Evaluation of the Hydrogeological Drought Using Groundwater Resource Index Based on GIS

Amin MOHEBBI TAFRESHI [1]
Farideh ASADIAN [2]
Ghazaleh MOHEBBI TAFRESHI [1]
Mohammad Hossein Bijeh KESHAVARZI [3](✉)

Summary

In this research, to assess the hydrogeological drought situation, a new index, Groundwater Resource Index (GRI), was used for spatial and temporal examination of hydrogeological trend of drought with use of groundwater level data in two steps. In the first step, to examine the hydrogeological temporal drought trend in the wells, three wells with the maximum, minimum and moderate drop in groundwater level, were selected. Results showed that in water-abundance peak the drought that equals to GRI becoming negative starts during 2003 in well No. 10 and during 2000 in well No. 18. GRI value in well No. 16 was negated once during 2002 and once during 2004. In water shortage peak the drought which equals to GRI becoming negative starts during 2004 in well No. 10 and during 2000 in well No. 18. GRI value in well No. 16 was negated once during 2002 and once during 2008. In second step, to develop a spatial overview from each point within the study area, due to the scattering monitoring wells, kriging method was used to draw the iso GRI value maps and to interpolate the GRI values. Results showed that there is no steady trend for GRI changes in the whole plain due to the changes in the surface constituents' substance, surface topography, the bedrock and the exploitation of groundwater resources. Furthermore, results showed that GRI values were negative in 2008 all over the plain, and with the passage of time, harsher drought is going to occur to the northwest of plain.

Key words

Geographic Information System (GIS), Groundwater Resource Index (GRI), groundwater level, hydrogeological drought, monitoring

[1] Young Researchers and Elite Club, Science and Research Branch, Islamic Azad University, Tehran, Iran
[2] Department of Geography, Faculty of Humanities, Science and Research branch, Islamic Azad University, Tehran, Iran
[3] Young Researchers and Elite Club, North Tehran Branch, Islamic Azad University, Tehran, Iran
✉ e-mail: Keshavarzi64.mh@gmail.com

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Introduction

The Drought happens due to Climate variability under different climatic conditions on all continents (van Huijgevoort et al., 2012). Drought as a natural disaster causes financial damages even death casualties. Drought damages ecosystems, economic and social conditions, and agricultural production (Vicente-Serrano, 2006). Due to its frequent occurrence in arid and semi-arid regions around the world, identifying drought is essential for managing water resources in hot region. Scientists of water science and meteorology have suggested various indexes to assess and monitor drought. Each index was designed based on application of different calculation's methods and variables (Richard and Heim, 2002). According to Quiring et al. (2007), drought indices are useful tools for providing information to decision-makers in business, government, and to public stakeholders. Based on this, drought indices can be used to determine drought assistance (Wilhite et al., 1986), to calculate the probability of drought termination (Karl et al., 1987), to assess forest fire hazard and dust storm frequency (Cohen et al., 1992) to provide an early drought warning system (Lohani et al., 1998; Lohani and Loganathan, 1997), to predict crop yield (Kumar and Panu, 1997), to examine the spatial and temporal characteristics of drought, the severity of drought, and to make comparisons between different hydrogeological regions (Alley, 1984; Kumar and Panu, 1997). According to the definition offered by Mendicino et al. (2008), an objective explanation of the drought situation can be made by choosing a drought index appropriate to the drought conditions occurring in one area. Thus, it can be possible to adopt an appropriate management approach to cope with this phenomenon. Currently, there are various indexes for monitoring drought. The Palmer Drought Severity Index (PDSI) and the Moisture Anomaly Index (Z-index) (Palmer, 1965), the Surface Water Supply Index (SWSI) (Shafer and Dezman, 1982), the Standardized Precipitation Index (SPI) (McKee et al., 1993), and the Reconnaissance Drought Index (RDI) (Tsakiris et al., 2007) are the most frequently used indexes. None of these indexes include groundwater as a variable. All of them focus on surface water or meteorically data. Due to the shortage of surface water resources in hot countries and occurring hydrogeological drought, groundwater resources gained importance. Thus, assessing the behavior of groundwater drop to suggest preservative and management strategies for water resources seems to be essential and requires an index that can be used in the case of hydrogeological drought.

Groundwater Resource Index (GRI) is a new index for drought, which monitors the trend of hydrogeological drought in a specific region within a specific time span using multi-analysis theory. This index is based on the fluctuation in the level of groundwater resources. Since this index was developed by Mendicino et al. (2008), many studies have been conducted around the world using it. For example, in Bahabad plain in central Iran the impact of the climatic drought on the level of groundwater resources was researched. In this research, the correlation between GRI and SPI indexes has been examined. The results indicated a significant relation between them, especially in a long term scale (Imani and Talebi, 2011). The significant relation between the hydrogeological drought and climatic drought indexes was examined in the study in Fasa plain of Fars province in southern Iran. The results indicated that there was a 99% significant relation between these two indexes. Furthermore, with regard to the decrease in GRI value in 2008-2009 in this region, occurring harsh hydrogeological drought has been verified (Seif et al., 2011). Another research conducted in Marvast plain of Yazd province in Iran examined the trend of the hydrogeological drought in 1986-2009. The results showed that in average the trend moved to drought and GRI value considerably decreased from 2001 on (Malekinezhad and Poorshariaty, 2011). Malekinezhad and Ghaderi (2011) examined the hydrogeological drought in Sabzevar Plain, northern Iran using GRI. Najafi and Jalili (2011) examined the drought according to GRI in their research conducted in Ardebil Plain, northwestern Iran. In this research they studied the trend of groundwater resources decrease. The results indicated that the degree of drought has increased in this region as the time passed (Najafi and Jalili, 2011). Adhikary et al. (2013), Ekrami et al. (2013), Bakhtiare Enayat et al. (2016), Karimirad et al. (2015) and Khosravi et al. (2015) used GRI to examine the trend of hydrogeological drought using temporal trend regardless of spatial resolution.

This study examined the trend of hydrogeological drought in a hot region with groundwater shortage. The innovative part of this research is using GIS for examining the spatial and temporal trend in the studied plain. This study has been carried out in Torbat-e Jam-Fariman plain from 1995 to 2010.

Materials and methods

Torbat-e Jam-Fariman plain (210213N-327669N and 3874210E-3962452E) with an area of 6388 square km is located in the 41N zone (According to UTM coordinate system), Northeastern Iran, in Kop-e Dagh structural zone. The main geological structures in the study area were Precambrian. According to Emberger (1945) classification, the climate of this region with an average annual rainfall from 200 mm (in south east of the plain) to 250 mm (in center and northwest of the plain) and the average annual temperature of 14°C (in southeast of the plain) to 10°C (in center and northwest of the plain) can be classified dry (in southeast of the plain) to semi-dry (in center and northwest of the plain).

To examine the hydrogeological drought in the studied plain monthly groundwater level data in 19 monitoring wells from the period 1995-2010 was used. This information was collected by the Khorasan Razavi regional water authority of Iran (Farkhari, 2012).

Fig. 1 shows the locations of the wells for monitoring the groundwater level. To detect hydrogeological drought and assess its intensity of the different levels in plain, GRI method was used. In this method invented by Mendicino et al. (2008), according to Eq. 1 (Mendicino et al., 2008) the groundwater level for one well in the study time (for example, in this study, for GRI_{1995}, groundwater level in the year "1995" and month "m", for GRI_{1996}, groundwater level in the year "1996" and month "m" and etc.) is subtracted from the average groundwater level for the same well in the specified period (for example, in this study, average groundwater level in 1995-2010 period in the month "m"). Then, the obtained number is divided by the standard deviation of groundwater level for all wells in the study time (for example, for GRI_{1995}, standard deviation of groundwater level in all wells in year "1995" and month "m"). Finally, the degree of groundwater resource index for the study time is obtained (for example, GRI in the year "1995" and month "m" that is shown as $GRI_{1995, m}$). Like SPI index, this index has seven risk

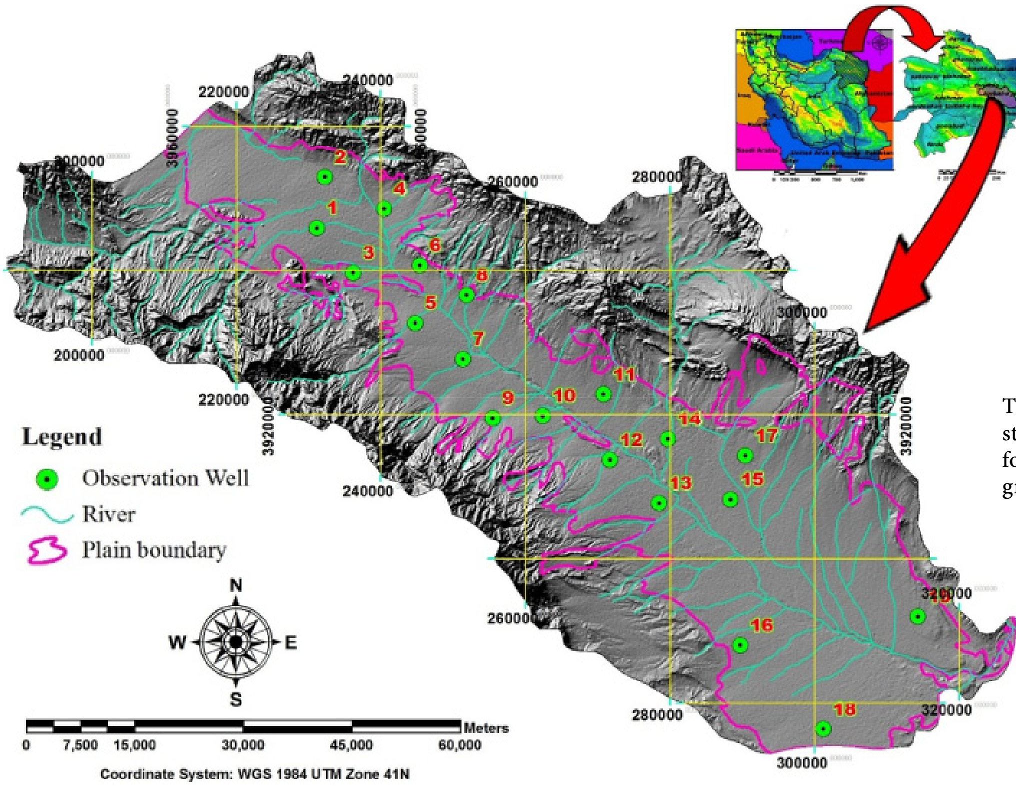

Figure 1.
The location of the studied area and wells for monitoring the groundwater level

Table 1. Characteristics of monitoring wells

Well No.	UTM-X	UTM-Y	UTM-Z	Depth of well
1	231200	3945900	1317.77	160
2	232300	3953000	1271.7	107
3	236200	3939700	1258.56	120
4	240500	3948600	1230.26	85
5	244800	3932700	1211.44	145
6	245400	3940700	1170.43	100
7	251400	3927700	1124.27	85
8	251900	3936600	1154.14	106
9	255500	3919500	1118.02	107
10	262400	3919800	1067.31	85
11	270800	3922800	1034.05	76
12	271700	3913700	1011.57	88
13	278500	3907700	953.69	76
14	279700	3916600	998.55	100
15	288400	3908200	913.48	105
16	289700	3888000	880.8	156
17	290400	3914300	992.82	156
18	301200	3876400	822.77	75
19	314300	3892000	804.73	30

Table 2. Drought classification based on Groundwater Resource Index (GRI), (Mendicino et al., 2008)

GRI range	Drought Classification	Risk class
+2 and more	Extreme wet	1
+1.5 to +1.99	Severe wet	2
+1 to +1.49	Moderate wet	3
+0.99 to -0.99	Nearly normal	4
-1 to -1.49	Moderate drought	5
-1.5 to -1.99	Severe drought	6
-2 and less	Extreme drought	7

categories ranging from +2 to -2. If GRI value approaches to +2, wetter condition is predicted. Otherwise, if GRI value approaches to -2, harsher condition is predicted. In this categorization, the starting point of drought or wet is zero, which indicates normal situation according to Eq. 1.

$$GRI_{y,m} = \frac{D_{y,m} - \mu D}{6D} \quad (1)$$

In Eq. 1, GRI is the groundwater resource index for one well in the year y and month m, $D_{y,m}$ is the groundwater level in one well in the year "y" and the month "m", μD is the average of groundwater level in the specified period, d and 6D is the standard deviation of groundwater level in all wells in the study time.

To examine the trend of hydrogeological drought in the region spatially and temporally using GRI method, two steps were taken. In the first step, to examine the hydrogeological temporal drought trend in the wells of the studied region, three wells with the maximum, the minimum and the moderate groundwater level drop (compared to other groundwater levels of the wells) were selected. After calculating GRI value, the change in groundwater level and GRI was examined in two peaks, water-abundance and water shortage. These two peaks were selected according to groundwater levels in all wells. The month in which all of the wells have maximum levels (among other months in one year), is named water-abundance peak (In this study it was May), and the month in which all of the wells have minimum levels (among other months in one year) is named water-shortage peak (in this study it was September). In the end of this step, to develop a general overview in examining the hydrogeological drought all over plain, the mean changes in groundwater level and GRI were analyzed. At the second step, the zoning maps of GRI changes during the water-abundance peak and water-shortage peak were developed for examining the hydrogeological drought temporally and spatially and for spatial zoning of the drought in plain by interpolating GRI values obtained from the wells using ArcGIS10.1 software and Kriging method.

Results

The temporal evaluation of the hydrogeological drought

For temporal evaluation of the hydrogeological drought, two trends of GRI and groundwater level in water-abundance peak and water-shortage are needed. For example, in this study, Figs. 2 to 7 show the temporal changes in the groundwater level and GRI in water-abundance peak (May) and water-shortage peak (September) for the well No. 10 (maximum drop), well No. 18 (minimum drop) and well No. 16 (moderate drop). Getting higher these two trends (groundwater level and GRI trends) indicate better situation (tending to the wet conditions) and getting lower of these show tending to the drought (Khosravi et al., 2015). As it can be seen, the general trend of groundwater level and GRI value in the three wells was descending, which indicates the movement to hydrogeological drought. According to the Figs. 2 to 4, in water-abundance peak the drought which equals to GRI becoming negative, started during 2003 in well No. 10 (Fig. 2) and during 2000 in well No. 18 (Fig. 3).

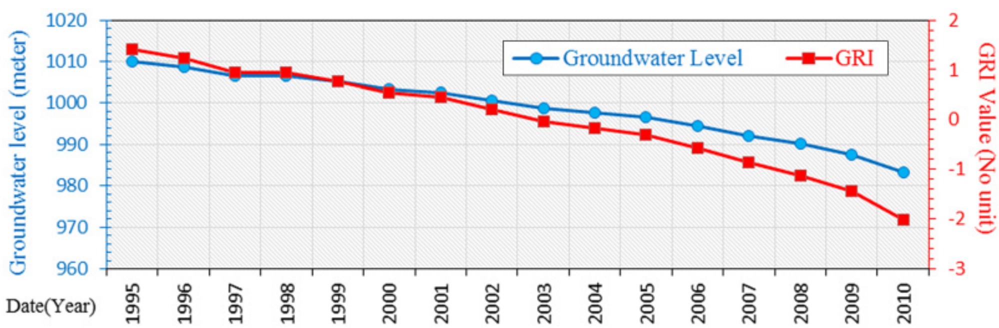

Figure 2. Groundwater level and GRI changes in water-abundance peak (May) in the specified period (well No.10)

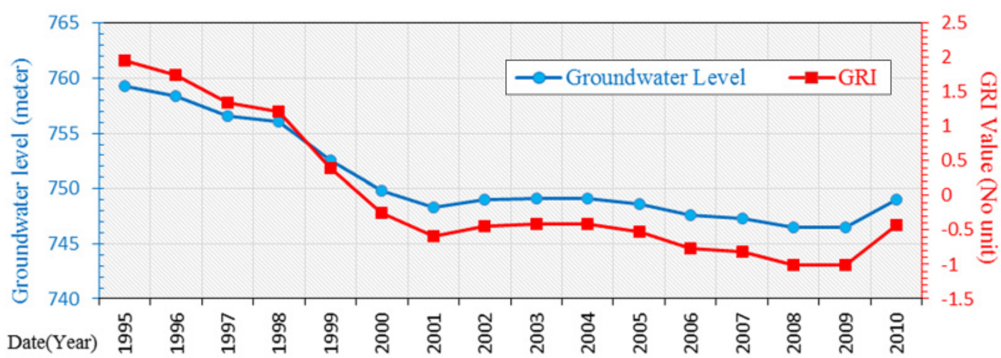

Figure 3. Groundwater level and GRI changes in water-abundance peak (May) in the specified period (well No.18)

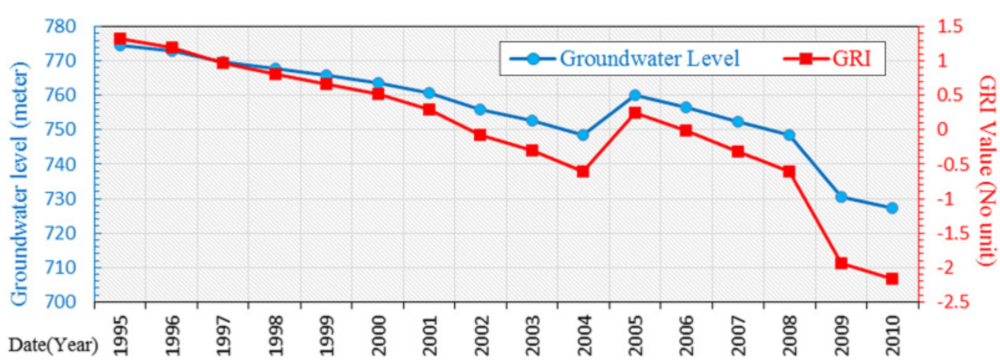

Figure 4. Groundwater level and GRI changes in water-abundance peak (May) in the specified period (well No.16)

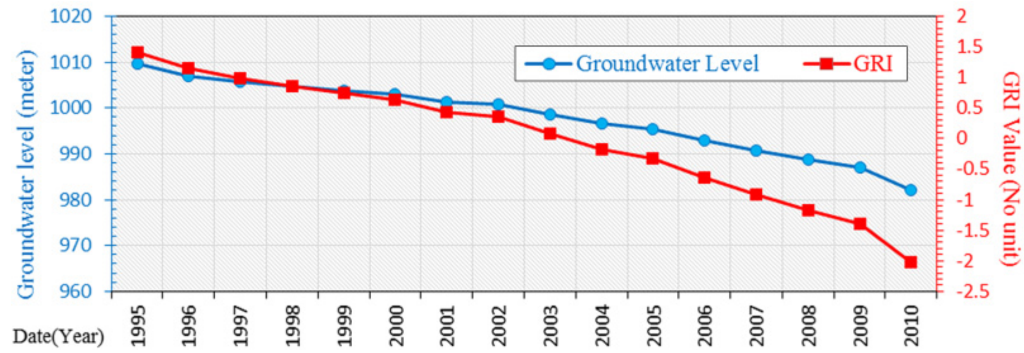

Figure 5. Groundwater level and GRI changes in water-shortage peak (September) in the specified period (well No.10)

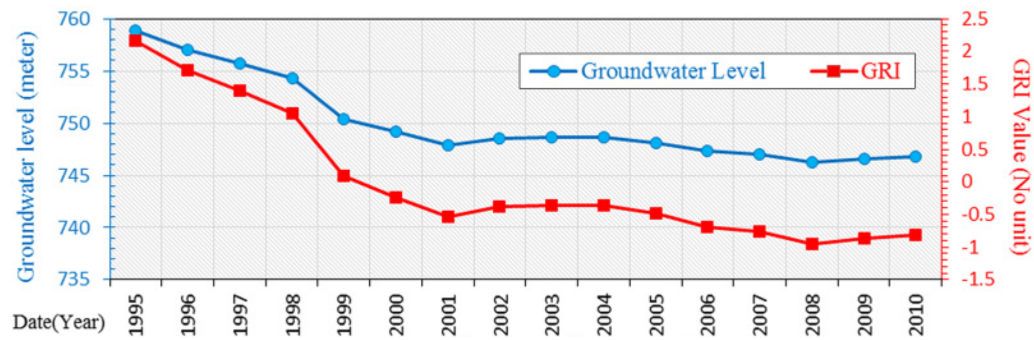

Figure 6. Groundwater level and GRI changes in water-shortage peak (September) in the specified period (well No.18)

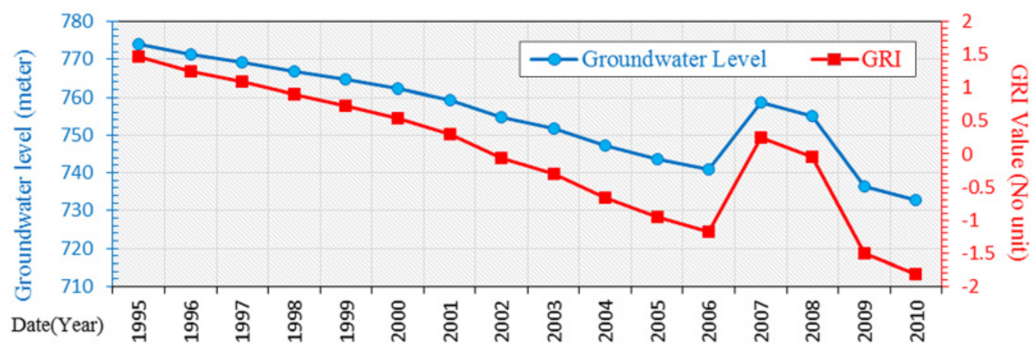

Figure 7. Groundwater level and GRI changes in water-shortage peak (September) in the specified period (well No.16)

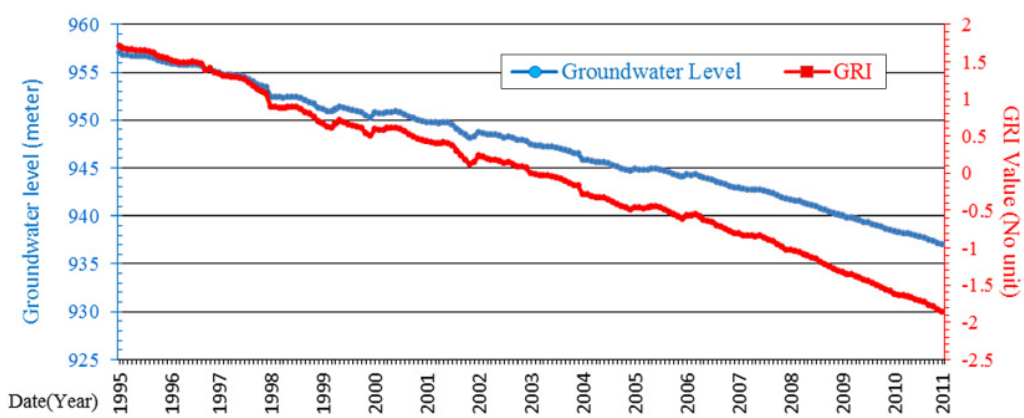

Figure 8. Mean changes of Groundwater level and GRI in the specified period in the study plain

GRI value in well No. 16 was negative once during 2002 and once during 2004 (Fig. 4).

According to Figs. 5 to 7, in water-shortage peak the drought which equals to GRI becoming negative started during 2004 in well No. 10 (Fig. 5) and during 2000 in well No. 18 (Fig. 6). GRI value in well No. 16 (Fig. 7) was negative once during 2002 and once during 2008.

To develop a general overview in examining the hydrogeological drought all over the plain, the mean change in groundwater level and GRI was used. Fig. 8 shows the changes in groundwater

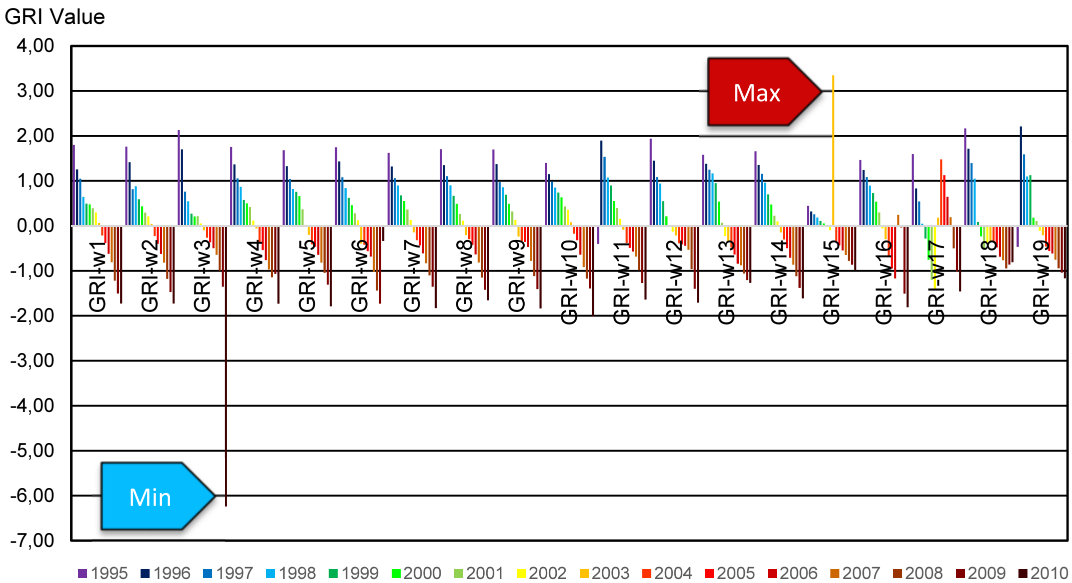

Figure 9. The GRI values in monitoring wells during water-shortage peak

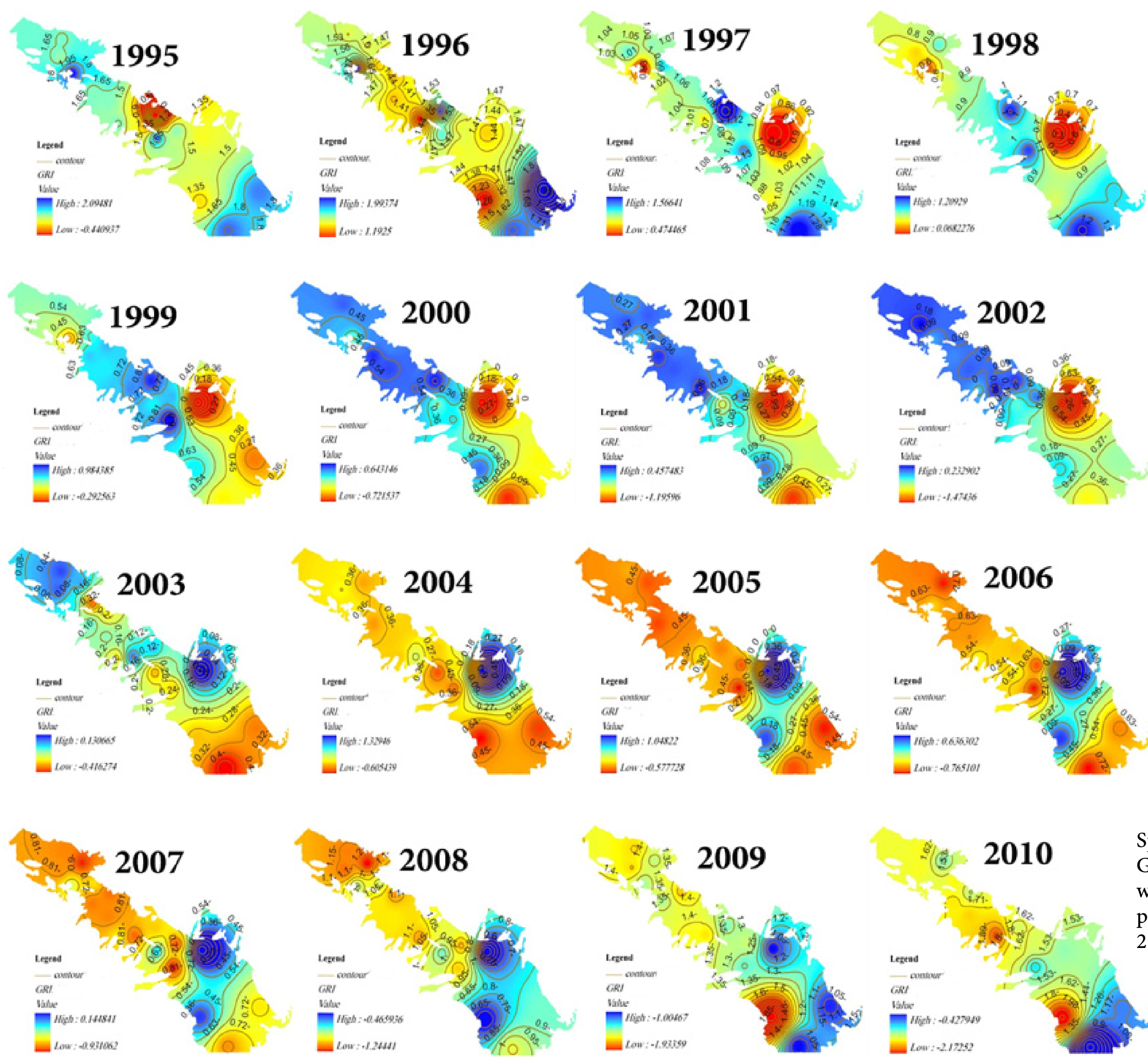

Figure 10. Spatial changes of GRI value during water-abundance peak from 1995 to 2010

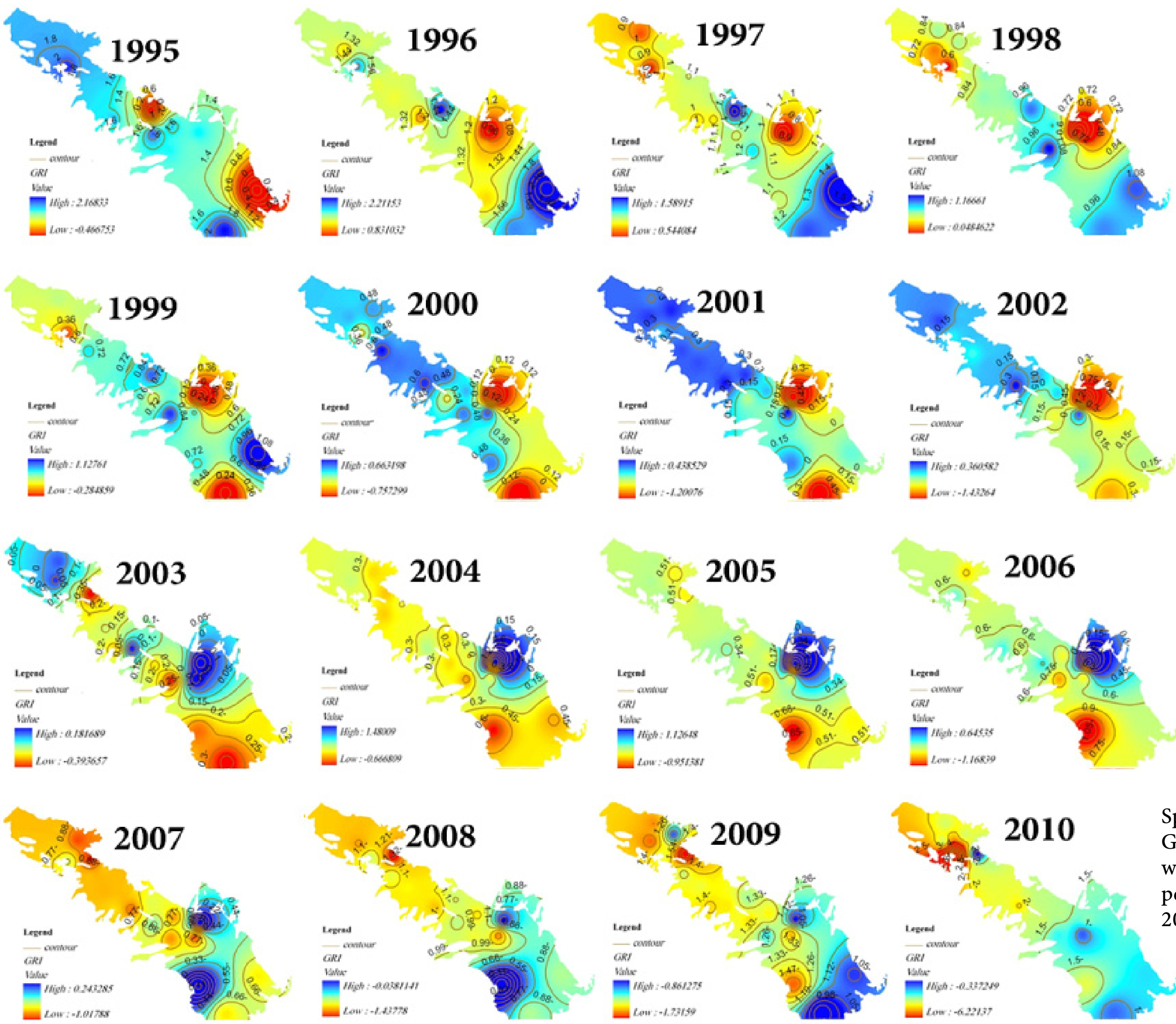

Figure 11. Spatial changes of GRI value during water-shortage peak from 1995 to 2010

The spatial evaluation of the hydrogeological drought

In second step, to develop a spatial overview from each point within the study area, because monitoring wells were scattered, kriging method in ArcGIS10.1 software was used to draw the iso GRI value maps. Kriging method for interpolating is suitable for heterogeneous distributed locations (Tonkin and Larson, 2002). Fig.10 and Fig.11 show the temporal and spatial changes in GRI values in the selected study area according to calculated GRI values in monitoring wells. As it can be observed, there is no steady trend for GRI changes in the whole plain due to the differences in the surface constituents' substance, surface topography, the bedrock and the exploitation of groundwater resources. Furthermore, according to Trambauer et al. (2014), this (no steady trend) could be expected due to the persistence of the groundwater storage and low intensity of indicators of drought/wetness in studied years in different locations of plain. According to Fig.10 and Fig.11, GRI value was negative in 2008 all over the plain. This means that since 2008, the entire plain has suffered a drought condition.

Fig.12 presents hydrogeological drought classification according to GRI values. As it can be seen in Fig.12, with the years passing, harsher drought is going to occur in the northwest of the plain. This indicates the higher vulnerability of that area to hydrogeological drought compared to the other areas of the plain. Due to the lesser thickness of alluvium and the lower volume of groundwater the greater vulnerability of that area to water harvesting can be justified.

Conclusion

The results in the studied plain indicate the occurrence of slight hydrogeological drought since 2001 in the limited parts of the studied area. Gradually, the drought with more harshness was extended into other areas and since 2008 the degree of GRI was negative throughout plain indicating the occurrence of hydrogeological drought all over the studied area. In addition, according to the developed zoning maps and GRI value, the northwest areas of the plain in the specified period were more vulnerable to the drought compared with other areas of plain.

Such conditions' occurrence in dry climates indicates a serious drought risk, and if proper management measures are not taken, the target areas will no longer be able to return to the initial conditions and may become more acute. The clear example of this is

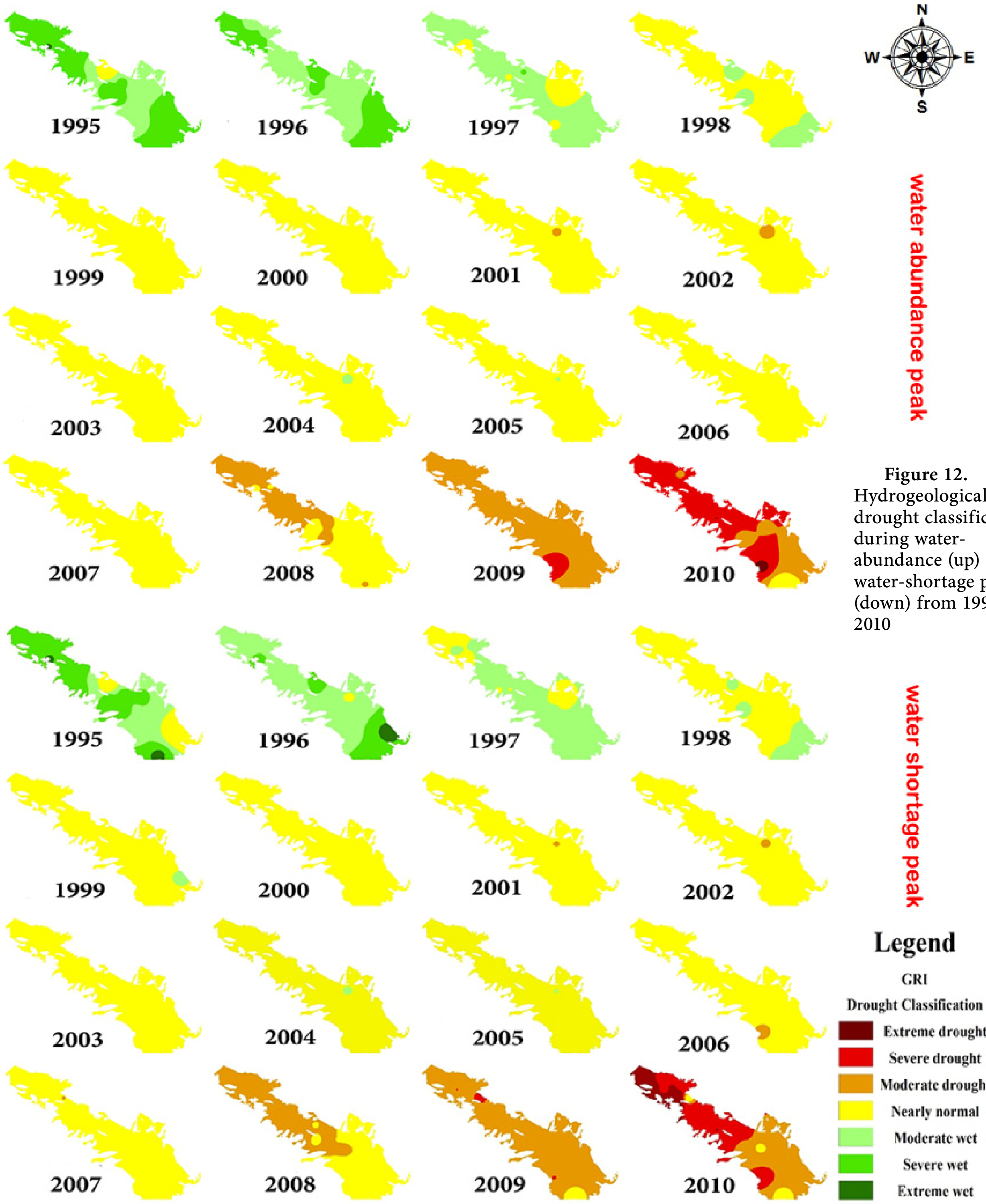

Figure 12. Hydrogeological drought classification during water-abundance (up) and water-shortage peak (down) from 1995 to 2010

the condition in the studied plain. In this area, after a mild period of drought from 2000 to 2002, the plain condition was slightly improved from drought and relatively stable conditions were established between 2003 and 2007. With the start of the next drought in 2008 plain's vulnerability against occurrence of drought is much higher and the plain was placed in worse conditions of drought.

This indicates the necessity to pay special attention to this area and to adopt management strategies such as modifying the utilization of the wells in regions like the studied area.

One of the managerial strategies can be to use the groundwater mathematic modeling of the study area to predict the groundwater level in the next 10 years. Based on this, considering different scenarios, we propose the use of GRI to study and predict the drought.

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