Natural Hazards
https://doi.org/10.1007/s11069-020-04103-8

ORIGINAL PAPER

Regionalization of drought severity–duration index across Iran

Mohammad Ghadami[1] · Tayeb Raziei[2] · Mohsen Amini[1] · Reza Modarres[1]

Received: 28 November 2018 / Accepted: 4 June 2020

Abstract
Drought is the most important threat to both environmental and socio-economic features of the arid and semi-arid regions of the world as it is closely associated with agricultural production losses, water supply shortage, and security. This study aims to regionalize extreme drought severity–duration (SD) index probability across Iran. The 12-month Standardized Precipitation Index (SPI) time series were calculated for the studied stations and subsequently used to compute the annual extreme SD index. Applying a cluster analysis (CA) to the stations, SD index, the studied area was classified into four regions and their homogeneity was tested by the L-moment approach. Results indicated that the regions identified are homogeneous. Based on the L-moment ratio diagram the 2-parameter log-normal distribution was selected as the regional statistical distribution for all regions identified, by which the regional drought SD associated with different return periods was estimated. The spatial pattern of computed drought SD indicates that the eastern, northwestern and western parts of the country are exposed to very high drought severity in all return periods. As the return period is increasing, very high and severe droughts dominate larger areas, so that, for long return periods, approximately all the country would turn towards extreme and severe drought events even across regions possessing high annual precipitation amount.

Keywords Regional drought frequency analysis · Drought severity · L-moments · SPI · Risk · Iran

1 Introduction

Drought is a situation in which precipitation shortage accompanied by higher than normal temperature may cause water deficit and stress in any climate of the world (Mishra and Singh 2010). Among the natural hazards threatening human livelihood and environment,

✉ Reza Modarres
reza.modarres@iut.ac.ir

Tayeb Raziei
tayebrazi@yahoo.com

[1] Department of Natural Resources, Isfahan University of Technology, Isfahan, Iran

[2] Soil Conservation and Watershed Management Research Institute (SCWMRI), Agricultural Research, Education and Extension Organization (AREEO), Tehran, Iran

Published online: 10 June 2020

drought is the most important one in both frequencies of occurrence and magnitude of damages (Kenekh 2003). More than 11% of natural hazards throughout the world, especially in rural areas, are related to drought events (Karand 2004). Drought monitoring and prediction, therefore, may assist in reducing the adverse impacts of foreseen drought events.

Drought indices are commonly used to characterize drought events and their characteristics. Some of these indices are the Palmer Drought Severity Index (PDSI) introduced by Palmer (1965), the Standardized Precipitation Index (McKee et al. 1993), the Effective Drought Index (EDI, Byun and Wilhite 1999), the Reconnaissance Drought Index (RDI) introduced by Tsakiris and Vangelis (2005) and the Standardized Precipitation Evapotranspiration Index (SPEI) proposed by Vicente-Serrano et al. (2010). Among these indices, the SPI is more flexible for drought identification, assessment, and monitoring in different time scales (Abdolverdi and Khalili 2010). As a result, the SPI has been used to evaluate water shortages, monitor dry and wet periods and investigate drought on a regional basis (Bonaccorso et al. 2003). The SPI has been applied in many regions of the world. For example; Labedzki (2007), Kumar et al. (2009), Santos et al. (2011), Bazrafshan et al. (2014) and Ganguli and Reddy (2014) have used SPI for drought analysis in Poland, Andhra Pradesh (India), Portugal, Iran, and India, respectively.

Loukas and Vasiliades (2004) analyzed temporal and spatial characteristics of drought in the Thessaly region in Greece and indicated that moderate and severe droughts are common in the region. Guenang and Kamga (2014) used SPI to assess drought occurrences in Cameroon during 1951–2005 and found that in nearly all stations, drought duration and intensity have increased as detected by SPI at both short and long time scales.

The identification of drought characteristics including frequency and spatio-temporal changes is of great importance for water security and sustainable development (Huang et al. 2014). Many studies have been devoted to monitoring and probabilistic analysis as well as spatio-temporal characterizing of drought. For example, Huang et al. (2014) studied the spatio-temporal changes of drought from 1961 to 2005 in the Wei river basin, China, using the SPI and concluded that the surrounding areas of Huanxian's meteorological station has a high drought risk while the western and northern parts of the basin have a relatively low risk. Halwatura et al. (2015) investigated the severity–duration–frequency (SDF) of short and long-term droughts in 11 different climatic regions of Australia using SPI, RDI, and SPEI drought indices. For both short and long-term drought aggregation, the drought events were found severe, prolonged and a common feature in the arid regions, while they were relatively rare in the tropical and temperate regions. Using the copula approach, Xu et al. (2015) analyzed drought frequency and its spatio-temporal variability in southwest China. They reported that the most severe drought events in southwest China during 1961–2012 had a lifetime spanning from August 2009 to June 2010, covering about 98% of the study area (867,000 km^2).

Iran is located between 25° N and 40° N with dominant arid and semi-arid climates due to being situated under the northern hemisphere subtropical high-pressure belt. This leads to irregular precipitation occurrences in time and space especially in the central and eastern parts of the country where the annual precipitation may reach less than 50 mm. However, due to the pronounced effects of Zagros and Alborz mountain ranges in the western and northern Iran, respectively, the precipitation amount in the mountainous regions of western and northern Iran is much higher. In the stripe of coastal areas of the southern Caspian Sea, the annual precipitation may reach to 2000 mm/year due to the interaction between the sea and topography of the region. In addition to low mean nationwide annual precipitation amounts of the country (250 mm) which is about one-third of the mean global precipitation, its inappropriate spatial and temporal distribution intensifies water scarcity and associated challenges in Iran (Masoudian and Kaviani. 2007). The rainfall season of Iran usually starts from October and ends in June. The autumn, winter, and spring are the main rainy seasons across most parts of the country while sporadic summer rainfall usually occur along the Caspian Sea in the north as well as southeastern Iran. Many mechanisms provide rainfall to Iran among which the Mediterranean system is the strongest which provides autumn and winter season rainfall in the western and northern regions. In the southeastern region, the Indian Ocean and Oman Sea are the main moisture source in the region for monsoon summer rainfall.

According to Raziei (2017), Iran is composed of 9 out of 31 possible Köppen–Geiger climate types over the globe. Accordingly, most parts of central, eastern and southern Iran are characterized by BWh and BWk dry/semi-dry climate types, whereas the coastal areas of the Caspian Sea in the north and most parts of the mountainous areas of Zagros and Alborz in the west and north of Iran have moderate climate types (Csa). However, the eastern slope of Zagros and the southern slope of Alborz that are connected to the central arid and semi-arid climate of central-eastern Iran are distinguished by the BSk climate. The southern parts of the Zagros region are mostly dominated by the BSh climate. Dsa and Dsb colder/cooler climate types are found in some parts of the mountainous areas of Zagros and Alborz, while Csb and Cfa are the localized climate types that can be found in coastal areas of the Caspian Sea. According to this study, most parts of Iran are characterized by BWh and BWk dry climate types with a long dry season and irregular precipitation occurrences. Therefore, climatic conditions of most parts of Iran are featured by precipitation and water scarcity, hot and dry summers, and prolonged droughts, that have induced critical problems to water resources management across the country. With regard to precipitation time variability, i.e., dry/wet periods, applying an S-mode principal component analysis (PCA) to monthly precipitation time series of 155 synoptic stations distributed over Iran covering the 1990–2014 time period, Raziei (2018) has regionalized Iran into five distinct subregions with different monthly precipitation time variability. According to this study, the northwestern, western, southeastern, central-northeastern, and northern Iran along the Caspian Sea area were found as five distinctive Iranian precipitation sub-regions, each possessing different monthly precipitation time variability when compared to the remaining subregions. The identified sub-regions are also in agreement with similar regions implemented by Raziei et al. (2010, 2011), applying the same methodology to the time series of different SPI time scales computed with the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis and the Global Precipitation Climatology Centre (GPCC) dataset for the common period 1948–2007 at grid points covering the country.

Iran has experienced recurrent droughts in recent years. For instance, 10 out of 31 provinces of the country were affected by a long-term and severe drought during the period 1998–2001 (Raziei et al. 2009). Yazdani and Haghsheno (2008), reported that Iran has experienced 17 drought seasons in the past 50 years; the worst one occurred in 1999 that caused irrecoverable damages to agriculture and water resources. Soleimani et al. (2005) reported that water storage behind dams of Iran had decreased by 50% at the end of December 1999 when compared to 1998. Tabari et al. (2011) analyzed precipitation and drought severity time series in eastern Iran, concluding that the eastern parts of the country became drier from 1966 to 2005. Moradi et al. (2010) investigated the meteorological drought characteristics of Fars province, Iran, during 1977–2008 and reported that the worst drought event that occurred in the province was observed in November 1999 lasting 6 months. Golin et al. (2014) did a survey on trends of meteorological and agricultural drought in Iran and found that nearly the entire country experienced the most severe drought between 1998 and 2001. Modarres et al. (2016) examined changes of extreme drought and flood events in Iran during the 1950–2010 and concluded that the extreme/severe droughts show a monotonic change.

In spite of all efforts carried out on drought monitoring and identification in Iran, investigation of spatio-temporal characteristics of drought frequencies has not been comprehensively investigated. Thus, the main purpose of this study is to regionalize drought severity–duration–frequency (SDF) across Iran. In addition, we are seeking regions with similar drought conditions. This is the first attempt at regional drought frequency analysis across the entire country that should increase our knowledge on drought characteristics in different regions of Iran, which is useful for national and regional drought preparedness and management. Herein, the L-moment method commonly used for regionalization (Yurekli et al. 2009) is jointly utilized with cluster analysis (CA) for the regionalization of Iran based on drought characteristics. The data and methodologies used for the analysis are given in Sect. 2, results and discussions are presented in Sect. 3, and the conclusion and recommendations for the future studies on drought in Iran are given in Sects. 4 and 5, respectively.

2 Materials and methods

2.1 Data

Monthly precipitation time series from 56 synoptic stations for the period 1985–2014 were obtained from the Islamic Republic of Iran Meteorological Organization (IRIMO) and used for computing SPI at a 12-month time scale. The selected stations are well distributed across the country and they are representative of all climatic and topographic features of Iran (Fig. 1). The selected time period for the study is also chosen in which all the stations have complete data records with no missing values.

2.2 Standardized Precipitation Index (SPI)

Based on monthly precipitation data as the input, the SPI time series can be computed at different time scales ranging from 1 to 48 months. The shorter time scales (say 3 and 6 months) describe the drought events affecting agricultural activities while the longer time scales (12 and 24 months) are more suitable for water resources management purposes (Raziei et al. 2009). In this study, the 12-month SPI time series are calculated for the considered stations and subsequently were used to derive the drought severity–duration index (SD) computed with Eq. 1 (Santos et al. 2011; Modarres et al. 2016):

$$\mathrm{SD} = -\sum \mathrm{SPI}. \tag{1}$$

Here the consecutive negative SPI values in each year are summed up and multiplied by -1 to change the sign of the value before using in a frequency distribution fitting. The highest value of the accumulated SPI for each year is considered as the extreme annual drought severity. Figure 2 illustrates the calculation of SD based on the SPI = 0 threshold for drought condition.

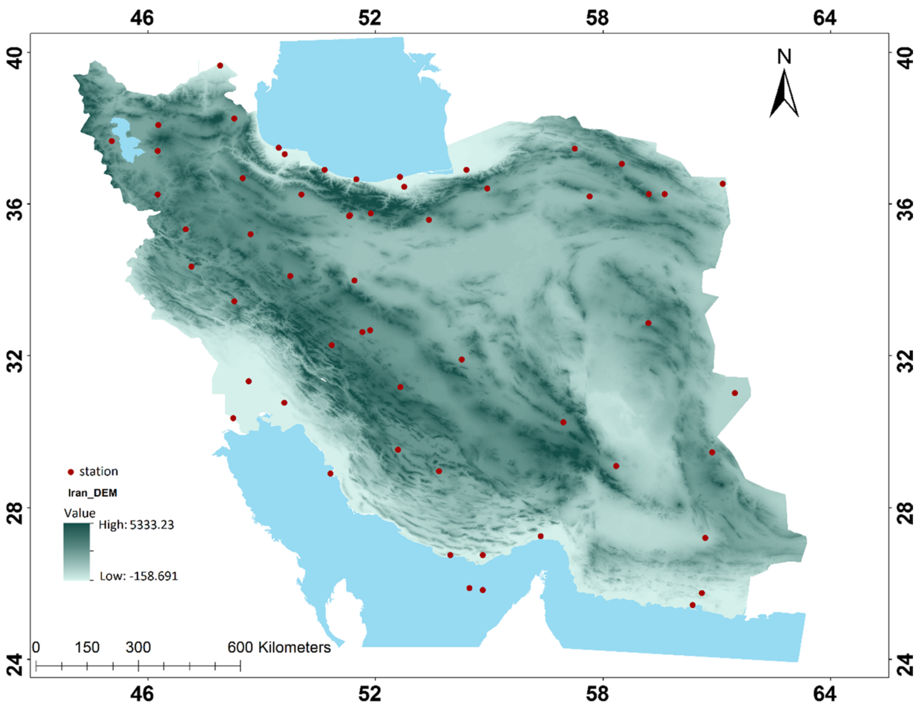

Fig. 1 The location map of the selected stations on the DEM map of Iran

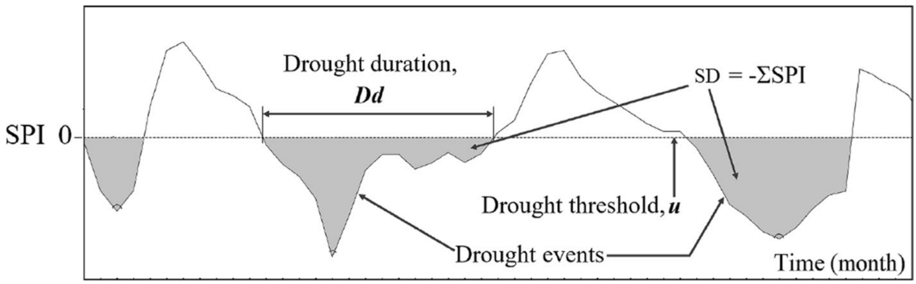

Fig. 2 Definition and calculation of SD based on drought characteristics (adapted and modified from Espinosa et al. 2019))

3 Regionalization procedure

3.1 Delineation of groups

In the first step of drought regionalization, the stations are classified into a number of groups using cluster analysis (CA) considering their drought SD index. The aim of CA is to assign objects (stations) to a set of exclusive groups/clusters with the maximum similarity of the group members and dissimilarity between groups (Modarres 2010). In this study, the ward's minimum variance method of the hierarchical cluster analysis (Kaufman and Rousseuw 1990) is used for partitioning the stations into different regions with different drought SDs, based on dissimilarity squared Euclidean distance measure. For the sake of brevity, interested readers are referred to Modarres (2006) and Modarres and Sarhadi (2011) for more details of the approach.

3.2 Regional frequency analysis

Regional frequency analysis of drought SD is carried out by the L-moment approach (Hosking and Wallis 1997) which is the modification of the probability-weighted moments (PWM) introduced by Greenwood et al. (1979). L-moments are more appropriate and easier than the PWM since the L-moments can directly describe the size of scale and shape of a given probability distribution, and thus from this point of view, they are comparable to the ordinary moments. The L-moment approach includes three steps which are applied herein for each group of the drought SD identified by CA:

1. Homogeneity testing: in this step, we use the H_1 heterogeneity measure to investigate homogeneity of each sub-region. A sub-region is defined as homogeneous if $H_1 < 2$ and is relatively heterogeneous if $2 < H_1 < 3$ and heterogeneous if $H_1 > 3$.
2. Selecting regional frequency distribution: L-moment ratio diagram (MRD) is drawn to select the best regional fitted distribution. This diagram describes the L-Coefficient of Skewness (LCs) against L-Coefficient of Variation (L-Cv) for each station in a sub-region on the LCv–LCs line drawn for each individual theoretical distribution.
3. Estimation of SD at different return periods: using the L-moment approach, the parameters of the best distributions functions fitted to the regional and at-site drought annual SD time series are estimated by the maximum likelihood method. Based on the selected distribution, the SD values at different return periods, namely 2-, 10-, 50- and 100-year return periods are estimated. It should be noted that as the selected time series are limited to 30 years, some possible uncertainty may be involved in the estimation of longer return periods such as 50 and 100 year return period. This uncertainty may decrease by careful selection of the distribution function, but still the results need to be used and interpreted cautiously.

4 Results and discussion

4.1 The spatial pattern of drought SD

The spatial pattern of drought SD over Iran is discussed by illustrating the map of annual mean and maximum drought SD in Fig. 3. Based on historical drought data, the mean SD values over the country ranges from 5 to 6 for most regions of the country. The eastern and northwestern areas show the highest value of average drought SD (between 6 and 7). The lowest average SD (SD = 2–3) is restricted to some stations across the southwestern region near the Persian Gulf.

The recorded maximum SD during the historical period ranges from 19 to 23 across major parts of the country. Similar to the average drought SD, the eastern region is characterized by relatively high drastic drought events with the maximum SD = 23–27. In this region, some stations have experienced the highest drought SD ranges that vary between 27 and 41, especially in Doshan Tappeh station which experienced a maximum SD of 41

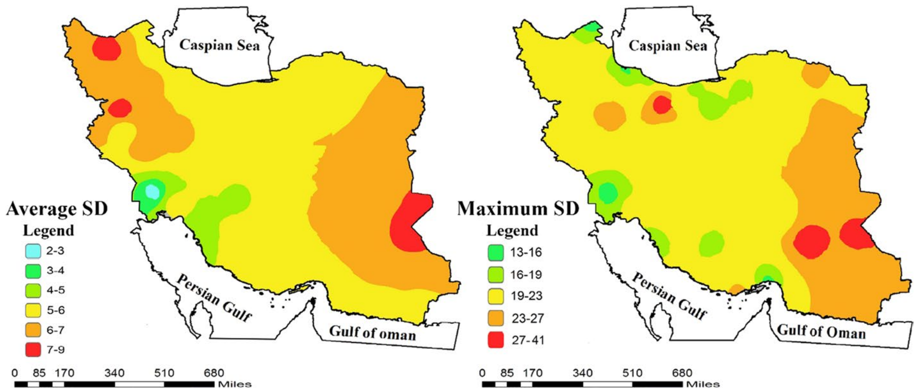

Fig. 3 The spatial pattern of the annual average and maximum SD for the period 1985–2014

in 2014. The lowest maximum drought SD is also observed in the areas near the Persian Gulf, where the lowest average SD was also observed. As seen in Fig. 3, the lowest average SD can also be observed in some parts of the coastal areas of the Caspian Sea in the north, implying that the available moisture from the sea can reduce the adverse impacts of drought conditions.

The variation of nationwide time series of drought SD values during 1985–2014 is illustrated by boxplots in Fig. 4. Each boxplot represents the nationwide variation of drought SD, i.e., each one represents 56 SD values. We can see the drought SD exhibits a high year to year fluctuation during historical record. Though drought SD varies between 0 to 10 in many years, there are years in which some stations show higher SD values than the long-term average. The maximum SD values mainly emerge in 1999–2001, 2008 and 2014 when drought SD had increased remarkably.

4.2 Regionalization of drought SDs

Application of hierarchical agglomerative clustering on drought SD time series corresponding to 1985–2014 time period has resulted in 4 groups of stations characterizing different geographic areas of the country which are illustrated in Fig. 5. Groups A, B, C, and D include 17, 11, 16 and 12 stations, respectively. The heterogeneity measures

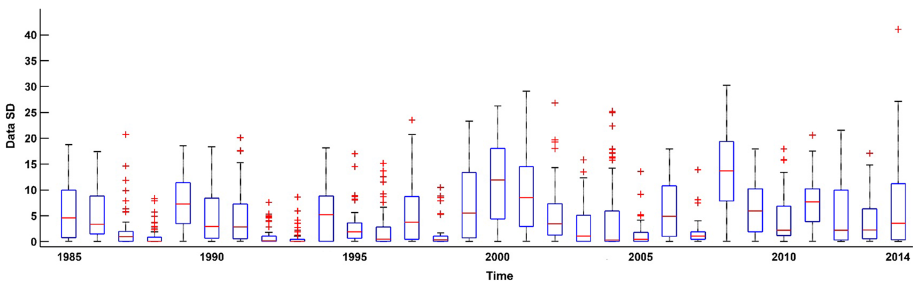

Fig. 4 Temporal changes of annual maximum SD across Iran during 1985–2014. Each boxplot includes 56 values

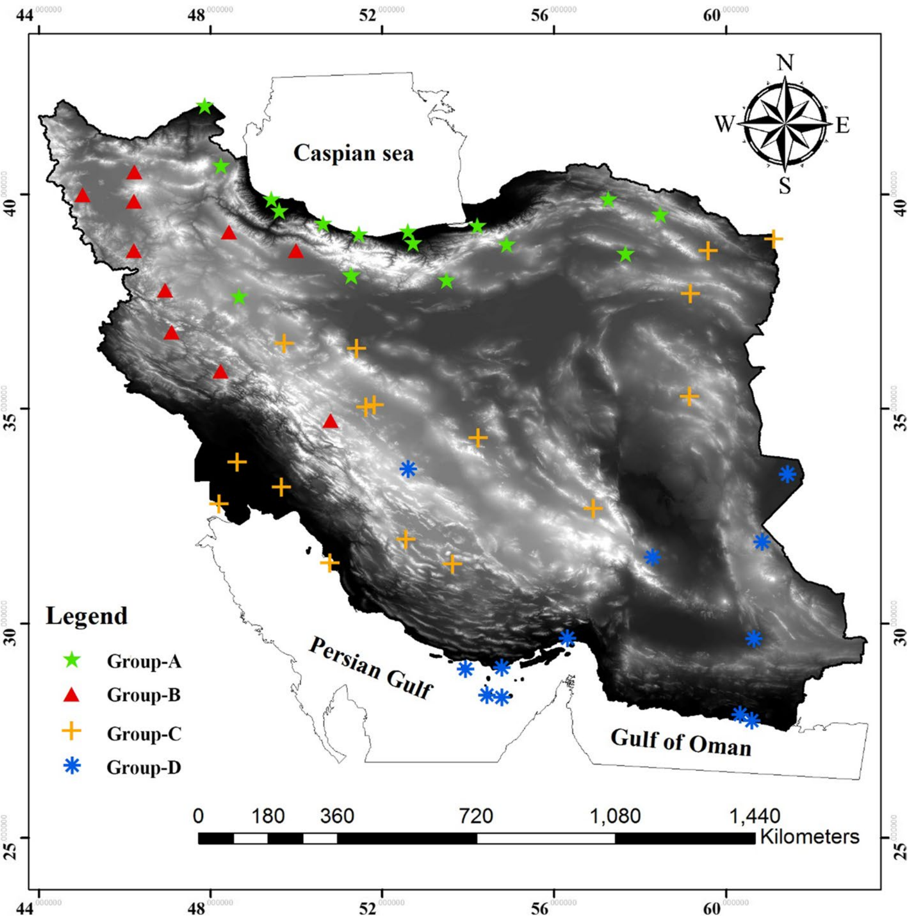

Fig. 5 Spatial map of drought groups on SD time series

H_i indicate that all 4 defined groups are homogenous (Table 1). This table implies that a regional frequency distribution can govern the probabilistic behavior of drought SD in each homogeneous group. In other words, this homogeneity refers to the similarity of statistical features of drought SD in each region.

Table 1 The result of heterogeneity measures for drought SDs at different groups

	Heterogeneity measures		
	H1	H2	H3
Group A	− 0.57	− 0.37	− 0.9
Group B	0.52	0.86	0.08
Group C	0.17	− 0.81	− 1
Group D	− 0.63	− 0.67	− 0.6

Group A corresponds to northern Iran, covering the coastal areas of the Caspian Sea and the Alborz Mountains with northwest to northeast axis. Group B includes northwestern and western Iran and mainly covers the Zagros Mountains. Group C includes low land areas of the central plateau of Iran and southwestern margins of the Persian Gulf. This region usually refers to arid and semi-arid territories of the country. Finally, group D includes southern Iran along the coast of the Persian Gulf and Oman Sea and the southeastern parts of the semi-arid central plateau on the border of Afghanistan and Pakistan.

The annual average, maximum and standard deviation of the drought SDs in each group are presented in Fig. 6. Based on the mean regional SD time series the drought severity is relatively higher in group D that covers southeastern Iran, while lower drought SDs were observed in groups A and C. Although an exceptional drought SD is observed in Doshan Tappeh station in group A, the between-group comparison of the maximum SD indicates that drought severity is almost the same in all groups identified.

The time variability of drought severity in Fig. 6 shows three common drought periods with relatively higher drought severity in most regions identified. These periods are 1990–1994, 2000–2004 and 2010–2014. In each region, the maximum drought SD in the study period is also observed in these periods. Finally, the figure shows that in each year drought with different severity and duration has occurred in different parts of the country. In other words, drought is a common feature of the climate and water resources interaction across the country.

4.3 Regional frequency distribution

As shown in Fig. 7, the L-moment Ratio Diagram (MRD) was computed for each region in order to find the regional distribution of drought SD. In all groups, the L-CV and L-CS of the stations and their average are more closely scattered around the 2-parameter log-normal distribution (LN2). Therefore, the LN2 distribution is selected as the parent distribution for the drought SD groups. It should be noted that the 3-parameters distributions were also examined, but none of them are appropriate as the parent distribution for these groups.

4.4 Spatial pattern of drought SD at different return periods

The LN2 distribution was fitted to the annual SD time series of the stations and the estimated at-site SD values corresponding to 2, 10, 50, and 100-year return periods were interpolated using the Inverse Distance Weighting (IDW) method. The spatial patterns of drought SDs with different return periods across the country are presented in Fig. 8. For the 2-year return period, the SD values vary between 1 and 5, and the country is mainly covered by moderately SD values between 2 and 4 although a few stations experienced higher SDs (i.e., SD = 4–5). For 2-year return period, the northwestern and eastern areas seem to suffer from higher drought SD values. The spatial pattern of the 10-year return period shows that the SD values vary between 6 and 17 over the country. Major drought conditions with SDs between 12 and 14 are observed in most parts of the country. Similar to the 2-year return period, the most severe drought conditions are observed in the eastern and northwestern territories where the SDs reach values between 14 and 17.

For the 50-year return period, the SD values have divided the country into three distinct regions namely the west, middle and east of Iran. However, in this return period, the highest SD value is observed in the western and eastern regions and the major parts of the country are affected by SDs between 24 and 28. The 100-year return period SD values that

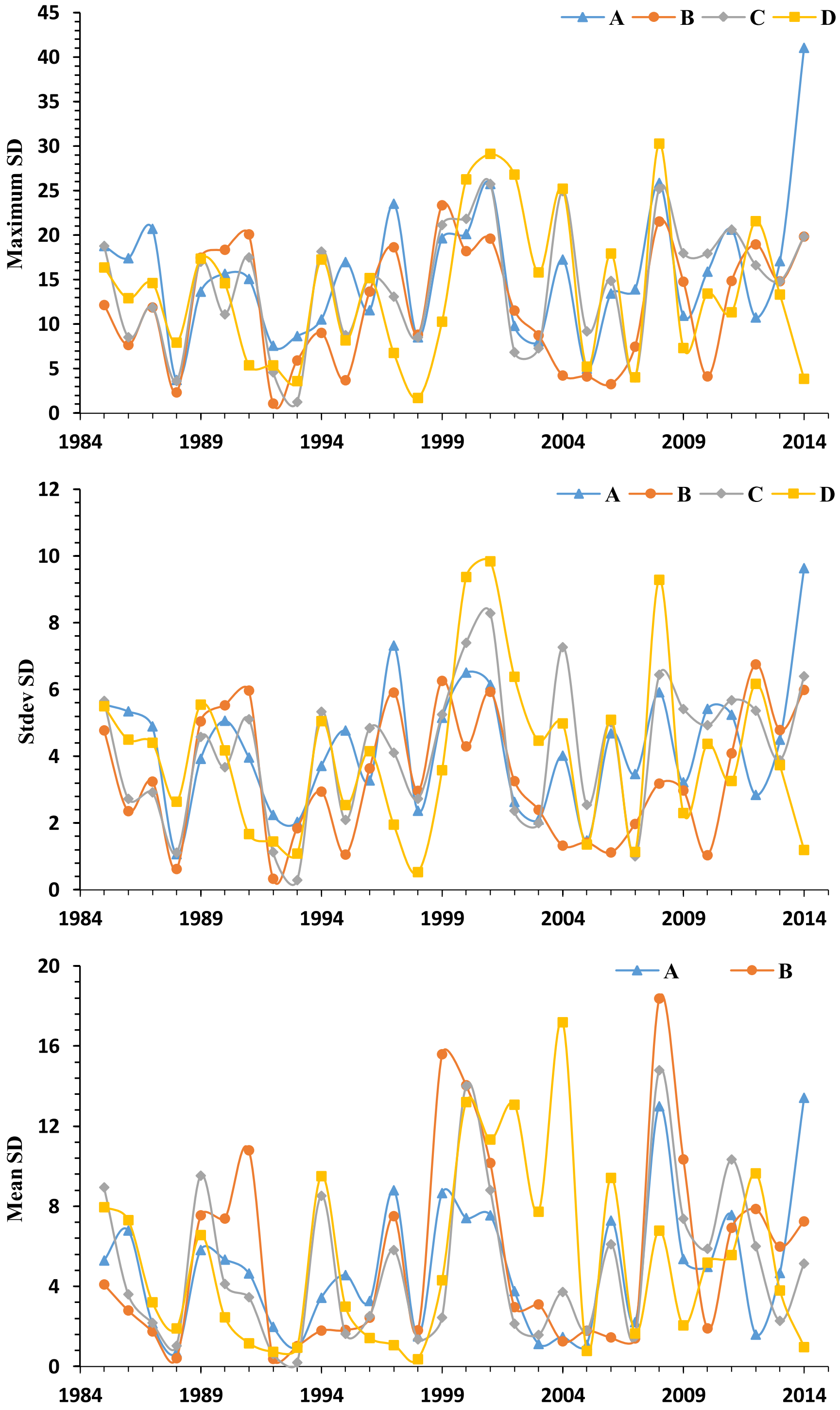

Fig. 6 Temporal changes of mean, maximum and standard deviation of SDs in each drought group

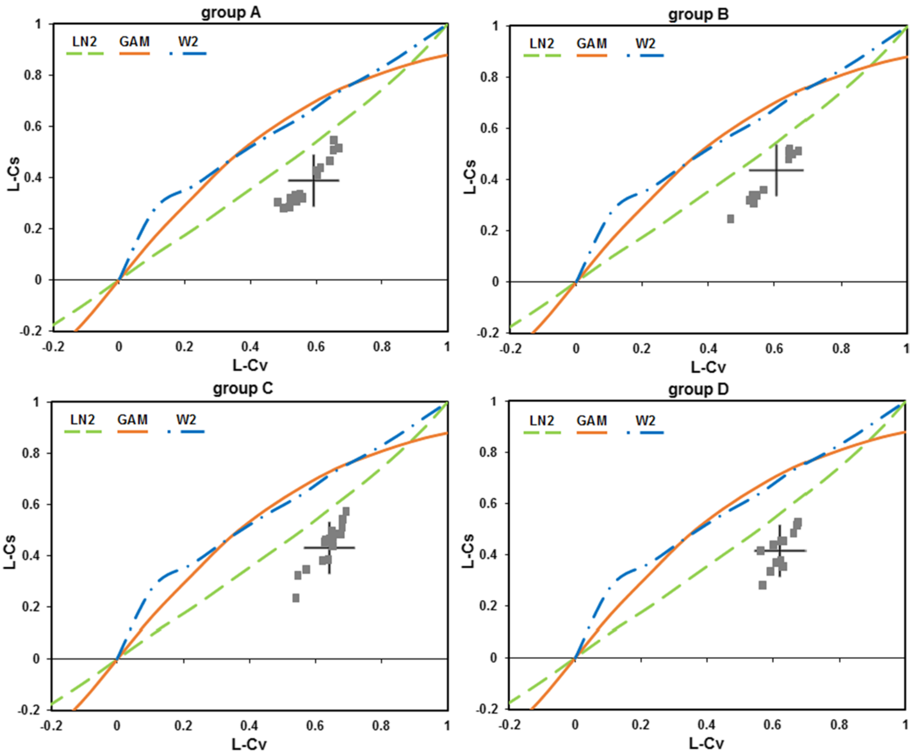

Fig. 7 The L-moment Ratio Diagram (MRD) for the drought SD groups. LN2, GAM, and W2 correspond to 2-parameter log-normal, gamma, and Weibull distributions, respectively

range between 27 and 41 are more homogeneously distributed over the country. Nonetheless, for this return period, the extraordinary drought SDs with values between 48 and 56 are observed in a small area of western Iran and in a relatively wider area in the east of the country.

In order to see the areal extent of SD in different return periods, the area of each SD in Fig. 8 is given using a bar chart in Fig. 9. The values in this figure show the percentage of each SD class of drought for each return period.

5 Conclusion

In the last decades, frequent droughts adversely impacted water resources in Iran. In this study, for the first time, the risk of drought severity–duration is estimated for the entire country using the SD drought index. Applying a hierarchical agglomerative clustering on the drought SD time series, four regions characterized with different drought SD magnitudes and frequencies were identified for Iran that partly agree with the precipitation climates of Iran identified by Dinpashoh et al. (2004) using multivariate analysis applied to 12 selected precipitation-based variables at 77 Iranian synoptic stations. The regions identified herein also partly agree with the modes of precipitation variability identified by Raziei (2018) applying S-mode PCA to the monthly precipitation time series of 155

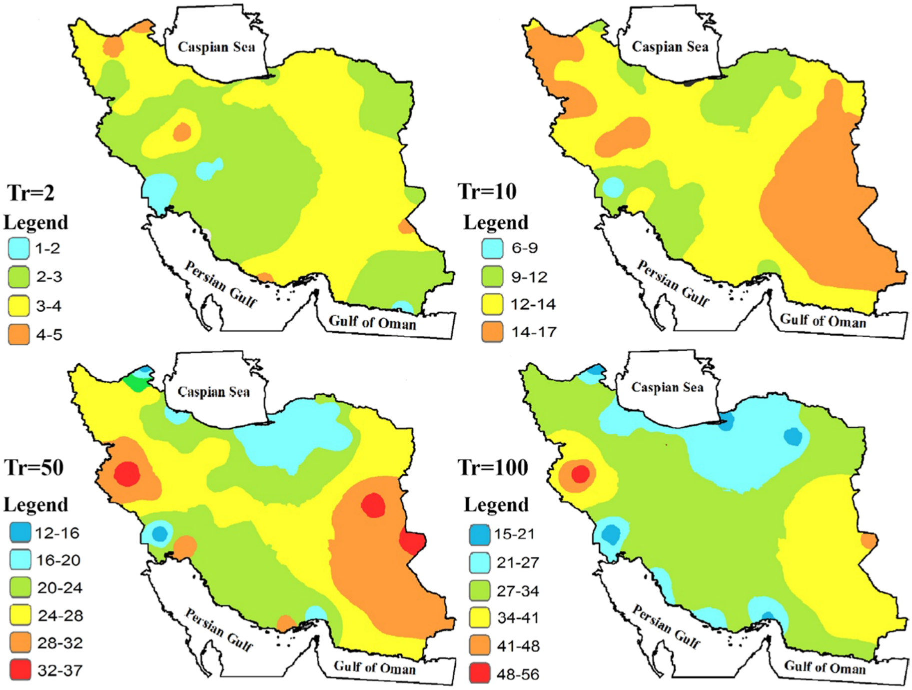

Fig. 8 Spatial pattern of 2, 10, 50 and 100-year return period SD across Iran

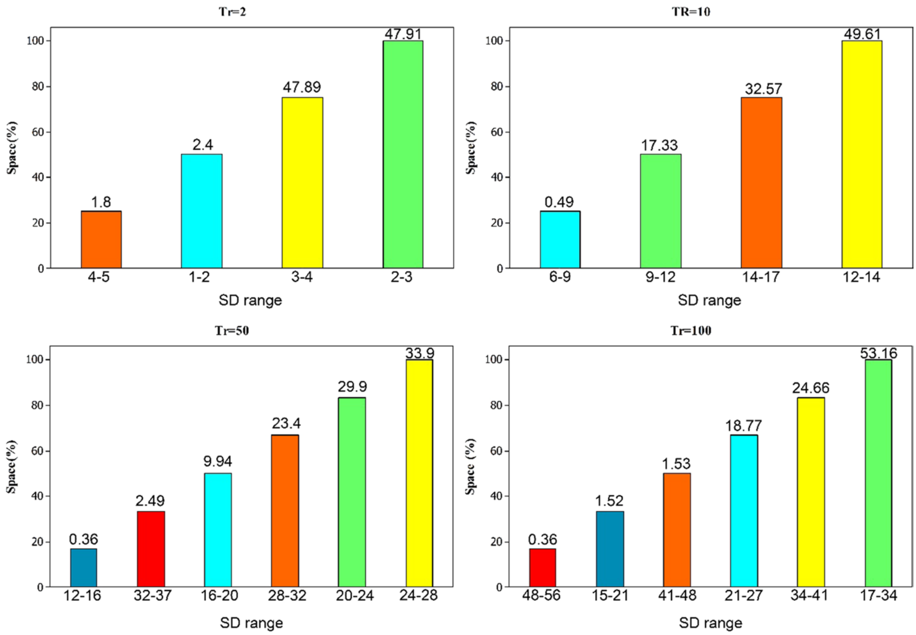

Fig. 9 Percentage of Iran's area faced with different SDs at different return periods

synoptic stations distributed over Iran. The spatial patterns of extreme and average annual SDs over the country showed that the northwestern and southeastern Iran has exposed to higher drought SDs during 1985–2014. It is interesting to notice that these two regions are considered as rainy and dry regions of the country, respectively (Dinpashoh et al. 2004; Modarres and Sarhadi 2011). The northwestern regions receive more than 600 mm annual precipitation in average which is mostly provided through Mediterranean climate systems. The southwestern regions receive 150 mm annual rainfall, mostly from Monsoon systems. It is therefore difficult to understand the “physical” mechanism behind this similarity of drought severity–duration characteristics.

This suggests that severe droughts can occur everywhere in the country regardless of climate conditions. This statement is confirmed by the occurrence of severe drought events in the most humid climate of the country in northern Iran in recent years, where it has the highest amount of precipitation in the country and characterized with CSA (warm temperate climate with hot and dry summer), CSB (warm temperate climate with warm and dry summer), and CFA (warm temperate fully humid climate with hot summer) climate types as identified by Raziei (2017) using Köppen-Geiger climate classification.

Except for 2-year return period that presents approximately average SD across the whole country, almost all areas of Iran will hit by extremely severe drought SDs when higher return periods are considered. In other words, severe droughts with higher return period, i.e., lower frequency of occurrence, affects approximately the entire country very often. For example, the many places of the country experience severe 10-year return period drought and experience extreme 50 to 100- year return period drought.

This is, therefore, a warning message for the Iranian water resource planners and managers that the extremely severe drought events tend to cover the whole country, leading to widespread damages and losses. This implies that if frequent severe drought events are accompanied by water resources mismanagement in the twenty-first century, the water problems will pass the critical thresholds to irreversible conditions which can destroy the society and economy of Iran.

5.1 Future studies

Regional frequency analysis of drought in Iran has been studied locally or regionally (for example, Shafaei and Dinpashoh 2018), but no study has considered the whole country yet. Therefore, we need to launch studies that considered a bigger data set of drought in Iran. In addition, the hydrological drought conditions and its relationship with meteorological drought in Iran is an essential task for further studies. The risk of hydrologic drought in relation to the risk of meteorological drought (as estimated in this study) should also be considered. It is also highly recommended to estimate non-stationarity of meteorological drought in relation to atmospheric–oceanic indices in future studies.

Acknowledgements The support of this study by the Iran National Science Foundation under contract number 96001842 is highly acknowledged. The corresponding author would also like to appreciate Center of excellence on risk management and natural hazards, Isfahan University of Technology, Isfahan.

References

Abdolverdi J, Khalili D (2010) Probabilistic analysis of extreme regional meteorological droughts by L-moments in a semi-arid environment. Theor Appl Climatol 102:351–366

Bazrafshan J, Hejabi S, Rahimi J (2014) Drought monitoring using the multivariate Standardized Precipitation Index (MSPI). Water Res Man. 28:1045–1060
Bonaccorso B, Bordi I, Cancelliere A, Rossi G, Sutera A (2003) Spatial variability of drought: an analysis of SPI in Sicily. Water Res Man 17:273–296
Byun HR, Wilhite DA (1999) Objective quantification of drought severity and duration. J Clim 12:2747–2756
Dinpashoh Y, Fakheri-Fard A, Moghaddam M, Jahanbakhsh S, Mirnia M (2004) Selection of variables for the purpose of regionalization of Iran's precipitation climate using multivariate methods. J Hydrol 297:109–123
Espinosa LA, Portela MM, Filho JDP, Carvalho Studart TM, Santos JF, Rodrigues R (2019) Jointly modeling drought characteristics with smoothed regionalized SPI series for a small island. Water 11:2489. https://doi.org/10.3390/w11122489
Ganguli P, Reddy MJ (2014) Evaluation of trends and multivariate frequency analysis of droughts in three meteorological subdivisions of western India. Int J Climatol 34:911–928. https://doi.org/10.1002/joc.3742
Golin S, Mazdiyasni O, Aghakouchak A (2014) trends in meteorological and agricultural drought in Iran. Theor Appl Climatol. https://doi.org/10.1007/s00704-014-1139-6
Greenwood JA, Landwehr JM, Matals NC, Wallis JR (1979) Probability weighted moments: Definition and relation to parameters of several distributions expressible in inverse form. Water Res Res 15:1049–1054
Guenang GM, Kamga FM (2014) computation of standardize precipitation index (SPI) and its use to assess drought occurrences in Cameroon over recent decades. J Applied Meteorol and Climatol 53:2310–2324
Halwatura D, Lechner AM, Arnold S (2015) Drought severity–duration–frequency curves: a foundation for risk assessment and planning tool for ecosystem establishment in post-mining landscapes. Hydrol Earth Sys Sci. 19:1069–1091. https://doi.org/10.5194/hess-19-1069-2015
Hosking JRM, Wallis JR (1997) Regional frequency analysis: an approach based on L-moments. Cambridge University Press, Cambridge
Huang SH, Chang J, Huang Q, Chen Y (2014) Spatio-temporal Changes and Frequency Analysis of Drought in the Wei River Basin. Water Res Man, China. https://doi.org/10.1007/s11269-014-0657-4
Karand L (2004) Drought early warning and impact assessment in china, in: proceeding of an export group meeting
Kaufman L, Rousseuw PJ (1990) Finding groups in data: an introduction to cluster analysis. Wiley, New York, p 344
Kenekh HF (2003) Climate variation drought and desertification. W. M Annual report, Geneva
Kumar MN, Murthy CS, Sesha Sai MVR, Roy PS (2009) On the use of Standardized Precipitation Index (SPI) for drought intensity assessment. Meteorol Appl 16:381–389. https://doi.org/10.1002/met.136
Labedzki L (2007) Estimation of local drought frequency in central Poland using the standardized precipitation index spi. Irrig Drain 56:67–77. https://doi.org/10.1002/ird.285
Loukas A, Vasiliades L (2004) Probabilistic analysis of drought spatiotemporal characteristics in Thessaly region, Greece. Nat Haz Earth Sys Sci 4:719–731
Masoudian A, kaviani MR (2007) climatology of Iran. Esfahan university publishers
McKee TB, Doesken NJ, Kleist J (1993) the relationship of drought frequency and duration to time scales. In: Proc Eighth Conference Appl Climatol, American Meteorological Society pp. 179–184
Mishra AK, Singh VP (2010) a review of drought concepts. J Hyd 391:202–216
Modarres R (2006) Regional precipitation climates of Iran. J Hydrol (NZ) 45:13–27
Modarres R (2010) Regional dry spells frequency analysis by L-moment and multivariate analysis. Water Resour Man. 24:2365–2380. https://doi.org/10.1007/s11269-009-9556-5
Modarres R, Sarhadi A (2011) Statistically-based regionalization of precipitation climates of Iran. Global Planet Change 75:67–75
Modarres R, Sarhadi A, Burn D (2016) changes of extreme drought and flood events in Iran. Global Planet Change 144:67–81
Moradi HR, Rajabi M, Faragzadeh M (2010) Investigation of meteorological drought characteristics in Fars province, Iran. Catena 84:35–46
PalmerWC (1965) Meteorological drought. Tech. Report no. 45, U.S. Department of Commerce Weather Bureau Research, Washington, DC
Raziei T (2017) Köppen-Geiger climate classification of Iran and investigation of its changes during 20th century. Earth Space Phys 43(2):419–439 **(in Persian)**
Raziei T (2018) A precipitation regionalization and regime for Iran based on multivariate analysis. Theor Appl Climatol 131:1429–1448

Raziei T, Saghafian B, Paulo AA, Pereira LS, Bodri I (2009) Spatial Patterns and Temporal Variability of Drought in Western Iran. Water Res Man 23:439–455. https://doi.org/10.1007/s11269-008-9282-4

Raziei T, Bordi I, Pereira LS, Sutera A (2010) Space-time variability of hydrological drought and wetness in Iran using NCEP/NCAR and GPCC datasets. Hydrol Earth Syst Sci 14:1919–1930

Raziei T, Bordi I, Pereira LS (2011) An application of GPCC and NCEP/NCAR datasets for drought variability analysis in Iran. Water Resour Manag 25:1075–1086

Santos JF, Portela MM, Pulido-Calvo I (2011) Regional Frequency Analysis of Droughts in Portugal. Water Res Man. 25:3537–3558. https://doi.org/10.1007/s11269-011-9869-z

Shafaei S, Dinpashoh Y (2018) Analysis of Drought Characteristics of Tabriz (1951–2015). Water Soil Science 28:117–130 **(in Persian)**

Soleimani K, Ramezani N, Ahmadi MZ, Bayat F (2005) Drought and precipitation trend analysis in Mazandaran watershed. Khazar Agric Nat Resour Bull 1:13–28

Tabari H, Abghari H, Talaee H (2011) Temporal trends and spatial characteristics of drought and precipitation in arid and semiarid regions of Iran. Hydrol Process. https://doi.org/10.1002/hyp.8460

Tsakiris G, Vangelis H (2005) Establishing a drought index incorporating evapotranspiration. EurWater 9–10:1–9

Vicente-Serrano SM, Beguería S, López-Moreno JI (2010) a multiscalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index. J Clim 23:1696–1718

Xu K, Yang D, Xu X, Lei H (2015) Copula based drought frequency analysis considering the spatio-temporal variability in southwest China. J Hydrol 527:630–640

Yazdani S, Haghsheno M (2008) Drought management and recommended solutions on how to deal with droughts. Americ-Eurasian J Agric Environ Sci 2:64–68

Yurekli K, Modarres R, Ozturk F (2009) Regional daily maximum rainfall estimation for Cekerek Watershed by L-moments. Meteorol Appl 16:435–444