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Groundwater Quality Assessment Based on Geographical Information System and Groundwater Quality Index

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Iran is located in an arid and semi-arid part of the world. Accordingly, the management of the water resources in the country is a priority. In this regard, determining the quality and pollution of surface water and groundwater is very important, especially in areas where groundwater resources are used for drinking. Groundwater quality index (GQI) checks the components of the available water with various quality levels. To assess the quality of drinking groundwater of Yazd-Ardakan plain according to GQI in geographical information system (GIS) environment, the electrical conductivity, sodium, calcium, magnesium, chlorine, pH, sodium adsorption ratio, bicarbonate, sulfate, potassium, water hardness, and all substances dissolved in the waters of 80 wells were determined. The samples were obtained from Yazd Regional Water Organization from 2005 to 2014. Using this data, the map components were plotted by Kriging geostatistical method. Then, the map of GQI was prepared after normalizing each map component, switching to a rating map, and extracting the weight of each component from the rating map. Based on the GQI index map, the index point which was 87 in 2005 has increased to 81 in 2014. These maps show a decline in groundwater quality from west to the east region. This decline in groundwater quality is due to the existence of Neogene Organizations in the east and geomorphologic unit of the bare epandage pediment in the west. The map removal and single-parameter sensitivity analysis showed that GQI index in Yazd-Ardakan plain is more sensitive to the components of electrical conductivity (EC), total dissolved solids (TDS), and total hardness (TH). Therefore, these components should be monitored more carefully and repeatedly.

Keywords: Water Quality; Groundwater Quality Index (GQI); Geographical Information System (GIS); Sensitivity Analysis; Yazd-Ardakan Plain

1. Introduction

Iran is located in an arid and semi-arid part of the world. Accordingly, the management of the water resources in the country is very important. Unfortunately, in addition to the quantity of available water, the quality of water resources and its pollution are among the limiting issues in terms of water supply. Therefore, determining the quality and pollution of surface water and groundwater are very important, especially in areas where groundwater resources are used for drinking (1, 2). In this regard, monitoring and zoning of water, as important variables, should be considered in planning (3, 4). Because of some unique features (compared to surface water resources), the groundwater has been regarded as one of the main resources of water supply in many countries, including Iran (5, 6).

Because of the large volume and number of data and components, it is difficult to assess the water quality. Furthermore, in evaluating the quality of groundwater, the use of appropriate tools and techniques for qualitative data processing is very efficient. One useful method for assessing water quality is groundwater quality index (GQI), which is calculated for groundwater (3, 7). GQI checks the components in the available water with various quality levels. It provides a method for briefing the general condition of water quality. This condition can be well-presented and helpful to understand whether the overall quality of groundwater is a potential danger for different uses. Finally, this method helps assess the aquifer vulnerability and shows the success in maintaining and improving it.

In fact, water quality index combines different parameters of water quality to provide the final index value which can be used for comparisons by location (8). In calculating GQI, detecting the factors which cause the minimum and maximum sensitivity of GQI is very important. For this purpose, sensitivity analysis method is used. The result of sensitivity analysis is used to determine the elements, which have the greatest impact on the overall quality of water in an aquifer. Therefore, their frequent, correct, and precise monitoring is necessary. A sensitivity analysis technique of GQI which can be conducted in GIS environment is the map removal and single-parameter sensitivity analysis (2, 3).

Machiwal et al. (9) evaluated the groundwater quality of Rajasthan located in West India using GIS. To this effect, 53 wells were sampled and the components and indexes of calcium, magnesium, sodium, potassium, sulfate, hardness, pH, TDS, and EC were measured in each sample. Then, the maps of these components were prepared using the Kriging method. Based on these maps, the normal maps were plotted, and grounded on the normal maps, the rating maps were provided. Finally, through obtaining the GQI map and conducting the sensitivity analysis, it was found that the water quality index is more sensitive to water hardness, sulfate, and sodium components (4).

Heshmati et al. (10) investigated the groundwater quality of Shahrekord using the GQI model and geographic information system (GIS). Based on the average result of the GQI index map, the groundwater quality of Shahrekord is appropriate. The movement from the northwest of the region toward its southern part shows a decrease in groundwater quality. The map removal and single-parameter sensitivity analysis showed that GQI index in Shahrekord aquifer is more sensitive to TSS and partly sodium (10). Saeedi et al. employed the groundwater quality index to map the regions which have indexes of mineral water (11).

Khan et al. (2011) evaluated the impact of changing patterns of land use on groundwater quality of hard-rock aquifer system at Mahshvaram (near Hyderabad, India) using GIS and GQI (8). The objective of this study was to assess the groundwater quality of Yazad-Ardakan plain (from 2005 to 2014) for drinking purpose based on GIS and GQI index. This condition can be well-presented and helped understand whether the overall quality of groundwater is a potential danger for different uses. Finally, this method helps assess the aquifer vulnerability and shows the success in maintaining and improving it (2, 12).

2. Materials and Methods

2.1. Location of the Study Area

Yazd-Ardakan plain with an area of 4117 km^2 is located at the center of Yazd, between the longitudes of 53° 46´ to 55° and latitudes of 31° 49´ to 32° 55´. To the north, it borders Siyah-Kouh Desert and to the south, it reaches Shirkooh Heights. To the east, it is limited to Khranq sub-basin, and to the west, there is the sub-basin of Taqstan and Nadooshan. The highest point of this region is Shirkooh peak with the height of 4075 m and its deepest point is 970 m above sea level. Its average height is 1565 m above sea level. The entrance of groundwater is located in the southern part of the plain at Shirkooh. The end part of the plain is located in the northern part, near Siyah-Kouh. The groundwater has a general direction of south to north (Figure 1). This plain is one of the largest and the most important plains of Yazd and part of the dry zone of the Central Iranian Plateau (13). This area has little and erratic rainfalls (the average rainfall in the area is 118 mm per year). Its evaporation rate is between 2200 to 3200 mm (13). The largest water reserve is located in this area.

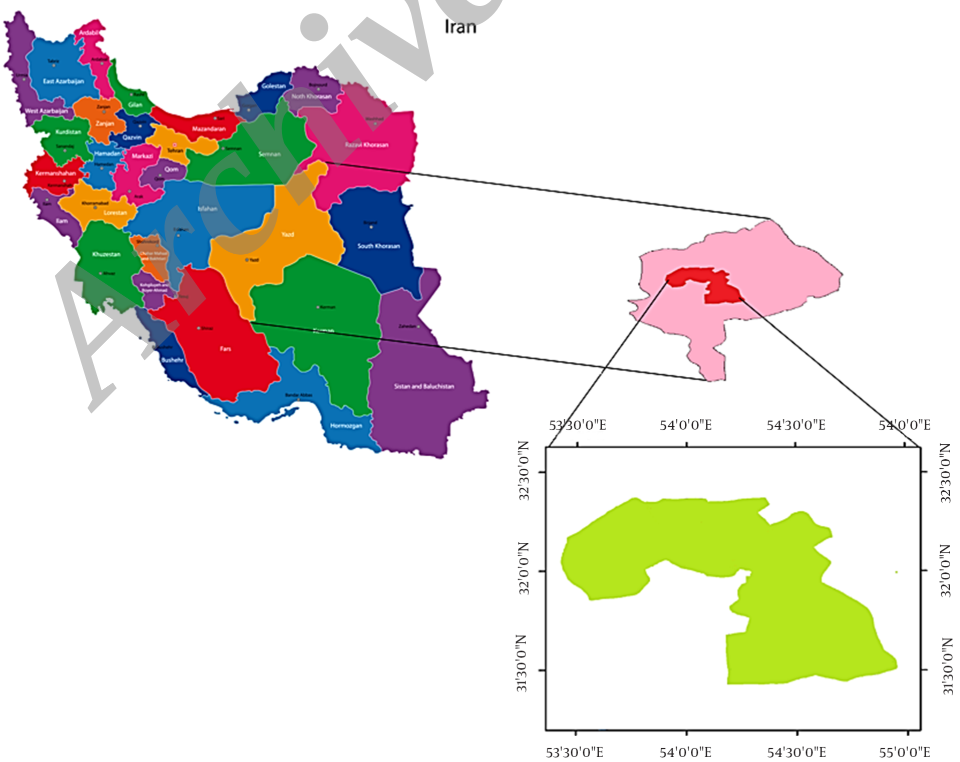

Figure 1. Location of Study Area in the Country and Yazd Province

2.2. Data Collection

In this study, the water samples of 80 wells provided by Regional Water Organization were used. To assess the changes of groundwater quality, the electrical conductivity, sodium, calcium, magnesium, and chlorine components, sodium adsorption ratio, bicarbonate, sulfate, potassium, as well as pH, water hardness, and all substances dissolved in the waters of these 80 wells were calculated according to GQI in GIS environment from 2005 to 2014. Finally, WHO standards were used to compare and investigate the quality status of the water.

2.3. GQI Mapping Process

2.3.1. First Step

In the first step, the concentration maps for each parameter of spot data were prepared using Kriging interpolation method as the initial maps in GIS 9.3. The Kriging method was used because unlike other interpolation methods (such as the nearest point or moving average), it is based on statistical method. This method executes the weight average on spot data where the output is equal to the sum of the coefficients of the spot values and the weights divided by the sum of the weights.

2.3.2. Second Step

To express the data as the global norm, the concentration measured in each C cell in the initial map was presented as its ideal standard value of Ć (3, 5, 14). In the resulting maps, the pixel value is between -1 to +1.

(1)

$$NI = \frac{(C-C)}{(C+C)}$$

2.3.3. Third Step

At this stage, each normalized difference index (NDI) map is converted to a rating map ranging from 1 to 10. Level 1 represents the lowest impact on groundwater and level 10 the highest impact. The minimum value of each pixel, which is -1 in the NI map, is equal to 1 in the rating map and the maximum value, which is +1 in the NI map, is equal to 10 in the rating map. To provide the rating map, the following polynomial equation was used (3).

(2)

$$R = 0.5 \times NI^2 + 4.5 \times NI + 5$$

Where, R is the weight of each pixel based on its NI value and NI is the normal map of each component.

2.3.4. Fourth Step

The average pixel value of each component was extracted from the rating map and used in the next step as the component weight.

2.3.5. Fifth Step

The GQI map was obtained from the following equation:

(3)

$$GQI = 100 - \left[\frac{W_1R_1 + W_2R_2 + \ldots W_nR_n}{n}\right]$$

Where, w_i is the relative weight of each component, which its value is between 1 and 10, R_i is the rating map of each component, and n is the number of quantitative components used to determine the GQI. GQI map pixel values are placed between 0 and 99. The pixel value close to 100 shows the better quality of groundwater and conversely, the pixel value close to zero shows the lower quality of groundwater (9).

2.3.6. Sixth Step

The water qualitative groups in the GQI map were divided into 3 classes of good, fair, and poor, scoring from 0 to 100. The class which is close to 100 shows better quality and the class which is close to 0 shows lower quality.

2.4. GQI Sensitivity Analysis in Terms of Components Removal

The sensitivity analysis was done using the map removal (10). In the analysis of 12-rank GQI map, each time, the effect of each rating map removal on GQI general map (prepared using the 12 components), was investigated. To this effect, the change index maps were calculated using the following equation:

(4)

$$V_{wi} = 100 \times \left[\frac{GQI_{12} - GQI_{wi}}{GQI_{12}}\right]$$

Where, V_{wi} is the change index (%) without the i^{th} map, GQI_{wi} is the water quality index map without i^{th} rating map and GQI_{12} is the water quality index map with 12 qualitative components. All these steps and sensitivity analysis of components were conducted in ArcGIS 9.3 environment (10).

2.5. Interpolation Using Kriging Model

The first step in determining water quality, using the interpolation method, is the selection of an appropriate model for data zoning. Much research has been conducted in terms of spatial analysis, interpolation methods, and zoning methods. Maghami et al. (4) as well as Jafari and colleagues (15) are among the researchers who did some studies in this regard. The results of these studies indicate the high accuracy of Kriging method for interpolation.

This is the most important method of interpolation which is based on statistical models and relationships. The raster layer produced by this method displays a very detailed surface. Unlike the other methods, Kriging method is a global method, i.e. all observations of the region are employed. Therefore, Kriging interpolation method was used to achieve the objectives of this study (4, 15).

3. Results and Discussion

3.1. Groundwater Quality Assessment Using GQI Model

The statistical abstract of the factors examined in groundwater of Yazd, Meibod, Mehriz, and Ashkezar is presented in Table 1. The obtained results regarding the minimum, maximum, and the average qualitative value of groundwater, over the 10 year period show that the parameters of Mg, Cl, TH, TDS and EC had an upward trend and the parameters of pH, HCO_3, Na, SO_4, Ca, SAR, and K had a downward trend. The values of TH, TDS and EC were higher than the permissible levels (14). Apart from the above mentioned parameters, the amounts of the remaining parameters were normal and did not exceed the WHO (World Health Organization) standards. In 2005, in the study area, the level of TH was equal to 496 mg/L. In 2014, its level was 915 mg/L which was 2 times more than the permissible level. This increase reflects the hardness of groundwater and its low quality in the study area.

In 2005, in the study area, the level of EC was equal to 2304 μΩ-cm. In 2014, its level was 4289 μΩ-cm, which was 5 times more than the permissible level. According to Wilcox classification, the water salinity belongs to the very severe class. In 2005, in the study area, the level of TDS was 3 times more than the permissible level and was equal to 1488 mg/L. In 2014, its level was 2794 mg/L, which is 6 times more than the permissible level. Therefore, it reduces the water quality in the region.

3.2. The Weight Determination of Qualitative Parameters of Groundwater

Determining the most effective component is very important in groundwater quality index (GQI). For example, Table 2 shows the statistical abstract of 12 rating maps related to 12 components in 2014. The mean of pixels numerical value in each rating map is considered as the component weight. To obtain the GQI map of groundwater, this weight is placed in Equation 3. According to the investigation of components in the statistical period, the components of EC, TDS, TH, pH and Mg have the highest rating average, which reduce the groundwater quality. The components of EC, TDS, and TH, with the respective averages of 8.04, 8, and 6.06, have greater impacts on groundwater quality compared to the other components of the study area. The components of K, SAR, Cl, SO_4, Na, HCO_3, and Ca have the lowest rating averages (less than 2) and the least impact on groundwater quality. In Rajasthan (India), TH, EC, TDS, and Mg, with the respective weights of 7.45, 5.89, 5.82 and 5.42 have the greatest impact and the components of SO_4 and Na with the weights of 3.07 and 3.77 have the lowest impact on GQI (9).

The sensitivity analysis using the map removal method was conducted through Equation 4 in GIS environment. Generally, the GQI sensitivity, intensity, and components differ from one aquifer to the other.

Using the Kriging interpolation method and 12 components, the groundwater GQI map of the study area has been provided for each year of the statistical period (2005 to 2014) based on the established relationships and GIS (Figure 2). If the GQI score is greater than 80, it will be classified in the good class. If its score is between 60 and 80, it will be classified in the moderate class and if the score is less than 60, it belongs to the inappropriate class. The results of GQI maps show that the groundwater quality in the study area is classified in the moderate to good class. The process shown by the obtained maps indicated that the water quality is declining. In 2005, the groundwater quality index has been 87. In 2014, its value reached 81 (Figure 3). In general, Yazd-Ardakan plain can be divided into 3 zones of western, middle, and eastern margin. The groundwater quality is reduced by moving from the west towards the east of the province.

The areas, which maintained their relative quality andhad an appropriate groundwater quality are mainly located in the west, southwest, and southeast of Yazd, in the desert geomorphology unit of the epandage pediment and erosional pediment. The GQI maps show that the worst groundwater quality belongs to the eastern part of Yazd-Ardakan plain. The assessment of changes of groundwater levels in 4 decades show the downward trend of water quality and the average decline of the water table is about 0.5 meter per year (13). The results of the water quality changes in recent decades have shown that, by increasing the frequency of droughts and severe decline of groundwater table, its quality dropped, especially from 2006 to 2011 (Figure 3).

To evaluate the quality of groundwater in Yazd-Ardakan plain, the GQI model was used based on GIS during the statistical period of 2005 to 2014. In GQI method, the types of parameters are optional. This makes it possible for a researcher to investigate the qualitative changes according to the needs and problems of each region. In this method, if a parameter is greater than the standard value, it will be adjusted by other parameters, so it is better to be cautious when using this method. According to the results, the method of GQI in mapping Yazd-Ardakan plain was suitable. This method can reflect the changes in groundwater qualitative components. It can also determine the components that affect the groundwater quality by using the sensitivity analysis. The zoning results of this study showed that the Kriging method is the best interpolation method with a low root-mean-square error (RMSe) rate (6, 8, 21 and 22). To evaluate and analyze the extent of groundwater salinity and nitrate in Neyriz plain (Fars), Shabani and colleagues investigated different geostatistical methods such as Kriging, inverse distance, radial function, and position and general estimator. According to their results, the Kriging method was the most appropriate method (16).

Table 1. The Minimum, Maximum and Average Values of Qualititive Parametres of Grondwater in Yazd-Ardakan Plain

	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	WHO (2011)
HCO_3, mg/L											300
Maximum	60.35	69.35	106.01	216.95	207.43	62.29	97.97	189.14	201.41	211	
Minimum	20.61	29.16	102.72	104.07	162.47	21.73	52.42	62.03	56.47	96.47	
Average	30.9	39.3	103.42	107.86	194.47	45.5	65.5	137.75	121.82	137.69	
TH, mg/L											500
Maximum	1747.18	1828.54	146.08	147.86	10.66	36.86	105.87	119.72	2193.74	2274.08	
Minimum	146.60	221.71	2.54	3.92	1.19	2	4.06	3.54	206.14	203.60	
Average	496.29	501.52	51.53	59.59	7.65	21.22	48.43	53.87	881.51	915.77	
Na, mg/L											200
Maximum	130.12	146.08	147.86	10.66	36.86	105.87	119.72	150.68	81.01	63.09	
Minimum	4	2.54	3.92	1.19	2	4.06	3.54	4.88	1.42	2.45	
Average	48.22	51.53	59.59	7.65	21.22	48.43	53.87	22.36	25.09	24.87	
SO_4, mg/L											200
Maximum	300.74	209.04	131.91	211.48	131.45	216.92	135.09	28.15	25.11	28.12	
Minimum	20.76	7.13	31.39	52.59	33.21	12.11	47.03	127.37	200.13	191.37	
Average	60.25	75.63	72.71	81.18	84.42	76.21	73.12	91.01	61.22	89.97	
Mg, mg/L											30
Maximum	11.76	18.04	17.16	5.92	17.22	21.1	24.97	11.37	107.89	126.49	
Minimum	2.35	2.67	2.37	0.84	1.61	2.18	4.68	2.32	1.61	1.74	
Average	6.22	8.54	8.85	4.43	9.43	11.12	15.12	6.02	7.45	8.01	
Ca, mg/L											75
Maximum	54.86	20.98	38.01	82.43	29.32	49.61	50.68	24.99	46.13	30.79	
Minimum	9	1.30	3.06	2.01	4	2.78	15.52	3.03	12.44	11.57	
Average	27.60	61.61	22.54	36.54	9.65	30	38.83	9.90	16.20	19.60	
Cl (mg/L)											200
Maximum	94.36	115.19	72.73	64.01	72.88	69.82	122.79	126.93	90.45	74.20	
Minimum	2	3	1	3.70	6.36	3.72	2.41	4	1.50	1.68	
Average	14.32	18.18	12.23	11.34	13.12	15.21	38.36	32.54	14.28	29.44	
K, mg/L											12
Maximum	0.20	0.27	0.26	0.24	0.17	0.18	0.33	0.20	0.11	0.11	
Minimum	0.03	0.03	0.02	0.03	0.04	0.01	0.01	0.01	0.01	0.01	
Average	0.08	0.11	0.12	0.14	0.15	0.13	0.16	0.07	0.05	0.04	
pH											7.5-8.5
Maximum	7.98	7.80	8.06	8.80	7.91	8.37	8.10	7.98	8.08	7.90	
Minimum	7.54	7.46	5.67	6.23	7.60	6.60	7.18	7.65	7.58	6.93	
Average	7.76	7.35	7.54	7.68	7.70	7.78	7.88	7.79	7.79	7.62	
SAR, mg/L											300
Maximum	23.51	27.96	20.16	16.36	17.75	21.47	27.20	32.73	23.13	16.47	
Minimum	1.36	1	1.16	2.29	2.26	1.65	1.19	3	2	1.28	
Average	5.56	7.71	6.22	5.53	6.60	7.70	8.80	7.22	7.87	7.67	
EC, µs/cm											750
Maximum	11141.13	13940.5	9397.2	8554.22	9435.5	8879.56	14650	16960.01	10419.07	10133.75	
Minimum	488.90	311.83	547.8	965.34	1292.68	872.82	538.6	487.57	532.08	595.65	
Average	2304.70	2502.46	2443.5	2314.21	2578.78	2654.21	8564.39	3404.63	4148.34	4289.01	
TDS, mg/L											500
Maximum	7393.41	9163.33	6021.81	5068.49	5987.39	5734.91	9592.34	5771.10	6824.18	6548	
Minimum	251.67	170.15	343.26	638.73	810.96	551.04	349.72	526.56	341.02	396.01	
Average	1488.80	1756.16	1949.19	1822.70	2134.12	2256.65	2976.87	2365.21	2649.92	2794.46	
GQI											-
Maximum	91	90	88	88	87	86	87	88	89	89	
Minimum	82	79	78	81	83	80	77	80	79	78	
Average	87	86	84	84	85	83	80	82	82	81	

Table 2. The Statistical Parameters of Rating Map Related to 12 Qualititive Components of Groundwater

Components Rating Map	Maximum	Minimum	Mean ± SD
EC, µs/cm	9.25	4.49	8.04 ± 0.98
K, mg/L	1.06	1	1.02 ± 0.01
SAR, mg/L	1.36	1.02	1.17 ± 0.06
pH	4.97	4.48	4.89 ± 0.03
Cl, mg/L	3.04	1.05	1.90 ± 0.45
TDS, mg/L	9.22	4.48	8 ± 1
Mg, mg/L	3.73	1.39	2.52 ± 0.55
SO_4, mg/L	1.89	1.04	1.33 ± 0.15
Na, mg/L	2.79	1.08	1.78 ±0.35
TH, mg/L	8.08	3.19	6.06 ± 1.13
HCO_3, mg/L	1.16	1.05	1.08 ± 0.01
Ca, mg/L	3.20	1.14	1.87 ± 0.42

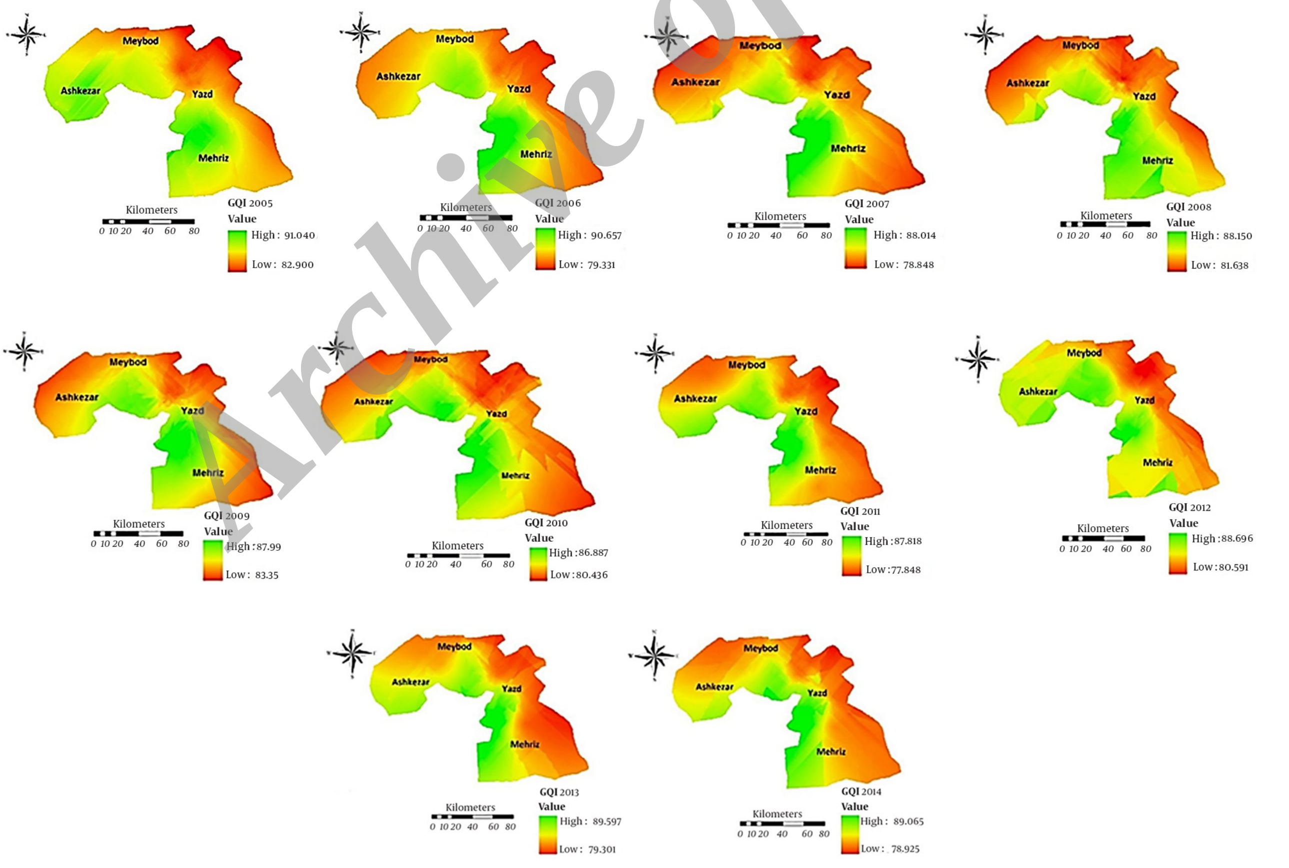

Figure 2. GIS Maps of Yazd-Ardakan Plain Groundwater Based on the Maps of 12 Measured Componenets

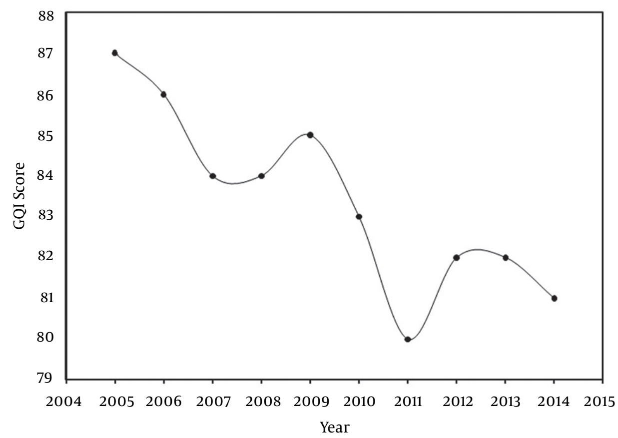

Figure 3. The Changes in Groundwater Quality Index From 2005 to 2014

Our results show that the groundwater quality in Yazd-Ardakan Plain is classified as moderate to good. However, the results of GQI maps indicate that the water quality is declining. In general, the groundwater quality reduces by moving from west to the east part of the province. The appropriate groundwater quality are mainly located in the western part of Yazd, in the desert geomorphology unit of the epandage pediment and erosional pediment. The eastern part of the region is mainly covered by Neogene structures. These structures typically consist of plaster and salt layers with gypsum and common salt. The water which is closer to these salty structures has more minerals, which affects the surrounding groundwater. According to the results, apart from TH, TDS, and EC, the amounts of the remaining parameters are normal and do not exceed the WHO standards. By looking at the maps related to the parameters of TH, TDS, and EC during the statistical period of 2005 to 2014, it was found that the values of these parameters in the eastern and northern parts of the region were always high.

It can be due to the existence of Neogene manufacturers. These parameters have a high weight and GQI is more sensitive to them. In fact, these components in Yazd-Ardakan plain groundwater have more impacts on GQI model and their removal will cause greater changes in GQI. Therefore, they should be carefully evaluated and monitored. In an assessment of groundwater quality changes in Yazd-Ardakan plain, during the statistical period of 2000 to 2009, Ekrami and his colleagues have introduced TH and EC as the most important parameters affecting the groundwater quality of the study area (13). In Rajasthan, India, it was found that TH had a high weight and GQI was more sensitive to it (9). The average decline of the water ground surface is about 0.5 meter per year during the statistical period. This suggests the uncontrolled and non-normative withdrawal of groundwater. The successive and severe droughts exacerbate the decline of groundwater in the region. Unfortunately, the aquifer is placed in a state of crisis. The results are consistent with the studies conducted by Farajollahi (17) and Ekrami et al. (13). The recurrent drought and sharp drop in the groundwater aquifer can be the main reasons for the increase of parameters (Mg, Cl, TH, TDS, and EC) affecting the groundwater quality.

4. Conclusions

GQI expresses the data related to the water quality in an explicit manner. This index presents a way of summarizing the overall qualitative condition of water which is understandable for the audience. It can also explain the overall quality of groundwater and its threats in various uses of water. Finally, the regions with poor groundwater quality can be targeted for detailed studies and monitoring programs. According to the results, due to the nature of natural phenomena such as drought, their complete removal is not possible. The only principled way to prevent dangerous consequences of the water table decline and reduction of groundwater resources quantity and quality is the correct and systematic use of water and avoidance of uncontrolled groundwater withdrawal.

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Authors' Contributions

Zahra Derakhshan participated in the design of study, coordinated activities and revised manuscript. Seyed Ali Almodaresi participated in the design of the study, final revised of manuscript and intellectual helping for analyzing of data. Mohammad Faramarzian and Ali Toolabi performed data collection, carried out statistical and technical analysis of data, participated in design of study and drafted manuscript. All authors read and approved the final manuscript.

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