	0.26
Na^+	mg/L	1.38	1.62	1.44	0.05

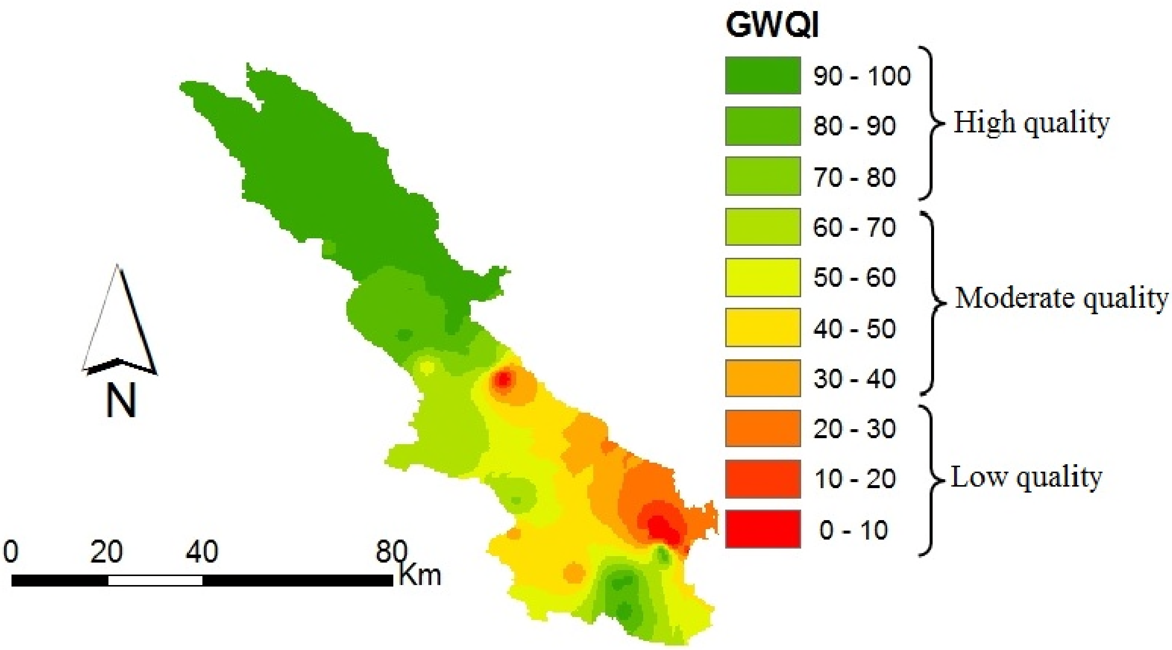

Fig. 4. The mean Groundwater Quality Index (GWQI) map of Marvdasht

Sensitivity of groundwater quality parameters

Table 4 presents the results of the map removal sensitivity analysis for the 11 parameters. Parameters of Mg^{2+}, TH and Na^{+} have the mean value of the variation index of 1.20%, 1.15% and 1.12%, respectively. Therefore, the individual removal of Mg^{2+}, TH and Na^{+} from the calculation of GWQI appears to cause the highest variation in the unperturbed index. Tables 1 and 2 reveal that Mg^{2+} with the greatest rank value has the highest influence on GWQI, this result is in agreement with the findings of Babiker et al. (2007) and Machiwal et al. (2011). It can be concluded that the parameters that reflect relatively lower water quality (high rank value) have a large impact on the GWQI (Babiker et al. 2007). The parameters TDS (VI = 0.41%) and SO_4^{2-} (VI = 0.36%) have the lowest impact on the GWQI map. It means that removing these parameters (TDS and SO_4^{2-}) does not have a significant influence on the GWQI.

Table 3- Results of the map removal sensitivity analysis

Parameter	Unit	Variation index (VI) (%)			
		Minimum	Maximum	Mean	Standard deviation
pH	—	0.54	0.81	0.64	0.05
EC	µS/cm	0.44	0.85	0.75	0.06

TDS	mg/L	0.26	0.50	0.41	0.04
TH	mg/L	0.32	1.28	1.15	0.02
HCO_3^-	mg/L	0.01	0.42	0.18	0.08
SO_4^{2-}	mg/L	0.04	0.71	0.36	0.03
Cl^-	mg/L	0.34	0.65	0.52	0.03
Ca^{2+}	mg/L	0.31	0.78	0.62	0.07
Mg^{2+}	mg/L	0.66	1.42	1.20	0.10
K	mg/L	0.88	1.12	0.95	0.04
Na^+	mg/L	0.94	1.33	1.12	0.06

Conclusions

This study was carried out in the Marvdasht aquifer located in a semi-arid region of Iran to evaluate groundwater quality using 5 years (2010–2015) of groundwater quality data. The mean maps of 11 groundwater quality parameters showed that except for TDS, EC and TH, other water quality parameters were almost within the permissible limits for drinking water according to WHO (2011). A GWQI of 71 indicates that Marvdasht groundwater is generally good quality for drinking. The GWQI map revealed that the northern region of the study area had the best quality groundwater. However, based on the maximum permissible limit for drinking water, poor quality groundwater exists in only 2% of the study area in the south and southwestern regions. The GWQI GIS-based map methodology used in this study is a simple way to understand and interpret the groundwater quality, and to assist water resources managers and environmentalists in decision making in high risk areas. Sensitivity analysis showed that Mg^{2+}, TDS and Na^+ were the most important parameters for calculating GWQI maps. Therefore it is recommended that in future assessments of Marvdasht groundwater quality that the Mg^{2+}, TDS and Na^+ parameters be measured with a higher frequency with greater accuracy.

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