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Hydrogeological Drought and Groundwater Quality Changes Using GRI and GQI in Semnan and Damghan Plains, Iran

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Author
Pouyan Dehghan Rahimabadi, *M.Sc.*[1]
Hossein Azarnivand, *Ph.D.*[2*]
Arash Malekian, *Ph.D.*[3]

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[1] Ph.D. Candidate, Faculty of Natural Resources, University of Tehran, Iran
[2] Professor, Faculty of Natural Resources, University of Tehran, Iran
[3] Associate Professor, Faculty of Natural Resources, University of Tehran, Iran

*** *Correspondence***
Address: Department of Reclamation of Arid and Mountainous Regions, Faculty of Natural Resources, University of Tehran, Karaj, Alborz, Iran.
Cell Phone: +989121698222
Telephone Number: +982632227765,
Fax Number: +982632222045,
Email: hazar@ut.ac.ir

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ABSTRACT

Aims: In this study, the hydrogeological drought and groundwater quality changes are investigated over time in Semnan and Damghan plains.

Materials & Methods: The groundwater level and groundwater quality changes in of these plains have been evaluated using monthly piezometric wells data for April as the groundwater-recharging month and October as the groundwater-discharging month, and six groundwater quality factors including pH, Chloride (Cl^-), Total Dissolved Solids (TDS), Electrical Conductivity (EC), Calcium (Ca^{2+}) and Magnesium (Mg^{2+}) were considered to determine groundwater quality changes. Groundwater Resource Index (GRI) and Groundwater Quality Index (GQI) were used to determine hydrogeological drought and changes in its quality, respectively, in studied plains from 2004 to 2018.

Findings: The results illustrated that trends of groundwater level and GRI are decreasing, and there is no steady trend for these indices over the studied period and GRI value is higher in city surrounding regions in both plains. According to the results of GQI, EC and TDS factors have the highest effect on the groundwater quality, respectively, compared to other factors. GQI value is higher in central and northern parts than other parts in Semnan plain, while in Damghan plain, GQI value in central and western parts is higher than eastern parts.

Conclusion: The correlation between GRI and GQI showed positive results in both plains, with 0.542 in Semnan and 0.672 in Damghan, reflecting that groundwater quality changes with groundwater level changes.

Keywords: GQI; GRI; Groundwater; Hydrogeological Drought; Semnan.

CITATION LINKS

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Introduction

Groundwater resources constitute the primary source of clean, fresh water and have a vital role in food production in the agricultural sectors in arid and semi-arid regions [1]. In the last decades, groundwater availability and quality have changed because of urbanization and industrialization. Groundwater is the main water supply for drinking and irrigation purposes [2]. Therefore, water demand in these regions is considered a vital water problem studied at various levels [3]. Nowadays, the quantity and quality of groundwater are changing because of human activity and natural events, and once groundwater is polluted or its level is dropped, it is not easy to restore it. The pollution of groundwater with harmful and dangerous organic containment is one of the essential ecological issues [4]. Systematic exploitation of natural resources has a significant effect on managing the environment and preventing its degradation [5]. Therefore, quantitative and qualitative evaluation of groundwater is essential for proper management and sustainable planning to cope with the drought phenomenon. Managing natural ecosystems creates many environmental impacts challenging global issues [6]. We need a mathematical method to analyze the condition [7]. Over time, scientists have suggested various indices for monitoring groundwater conditions, and numerous research efforts have assessed the surface water groundwater level and quality worldwide. Surface Water Supply Index (SWSI) [8], Standardized Water–Level Index (SWI) [9-11] and Groundwater Resource Index (GRI) [11-15] are some indices for monitoring of groundwater hydrological drought, and several indices have been developed to be applied for monitoring the groundwater quality, such as National Sanitation Foundation Water Quality Index (NSFWQI) [16,17], Water Quality Index (WQI) [15,18-22] and Groundwater Quality Index (GQI) [23-27]. Thomas et al. (2017) applied GRACE Groundwater Drought Index (GGDI) based on satellite data to evaluate groundwater drought in a catchment in California, USA. The results highlighted that using GGDI, the effect of human activities and natural changes can be diagnosed. Nzama et al. (2021) investigated groundwater resources in a catchment in South Africa using GQI and Concentration Duration Curves (CDC), and the results indicated that it was feasible to categorize groundwater in the catchment. GRI was developed by Mendicino et al. (2008) and is an index to quantify groundwater monitoring. It is a novel index for hydrogeological drought, which assesses groundwater level fluctuation [14]. Groundwater drought shows critical groundwater conditions during a long-term meteorological drought, which in turn reduces groundwater use, so the term groundwater drought is used to describe the groundwater levels as drops as a direct consequence of drought [30]. When groundwater is affected by drought, the charge, the groundwater level, and finally, the groundwater discharge is reduced. This type of drought is called groundwater drought and occurs primarily on annual and monthly time scales. Groundwater fluctuations can affect its quality. Changing the groundwater quality is a prelude to the degradation of water resources and other resources, both directly and indirectly, so the need to evaluate and monitor its quality can help properly manage the use of water resources. One of the simplest and most far-reaching methods of mathematical and statistical complexity that can reflect groundwater quality conditions is the use of water quality indices, which are adopted as a powerful management tool in groundwater quality management [31].

One of the best ways to determine groundwater quality is GQI. This GIS-based method is provided by Babiker et al. (2007) and makes groundwater data with the various qualities available apprehensible. The general conditions of groundwater quality can be summarized using this index, and it helps to realize groundwater suitability. In other words, this method can improve understanding the groundwater quality. Ultimately, this method will help assess the vulnerability of the aquifer and demonstrate its success in maintaining and improving it. The present study has two parts: in the first part, the condition of the hydrogeological drought was investigated using GRI, and in the second part, the groundwater quality was examined based on GQI. Finally, the relationship between these indices is investigated. Semnan and Damghan plains are chosen to compare the changes in groundwater quality over time concerning groundwater level fluctuations in these different plains. These plains are located in the same province, and the results can be helpful for a better understanding of groundwater resources and be used for better management of these resources and suggest the priority of applying management strategies.

Materials & Methods

Study Area

Semnan and Damghan are situated south of the Alborz mountain range within Semnan province, Iran. The climate is arid in these plains since annual evaporation is higher than annual precipitation [32]. Generally, elevation decreases from north to south in both plains and ends northern parts of the Kavir desert. The groundwater flows from the eastern and northern parts toward the southern parts in Semnan plain [33], while it flows from the northeast and southwest to east in Damghan plain [34]. Groundwater has an essential role in the water supply. Agricultural activities around the urban areas have resulted in overexploitation, and water supply is mainly through the groundwater resources. In both plains, urban areas are situated in the central parts and surrounded by agricultural lands and afforested *Haloxylon spp*. Table 1 shows the properties of Semnan and Damghan plains, their location in Iran, and the piezometric and qualitative monitoring wells are illustrated in Figure 1.

Methodology

In this research, spatial and temporal groundwater changes in quantity and quality were analyzed in Semnan and Damghan plains. For this purpose, Groundwater Resource Index (GRI) and Groundwater Quality Index (GQI) were used to investigate hydrogeological drought and groundwater quality changes based on groundwater monthly data from 1994 to 2018. Data was annual and related to April as aquifer charging time and October as aquifer exploitation time. Groundwater level data and quality factors including pH, Chloride (Cl^-), Total Dissolved Solids (TDS), Electrical Conductivity (EC), Calcium (Ca^{2+}), and Magnesium (Mg^{2+}) were used to determine GRI and GQI, respectively. Table 2 shows the summary statistics of the data used in this study. After preparing the data, the required statistical values of groundwater level and quality factors were calculated. Then, the maps of these indices for the years 2004, 2011, and 2018 in months April and October were prepared in ArcMap 10.3. Kriging method was adopted to determine un-sampled points value using sampled points information for zoning the maps since used data have normal distribution [35] and have no extreme values [36]. Afterward, Pearson correlation was used to assess the relation between GRI and GQI.

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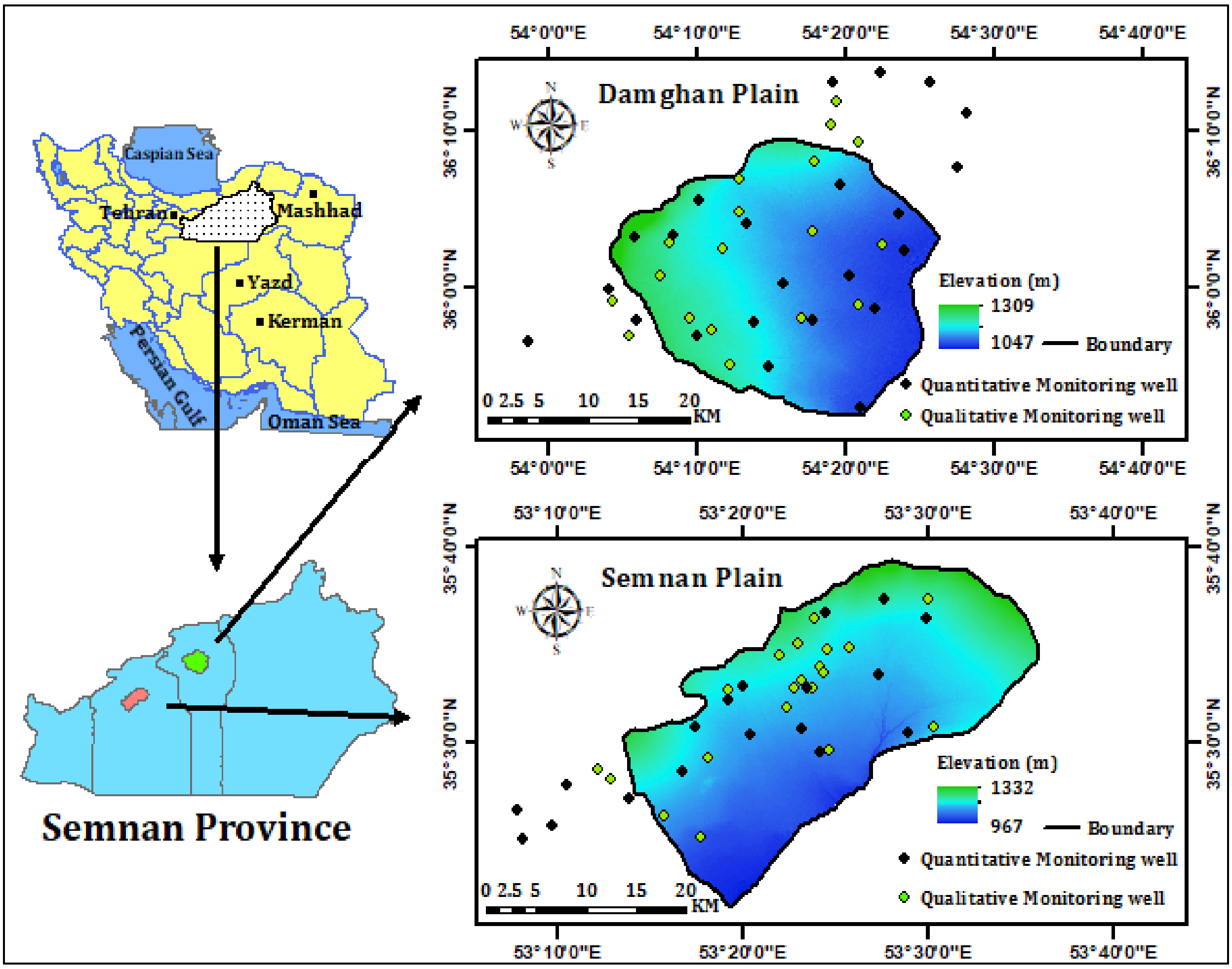

Figure 1) Location of studied areas and quantitative and qualitative monitoring wells.

Groundwater Resources Index

To investigate the hydrogeological drought, monthly groundwater level data in 18 and 23 monitoring wells in Semnan and Damghan plains, respectively, from 1994 to 2018 was used. Groundwater Resource Index (GRI) method was used to assess the intensity of hydrogeological drought. GRI is calculated as Eq. (1):

$$GRI_{y,m} = \frac{D_{y,m} - \mu_{D,m}}{\sigma_{D,m}} \qquad \text{Eq. (1)}$$

Where; $GRI_{y,m}$ is groundwater resources index for a well in yth year and mth month; $D_{y,m}$ is groundwater level in a well in yth year and mth month; $\mu_{D,m}$ is mean value of groundwater level over the time; $_{D,m}$ is the standard deviation of groundwater data. GRI is contingent on the groundwater level fluctuations. So, to prepare the GRI maps, firstly, the value of this index was calculated based on groundwater level for each well using Eq. (1). Then, interpolation was carried out in ArcMap 10.3. This index has seven risk categories ranging from more than +2 to less than -2. If the GRI value approaches more than +2, it indicates a wetter condition, and if it approaches less than -2, it shows a drought condition (Table 3). GRI values were calculated for all wells and groundwater levels to examine the temporal hydrogeological drought trend, which determined GRI changes. Then, the zoning maps were developed for temporally and spatially evaluation of the hydrogeological drought using GRI values.

Groundwater Quality Index

Six groundwater quality factors, including pH, Chloride (Cl^-), Total Dissolved Solids

(TDS), Electrical Conductivity (EC), Calcium (Ca^{2+}), and Magnesium (Mg^{2+}), were used to determine groundwater quality changes using monthly data in 20 and 18 monitoring wells in Semnan and Damghan plains, respectively, for the year 2004, 2011 and 2018. In order to calculate Groundwater Quality Index (GQI) and to prepare groundwater quality maps, the concentration map of each chemical variable was separately prepared based on World Health Organization (WHO) standards and Eq. (2):

$$C = \frac{c_i - c_{WHO}}{c_i + c_{WHO}} \qquad \text{Eq. (2)}$$

Where; C is the contamination value of each pixel in the map, c_i is the contamination of each factor, and is the contamination of each factor based on standards of WHO. This index ranges between -1 and 1. If the value is closer to -1 shows the lower contamination, and if it is closer to 1 shows the lower contamination [28]. In the next step, the normalized difference map was transformed into a rank map with the rank of 1 to 10 in order to remove the negative values using Eq. (3) [23]:

$$r = C^2 \times 0.5 + C \times 4.5 + 5 \qquad \text{Eq. (3)}$$

Table 1) Properties of Semnan and Damghan plains.

Plain	Semnan	Damghan
Longitude	35° 21' - 35° 39'	35° 51' - 36° 09'
Latitude	53° 14' - 53° 35'	54° 04' - 54° 26'
Elevation Range (m)	967-1332	1047-1309
Average Temperature (°C)	15.2	16.3
Average Rainfall (mm)	167.1	127.3
Area (ha)	54148.5	73250.7

Table 2) Summary statistics of used wells' piezometric and qualitative data.

Plain	Variable	Unit	Minimum	Maximum	Mean	Standard Deviation	Limitation (WHO, 2008) [37]	Kriging	
								RMSE	R
Semnan	Groundwater Level	m	990.07	1170.95	1063.43	50.15	-	18.95	0.80
	Cl^-	$mg.l^{-1}$	230.42	1546.68	552.81	224.93	250	4.17	0.39
	pH	-	6.94	8.50	7.90	0.28	6.5–8.5	0.24	0.16
	TDS	$mg.l^{-1}$	949	5160	2087.21	868.65	500	512.87	0.84
	EC	$\mu mohs.cm^{-1}$	1419	7750	3140.78	1308.45	500	767.11	0.84
	Ca^{2+}	$mg.l^{-1}$	56.11	697.39	212.69	155.33	75	6.91	0.79
	Mg^{2+}	$mg.l^{-1}$	34.02	212.63	105.15	42.87	50	2.55	0.48
Damghan	Groundwater Level	m	1041.46	1343.14	1109	63.64	-	20.03	0.89
	Cl^-	$mg.l^{-1}$	283.6	726.73	441.99	101.21	250	2.61	0.39
	pH	-	7.1	8.6	7.81	0.40	6.5–8.5	0.17	0.16
	TDS	$mg.l^{-1}$	925	1865	1355.28	247.23	500	238.87	0.36
	EC	$\mu mohs.cm^{-1}$	1388	2810	2035.03	374.04	500	348.24	0.34
	Ca^{2+}	$mg.l^{-1}$	46.09	200.4	89.85	27.30	75	1.10	0.10
	Mg^{2+}	$mg.l^{-1}$	21.87	102.06	50.43	15.43	50	1.06	0.58

Where; r is the corresponding rank value, and C is the contamination value of each pixel. In this transformation, -1, 0, and +1 change to 1, 5, and 10, respectively, and rank 1 represents the minimum effect on groundwater quality maps, while 10 shows the maximum effect.

To create a map that quantitatively represents all the chemical variables and the groundwater quality in comparison with the WHO's standards, the layers were combined using Eq. (4):

$$GQI = 100 - \left(\frac{(r_1 w_1 + r_2 w_2 + \dots + r_n w_n)}{N}\right) \qquad \text{Eq. (4)}$$

Where; r is the rate of the map, w is the relative weight for factors (average value of the concentration of the variable in r), N is several factors employed in the quality examination. If GQI is closer to 100, the water quality will be better. The factor that has the most significant impact on groundwater quality is most important in assessing groundwater suitability. The weight of each factor indicates the relative importance of that factor in groundwater quality. After preparing the GQI maps, they were classified according to Table 4.

Pearson correlation

Pearson correlation coefficient is an important coefficient to determine the ratio scale and normally distribution and varies from −1 to +1. This coefficient is computed as Eq. (5):

$$r = \frac{\sum_{i=1}^{n}(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i-\bar{x})^2 \sum_{i=1}^{n}(y_i-\bar{y})^2}} \qquad \text{Eq. (5)}$$

where r is Pearson correlation coefficient; x_i is the first variable in i[th] observation;

Table 3) Drought classification based on GRI [12].

GRI Range	Hydrological Drought Classification	Risk Class
+2 ≤ GRI	Extreme Wet	1
+1.5 ≤ GRI < +2	Severe Wet	2
+1 ≤ GRI < +1.5	Moderate Wet	3
-1≤ GRI < +1	Normal	4
-1.5 ≤ GRI < -1	Moderate Drought	5
-2 ≤ GRI < -1.5	Severe Drought	6
-2 ≤ GRI	Extreme Drought	7

Table 4) Classification of water quality based on GQI [32].

Status	GQI Value	Number of Subclasses*
Excellent Water Quality	90 ≤ GQI ≤100	2
Good Water Quality	70 ≤ GQI < 90	4
Medium Water Quality	50 ≤ GQI < 70	4
Low Water Quality	25 ≤ GQI < 50	5
Very Low Water Quality	0 ≤ GQI < 25	5

* Every five values are considered as a subclass.

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is the mean of the first variable in n observations; y_i is the second variable in i[th] observation; is the second variable in n observations. In the present study, the Pearson correlation coefficient was calculated between GRI and GQI using SPSS 17.0. The methodology of this study is summarized in Figure 2.

Findings

The Kriging interpolation method was used to prepare the maps in this research. To determine the accuracy of the interpolation method, Root Mean Squares Error (RMSE) and correlation coefficient (R) were used. The results of interpolation error for estimating the quantity and quality of groundwater are shown in Table 2.

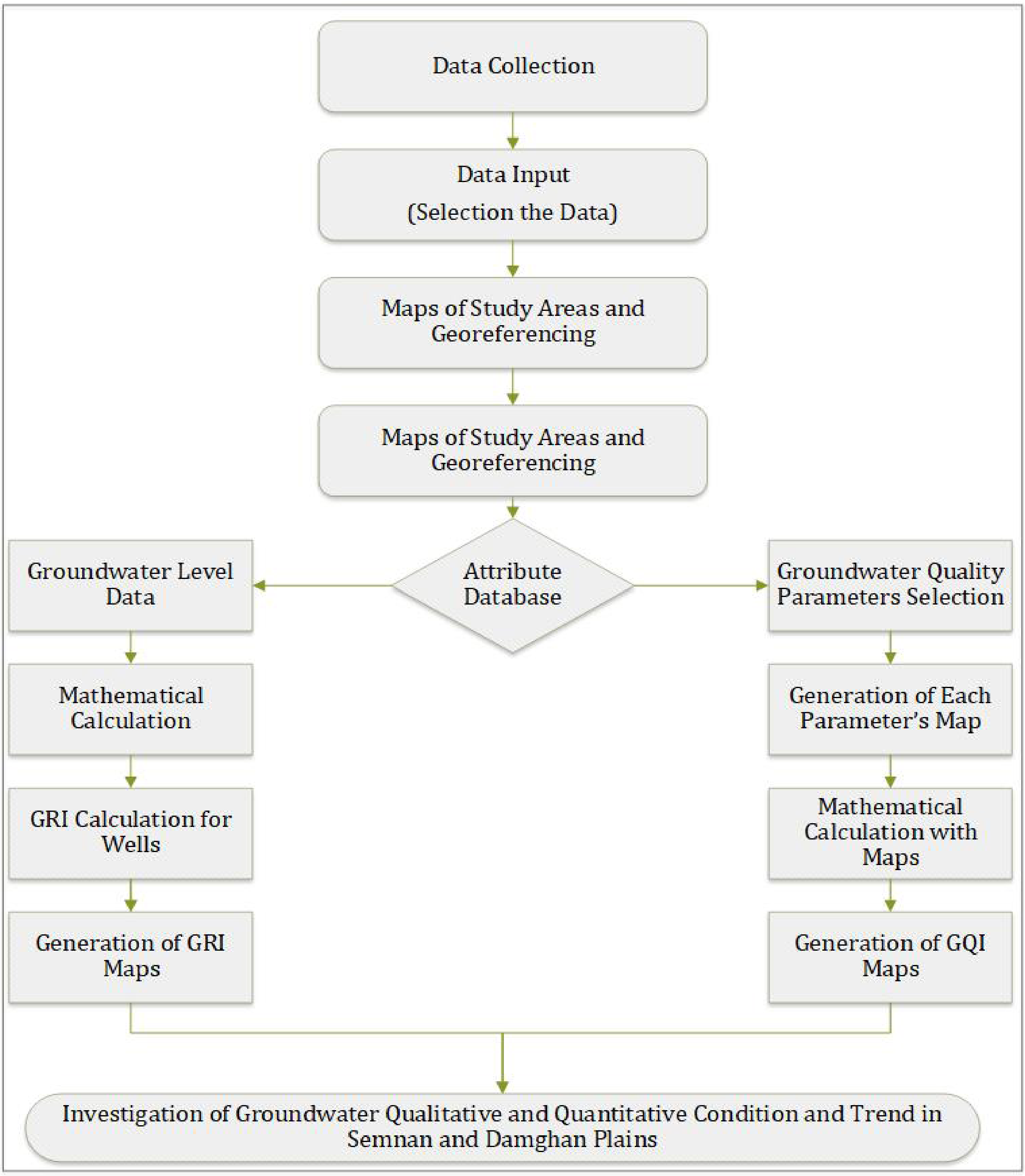

Figure 2) Flowchart of the adopted methodology.

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Spatial and temporal evaluation of hydrogeological drought

The trends of groundwater level and GRI in the groundwater-charging month (April) and groundwater-discharging month (October) were drawn for temporal evaluation of the hydrogeological drought. Figure 3 illustrates the changes in groundwater level and GRI values in both plains in April and October. The general trends of these indices are decreasing. In April, the groundwater level is higher than GRI before 2004, which indicates the tending to wet situation, and between 2004 and 2011, groundwater level and GRI values are almost the same, and after then the movement of trend is toward hydrogeological drought, which indicates tending to the drought situation. In October, groundwater level and GRI values are almost the same from 1994 to 1998, but GRI value is lower than groundwater level. In Damghan plain, the drought (GRI value lower than groundwater level) started from 1995 in April and October. Groundwater level and GRI trends are not steady in both plains over the studied period, and the trends have decreasing status.

In order to spatial evaluation of hydrogeological drought, the maps were generated using GRI value for each monitoring well. Figure 4 shows the classified maps of GRI for studied plains in 2004, 2011, and 2018. According to the maps, the worst condition of GRI occurred in 2018. GRI value is higher in central and north parts in both plains, but it was evident that overall, both studied areas were classified in normal class in 2004 and 2011. GRI value decreases in 2018 in both plains, whole both plains have suffered a drought condition, and the maps are categorized into moderate and severe drought classes. In Semnan plain, the maximum value of GRI was +1.33 in April 2011, and the minimum value was -2.07 in October 2018. In Damghan plain, the maximum and minimum values of GRI are +0.78 in October 2004 and -1.76 in October 2018, respectively.

Table 5) Properties of GRI and GQI maps for Semnan and Damghan plains.

Plain	Year	Month	GRI			GQI		
			Min	Mean	Max	Min	Mean	Max
Semnan	2004	April	-0.10	0.06	0.17	44.74	51.19	61.36
		October	0.03	0.13	0.24	44.38	51.11	60.72
	2011	April	-1.02	-0.29	1.33	45.36	50.52	58.20
		October	-0.89	-0.49	0.59	44.60	49.81	57.90
	2018	April	-1.83	-1.57	-1.27	44.40	50.43	56.22
		October	-1.80	-1.59	-1.49	43.54	50.32	63.44
Damghan	2004	April	0.23	0.34	0.64	57.43	61.56	65.21
		October	0.23	0.35	0.78	57.66	62.11	66.15
	2011	April	-0.81	-0.69	-0.53	59.39	61.85	64.80
		October	-0.80	-0.67	-0.49	58.09	60.59	64.26
	2018	April	-1.74	-1.61	-1.49	59.17	61.28	64.36
		October	-1.76	-1.63	-1.52	56.24	59.83	63.85

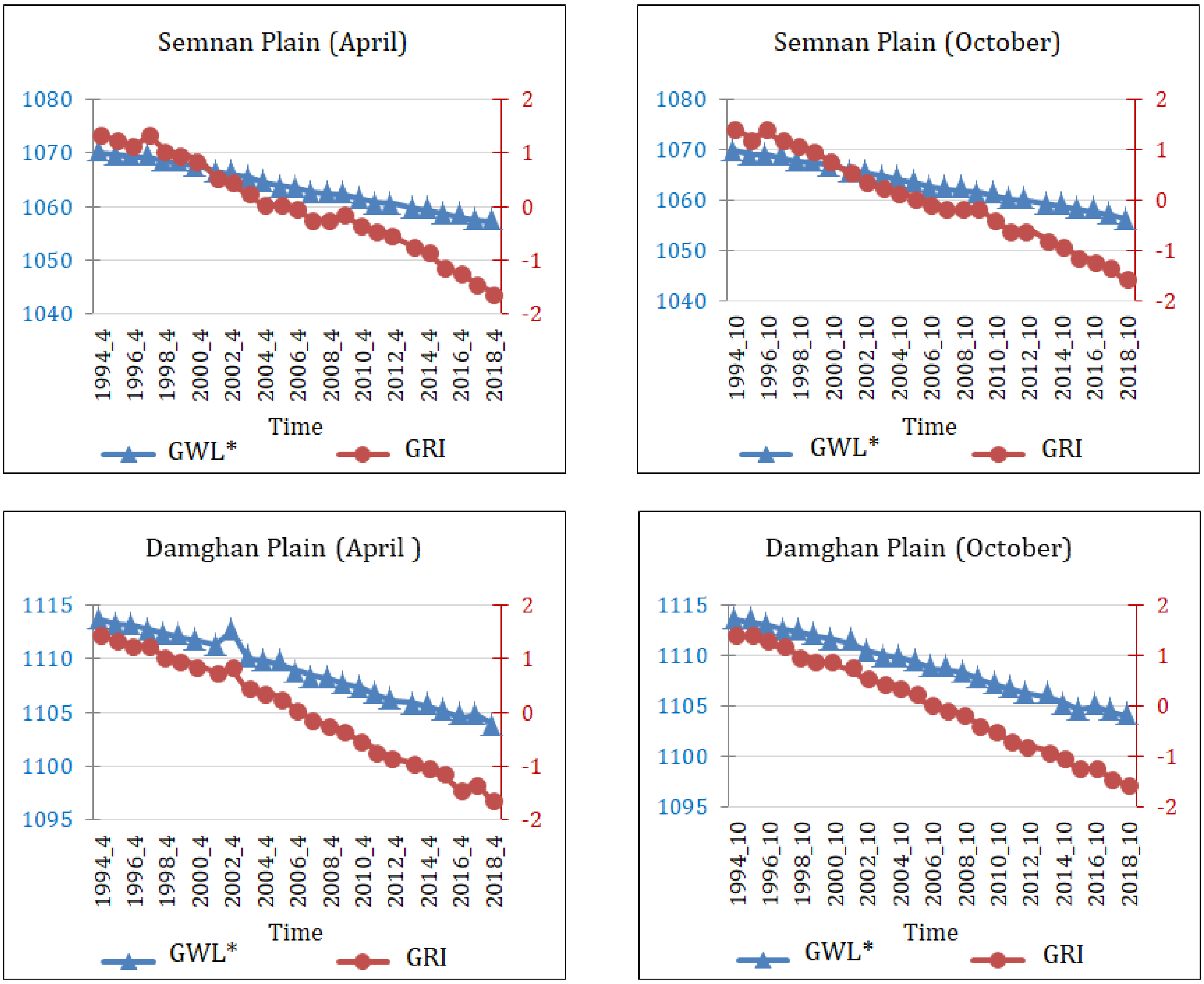

Figure 3) Groundwater level and GRI changes in Semnan and Damghan Plains in April and October.
*GWL: Groundwater level (m).

Spatial and temporal evaluation of roundwater quality

In this study, groundwater quality index (GQI) is a composite assessment of six factors (pH, Cl^-, TDS, EC, Ca^{2+}, Mg^{2+}), determining whether the water is suitable. These factors were analyzed based on their statistical measures, including minimum, maximum, and mean values, to generate GQI maps for 2004, 2011, and 2018. Figure 5 illustrates the temporal and spatial classified maps of GQI in both studied plains. As observed, the GQI are into "Low” and “Moderate” classes in Semnan plain. This plain's Northern and Eastern parts are classified into the "Low" class, and the Southern and Western parts of the basin are classified into the "Moderate" class. The area of subclass "Low II" is increasing. On the other hand, the subclass "Moderate III" area is decreasing. Thus, groundwater quality has a decreasing trend in Semnan plain over time. In Damghan plain, whole areas are classified into class "Moderate" but various subclasses. It is evident that the area of subclass "Moderate III" is increasing, and subclass "Moderate I" has disappeared in 2018. Table 5 shows the properties of generated maps for GRI and GQI.

Discussion

Hydrogeological Drought and Groundwater Quality

Recently, agricultural activities through

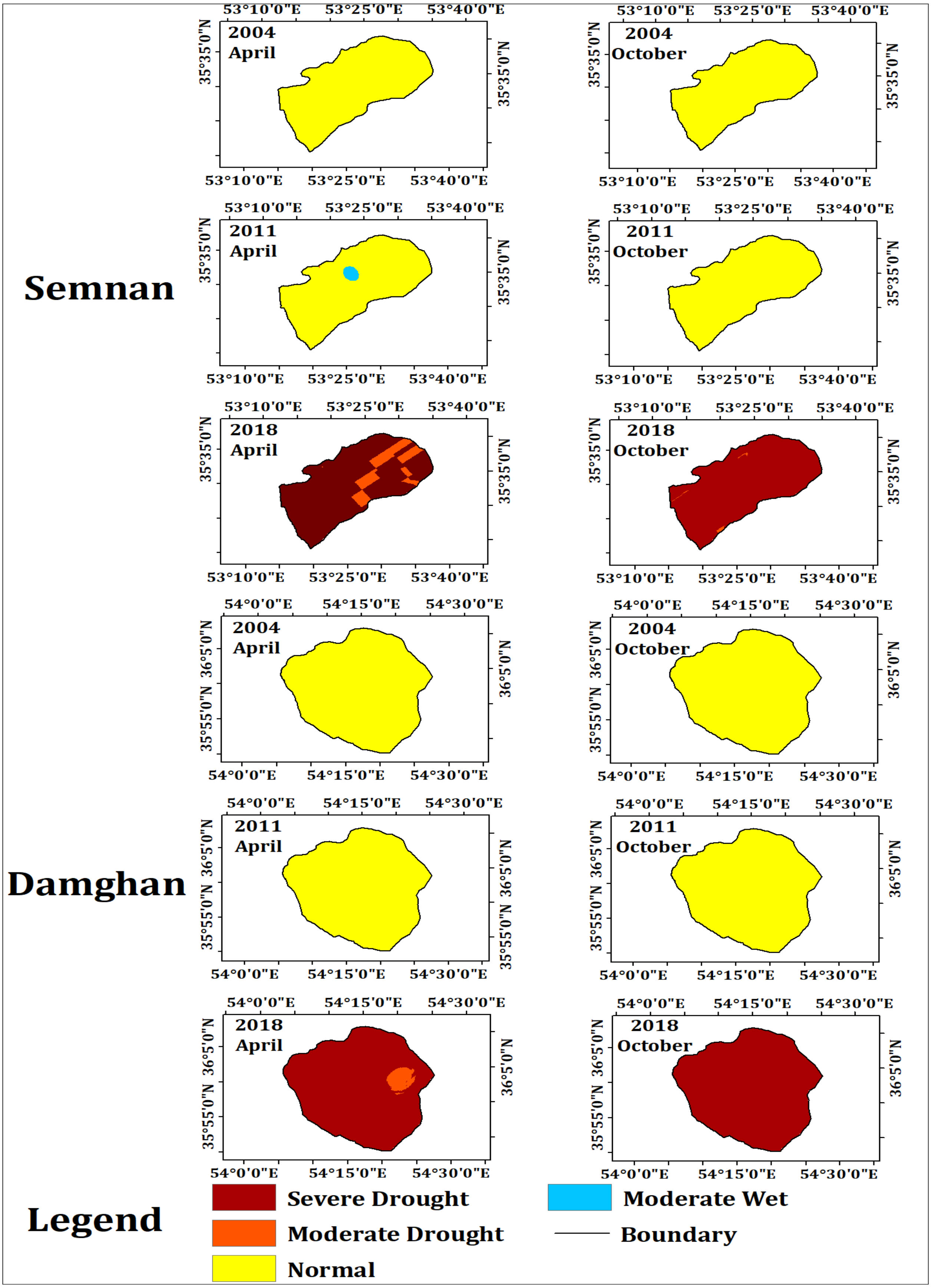

Figure 4) Classified maps of GRI for 2004, 2011, and 2018.

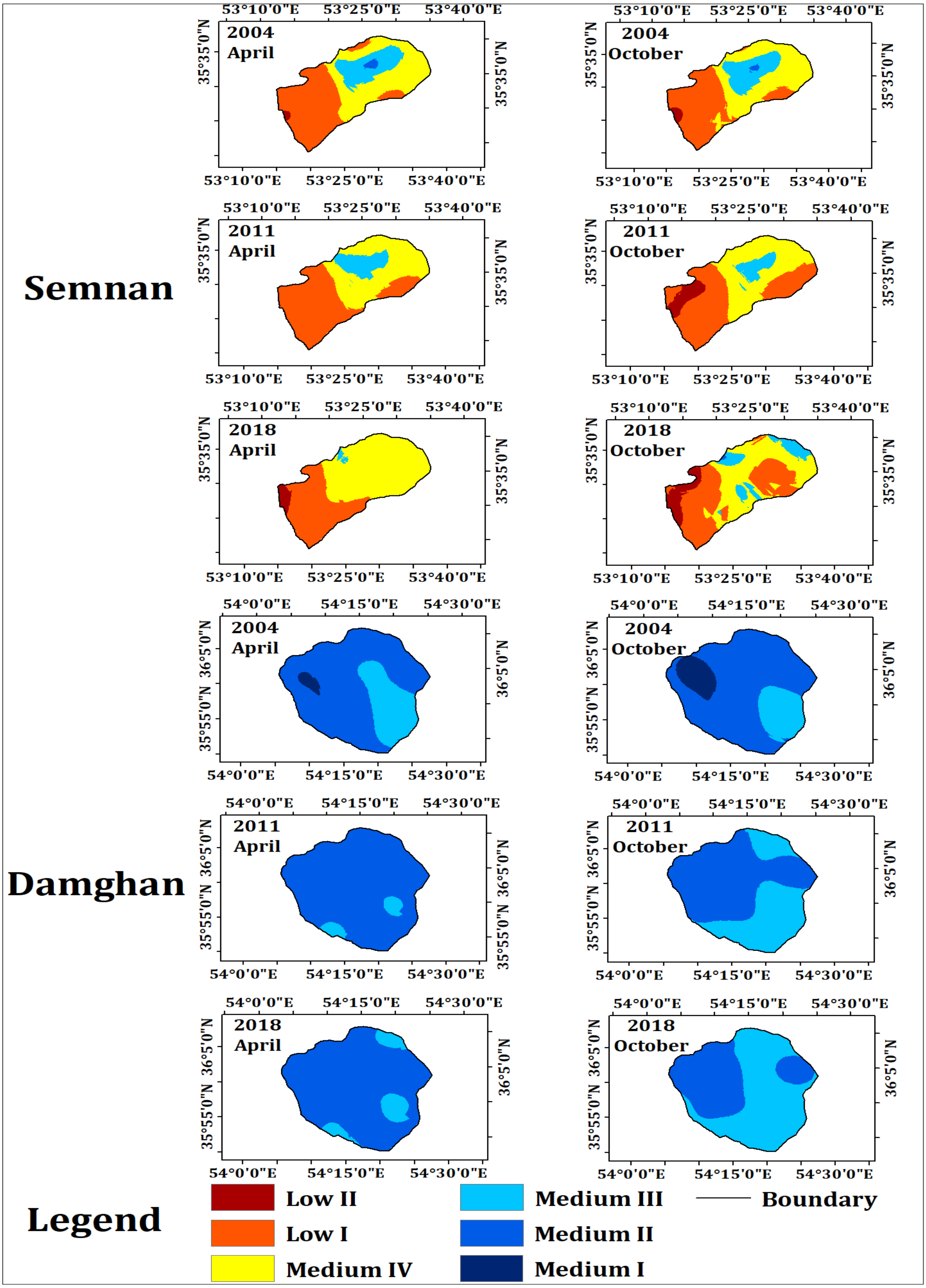

Figure 5) Classified maps of GQI for 2004, 2011, and 2018.

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drilling and pumping of exploitation wells have caused the drop in groundwater level, and due to the climate, which is dry in these plains, it can increase drought (38), and returning to the initial conditions will be so difficult or impossible if appropriate management is not taken as Bazrafshan et al. (2016) reported that climate change could affect groundwater fluctuations.

According to findings, GRI has no steady status, and the trend of groundwater volume is decreasing in both Semnan and Damghan plains from 2004 to 2018, which has led to a decrease in its quality. This issue has increased even more in recent years. During the study period, the quantity of groundwater has a decreasing trend, indicating the general drought trend. The results showed that in Semnan plain, groundwater quantity and quality decreases from north to south and in Damghan plain from northwest to southwest, over time, which is due to the hydraulic slope and also the height is higher in the north of both plains, which corresponds to the results of Heydari et al. (2015).

Correlation between GRI and GQI

The results of examining the time trend of GQI changes showed that the average GQI index decreases over time. The mean changes in GRI and GQI were used to develop a general summary for assessing hydrogeological drought and groundwater quality all over both plains. According to the results, the Pearson correlation between GRI and GQI are +0.542 and +0.672 in Semnan and Damghan plains, respectively. These values are positive in both plains, reflecting that groundwater quality has changed with groundwater level changes. In Semnan and Damghan plains, GRI values have been decreased, and GQI value has also decreased. The correlation between GRI and GQI is higher in Damghan plain than Semnan.

Conclusion

In this study, the results of GRI indicated that a slight hydrogeological drought has been occurred since 1994 and has gotten harsher in recent years. The GRI value has been negative throughout studied plains from 2007 in both charging and discharging months, which this decreasing trend showed worsening of the groundwater level, indicating the occurrence of hydrogeological drought all over both plains. GRI value in the central parts of studied plains is higher than surrounding areas that show higher consumption in agricultural lands located in the surrounding parts. In Damghan plain, the groundwater level is lower than the GRI value from 1995 in both groundwater charging and discharging months, and in Semnan plain from 1999 and 2012 for groundwater charging and discharging months, the groundwater level is lower than the GRI value, which means these plains are more vulnerable to hydrogeological drought since these years.

The results of GQI based on six quality factors and GIS illustrated that EC and TDS had the highest effect on groundwater quality, respectively, with the highest ranking of mean value compared to other factors. In Semnan plain, central and northern parts had higher groundwater quality than south and southwest parts, while in Damghan plain, western parts of the plain had higher groundwater quality than eastern parts of the plain. Also, the trend of groundwater quality is decreasing in Semnan plain, while in Damghan plain, the area of subclass "Moderate III" is increasing, and the subclass "Moderate I" has been disappeared in 2018. Finally, it is suggested that more research about monitoring and predicting the quantitative and qualitative condition of groundwater should be conducted for better management and planning in the studied plains.

Conflict of Interest

The author states that there are no conflicts of interest regarding the publication of this manuscript.

Ethical Permissions

Not declared by the authors.

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