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Discrepancy precipitation index for monitoring meteorological drought

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ABSTRACT

Widely employed precipitation drought indices, one way or another, impose probability distribution functions to the data when performing the drought analysis. This may be a plausible approach when the data do not have strong discrepancy which can impede the distribution. The precipitation data in semi-arid and especially in arid regions do have a strong discrepancy due to the sporadic rainfall occurring in such regions. Therefore, in the analysis of the drought for such regions, imposing any probability distribution function to the data could be futile. This study hence developed a new drought index called the Discrepancy Precipitation Index (DPI) for assessing and monitoring the meteorological drought. The method does not impose any probability distribution on the precipitation data. The method is based on the discrepancy of the data with respect to the mean value. The drought classifications are proposed based on the D-score values. Its drought classification ranges are straightforward as those of the Standard Precipitation Index (SPI). The method is applied to assess the meteorological drought at several stations located at different climatic regions such as the arid climate (Mauritania), semi-arid climate (Afghanistan) and the Mediterranean climate (Turkey). The results reveal that the DPI is more representative drought assessment tool for the arid climate regions. At semi-arid climate regions, the DPI can be an alternative drought index to the widely employed (the log-SPI and/or the gamma-SPI) indices. For the Mediterranean climate regions, the DPI can be used together with the other indices. The Discrepancy Measure (DM) is introduced to assess the strength of the discrepancy of the precipitation data series. As the DM of a precipitation series increases, the DPI captures more historical droughts.

1. Introduction

Drought is a natural disaster whose consequences can be, socially and economically, devastating as it has been experienced in some parts of the world, like the ones occurred in 1980s in sub-Sahara and eastern Africa that had caused mass migration, starvation, famine and death of millions (Sheffield et al., 2006; Kasei et al., 2010). It has become more common and often due to the climate change effects, especially in the semi-arid, and arid regions of the world (Masih et al., 2014).

Researchers have tried to develop drought indices for the purpose of drought monitoring and assessment. The fist studies go back to 1960s with the introduction of the Palmer Drought Severity Index (PDSI). It is based upon a set of empirical relations derived by Palmer (1965) to express the regional moisture supply standardized in relation to local climatological norms. This method requires information of precipitation and temperature. The PDSI needs the computations of soil moisture, potential evapotranspiration, potential recharge and runoff. The details, the limitations and the assumptions involved in the PDSI method is summarized by Alley (1984). The Deciles method for drought assessment was suggested by Gibbs and Maher (1967). The precipitation records are first ranked from the highest to the lowest. Then, the distribution is split into ten parts on the basis of equal probabilities. Although it is simple method, it does not provide reliable results (Mishra and Singh, 2010; Yacoub and Tayfur, 2017). The Surface Water Supply Index (SWSI) developed by Shafer and Dezman (1982) requires rainfall, streamflow, reservoir storage, and snow data and does the analysis on monthly time scale.

The Standard Precipitation Index (SPI), developed by McKee et al. (1993), is, on the other hand, a simple and practical method requiring the computation of only two parameters. It does not consider moisture condition and therefore it can be effectively used in both summer and winter. It is not affected by the topography. It is simply a fine transformation of precipitation time series into a standardized normal distribution (z-distribution). In other words, it requires the transformation of original data distribution to the normal distribution. There is also the log-normal SPI by which the data is first log transformed and then fit to the normal distribution. The results of the log-SPI are expected to be similar to those of the normal SPI. The normal-SPI and log-SPI are simple

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Table 1
Drought classification according to D-score values.

D-score (DPI value)	Category	Remark
0.0 to −0.19	Near normal	about 36% more or less than the mean value
−0.20 to − 0.39	Moderate drought	about 37–59% less than the mean value
−0.40 to − 0.59	Severe drought	about 60–74% less than the mean value
−0.60 or less	Extreme drought	about 75% or more less than the mean value

and user-friendly methods. However, these methods may not be capable of identifying regions that may be more 'drought prone' than others (Mishra and Desai, 2005). In the gamma-SPI method, the long-term precipitation records are fit to the gamma distribution (Tsakiris and Vangelis, 2004). It is an effective method yet requiring cumbersome computations and parameter estimations. The Percent of Normal Precipitation Index (PNPI), developed by Willeke et al. (1994), does the calculations in monthly time scale. It is simple, yet it can give reliable results when applied to single region or a single season (Eslamian et al., 2017). This index assumes the normal distribution of the precipitation data. The Effective Precipitation Index (EPI), developed by Byun and Wilhite (1999), is used in daily time scale.

There are many new indices that have been developed since early 2000s using not only the precipitation but also soil moisture, snow, and evaporation effects, such as the RDI (Reconnaissance Drought Index developed by Tsakiris and Vangelis (2005)), the Non-Stationary RDI (Bazrahshan and Hejabi, 2018), the SPEI (the standardized precipitation evapontranspiration index, Erhardt et al., 2019; Wang et al., 2019), the integrated drought monitoring index (IDMI) (Kumar et al., 2021), among many. Mishra and Singh (2010) and Eslamian et al. (2017) reviewed the mostly employed drought indices, together with their advantages and limitations. The reader is encouraged to look up those papers for the details of indices.

As summarized above, there are many drought indices some of which are requiring cumbersome computations and parameter estimations, some require data on many hydrological and meteorological variables that are not easily available in many countries, and some can only be applied to daily or monthly time scales, and some impose certain distribution functions and finally some are reliable for only specified periods and regions. As also briefly touched upon above, the widely employed precipitation drought indices (the normal SPI, the log-SPI, the gamma-SPI, the PNPI, etc.) impose probability distribution functions to the data when performing the drought analysis. The high rate of the discrepancy in the data, on the other hand, can impede the imposed distribution, resulting in misleading results. The precipitation data in semi-arid and especially in arid regions have strong discrepancy due to sporadic rainfall in such regions.

Hence, this study proposes a new drought index, called the Discrepancy Precipitation Index (DPI), which does not require imposing of any probability distribution function for the precipitation data. The drought classifications are proposed using the D-score values and its application is shown for different climatic regions using the annual precipitation data series.

2. Discrepancy precipitation index (DPI)

The theory of discrepancy in mathematics goes back to Weyl (1916) who defined it as the study of inevitable irregularities of distributions. The discrepancy (irregularity) in mathematics measures how far a given distribution deviates from an ideal one (Weyl, 1916). The use of the discrepancy measure in water resources engineering is seen in the studies of White et al. (1973) and Kashefipour and Falconer (2002). White et al. (1973) applied the theoretical methods to field and laboratory sediment data. Kashefipour and Falconer (2002) developed empirical equations for the dispersion coefficient using field data based on the flow and river characteristics. In both cases, the sediment, flow and river characteristics data ranged in a very wide range showing high irregularities. For example, the longitudinal dispersion coefficient data varied sporadically in a wide range from 1.9 m^2/s to 937.4 m^2/s and so as the discharge data from 0.9 m^3/s to 892 m^3/s (Tayfur, 2009).

The proposed drought index is based on the discrepancy of precipitation data with respect to the mean value. It is mathematically expressed by Eq. (1):

$$DPI = D_i = log\left(\frac{P_i}{\overline{P}}\right) \tag{1}$$

$$\overline{P} = \frac{1}{N}\sum_{i=1}^{N} P_i \quad \mathrm{i} = 1, 2, 3, \cdots, \mathrm{N} \tag{2}$$

where D_i is called the discrepancy value (D-score) for the i^{th} precipitation, P_i is the i^{th} precipitation in data series, $\overline{P}$is the mean value of the precipitation data series—typically considered to be a 30-year mean (Willeke et al., 1994, Hayes, 2006)—defined by Eq. (2). According to Eq. (1), D = 0 when P_i is equal to $\overline{P}$and D is positive when $P_i > \overline{P}$ and D is negative when $P_i < \overline{P}$.

The drought classification is categorized according to D-score values, as presented in Table 1. According to Table 1, if any precipitation value is less than about 75% of the mean value, then there is an extreme drought. For example, if the mean value is 1000 mm and if a received rainfall is 250 mm (which is 75% less than the mean), the D-score would be D = −0.60, implying an extreme drought. Similarly, if the received

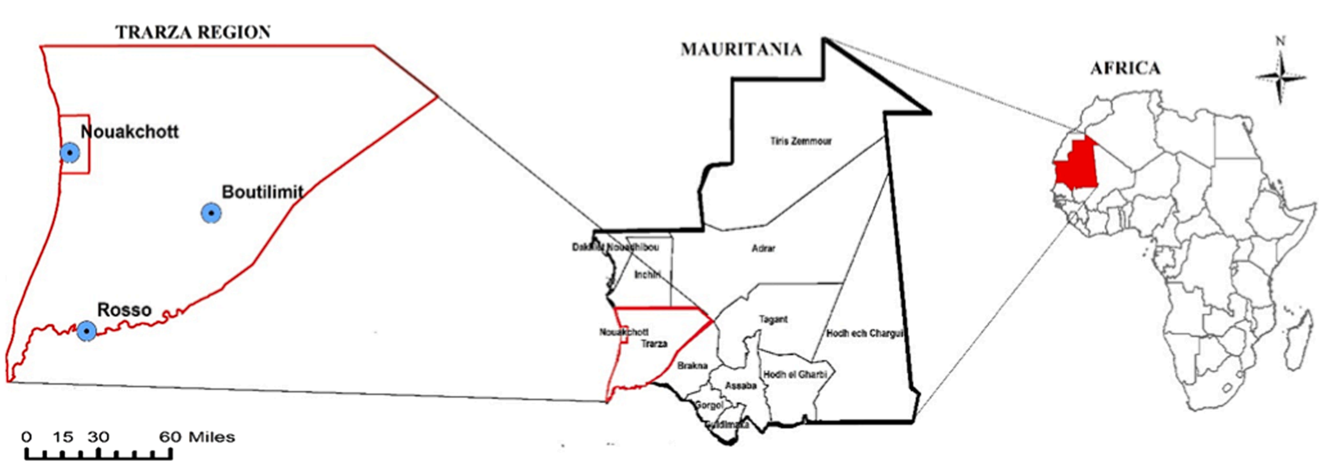

Fig. 1. Map of Mauritania, Trarza region and the rainfall stations.

Table 2
Location of the meteorological stations and the annual rainfall characteristics at Trarza region stations (Annual precipitation data from 1970 to 2013).

	Boutilimit	Nouakchott	Rosso
Latitude (North)	17.54	18.07	16.51
Longitude (West)	14.69	15.95	15.80
Altitude (m)	48.59	4.44	6.26
Mean rainfall (mm)	146.22	89.97	234.12
Rainfall St. Dev. (mm)	77.56	63.37	94.12
Sample variance (mm^2)	6016	4016	8859
Rainfall range (mm)	286.1	223.2	436.7
Min. rainfall (mm)	25.3	2.7	41.1
Max. rainfall (mm)	311.4	225.9	477.8
Kurtosis	−0.27	−0.83	−0.0075
Skewness	0.57	0.62	0.30

rainfall is 400 mm (which is 60% less than the mean value), the corresponding D-score is D = −0.40 implying the severe drought. If received rainfall is 600 mm (40% less than the mean value), D-score is D = −0.20 implying a moderate drought.

The D-score ranges for the drought classifications given in Table 1 are suggested in accordance with the PNPI method (Barua et al., 2010). The D-score limits of −0.2, −0.4, and −0.6 (corresponding to the moderate, severe, and extreme drought categories given in Table 1) are straightforward and thus appealing, as the z-score limits of z = −1, −1.5, and −2, respectively, in the SPI method (Barua et al., 2010). As presented in the next section, the successful prediction of the historical droughts by the DPI, especially in the arid climatic regions, confirms to the suitability of the D-score ranges set for the drought classifications presented in Table 1.

The DPI method does not impose any transformation or any other probability distribution function. It does not require the normal distribution of the data. It requires only the long term precipitation data

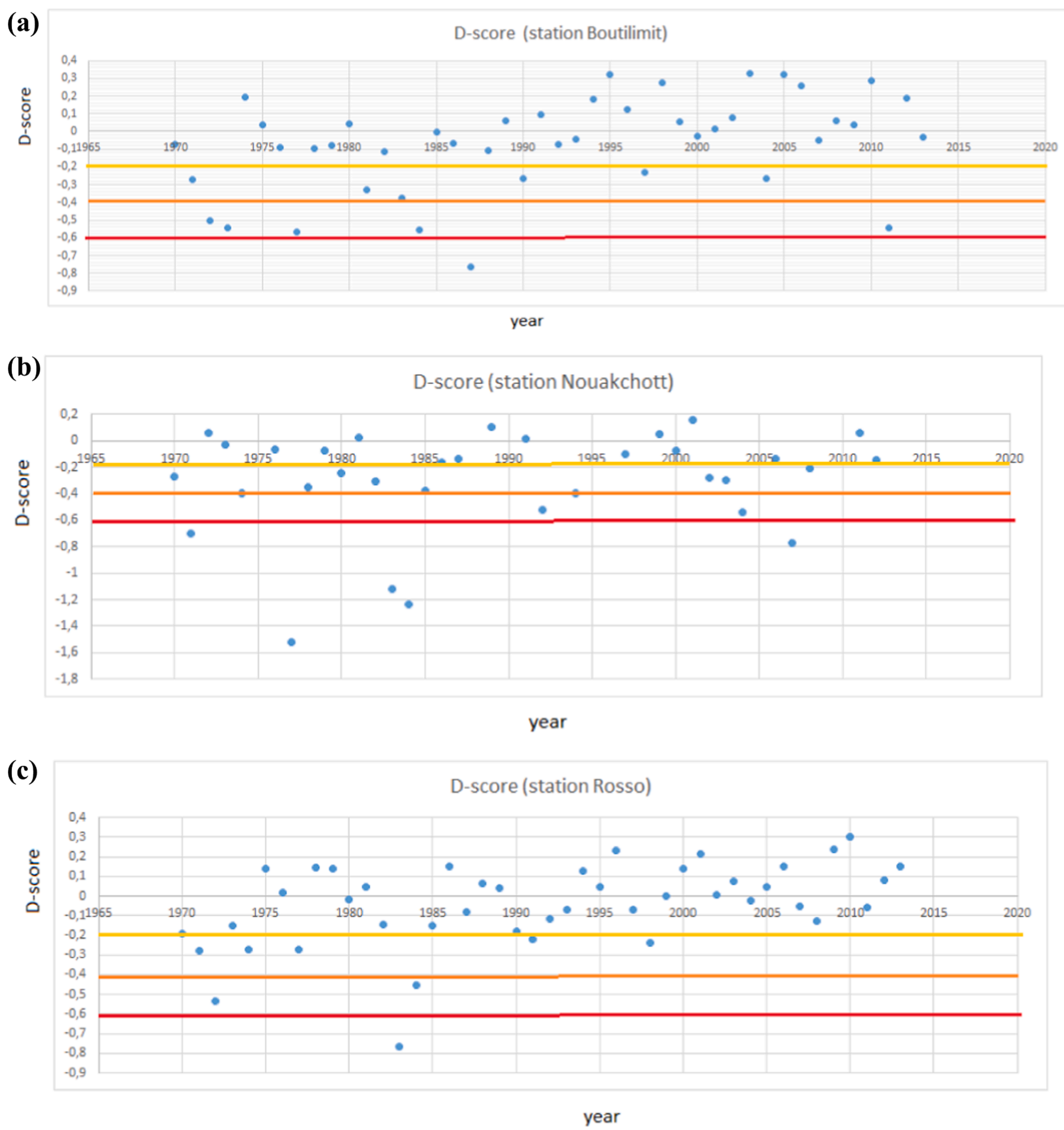

Fig. 2. D-scores for stations of (a) Bautilimit, (b) Nouakchott and (c) Rosso.

Table 3
Historical Droughts at Trarza Region as detected by the DPI and the Log-SPI.

Stations	DPI			log-SPI and gamma-SPI (Yacoub and Tayfur, 2017)		
Boutilimit	Extremely Drought	Severe Drought	Moderate Drought	Extremely Drought	Severe Drought	Moderate drought
	1987	1972	1971	1987	1972	1981
		1973	1981		1973	1983
		1977	1983		1977	
		1984	1990		1984	
		2011	1997		2011	
			2004			
Nouakchott	1971	1974	1970	1977	1971	1974
	1977	1992	1978	1983	2004	1978
	1983	2004	1980	1984	2007	1982
	1984		1982			1985
	2007		1985			1992
			1994			1994
			2002			
			2003			
			2008			
Rosso	1983	1972	1971	1983	1984	1971
		1984	1974	1972		1974
			1977			1977
			1991			
			1998			

which can be easily available in most part of the world. Its computation is easy as given by Eq. (1). The categories and the related ranges of the DPI (Table 1) are straightforward as the z-values of the SPI method. Therefore, from a practical point of view, its use and application and the communication with the public becomes quite easy and favorable.

3. DPI applications

The proposed DPI is applied to drought assessment in different climatic regions: (1) The arid climate (sub-Sahara, Mauritania), (2) The semiarid climate (Afghanistan), and (3) The Mediterranean climate (Turkey).

3.1. Arid climate

The introduced DPI is applied to assess the drought conditions at three meteorological stations located in Trarza region of Mauritania. Yacoub and Tayfur (2017) had already assessed the droughts at these stations using several drought indices of the normal-SPI, the log-SPI, the gamma-SPI, the Chinese z-index, the PNDI, and the Deciles. They concluded that the log-SPI and the gamma-SPI are more representative of the droughts in this region. As a matter of fact, for the three stations, the gamma-SPI and the log-SPI behaved similarly and captured the same drought years at Trarza region (Yacoub and Tayfur, 2017). Therefore, the application of the DPI to the same region is also compared against these indices.

Mauritania is located in western Africa having the arid Sahara desert in the north and the semiarid Sahel in the south (Fig. 1). The rainy season is from July to September, varying from less than 20 mm in the north to more than 500 mm in the south-east. The average annual rainfall is about 100 mm and the average minimum and maximum temperatures vary from 16 °C in January to 36 °C in June. Trarza is a region located in southwest Mauritania bordering the Senegal River (Fig. 1). The DPI is applied to assess the droughts at stations of Boutilimit, Nouakchott, and Rosso, as shown in Fig. 1. The latitudes, longitudes and altitudes and the annual rainfall characteristics for each station are given in Table 2. The data obtained from the National Office of Meteorology of Mauritania contains the annual precipitation recorded from 1970 to 2013.

Fig. 2 presents the DPI scores for the three stations. As seen, extreme, severe and moderate drought conditions were captured for all the stations. At Boutilimit station 1 extreme, 5 severe and 6 moderate years were captured. These had occurred mostly in early 1970s, early 1980s (Fig. 2a). 4 extreme, 3 severe and 10 moderate drought years were predicted by the DPI at Nouakchott station (Fig. 2b). Compared to other two stations, the DPI captured fewer extreme, severe and moderate drought years at Rosso station (Fig. 2c).

Table 3 shows the comparison between the drought years predicted by the DPI and the log-SPI carried out by Yacoub and Tayfur (2017). Note that the log-SPI and the gamma-SPI produced the same results and captured the same drought years at Trarza region according to Yacoub and Tayfur (2017). As seen, the DPI captured more less the same years of droughts occurred at the three stations, as the log-SPI (and the gamma-SPI). Although both indices captured the same years of the extreme and severe droughts, the DPI predicted ‘moderate drought’ conditions also occurred in 1971, 1990, 1997 and 2004 at Batulimit station. Note that 1971 and 2004 were captured as drought years in other two stations by the log-SPI. Both indices captured almost the same years for the severe and extreme droughts at Nouakchott station. The DPI captured extreme droughts also in 1971 and 2007, as they were predicted by the log-SPI as severe droughts. Similarly, 1974 and 1992 were predicted as the moderate drought by the log-SPI while they were captured as the severe drought by the DPI. At Rosso station, the log-SPI predicted extreme drought in 1972, which was captured as severe drought by the DPI. Similarly, 1991 and 1998 were also predicted as moderate drought years by the DPI.

According to Table 3, the DPI predicted, in total, 12, 16, and 8 drought years at Boutilimit, Nouakchott, and Rosso stations, respectively, while the log-SPI predicted 8, 12, and 6 drought years. These results indicate that the DPI tend to predict more ‘moderate drought’ conditions, as compared to the log-SPI. The annual mean rainfalls are 90, 146, and 234 mm at Boutilimit, Nouakchott, and Rosso stations, respectively. According to the results presented in Fig. 2 and Table 3, for stations receiving high rainfalls, both indices predict the same drought conditions. For very low rainfall occurred stations, the DPI tend to predict especially more moderate drought conditions that seems more plausible since some of these years were captured as drought years at the neighboring stations by the log-SPI. These results imply that for arid climate conditions as presented for Trarza region, the DPI can be more representative than the log-SPI (and the gamma-SPI) which was found by Yacoub and Tayfur (2017) to be the most suitable drought index for the region.

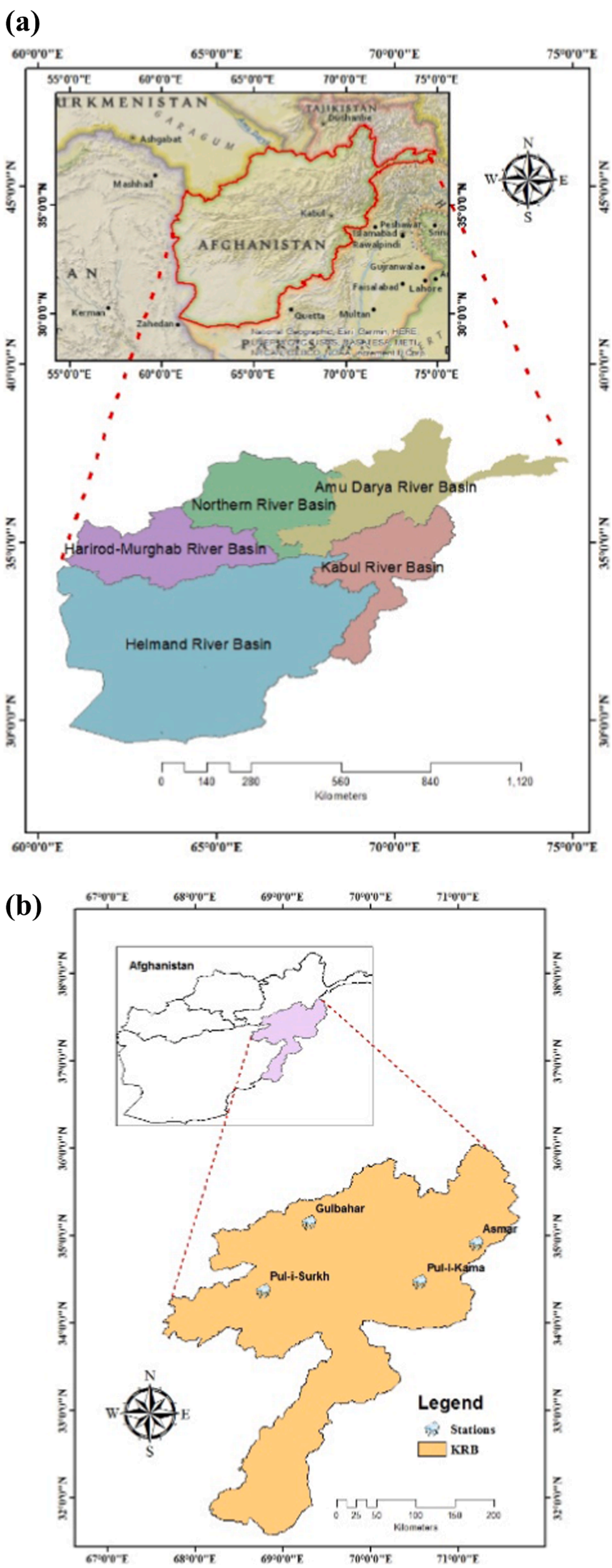

Fig. 3. Maps of (a) Afghanistan and the river basins, and (b) Kabul River Basin and the gauging stations.

Table 4
Location of the meteorological stations and the annual rainfall characteristics at Kabul River Basin stations (Annual precipitation data from 1979 to 2016).

	Asmar	Gulbahar	Pul-i-Surkh	Pul-i-Kama
Latitude (North)	34.92	35.15	34.37	34.47
Longitude (East)	71.20	69.29	68.77	70.56
Altitude (m)	832	1625	2216	558
Mean rainfall (mm)	525.9	381.3	321.3	212.8
Rainfall St. Dev.	167.9	87.2	109.3	78.0
Sample variance	28,182	7602	11,942	6087
Rainfall range (mm)	622.0	443.6	532.6	304.9
Min. rainfall (mm)	176.9	151.8	70.5	58.8
Max. rainfall (mm)	908.1	595.4	603.1	363.7
Kurtosis	2.53	3.69	3.28	2.14
Skewness	−0.031	0.033	0.307	0.109

3.2. *Semi-arid climate*

Afghanistan, located in central Asia, is one of the non-coastal countries with a total area of around 652 000 km^2 (Fig. 3a). Based on the geographical characteristics, the country is divided into five major river basins as Hilmand, Harirod-Murghab, Northern, Panj Amo, and Kabul (see Fig. 3a).

Kabul River Basin (KRB) is located between latitudes 33 °N and 37° N, and longitudes 67 °E and 74°E. Its key river branches are Laghman Alingar, Panjsher, Logar, and Kunar rivers (Fig. 3b). Of 34, 13 provinces of the country are located in the KRB and it is the fastest-growing population area inhabiting about 35% of Afghanistan's population. The basin is located under semi-arid and continental type climate conditions with cold winters and hot summers. The average yearly rainfall in the basin is estimated to be 430 mm and the average yearly temperature is recorded as 9 °C. The maximum temperature of the basin can reach up to 48 °C in the downstream part of the basin in Nangarhar region. The basin provides water to around 13 million people for their critical daily needs, as well as for agricultural and power generation purposes.

The precipitation data recorded from 1979 to 2016 at the meteorological stations of Asmar, Gulbahar, Pul-i-Surkh, and Pul-i-Kama are employed for the DPI application. The latitudes, longitudes and elevations of the stations are given in Table 4. The data obtained from the Ministry of Energy and Water of Afghanistan contains the annual precipitation recorded from 1979 to 2016. The precipitation data is not available before 1979 due to lack of meteorological stations within the basin. Table 4 summarizes the latitudes, the longitudes and the altitudes and the annual precipitation characteristics at the respected stations. The average annual precipitation of these four stations is about 360 mm.

Fig. 4 shows the DPI drought applications, respectively, to the precipitation data measured at the four meteorological stations. As seen, the DPI did not capture any extreme drought at any station but at Pul-i-Surkh station. It captured few severe and moderate drought conditions at Asmar and Gulbahar stations. However, it predicted more moderate droughts at Pul-i-Surkh and Pul-i-Kama stations. Fig. 4 indicates that droughts mostly occurred after year 1999. Also, another observation is that droughts tend to happen in consecutive years. In addition, more droughts occurred at Pul-i-Kama station and this may be due to the fact that this station generally receives less precipitation (see Table 4).

Table 5 presents the comparison of the drought years predicted by the DPI and the log-SPI and the gamma-SPI carried out by Alami et al. (2017). Note that, as it was the case in Yacoub and Tayfur (2017), the log-SPI and the gamma-SPI produced the same results for the stations at Kabul River Basin (Alami et al., 2017). As seen in Table 5, the extreme drought years (2000 and 2001) were mostly predicted as severe drought years by the DPI except for the station Pul-i-Surkh where 2001 was captured as the extreme drought by the gamma-SPI and the DPI. Similarly, the severe drought years (2000, 2002 and 2004) captured by the gamma-SPI were predicted as the moderate drought years by the DPI. Note that some moderate drought years (2005, 2010 for Asmar; 2004,

Fig. 4. D-scores for stations of (a) Asmar, (b) Gulbahar, (c) Pul-i-Surkh and (d) Pul-i-Kama.

2013 for Gulbahar) were not captured by the DPI. On the other hand, some moderate drought years such as the 2005 captured by the DPI for Pul-i-Kama station were not predicted by the gamma-SPI. At Pul-i-Surkh station, the gamma-SPI and the DPI captured the same drought years.

3.3. *Mediterranean climate*

The Mediterranean climate is characterized by dry summers and wet winters. The rainy season is from October to May and there is generally no rain from May to October. The temperatures can reach to 40 °C in July and August and below 10 °C in winter months. This region had sometimes faced drought conditions such as the ones in 1989, 2003, and 2005 (Feyen and Dankers, 2009).

The DPI is applied to assess the drought conditions at three meteorological stations (Cesme, Kusadasi, ve Nazilli) in the Aegean region of Turkey (see Fig. 5). The data obtained from the State Meteorological Office (DMI) of Turkey contains the annual precipitation recorded from 1960 to 2020. The mean annual rainfall in the Aegean Region is about 625 mm (Bahadir, 2011). The related statistics for the measured annual precipitation data and the latitudes, the longitudes and the elevations of the respected stations are summarized in Table 6. The mean annual precipitation of the three stations is about 585 mm.

Figs. 6 and 7 show the z-scores and D-scores, respectively, for the three stations. As seen, in Fig. 6a, at Cesme Station; according to the log-SPI method, extreme, severe, and moderate drought conditions had occurred in 1960s and late 1980s and early 1990s. On the other hand, the DPI only shows severe drought conditions in 1960s and late 1980s and moderate droughts in early 1990s (Fig. 7a). At Kusadasi Station, the log-SPI did not capture any drought condition (Fig. 6b) while the DPI captured moderate droughts (Fig. 7b). With regard to Nazilli Station, the log-SPI captured an extreme, and few severe and moderate droughts (Fig. 6c) while the DPI only captured extreme and few moderate drought conditions (Fig. 7c).

Table 7 summarizes the drought years captured by both indices. As seen, the log-SPI captured 10 drought years (2 extreme, 2 severe and 6 moderate) while the DPI predicted 6 drought years. The extreme ones by the log-SPI were mostly in severe category according to the DPI. The severe ones by the log-SPI were mostly in moderate drought years by the DPI. It is interesting to note that the log-SPI did not capture any drought years at Kusadasi station while the DPI predicted 4 moderate drought years (1963, 1985, 1989 and 1992). Considering that these years were among the extreme and severe drought years at the neighboring stations (Nazilli and Cesme), the predictions made by the DPI can be considered more plausible. On the other hand, the log-SPI predicted more drought years at Nazilli station as well, compared to the DPI.

4. Discussion

Yacoub and Tayfur (2007) applied the normal-SPI, the log-SPI, the gamma-SPI, the Chinese z-index (CZI), the PN, and the Deciles for the drought analysis at the three stations in Trarza region. According to their results, the PN predicted too many drought years, the normal-SPI and

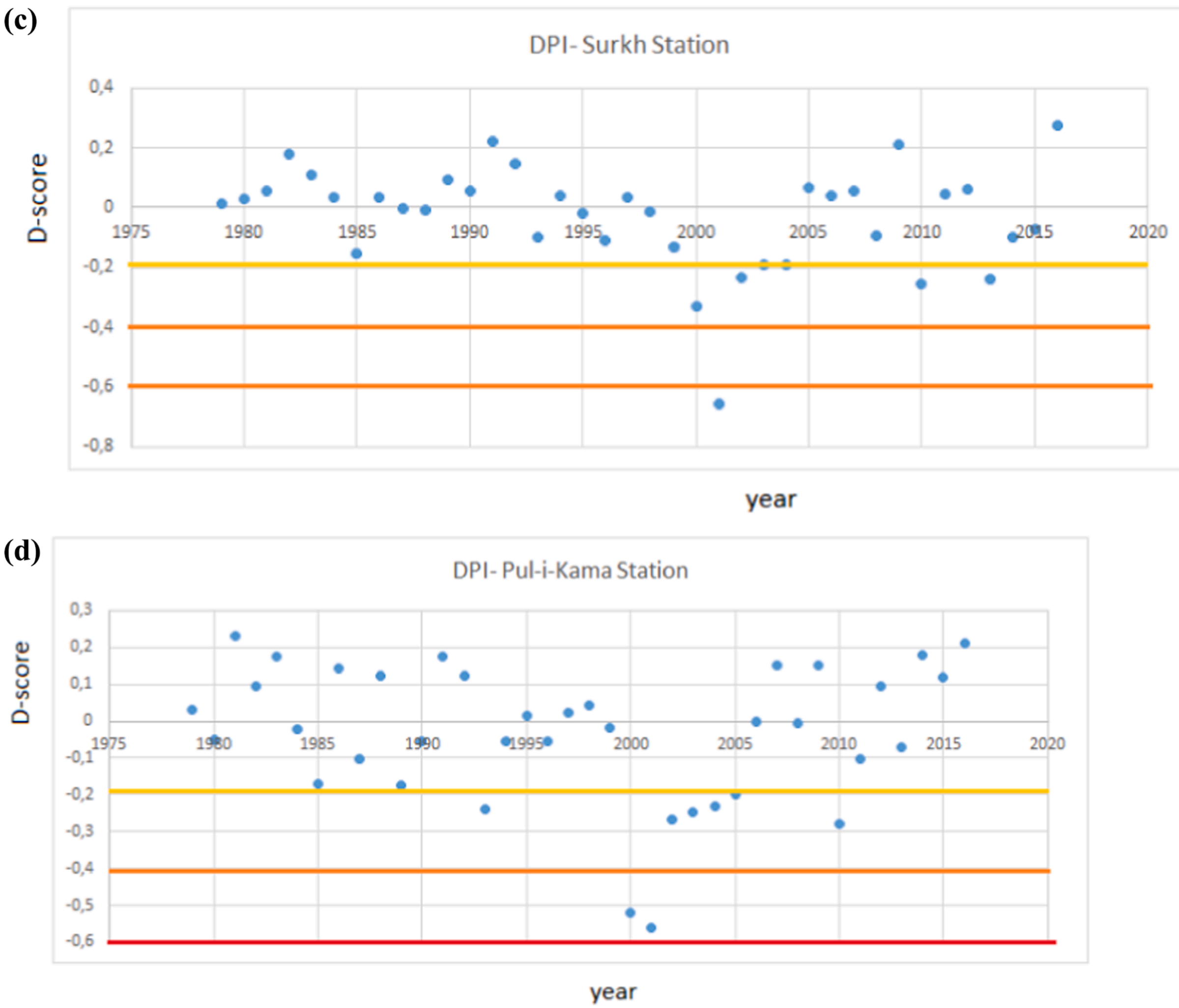

Fig. 4. (*continued*).

Table 5
Historical Droughts at Kabul River Basin as detected by the DPI and the Log-SPI.

Stations	DPI			log-SPI and gamma-SPI (Alami et al., 2017)		
	Extremely Drought	Severe Drought	Moderate Drought	Extremely Drought	Severe Drought	Moderate drought
Asmar	–	2000 2001	2002 2004	2000 2001	2002 2004	2005 2010
Gulbahar	–	2001	2000 2002	2001	2000 2002	2004 2013
Pul-i-Surkh	2001	–	2000 2002 2010 2013	2001	2000	2002 2010 2013
Pul-i-Kama	–	2000 2001	1993 2002 2003 2004 2005 2010	2000 2001	–	1993 2002 2003 2004 2010

CZI did not predict any extreme droughts and the Deciles only predicted too many extreme droughts. The log-SPI and the gamma-SPI, on the other hand, captured the same drought characteristics and years at the three stations, more compatible with the historical observations. Therefore, they recommended these indices for the Trarza region.

The DPI applications for the same region (Trarza region) shows that although the DPI almost captured the same drought years with the same drought characteristics at the three stations as the gamma-SPI (and the

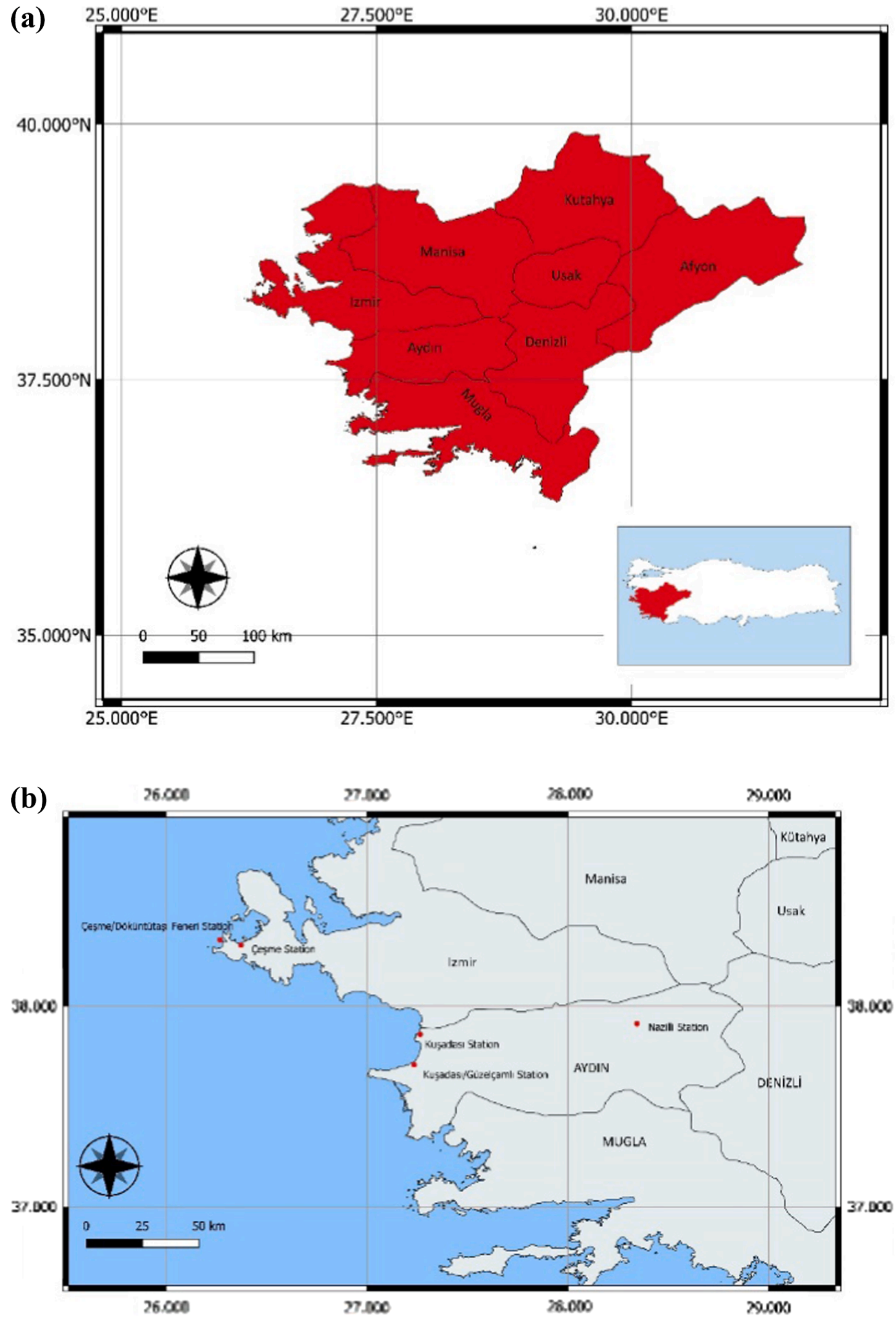

Fig. 5. Maps of (a) Aegean region and (b) the meteorological gauging stations.

log-SPI), the DPI captured more drought years, confirming to the reality since the captured years were predicted as the drought years by the gamma-SPI at the neighboring stations. Furthermore, the years 1970, 1980, 1990 and 1991 at Trarza region were not predicted as the drought years by the gamma-SPI, as opposed to the DPI (see Table 3). According to the studies of Nouaceur (1995) and Trape (2009), these years were in fact experienced as the drought years. In a similar fashion, the years 1997, 1998 and 2002 were not captured as the drought years by the gamma-SPI for Trarza region (see Table 3), as opposed to the DPI being compatible with the experienced drought years (Masih et al., 2014). According to the UN-Water Activity Information System (UNW-AIS)/ Report (https://www.ais.unwater.org/ais/pluginfile.php/605/mod_page/content/23/Mauritania.pdf), 2002–2003 is classified as drought period. According to Ba and Mughal (2020), the year 2008 was a

Table 6
Location of the meteorological stations and the annual rainfall characteristics at Aegean region (Annual precipitation data from 1960 to 2020).

	Cesme (Izmir)	Kusadası (Aydın)	Nazilli
Latitude (North)	38.18	37.51	37.54
Longitude (East)	26.22	27.15	28.20
Altitude (m)	8	22	84
Mean rainfall (mm)	567.0	619.0	567.7
Rainfall St. Dev.	151.2	149.8	136.2
Rainfall range (mm)	695.7	559.9	712.4
Min. rainfall (mm)	174.0	355.0	143.8
Max. rainfall (mm)	869.7	914.9	856.2
Kurtosis	2.69	2.09	3.35
Skewness	−0.46	0.19	−0.11

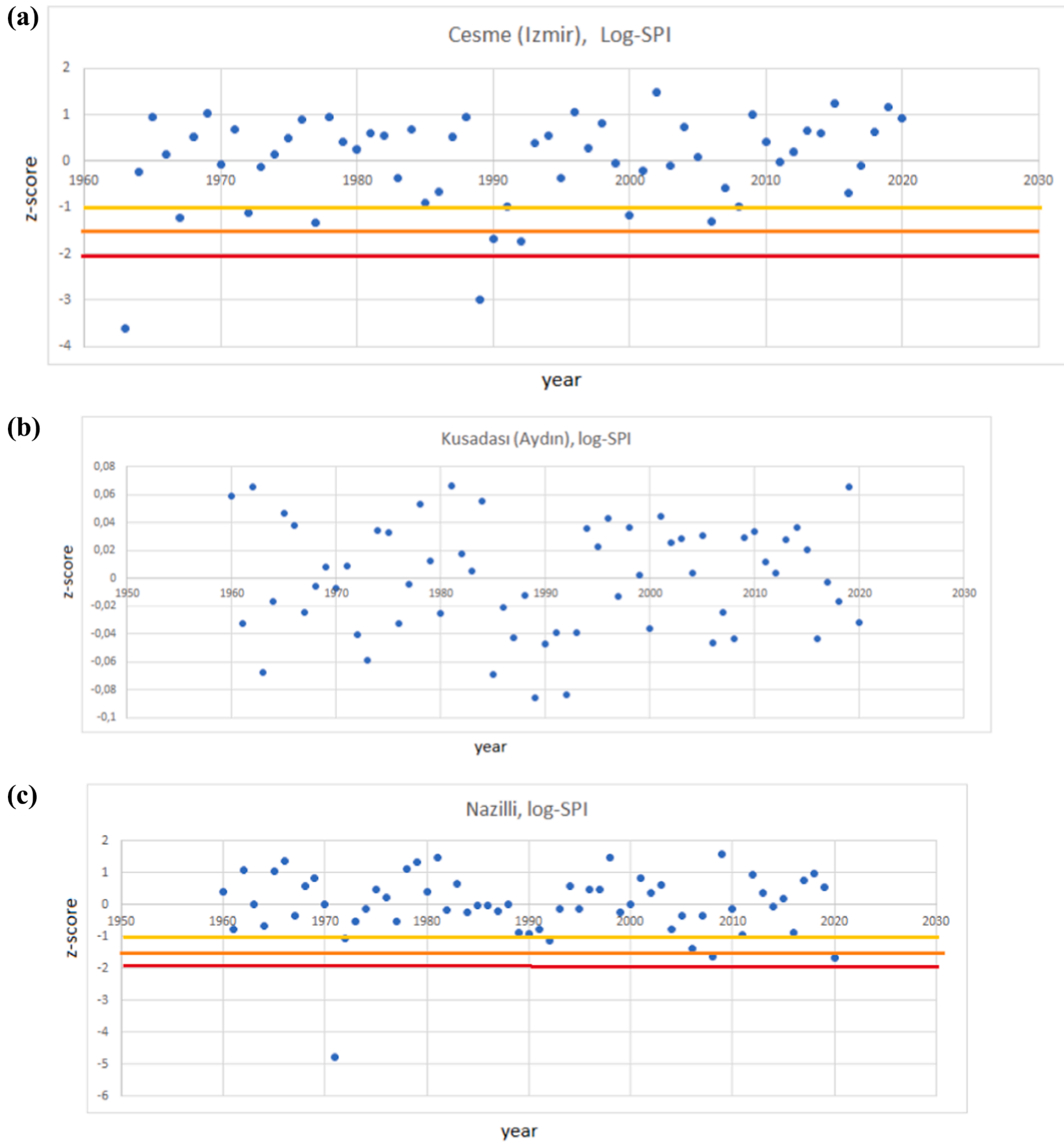

Fig. 6. z-Scores for stations of (a) Cesme, (b) Kusadasi and (c) Nazilli.

localized drought with about 45% of rural households reporting livestock losses. Note that 2002, 2003 and 2008 were not also captured by the gamma-SPI as drought years (see Table 3), as opposed to the DPI. In short, the literature shows that some historical drought years experienced at the arid region of Trarza were not captured by the gamma-SPI (or the log-SPI) but they were predicted by the DPI conforming to its suitability to the drought assessment at arid climatic regions.'

The DPI predicted, in total, 12, 16, and 8 drought years at Boutilimit, Nouakchott, and Rosso stations, respectively. To further investigate the relation between the number of drought years and the precipitation received, the Discrepancy Measure is introduced as follows:

$$DM = \frac{1}{N}\sum_{i=1}^{N}\left|log\left(\frac{P_i}{\overline{P}}\right)\right| \quad (3)$$

where DM is the Discrepancy Measure of the precipitation data series and N is the number of observations.

Table 8 shows the DM values for the three stations in Trarza region. As seen, the DP is 0.3253 at Nouakchott station, followed by DP = 0.2052 at Bautilimit and DM = 0.1595 at Rosso. The discrepancy is much higher at Nouakchott station and therefore, the DPI captured more drought years at this station. The captured number of drought years increases with the increase in the discrepancy. As seen, in Table 8, P_{max}/P_{min} and P_{mean}/P_{min} values are quite high at Nouakchott station, confirming the high discrepancy rate. Hence, in this arid region, the DPI captured more historical drought records than the gamma-SPI.

Alami et al. (2017) applied the same indices (the normal-SPI, the log-SPI, the gamma-SPI, the CZI, the PN, and the Deciles) to assess the drought at four meteorological stations in Kabul River Basin (KRB). According to their results, the PN did not capture any extreme droughts, the Deciles captured too many extreme and severe droughts but moderate ones. The normal-SPI and the CZI captured the same drought years

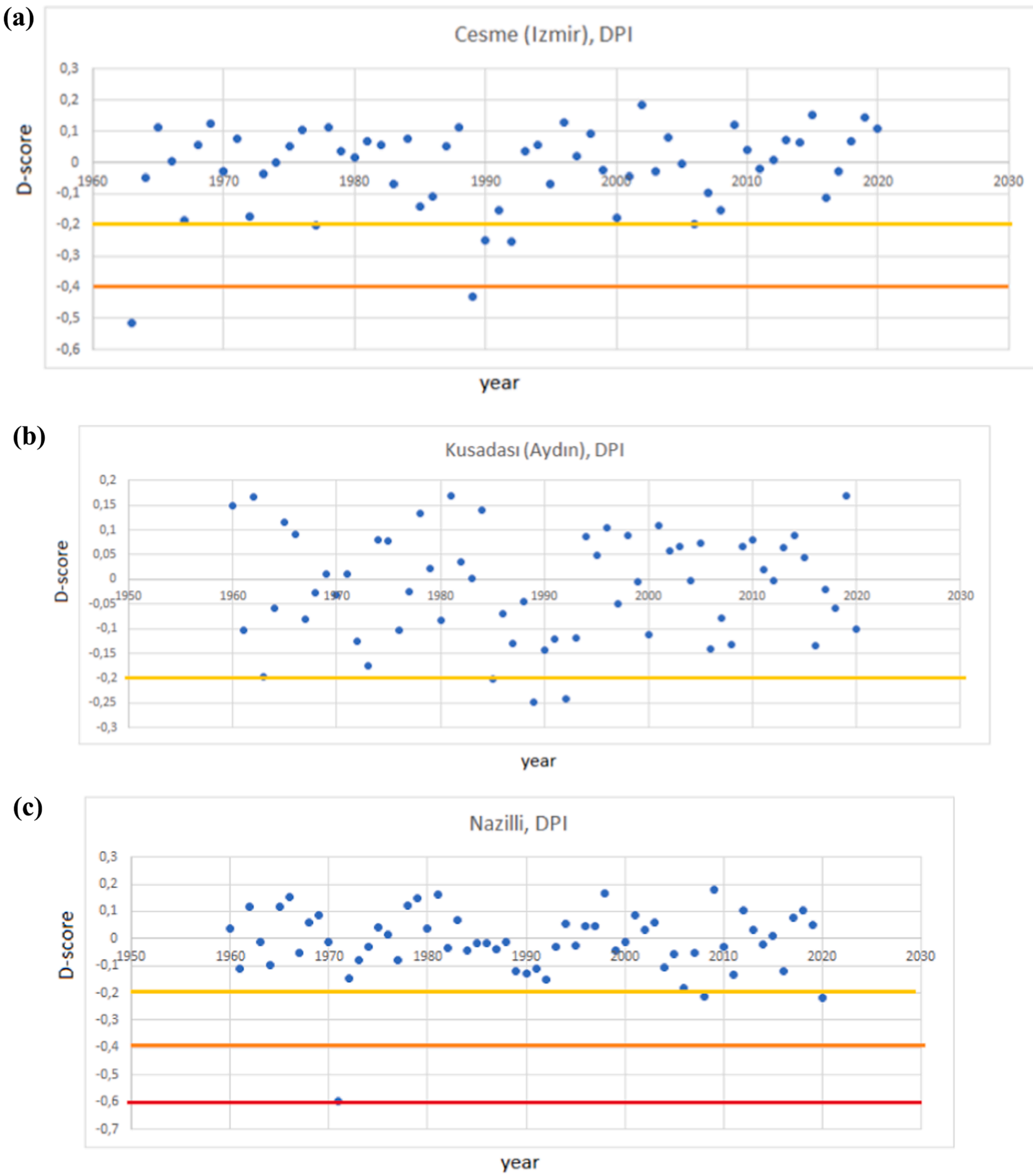

Fig. 7. D-scores for stations of (a) Cesme, (b) Kusadasi and (c) Nazilli.

with the same characteristics. The log-SPI and the gamma-SPI behaved the same. Based on the historical observations, they suggest the log-SPI and the gamma-SPI as drought monitoring tools for this basin.

According to Table 5, the log-SPI captured 6, 5, 5, and 7 drought years while the DPI 4, 3, 5, and 8 years at Asmar, Gulbahar, Pul-i-Surkh and Pul-i-Kama stations, respectively. The DPI while predicting fewer drought years in Asmar and Gulbahar, it made more capturing at Pul-i-Kama station. The DM values for these stations are given in Table 8 where one can see that the DM value is the highest for Pul-i-Kama station, among others. The P_{max}/P_{min} and P_{mean}/P_{min} values also confirm the high rate of the discrepancy for this station. The DPI and the log-SPI made the same number of capturing for Pul-i-Surkh station where the DM is 0.1237. As the DM decreases, the capturing of drought years by the DPI becomes fewer. In this region, it can be said that the log-SPI (or the gamma-SPI) and the DPI performs comparatively for the stations having low DM values.

The discrepancy measures for the stations at Aegean region are also presented in Table 8. As seen, the DP values are less than 0.1032 and the P_{max}/P_{min} is less than 6 and P_{mean}/P_{min} is less than 4. The values in Table 4 for these stations imply that the discrepancy is low, especially in Kusadasi station. As presented in Table 7, the log-SPI captured 10 drought years while the DPI predicted 6 drought years. Furthermore, the extreme and severe droughts captured by the log-SPI are predicted as the severe and moderate years. It is interesting to note that the log-SPI did not capture any drought years at Kusadasi station while the DPI predicted 4 moderate drought years that were among the extreme and severe drought years at the neighboring stations (Nazilli and Cesme), and thus the predictions made by the DPI for this station can be considered

Table 7
Summary of the drought years captured by the log-SPI and DPI at the 3 stations in Aegean Region.

	Extreme drought	Severe drought	Moderate drought
CESME STATION			
Log-SPI	1963	1990	1967
	1989	1992	1972
			1977
			2000
			2006
			2008
DPI	–	1963	1977
		1989	1990
			1992
			2006
KUSADASI STATION			
Log-SPI	–	–	–
DPI	–	–	1963
			1985
			1989
			1992
NAZILLI STATION			
Log-SPI	1971	2008	1972
		2020	1992
			2006
DPI	1971	–	2008
			2020

Table 8
Discrepancy measures.

Stations	DM	P_{max}/P_{min}	P_{mean}/P_{min}	P_{max}/P_{mean}
Bautlimit	0.2052	12.3	5.8	2.1
Nouakchott	0.3253	83.7	33.3	2.5
Rosso	0.1595	11.6	5.7	2.4
Asmar	0.1215	5.1	3.0	1.7
Gulbahar	0.0785	3.9	2.5	1.6
Pul-i-Surkh	0.1237	8.6	4.6	1.9
Pul-i-Kama	0.1447	6.2	3.6	1.7
Cesme	0.1031	5.00	3.26	1.53
Kusadasi	0.0909	2.58	1.74	1.48
Nazilli	0.0875	5.95	3.95	1.51

more plausible.

5. Concluding remarks

This study developed a new drought index, called the Discrepancy Drought Index (DPI). The index does not impose any distribution to the precipitation time series data. The study also proposed a Discrepancy Measures (DMs) to relate how the performance of the DPI is related to the degree of the DMs. The DPI was applied to predict drought years at stations located in the arid, the semi-arid and the Mediterranean region and its performance was compared against the log-SPI (and the gamma-SPI). The following conclusions are drawn:

1. The computation and the application of the DPI is easy and practical. It does not require cumbersome computations, parameter estimations and probability density function fittings. Its effectiveness is shown when applied to arid climatic region precipitation data having high rate of discrepancy.
2. The drought categories and the related D-scores (see Table 1) are compact and appealing for the use and favorable to communicate the drought to public. The successful prediction of the historical droughts by the DPI, especially in the arid climatic region, confirms to the suitability of the D-score ranges.
3. The DPI is more representative drought assessment and monitoring tool for especially arid climate regions. It captured the drought years experienced in arid region of Trarza.
4. The DPI can produce comparable results as the log-SPI (and the gamma-SPI) for assessing the drought at semi-arid regions. When the DM value increases in such a region then the DPI is more preferable.
5. At the Mediterranean region, the DPI and be used together with the other indices.
6. The DPI produces results as close as those of the log-SPI (and the gamma-SPI) when the discrepancy measure is less than 0.12. When DM is greater than 0.12, the DPI captures more droughts.
7. According to Table 8, $DM \geq 0.15$ indicates the series observed in arid region, $0.10 \leq DM \leq 0.15$ indicates the semi-arid region precipitation series while $DM \leq 0.1$ indicates the Mediterranean region.

The application of the DPI is presented using the annual precipitation data series. The main objective of this paper is the development of the DPI and its applications to different climatic regions to show its capabilities and the limitations. The applicability of the DPI can be surely shown for shorter duration (1, 3, 6, and 9 months) drought analysis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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