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Assessment of Hydro-meteorological Drought Effects on Groundwater Resources in Hormozgan Region-South of Iran

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ABSTRACT The impact of meteorological and hydrological drought on groundwater resources in coastal deserts in the south of Iran was investigated during 1991-2011, using Standardized Precipitation Index (SPI), Standardized Runoff Index (SRI), and Groundwater Resources Index (GRI). The results indicated that wet and drought spells governed the area in the first and second decades, respectively, which was similarly reflected by the three indices; GRI had a good correlation with SPI and SRI in 48-month time scale. This correlation was simultaneously in the eastern and western coasts and with a 6 months delay in the central plains. The findings can help to provide reasonable managerial strategy in relation to water resources management in the coastal plains.

Key words: *Cross correlation function, Drought indices, Drought monitoring, Water table depletion*

1 INTRODUCTION

Being one of the most damaging natural hazards, drought is placed in the first order in terms of both occurrence and the magnitude of the incurred damages (Bazrafshan *et al.*, 2015). Drought can affect the mineralization of nitrogen (Andresen *et al.*, 2015), the hydrological responses of ecosystems (Cerdà *et al.*, 1998), the crop yields (Bayen *et al.*, 2015) or the soil microbial biomass (Hedo de Santiago *et al.*, 2015). The efficiency of drought monitoring depends on the index that is selected based on the conditions of drought in the region. Different indices have been used to monitor the drought in meteorology, agriculture, hydrology, economic, and social parts that each of them reflects the characteristics related to the drought (American Meteorological Society, 1997). The NDVI, NDWI, SGI, SMAPI (Soil Moisture Anomaly Percentage Index), SPEI1, SPI, SRI, SVI, and SWI are among the different indices used in various studies (Bloomfield and Marchant, 2013; Ezzine *et al.*, 2014; Gudmundsson and Seneviratne, 2015; Wu *et al.*, 2016), among which SPI is the most known index for meteorological drought monitoring in all over the world (Mishra and Desai, 2005; Hayes *et al.*, 1999). Hydrological indices such as PHDSI (Palmer Hydrologic Drought Index) (Alley, 1984) and SWSI (Surface Water Supply Index) (Shafer and Dezman, 1982) have been

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proposed, but they have been less considered due to their complexity. So, an index like SPI can be used to solve these problems. This index is based on the monthly average runoff and is called Standardized Runoff Index- SRI (Shukla and Wood, 2008).

Use of only one index in exploring the drought impacts on complex systems, especially in hydrologic cycle, can't be useful to explore the drought characteristics (Steinemann and Cavalcanti, 2006). One of the main components of hydrologic cycle is the groundwater. The study of the groundwater function (recharge and discharge) against drought is somewhat difficult (Keyantash and Dracup, 2004), which requires to have a threshold in the groundwater that helps to evaluate and recognize the drought phenomenon. The innovative Groundwater Resources Index (GRI) was proposed and tested by Mendicino *et al*. (2008) to monitor the groundwater drought. Vicente-Serrano and Lopez-Moreno (2005) explored the hydrologic response of meteorological droughts using SPI; they found that the relation of these two factors was determinable in temporal scale less than 12 months. Mendicino *et al*. (2008) explored the drought using the SPI and GRI indices and found that lithological characteristics of the catchment had impact on the GRI; the correlation between SPI and GRI increased with increase in the SPI time scale, and the GRI was found to be more appropriate index to predict the water resources status than the SPI. Li *et al*. (2012) analyzed the drought by the use of SPI and found that frequency and intensity of drought increased at the beginning of 21st Century.

Groundwater is very important for human's life around the world, including Iran. The main reason of regional subsidence of ground level in sedimentary basins of arid and semi-arid regions is the over-exploitation of groundwater aquifers and the irregular discharge of these resources (Pacheco *et al.*, 2006). The danger of ground subsidence due to the loss of water table reached to the highest degree in global scale during 1950-1970 that synchronized with industrial and urbanization development (Waltham, 1989). Several works have shown the ground subsidence, especially in dry and low-rainfall regions all over the world, including Iran (Larson *et al.,* 2001; Stiros, 2001; Carminati and Martinelli, 2002;Hu *et al.*,2004; Khan *et al.*, 2008; Soltani *et al*., 2013; Lechner *et al*., 2016; Machowski *et al*., 2016). Precipitation and mean annual temperature fluctuations were found to have a high correlation with groundwater fluctuations (Chen *et al*., 2004).

Currently 277 of 600 plains within Iran are in critical condition (Forootan *et al.*, 2014; Joodaki *et al.*, 2014) in various parts of the country (Ahmadi and Sedghamiz, 2007; Mohammadi and Reihan, 2008; Akbari *et al.*, 2009; Solaimani and Sadeghi, 2009; Jamshidzadeh and Mirbagheri, 2011; Ajdary and Kazemi, 2014; Madani, 2014), due to over-exploitation of the groundwater and irregular discharge (Motaghi *et al.*, 2007). The aim of this research was to explore the climatic and hydrological droughts in coastal plains of south of Iran and its impact on depression of groundwater resources in the two recent decades.

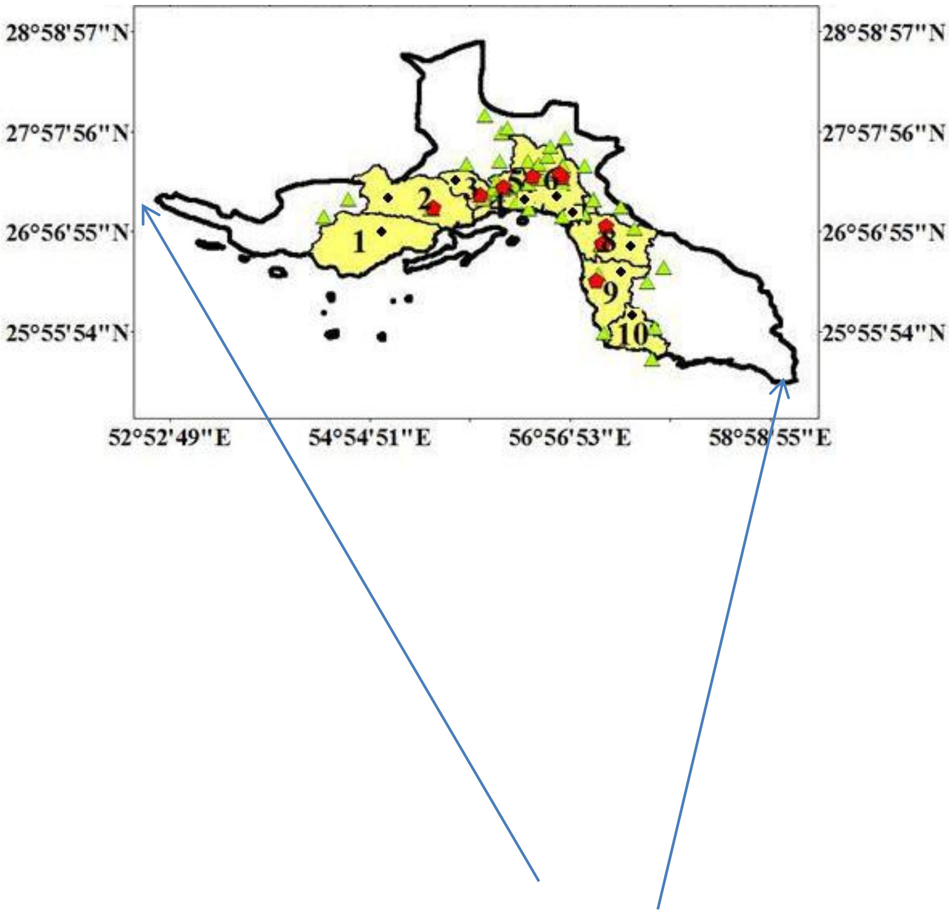
2 MATERIALS AND METHODS

2.1 Study area

Hormozgan Province, an area of 70697 km^2, is situated along coasts the Persian Gulf and Oman Sea. Coastal deserts constitute 54% of this province that are equivalent to 16% of the deserts in Iran. The annual mean temperature of the area is 27º c and the minimum and maximum relative humidity is 19% and 100%, respectively. Mean precipitation is 215.8 mm and the amount of available water in the province is 20000MCM. This province consists of two sub-basins, viz. Bandar-Sedij and Kol-Mehran, that are part of the Persian Gulf and Oman Sea watershed that possess 65 aquifers, 20 of which are located along the shore (Figure 1) where most of the population is found. Information the study plains are presented in Table 1 and Figure 1.

Table 1 Hydro-meteorological characteristics of study plains along the coasts of Hormozgan, Iran

	Plain Name	NO	Groundwater Level (m)	Discharge (m^3s^{-1})	Rainfall (mm)	Elevation (m)
Western	BandarLenge	1	35.0	4	188	40
	Kahorestan	2	18.3	4	178	46
Central	Isin	3	28.9	12	175	90
	EsatIsin	4	22.5	0.0091	176	90
	Sarkhoon	5	80.1	0.0091	213	165
Eastern	Shamil	6	30.4	1.5	230	60
	Minab	7	11.6	1	106	25
	Koryan	8	30.9	1	211	270
	Sirik	9	81.6	1.5	190	50
	Jask	10	41.0	1.5	127	25



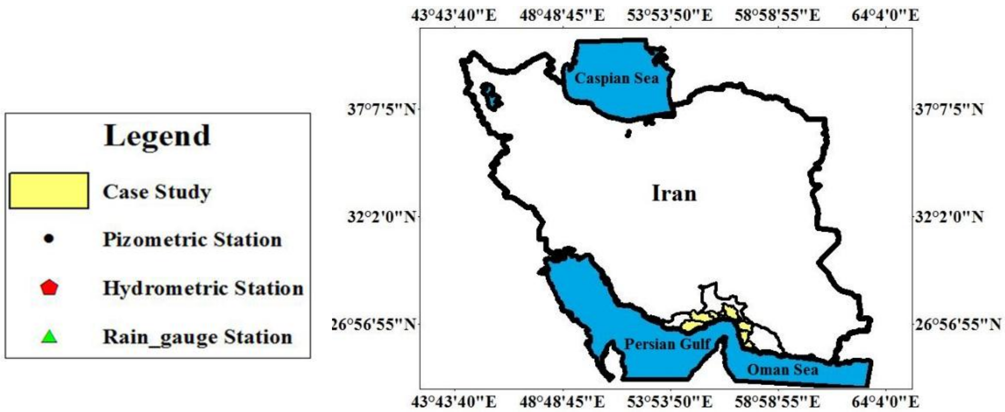


Figure 1 Position of the plains and rain gauge, hydrometric, and piezometric stations along the coasts of Hormozgan province, Iran (Ref: Authors)

2.2 Hydro-geologic status of the study plains

Alluviums and coastal plains with an area of 9134.3 km^{2}constitute about 13.4% of the south coasts, of which alluvial sediments and sand dunes with an area of 2890.8 km^{2}constitute 4.2% of it, especially in the eastern parts and the areas around Jask that are seen as active sand dunes (Farajzadeh *et al.,* 2015). Alluvial terraces are created by change in the base level of the rivers (Aghanabati, 2004). These terraces with an area more than 3167 km^2 cover 4.6% of the total area of the province. Loos alluviums of the rivers beds become finer from upward into the plain.

2.3 Computation of SPI, SRI, and GRI

Standardized Precipitation Index (SPI), developed by McKee *et al*. (1993), is computed by fitting monthly precipitation. For the small catchments, the best fitting is done by gamma distribution (Equations 1 and 2). Then, cumulative probability of gamma distribution is calculated and is transformed into normal distribution. In final phase, normal standardized Z variable or SPI relevant to each station is derived from normal cumulative probabilities curve in equi-probability levels (Equations 3 and 4). In the same way, SRI is computed based on the fitting normal distribution on discharge amounts (Shukla and Wood, 2008; Nalbantis and Tsakiris, 2009). Figure 2 shows the stages of SPI and SRI computation.

$$g(x) = \frac{1}{B^{\alpha}.\Gamma(\alpha)}.x^{\alpha-1}.e^{-X/\beta}$$

(1)

where (α> 0) is a shape factor, (β> 0) is a scale factor, and x> 0 is the amount of precipitation or discharge. $\Gamma(\alpha)$ is the gamma function which is defined as:

$$\Gamma(\alpha) = \int_0^{\infty} y^{\alpha-1}e^{-y}dy \qquad (2)$$

$$Z = SPI \text{ or } SRI = -\left[t - \frac{C_0 + C_1 t + C_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right] \qquad (3)$$

for 0.0<H≤0.5

$$Z = SPI \text{ or } SRI = +\left[t - \frac{C_0 + C_1 t + C_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right] \qquad (4)$$

for 0.5<H≤1.0

$C_0 = 2.515517,\ C_1 = 0.802853$

$C_2 = 0.010328,\ d_1 = 1.432788$

$d_2 = 0.189269,\ d_3 = 0.001308$

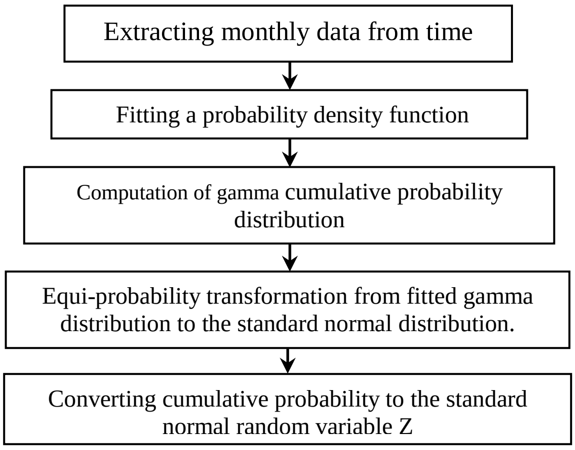


Figure 2 Steps of making of SPI and SRI (McKee *et al.*, 1993); Shukla and Wood, 2008; Nalbantis and Tsakiris, 2009)

GRI is calculated of the Equation 5 (Mendicino and Senator, 2008):

$$\mathrm{GRI}_{\mathrm{y,m}} = \frac{\mathrm{D}_{\mathrm{y,m}} - \mu_{\mathrm{D,m}}}{\mathrm{SD}_{\mathrm{Dm}}} \quad (5)$$

where $\mathrm{GRI}_{\mathrm{y,m}}$ is the index value in month m of year y; $\mathrm{D}_{\mathrm{y,m}}$ is the value of water table in month m of year y;$\mu_{\mathrm{D,m}}$ and $\mathrm{SD}_{\mathrm{Dm}}$are, respectively, the average and standard deviation of water table data in month m of year D.

Table 2 SPI, SRI, and GRI classification (McKee *et al.*, 1993; Shukla and Wood, 2008; Nalbantis and Tsakiris, 2009)

Drought classes	Values
Extremely wet	> 2
Very wet	2 to 1/5
Moderate wet	1/5 to 1
Normal	0/99 to -1
Moderately drought	-1 to -1/5
Severely drought	-1/5 to -2
Extremely drought	< -2

2.4 Mann–Kendall (MK) test

The MK trend test was first carried out by computing an S statistic as:

$$S = \sum_{i=2}^{n} \sum_{j=1}^{i-1} sign(x_i - x_j)$$

(6)

where n is the number of observations, x_j is the j^th^ observation, and sign is the sign function which can be computed as:

$$sign(x_i - x_j) = \begin{Bmatrix} if \;\; (x_i - x_j) < 0 & -1 \\ f \;\; (x_i - x_j) = 0 & 0 \\ f \;\; (x_i - x_j) > 0 & +1 \end{Bmatrix} \quad (7)$$

under the assumption that the data are independent and identically distributed, the mean and variance of the S statistic in Equation (6) are given by (Kendall, 1975) as:

$$E(S) = 0$$

(8)

$$Var\,(s) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m}(t_i - 1)(2t_i + 5)}{18}$$

(9)

where m is the number of groups of tied ranks, each with t_i tied observations. The original MK statistic, designated by Z, was computed as:

$$Z = \begin{Bmatrix} \frac{s-1}{\sqrt{Var(s)}} & if \quad S > o \\ 0 & if \quad S > o \\ \frac{s+1}{\sqrt{Var(s)}} & if \quad S > o \end{Bmatrix}$$

(10)

If$-Z_{1-\alpha/2} \leq Z \leq Z_{1-\alpha/2}$then the null hypothesis of no trend was accepted at the significance level ofα. Otherwise, the null hypothesis was rejected and the alternative hypothesis was accepted at the significance level ofα (Kisi, 2015; Alijani *et al*., 2016).

2.5 Cross-correlation function

To explore the relation between the coincidence and or lack of coincidence of hydro-meteorological drought by the use of GRI in the time scales of the studied plains, cross-correlation function was used. One of the most important advantages of cross-correlation method is the possibility of determining the correlation coefficient in desired time step including positive and negative steps (Chang *et* *al.,* 1997). Cross-correlation is a standard method to determine the degree of correlation between two time series. MINITAB 17 Software was used to execute the above formula.

If X_i and Y_i with $i = 1, 2, ..., N$ are two variables, R-value of cross-correlation between them is as Equation (11):

$$R_{ccf} = \frac{\sum_{i=1}^{n} (X_{(i)} - \bar{X})(Y_{(i-d)} - \bar{Y})}{\sqrt{\sum_{i=1}^{n} (X_{(i)} - \bar{X})} \sqrt{\sum_{i=1}^{n} (Y_{(i-d)} - \bar{Y})^2}} \qquad \begin{cases} For: \ Lag \ time: 0, ,\pm 1, \pm 2, \pm 3, ... \\ f: i - d < 0, \quad i - d \geq N \end{cases} \qquad (11)$$

In this equation, $\bar{X}$ and $\bar{Y}$ values are the mean value of each X_i and Y_i time series, respectively. If Equation 2 should be computed for all certain delay times $d = 1, 2, ..., N - 1$, one of the delay steps will have the highest value of correlation. Regarding the condition of Eq.4, $i < 0$ and $i \geq N$ are not considered and the value of the cross-correlation coefficient is always $- -1 \leq R \leq +1$(Chen *et al.*, 2004; Poveda *et al.*, 2001).

Piezometric wells statistics for the period of 1992-2011 were used to explore the trend of groundwater level changes and to determine the discharge and recharge and critical points in the area. Also, statistics of rain gauge and hydrometric stations in each plain were used for monitoring the drought and its impact on withdrawal and/or recharge of groundwater resources. Figure1 shows the distribution of piezometric, rain gauge, and hydrometric stations in the area of Hormozgan province.

Standardized Precipitation Index (SPI), Standardized Runoff Index (SRI), and Groundwater Resource Index (GRI) were used to monitor the drought, explore the trend of discharge and groundwater level changes, respectively.

2.6 Preparation of isopiezometric map using interpolation method

Isopiezometric map is the co-depth lines of the groundwater aquifer that are shown into contour lines. Decrease in the height of the lines from out into the in shows recharge in the region, while increase in the height shows discharge in the region. Some locally available wells were considered to observation the depth of water layer to provide these maps. With discharge of water from these wells and then acquiring groundwater level and interpolation of co-height levels, groundwater level map was delineated (Sun *et al*., 2009). Inverse Distance Weighted interpolation method (IDW) through Arc/MAP software was used to delineate the isopiezometric map. All of the interpolation methods were developed based on this theory that the correlation and similarity of adjacent points was more than far points. In IDW, it is assumed that the correlation and similarity of adjacent points is proportional to the distance among them that it can be defined as a reverse far function of each point from the adjacent points (Reuter *et al.*, 2007).

$$Z_o = \frac{\sum_{i=1}^{N} z_i d_i^{-n}}{\sum_{i=1}^{N} d_i^{-n}} \qquad (12)$$

where Z_O: the value of variable Z in point i; Z_i= the value of sample in point i; $d^{-n}{}_i$: the point to point distance of estimated samples and n=coefficient determining the weight based on the distance.

3 RESULTS AND DISCUSSION

3.1 Exploring the status of hydro-climatic variables

The changes in annual and seasonal precipitation in eastern, western, and central parts of the coastal deserts were similar (Figure 3), showing an increasing trend for all the coastal regions in the first decade, except 1992 and decreasing after 1995. The highest and the lowest precipitation were, respectively, observed in winter (mean of 123 mm) and in summer (average of 9 mm). On the other hand, precipitation changes in seasonal scale show the decreasing trend of precipitation in the two studied decades. Based on the statistics, the mean precipitation in two decades in the western, eastern, and central coasts was181, 208, and 184mm, respectively, which is in agreement with the findings of Tabari and Talaee (2011) and Some'e *et al.* (2012) in coastal deserts of Iran. Figure4 shows the changes of input run off in eastern, central, and western coasts. There was a high similarity between the discharge and precipitation changes in coastal deserts. The changes of the discharge have been so high in two decades that the decreasing trend becomes very conspicuous in the second decade (2000-2010). The mean amount of the discharge in two decades in the western, eastern, and central coasts was 4, 15, and 5 m^3/s, respectively. The lowest and the highest precipitations were, respectively, recorded in the western plains in summer and the central plains in winter; the lowest and the highest discharges were recorded in the western plains in summer and in the central plains in winter, respectively. The result showed a decreasing runoff trend over the past two decades, which was in agreement with the findings of Khalili *et al.* (2012) in some parts of Iran, but in contrast with the findings of Jiang *et al.* (2013) in China, and Kahya and Kalayci (2004) in Turkey. It seems human activities had a greater contribution to reduction of runoff than the hydro-climatic factors.

3.2 Groundwater hydrograph in coastal plains

The fluctuations of groundwater level in the eastern, western, and central plains show an ascending slope during 1991-2001 and descending trend during 2001-2010 (Figure 5 and Table 3), which exactly synchronize with the high precipitation years and the drought in the area, respectively. An interesting finding was a 0.5 m increase in the groundwater level in the western plains, despite the decreased precipitation the highest loss (5 m) was observed in the central plains and populated areas close to the provincial centre, followed by the eastern plains (3 m). This result is in agreement with the results from other parts of Iran (Nohegar and Hosinzade, 2003; Mohammadi and Reihan, 2008; Jamshidzadeh and Mirbagheri, 2011; Ajdary and Kazemi, 2014). The major cause for this crisis is stated to be rapid population growth and inappropriate spatial population distribution, inefficient agricultural sector, mismanagement and thirst for development (Madani, 2014).

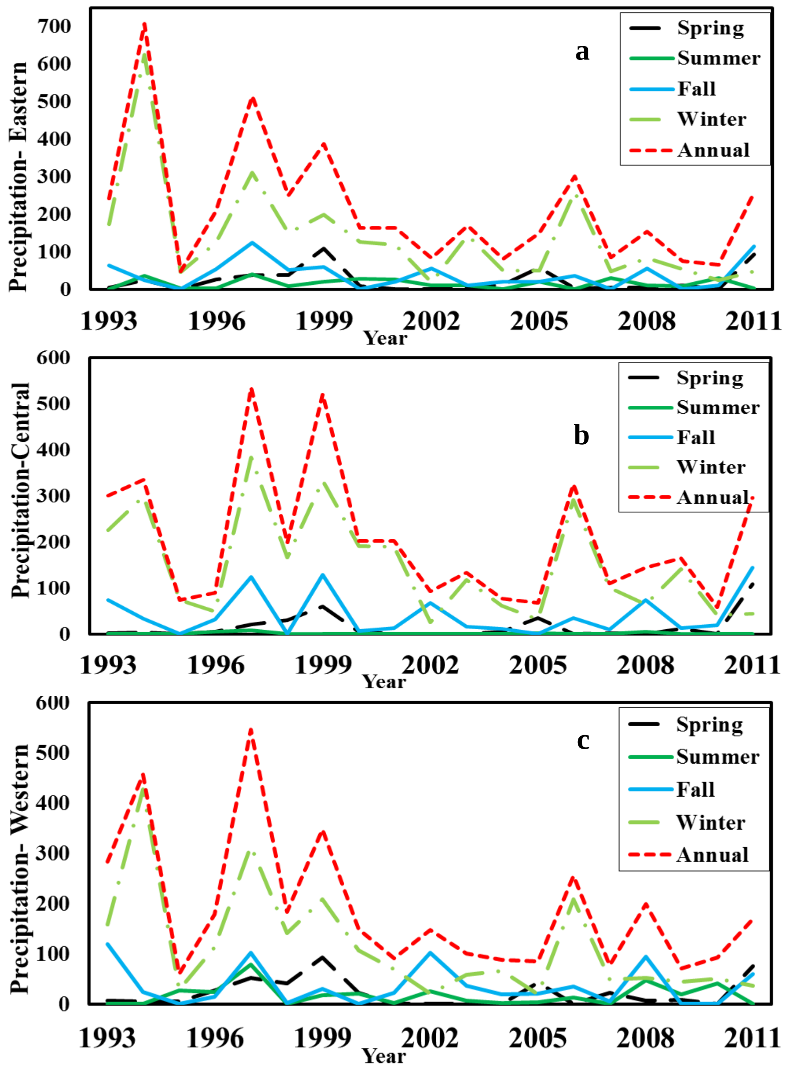
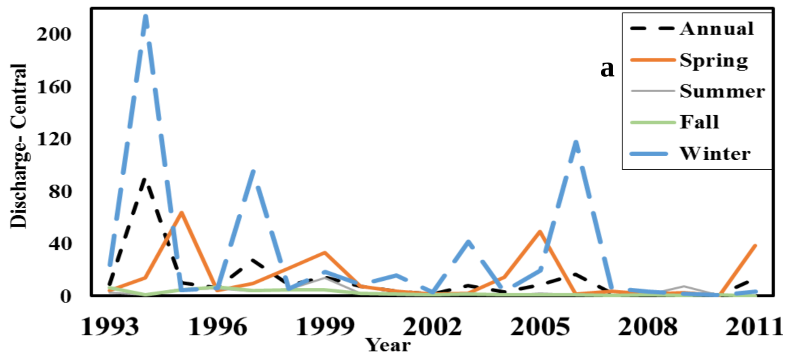


Figure 3 Diagram of annual and seasonal changes of the precipitation in eastern (a), central (b) and western (c) coastal plains



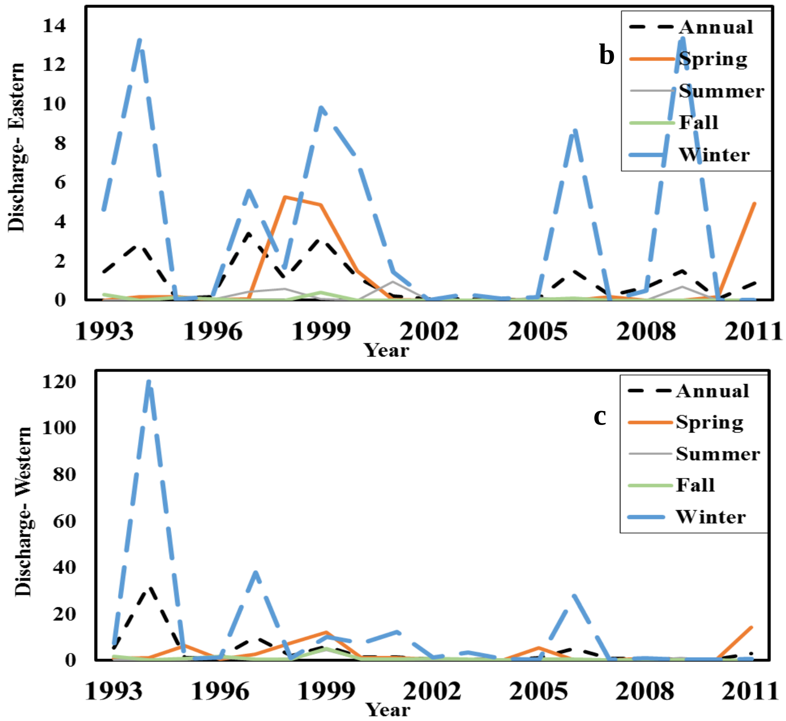


Figure 4 Diagram of annual and seasonal changes of the discharge in eastern (a), central (b) and western (c) coastal plains

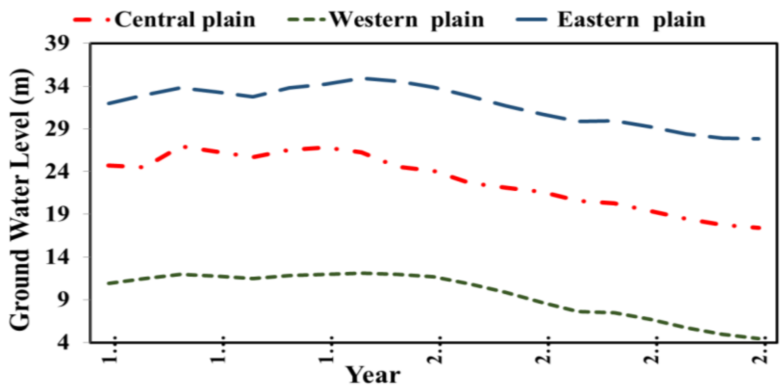


Figure 5 Hydrograph of coastal plains in eastern, western, and central plain parts

Table 3 Groundwater table fluctuations in coastal deserts of south of Iran

	Plain Name	Ground water level fluctuation	Z value (MK test)	Significance in the confidence level of 95%
Western Plains	Bandar Lenge	0.25	+0.98	No
	Kahorestan	0.67	+0.12	No
Central Plains	East Isin	7.27	-2.33	Yes
	Isin	1.86	-1.91	No
	Sarkhoon	7.05	-3.45	Yes
Eastern Plains	Jask	0.67	-0.34	No

Koryan	4.08	-2.1	Yes
Shamil	5.88	-2.5	Yes
Sirik	1.39	-1.04	No
Minab	6.50	-3.01	Yes

3.3 Exploring the relations of climatic and hydro-geologic drought with hydro-meteorological drought

The SPI and SRI indices were explored in 3, 6, 9, 12, 24, and 48 month time scales; GRI was explored monthly and the cross correlation coefficient was computed simultaneously to 6 months delay. Table 4 shows the values of cross correlation coefficient in simultaneously 6 month lead times. A high simultaneous correlation between SPI and GRI, and SRI and GRI in 48 month time scale was observed in all western and eastern plains, while the high correlation in central plains occurred with a 6 month delay. Changes of the groundwater level relative to the SPI and SRI in the three plains indicated that drought had occurred simultaneously in the eastern and western plains (Figure 8), but hydrogeological drought occurred with a lead time relative to the climatic and hydrological droughts in the central part, which could be attributed to the existence of alluvial formations of Asmari lime in central coasts of Iran. Based on the Figure8, there was wetness status in all study plains in the first decade, while there was a drought trend in the second decade. While Fiorillo and Guadagno (2010) and Bazrafshan *et al*. (2013) found a lag time between meteorology and hydrologic droughts and discharge, Eghtedar Nezhad (2015) showed simultaneous occurrence of the groundwater drought and hydrological drought. It seems that climatic and hydrologic droughts in arid and semi-arid regions with seasonal rivers take place simultaneously.

Table 4 Average cross correlation coefficients for drought indices in south of Iran

Zone	Delay Steps	0	1	2	3	4	5	6
Western Plains	SPI48-GRI	0.38**	0.40**	0.41**	0.43**	0.45**	0.49**	0.51**
	SRI48-GRI	0.53**	0.53**	0.54**	0.54**	0.54**	0.53**	0.49**
Central Plains	SPI48-GRI	0.75**	0.66**	0.65**	0.66**	0.64**	0.54**	0.42**
	SRI48-GRI	0.73**	0.74**	0.74**	0.74**	0.75**	0.75**	0.76**
Eastern Plains	SPI48-GRI	0.61**	0.71**	0.72**	0.74**	0.75**	0.77**	0.79**
	SRI48-GRI	0.58**	0.58**	0.57**	0.57**	0.57**	0.57**	0.56**

**Significant level (P< 0.05)

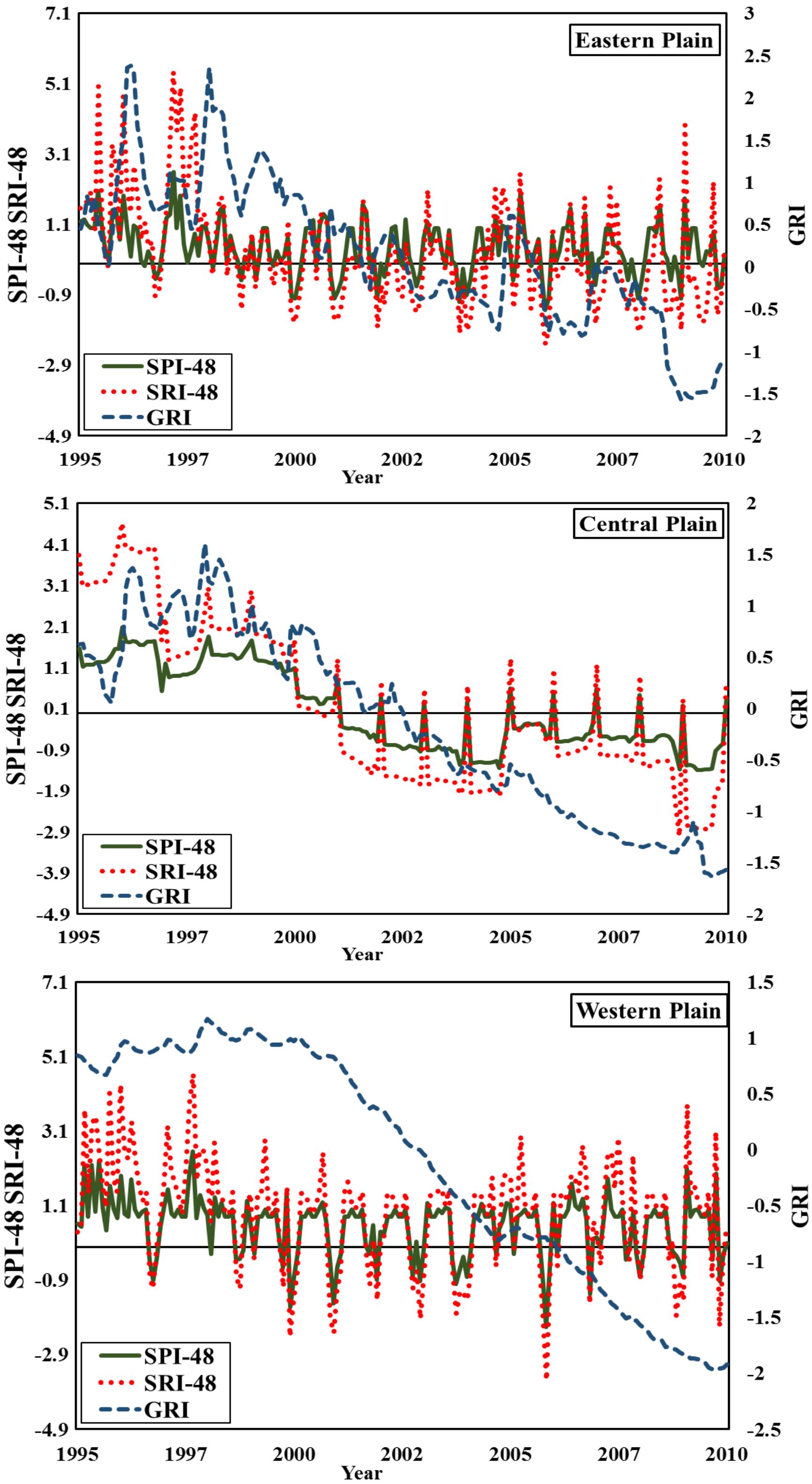


Figure 6 Plot of SPI48, SRI48, and GRI over time (1991-2011)

3.4 Determining the critical discharge and recharge points and probable subsidence regions

Some discharge regions were observed by exploring the seasonal isopiezometric maps of the study area that the probability of subsidence had been predicted. The high density of contour lines in a point and increase inisopiezometric level in the curve centre show the severity of discharge (Almedeij and Al-Ruwaih, 2006). This status was seen in eastern and central coastal plains in all seasons.

The highest and the lowest discharge were, respectively, observed in summer and winter. However, the highest recharge was observed in the interior part of the coast coastal plains. Actually, excessive discharge of the groundwater aquifers leads to the salt water intrusion into the coastal plains. As the distance from the cost increases, over-discharge lead to the further loss of the groundwater, which is observable in the isopiezometric lines (Figure7). This is in agreement with the results of Almedeij and Al-Ruwaih (2006) in Kuwait and Mair and Fares (2010) in USA.

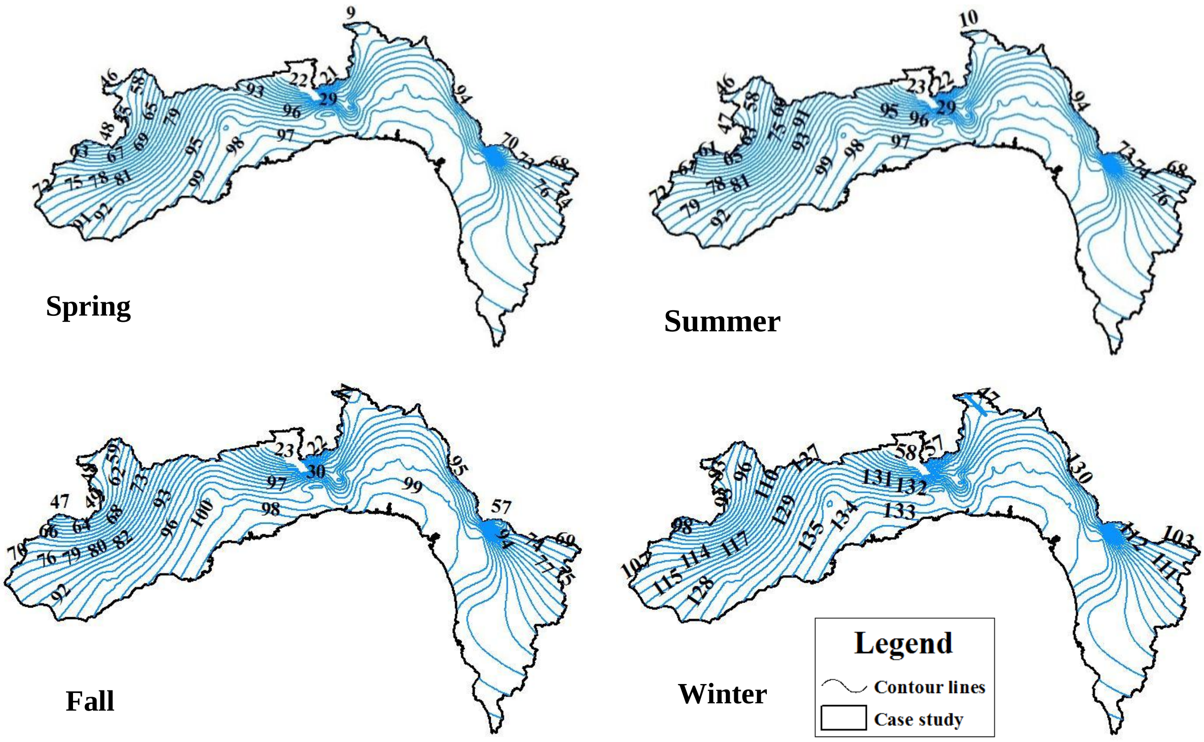


Figure 7 Seasonal isopiezometric maps of the study area

4 CONCLUSION

Application of three SPI, SRI, and GRI indices showed two different periods of wetness and climatic, hydrologic, and hydro-geologic droughts. Climatic and hydrologic droughts had a high and positive correlation, which means that these droughts occurred simultaneously. Further, these types of drought had a high and positive correlation with the fluctuations of the groundwater level, but hydro-geologic wetness and drought periods occurred with a 6 month lead time relative to the occurrence of climatic and hydrologic wetness and drought periods; the highest correlation was in 48 month time scale.

Regarding the discharge points, the eastern and central coastal plains were in the danger of subduction and degradation, including Isin, Sarkhoon, and Minab plains with a loss of 7.26, 7.05, and 6.5 meters, respectively, in the last two decades. A significant difference in water level in autumn and winter with other seasons were observed, as more than 90% of the precipitation occurred in autumn and winter.

The hydro-meteorological drought behaviour of the Hormozgan coastal plains is changing tempo-spatially on the long term. The aquifer system of these plains, as a main water resource for municipal, agricultural and industrial uses is under high pressure. Reduction in water extraction, especially in Minab, Shamil, Sarkhoon, and Isin are essential. Developing artificial recharge projects in the area can be helpful.

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ارزیابی اثرات خشکسالی هیدرومتئورولوژیکی بر منابع آب زیرزمینی در استان هرمزگان - جنوب ایران

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چکیده اثرات خشکسالی اقلیمی و هیدرولوژیکی بر نوسانات آب زیرزمینی در سواحل بیابانی جنوب ایران با استفاده ازشاخص‌های بارش استاندارد، جریان استاندارد و شاخص سطح آب زیرزمینی استاندارد طی دو دهه (۱۹۹۱ تا ۲۰۱۱) بررسی شد. نتایج نشان دادکه هر سه شاخص ویژگی‌های مشابهی از شرایط منطقه را منعکس کردند، همچون ترسالی دهه اول و خشکسالی دهه دوم. همچنین همبستگی خوبی بین GRI با SPI و SRI در پنجره زمانی ۴۸ ماهه مشاهده شد، که در سواحل شرقی و غربی این همبستگی به‌صورت همزمان و در دشت‌های مرکزی با ۶ ماه تاخیر بالاترین همبستگی مشاهده گردید. نتایج حاکی از آن است که ایجاد روابط کمی بین سه شاخص خشکسالی هیدروژئومتئورولوژیکی می‌تواند دید وسیعی به مدیران و برنامه‌ریزان منابع آب در جهت اتخاذ سیاست‌های صحیح در دشت‌های ساحلی بدهد.

کلمات کلیدی: افت تراز آب، پایش خشکسالی، تابع همبستگی متقاطع، شاخص‌های خشکسالی