

Comparison of various drought indices to monitor drought status in Pakistan

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Abstract Various drought indices are normally used to monitor drought and its risk management. Precipitation, temperature and other hydro meteorological parameters are the essential parts to the identification of drought. For this purpose, several drought indices have been developed and are being used around the world. This study identifies the applicability and comparison of drought indices in Pakistan by evaluating the performance of 15 drought indices. The indices include standardized precipitation index (SPI), standardized precipitation temperature index, standardized precipitation evapotranspiration index (SPEI), China Z-Index, deciles index, modified CZI, Z-Score, rainfall variability index, standardized soil moisture anomaly index, weighted anomaly standardized precipitation index, percent of normal precipitation index, self-calibrated Palmer drought severity index, composite index, percentage area weighted departure and reconnaissance drought index (RDI). These indices are

compared by utilizing long term data of 58 meteorological stations for the period 1951–2014. The performance, efficiency and significance are also tested by applying different statistical tests. The SPI, SPEI and RDI results showed a good capability to monitor drought status in Pakistan. The positive increasing trend (towards wetness) is noted by several of the aforementioned indices at 95% confidence level. In addition, historical drought years and intensity have been explored along with comparison of recent long episode of drought (1999–2002) and all the indices captured this period successfully.

Keywords Standardized precipitation index · Standardized precipitation evapotranspiration index · Reconnaissance drought index · Drought in Pakistan

1 Introduction

Drought is known to be the worst hydro-meteorological hazard of nature (Mishra and Desai 2005). It is a temporary event which lasts for months to years. According to Wilhite (2000), droughts can occur in any region in the world and in any kind of environment (arid, semi-arid or humid). The inter-annual variability in precipitation makes the arid region always at drought risk due to greater probability of below average precipitation (Smakhtin and Schipper 2008). According to the Centre for Research on the Epidemiology of Disasters (CREDES), the drought causes large scale economical losses in a region and makes it more vulnerable for other hydro-meteorological disasters (Guha-Sapir et al. 2014). Obasi (1994) reported extreme meteorological events contribute approximately 85% of the natural disasters. Droughts generally occur due to below normal precipitation over a region and strengthen with the passage of time (Rossi 2000). The timely information about the inception of

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drought and its propagation over an area is very useful for drought preparedness and mitigation. Therefore, information gained by using different drought indices can be very helpful for drought monitoring. The drought frequency and intensity provide valuable information to policy makers for making timely contingency plans (Morid et al. 2006).

Many drought indices are being used around the region as just a single drought index does not provide the comprehensive drought information since climatic conditions vary from region to region. These drought indices are used to determine the drought severity and its spatio-temporal extent (Hayes 2000). According to Mendicino et al. (2008), drought indices provide a comprehensive picture of drought, which are very useful to monitor drought. The choice of drought index is very important for effective monitoring of drought in a region. Some of the drought indices used by national hydro-meteorological organizations are; SPEI and PDSI (Palmer 1968) in the United States, CZI by the meteorological Centre of China (Wu et al. 2001), DI by National Meteorological Centre of Australia (Gibbs and Maher 1967), RDI in many meteorological services of European countries, and SPI (McKee et al. 1993)

which is a most commonly used indicator around the world to monitor and follow drought conditions as recommended by the world meteorological organization (WMO 2012; Hayes et al. 2011). Recent study by Adnan et al. (2015) on drought in Pakistan reflect good results using SPI only. No one (to be best of our knowledge) has used other indices to verify their capabilities pertaining to drought monitoring in Pakistan. The main focus of present study is the comparison of various drought indices and to evaluate the applicability and performance of drought indices in Pakistan. This would also be helpful to national hydro meteorological services for monitoring and early warning of drought, the water resource management and future climate change adaptation in the region.

2 Data and methodology

2.1 Study area

Pakistan lies in the domain of 23°39N–37°01N and 60°49E–77°40E with a total area of 796,096 km² (Fig. 1).

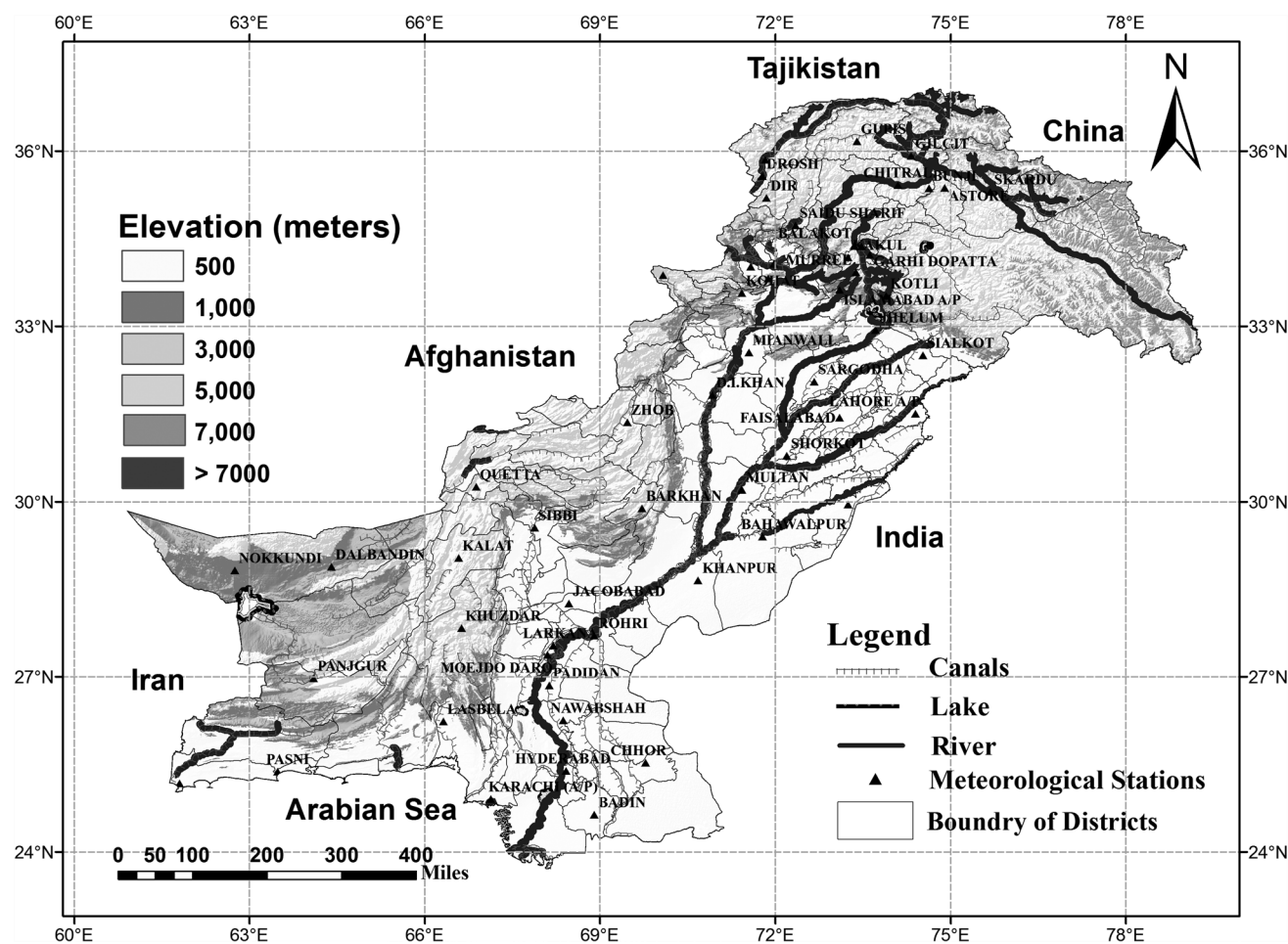


Fig. 1 Geographical location of Pakistan along with the In-situ meteorological network of Pakistan Meteorological Department (PMD)

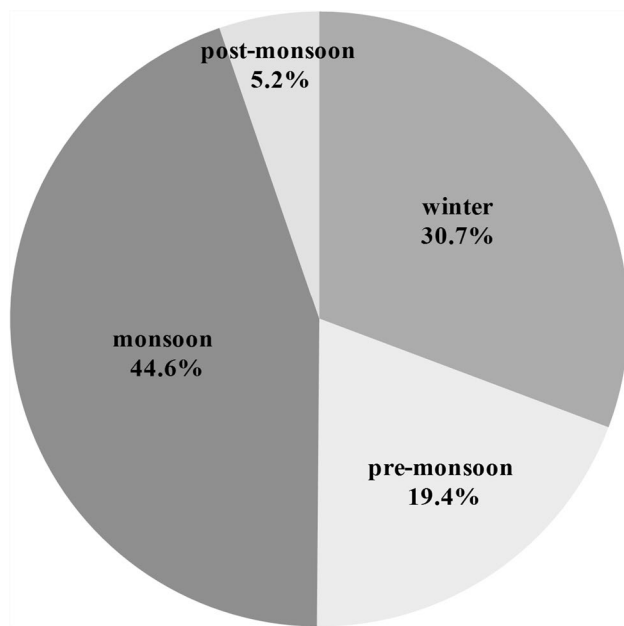


Fig. 2 Percentage distribution of seasonal precipitation during (1981–2010) of Pakistan

Due to diversified topography, it experiences tropical to subtropical types of climate. Generally, two major atmospheric phenomena, i.e. South Asian summer monsoon and western disturbances, cause rainfall in Pakistan during the summer and winter seasons. These rainfall systems contribute almost 45 and 31% of the annual rainfall during the monsoon (JAS) and winter (DJFM) seasons respectively (Fig. 2). The average temperature ranges from 12 to 20 and 19 to 35 °C during winter and summer respectively. The area weighted mean annual precipitation varies between 30 and 400 mm from low (south) to high (north) latitudes with a maximum 900–1800 mm in sub-mountainous region (Adnan and Khan 2009). The monsoon rainfall overcomes the moisture stress during Kharif season (May to September) and fulfills the water demands of crops during the Rabi season (October to April) as well. The arid region covers 75% land of Pakistan with a maximum in southern half of the country that makes it more vulnerable to drought.

2.2 Data

The long term (1951–2014) monthly climatic data of precipitation (mm) and temperature (maximum and minimum) have been used in this study. For calculating 15 drought indices, 64 year's data were obtained from 58 meteorological stations of Pakistan Meteorological Department (PMD). The idea here is to investigate the response of each index during the drought conditions over the whole country. These indices named; standardized precipitation index

(SPI), standardized precipitation temperature index (SPTI) or S-Index, standardized precipitation evapotranspiration index (SPEI), weighted anomaly standardized precipitation index (WASPI), rainfall variability index (RVI), standardized soil moisture anomaly index (SSMAI), Z-Score, modified CZI (MCZI), China Z-index (CZI), the deciles index (DI), percent of normal precipitation index (PNPI), Palmer drought severity index (PDSI), composite index (CI), PAWD, and reconnaissance drought index (RDI). The performance of 12 indices is assessed with SPI by using statistical criterion (Willmott 1982; Willmott and Wicks 1980); namely standard deviation (STDEV), standard error of mean (SEM), mean bias error (MBE), mean absolute error (MAE), standard error of estimate (SEE), coefficient of residual Mass (CRM), root mean square error (RMSE), coefficient of adjustment (CA), efficiency of model (EF), relative error in percentage (RE%), correlation coefficient (R), ratio between both average estimation of drought index (r), concordance index or index of agreement (D), and confidence level (C).

2.3 Drought indices

A total of 15 drought indices are used here. A detailed description can be seen in “Appendix”.

2.4 Statistical tests

Twelve indices performance is assessed with SPI by using statistical criterion as presented in Appendix Table 2, for example STDEV, SEM, MBE, MAE, SEE, CRM, RMSE, CA, EF, RE%, R, r , D, and confidence level (C) (Willmott 1982; Willmott and Wicks 1980). The STDEV measures the variability within the data, whereas SEM estimates the variability among different data. The SEE measures the accuracy, whereas MBE provides the difference between the mean of predicted and observed variable. Furthermore, MAE is less sensitive to extreme values than RMSE; therefore, it is preferred for small or limited datasets. The lower values of MAE, RMSE, MBE, SEE, and SEM show high efficiency and vice versa (Tanny et al. 2008). The positive and negative values describe over and underestimation respectively (Wackernagel 2003). CA represents the coefficient of adjustment. EF closer to 1 represents model is more efficient and suitable, whereas a negative value shows uncertainty and inconsistency in the result (Kouchakzadeh and Nikbakht 2004). Positive values of CRM show under estimate and negative values over estimate (Zare-Abyaneh et al. 2010).

The confidence index (C) may be calculated by the product of the model lineal correlation coefficient (R) by concordance (D). The values of concordance and confidence index vary from 0 to 1, where 1 indicates a complete

agreement between the observed and predicted indices and 0 indicates complete disagreement. The correlation coefficient (R) or coefficient of determination (R²) is a good test to determine the ability of the model to predict events and it has been accepted by the geographers as the most reliable measure to test the model’s ability to estimate events (McCuen and Snyder 1975). The values near to 1 indicate good relationship.

2.5 Significance test

2.5.1 Mann–Kendall test

The linear trend of monthly, seasonal, and annual precipitation and temperature are calculated using Mann Kendal Test, which has been broadly used to analyze the long term climatological and hydrological time series (e.g., Zhang et al. 2010, 2015; Tabari et al. 2011, 2012; Du et al. 2013; Gocic and Trajkovic 2014). The following procedure is used to calculate the variance of equation as:

$$Var(S) = \frac{1}{18} \left[n(n-1)(2n+5) - \sum_{p=1}^q t_p(t_p-1)(2t_p+5) \right] \tag{1}$$

where *q* number has the same value of sample data and *t_p* is the data values of the *p*th group. The statistics *S* is:

$$S = \sum_{j=1}^{n-1} \sum_{k=j+1}^n sgn(x_k - x_j) \tag{2}$$

where *j* and *k* are the data values, *n* represents the data length and *sgn*(θ) is the significant function varies from −1 to 1.

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{Var(S)}} & \text{if } S < 0 \end{cases} \tag{3}$$

The value of *Z* is approximately normal distributed and positive value of *Z* greater than 1.96 represents the significant increasing trend, whereas negative value lower than −1.96 indicates a significant decreasing trend.

2.5.2 Sen’s slope method

The true slope (change per unit time) of linear time series trend is determined by Sen (1968).

$$f(t) = Mt + C \tag{4}$$

where *f*(*t*) is the function of linear trend, *M* and *C* are the slope and constant of equation, respectively. This method estimates the magnitude of trend as follows:

$$Q = median \frac{X_i - X_j}{t_i - t_j} \tag{5}$$

where *x_i* and *x_j* are the data values at times *t_i* and *t_j* (*i* > *j*), respectively.

3 Results and discussion

The southern region (low latitude) receives less amount of precipitation as compared to northern parts (high latitude) of Pakistan. The amount of precipitation decreases as the distance from the sea increases in southern Pakistan (Adnan and Khan 2009). The latitudinal distribution of annual precipitation of the country shows a maximum increase between the 32°N to 36°N (Fig. 3). The main reason of high amount of annual rainfall in northern regions are the two seasonal weather systems i.e. summer monsoon and western disturbances (Ullah and Gao 2013), that occurs in summer and winter respectively. Whereas, some of the southern parts of Pakistan also receive rainfall during the summer or winter seasons because of these weather systems, however, the magnitude and frequency of rainfall is less than the northern regions. The failure in seasonal rainfall makes this region more vulnerable towards drought. Therefore, the frequency, severity and impacts of droughts are more widespread in southern parts of the country.

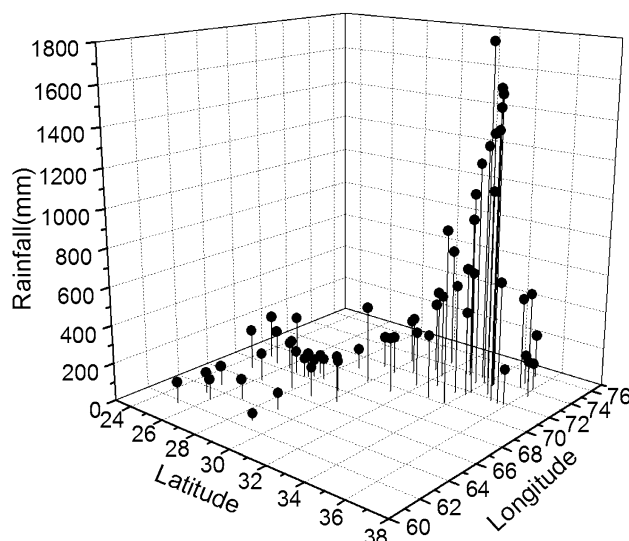


Fig. 3 Geographical distribution of annual rainfall of 58 meteorological stations of Pakistan

3.1 Analysis of drought indices

The SPI is calculated by probability fitted distribution of accumulated precipitation and it was transformed to a normal distribution (Edwards and McKee 1997). The normalized data of SPI behaves equally well for both dry and wet climates and thus could be used to monitor drier and wetter periods. The simplicity, versatility and least data information makes it more widely used index around the world. Most importantly, SPI responds well to the soil moisture deficiency during the drought years (1999–2002). Therefore, we used SPI as a prime index to calibrate the other indices. Thus the time series analysis of fifteen drought indices along with correlation

coefficient for SPI with respect to RVI, MCZI, Z score, CZI, S-index, RDI, SPEI, C Index, WASP Index, Sc-PDSI and SSMAI have been computed for 58 stations of Pakistan. The spatial analysis was performed to find the Pearson correlation coefficient (r) of SPI to other indices on annual basis (Fig. 4). Furthermore, the statistical error tests were also applied to determine the performance of each index to SPI. The value of the coefficient of determination (R^2) varies from 0.12 to 0.77. The highest value of Pearson correlation coefficient (r) was 0.88 for SPEI and the lowest 0.34 for SSMAI. It is noted that SPI has a very good correlation with SPEI, CI, RDI and Z-score (Fig. 4). The value of SPI tends to be higher (less negative) in direr period and lower (less positive) in the

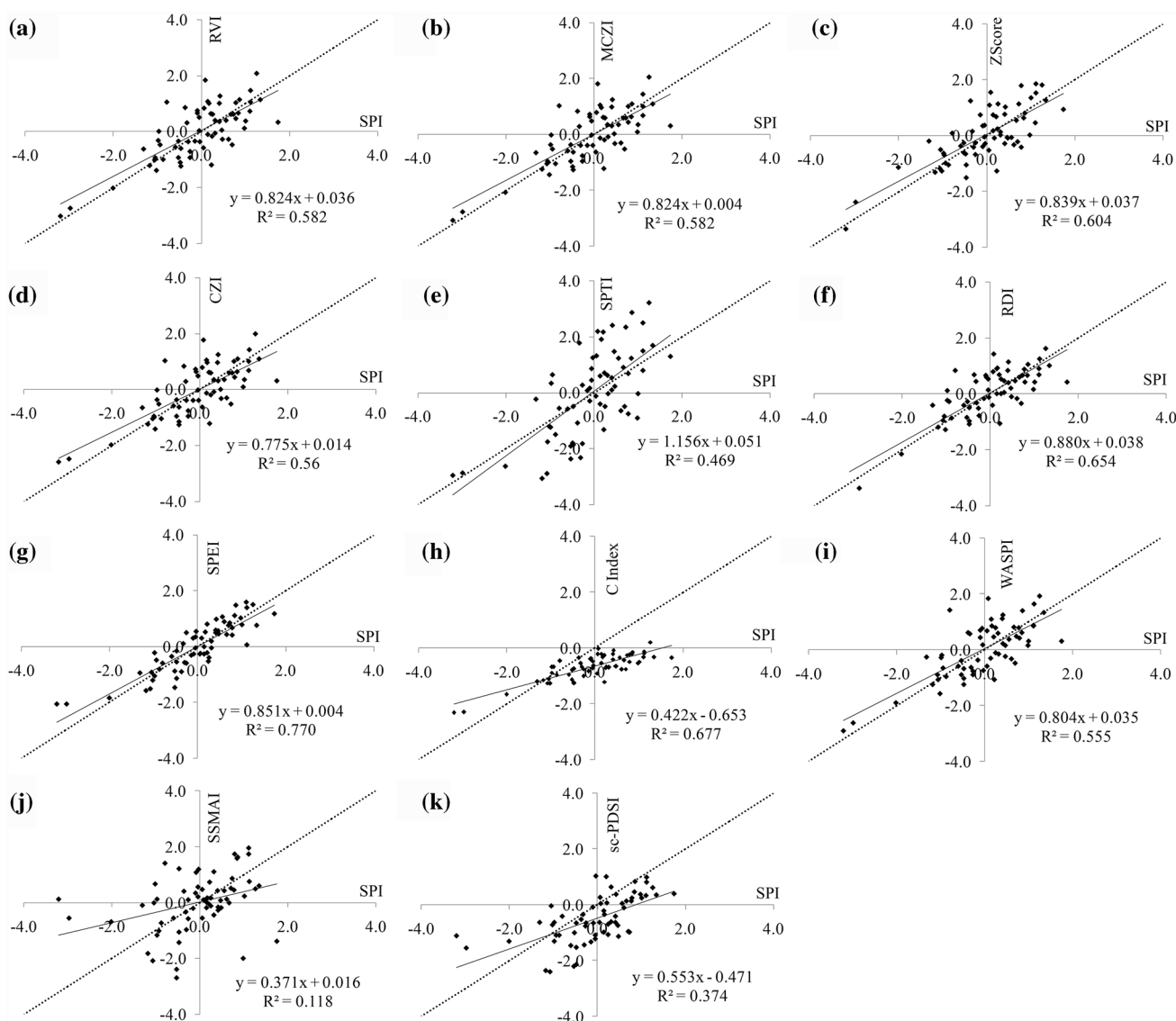


Fig. 4 Spatial correlation of SPI to 11 different drought indices over Pakistan

wet period as compared to CZI, RVI, MCZI and Z-score. The value of R^2 varies from 0.56 to 0.60 between SPI and these indices. Similarly, the SSMAI, Sc-PDSI and S-index also provide the lower values than the SPI during drought periods, whereas the WASPI slightly overestimates the drought conditions. The relative frequency of deciles, percent of normal (PCN), PAWD and SPI is calculated for dry and wet periods. The histogram shows the dry period along the x-axis as follows: Extreme drought (ED), severe drought (SD), Moderate drought (MD) and Mild drought (MID), whereas we add all the wet classes into a single class Wet (W) and Normal is shown by N (Fig. 5). The drought and wet classes in DI, PCN and PAWD are higher than SPI, while normal status is much lower. The total relative frequency (%) of SPI for dry, wet and normal period was 25, 27 and 48% respectively. Similarly, the total relative frequency of PAWD and PCN is 42% for dry and 38 and 36% for wet and DI is 41% for both periods respectively. These results depict the precipitation change impacts are much higher to the sensitivity of these indices, as compared to SPI.

The annual time series helps to identify the historical drought episode in a region. Therefore, the long term time series analysis of 15 drought indices has been conducted for Pakistan (Figs. 6, 7). The trend line was plotted by using linear regression method. The analysis shows an increasing trend for all the drought indices except for SC-PDSI and SSMAI, where it is slightly decreasing. The result shows that all the parameters responded well during the drought period. However, SPI, SPEI, RDI, CI, RVI, CZI, Z-score, MCZ score and WASPI respond better to drought identification and its onset. The negative values are reported less for SPI than for CZI; same result is also identified by Wu et al. (2001). MCZI has also shown good results for drought identification. Significant changes in the original CZI were observed by changing the median values with the mean of precipitation. As compared to SPI, Z-score shows lower and

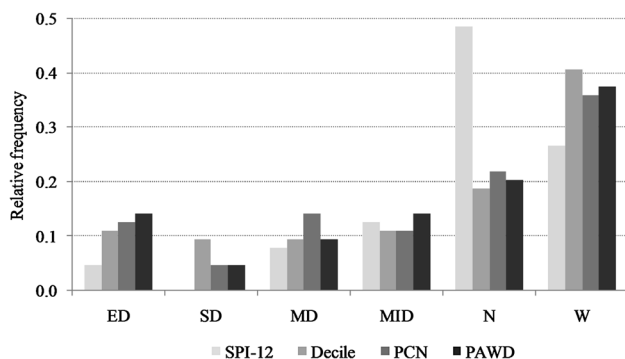


Fig. 5 Histogram of relative drought frequency classes of SPI and a decile, b PCN, c PAWD for Pakistan in 1951–2014

higher values during dry and wet periods respectively. The SPTI, SSMAI and Sc-PDSI showed variability during dry and wet periods. These indices indicate high negative values during the drought period. The value of deciles, area weighted departure (%) and percent of normal are also good indices to identify the drought period. These three indices also have the capability to capture the historical drought years relative to negative SPI i.e. the deciles (1 and 2), AWD below 40% and the percent of normal rainfall remains 60% (Fig. 7).

3.2 Statistical analysis

The efficiency of any model may be evaluated by using different statistical tests as discussed earlier. By comparing these results, we identified those models that respond well to monitor drought in Pakistan (Table 1). The efficiency of a model depends upon the error i.e. if the model shows lowest error, then its accuracy will be high and vice versa. The two indices (SPEI and RDI) show the lowest values of all the error and their sum of the error is lower than the rest of the drought indices. Moreover, their efficiency, concordance and confidence index is close to 1, indicating that the above two indices are good to monitor drought. The negative value of MBE represents high bias error, which shows prediction values are smaller than SPI. The SPEI has the highest efficiency (76%), correlation ($r=0.88$), concordance (0.93) and confidence index (0.82), and minimum error values makes it more suitable drought indicator after SPI. Similarly, RDI has 57% efficiency, 0.81 linear correlations and 0.89 concordances with a confidence level of 0.72. The evapotranspiration and precipitation data used for the calculation of SPEI and RDI make both indices helpful tool for the prediction and monitoring of drought in a region. The negative efficiency of SPTI (S-Index) and SSMAI shows ambiguity with respect to SPI. The statistical test results applied to different drought indices show the best response to drought monitoring in terms of their efficiency and confidence in climate of Pakistan after SPI (right to left), whereas the performance of deciles, %AWD and percent of normal are good indices to drought monitoring in the selected region.

The trend significance and magnitude of trend are calculated by using Mann Kendal and Sen's Slope tests on different drought indices (Fig. 6). All drought indices suggest increasing trends in precipitation. Most of the drought indices are statistically significant except PAWD, S-index, Sc-PDSI, SPI, SSMAI and Z-Score. The maximum magnitude of trend is noted in PCN of rainfall increase 0.44 mm per year, whereas the rest of the significant indices are increasing by a value of 0.01–0.02 mm per year (Fig. 8). This positive increase in all the drought indices represents the reduction of drought conditions across whole

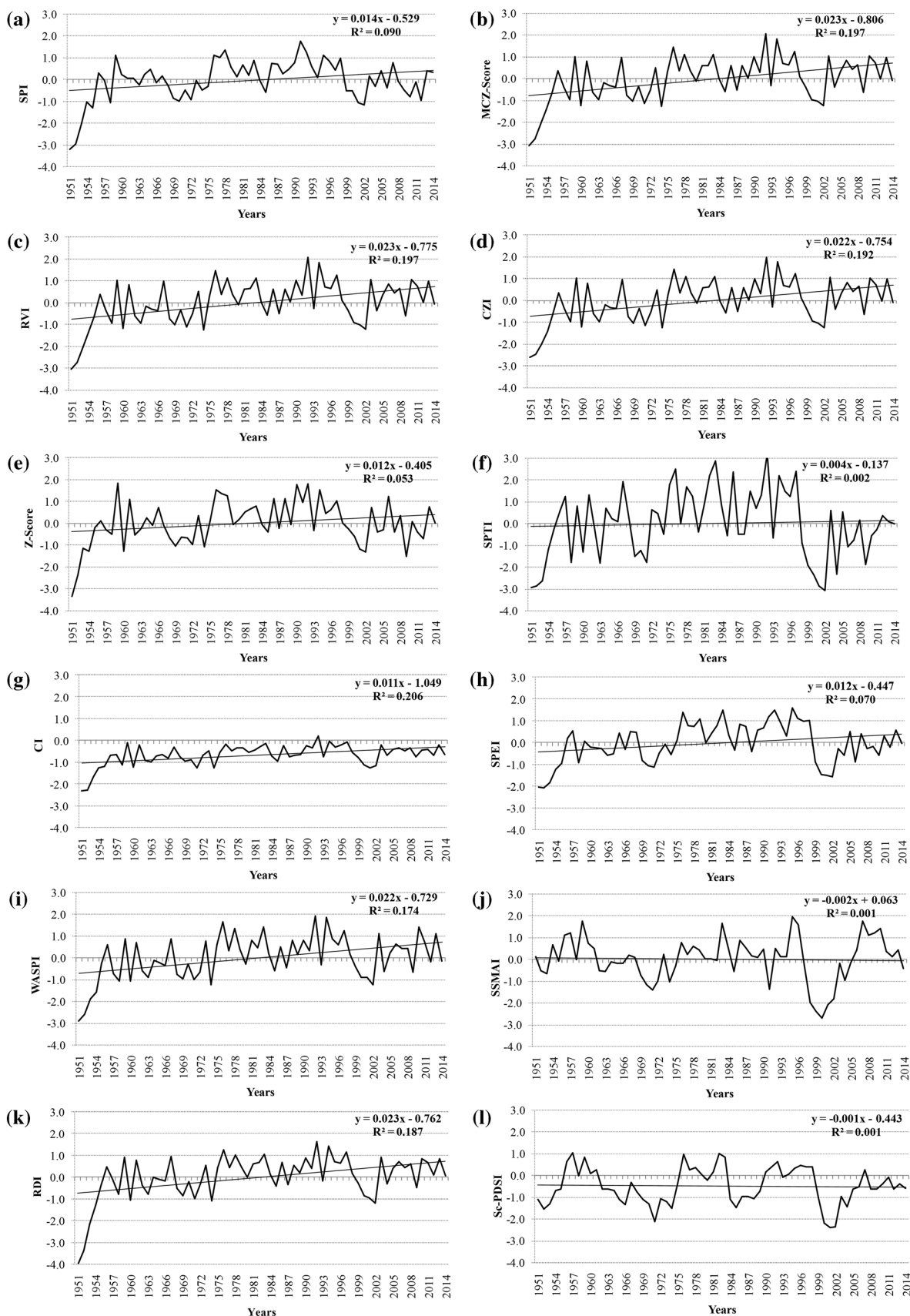


Fig. 6 Annual time-series analysis of different drought indices in Pakistan

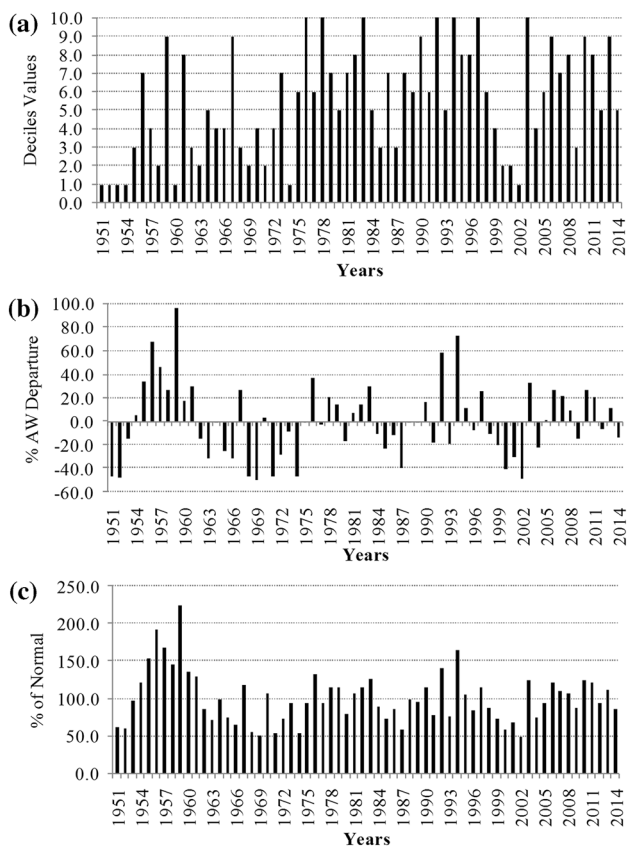


Fig. 7 Time-series analysis of **a** decile, **b** PAWD, **c** percent of normal (PCN) of Pakistan

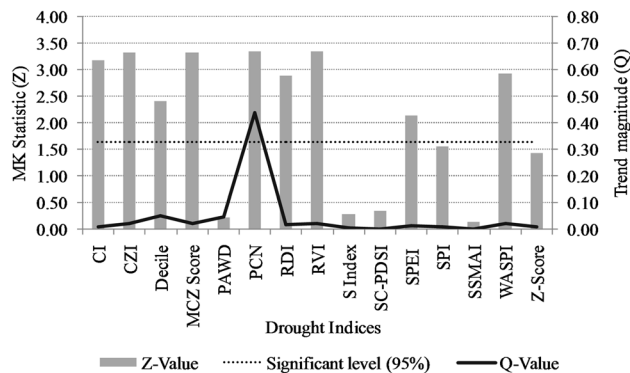


Fig. 8 Magnitude of trend by using Sen's Slope test of different drought indices. The hollow bars represent trends which are not statistically significant at 95% confidence level based on Mann Kendal test

Pakistan, however, there could be regional differences in different climate zones of Pakistan which warrant further investigation.

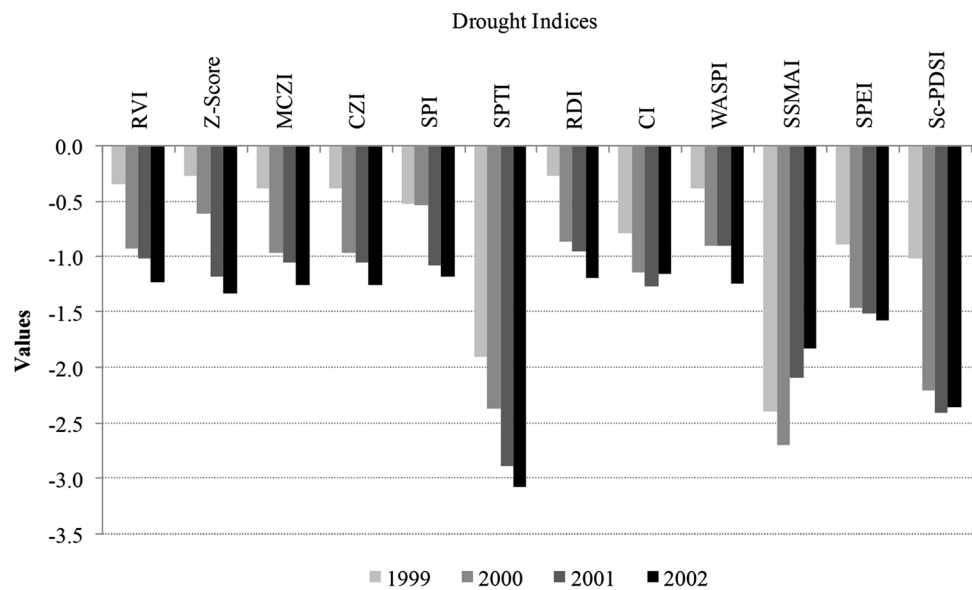
3.3 Drought episode (1999–2002)

Severe and longest drought episode experienced over most parts of Asia are during the years (1999–2002) as indicated by Malik et al. (2013). The comparison of recent long episode of drought (1999–2002) as well as the historical drought period and its intensity was determined. This period was identified by all the drought indices. However, the severity and intensity of drought for each of the index were different. The SPTI highly responded to drought as

Table 1 Statistical test to evaluate the performance of different drought indices across Pakistan

Statistical test	SPEI	RDI	Z-Score	CZI	MCZ Score	RVI	WASPI	CI	PDSI	SSMAI	SPTI
SUM	- 2.10	0.00	0.00	- 1.28	- 2.02	0.00	0.00	- 43.01	- 30.72	0.00	0.00
MEAN	- 0.03	0.00	0.00	- 0.02	- 0.03	0.00	0.00	- 0.67	- 0.50	0.00	0.00
STDEV	0.90	1.01	1.00	0.96	1.00	1.00	1.00	0.48	0.84	1.00	1.56
RMSE	0.45	0.60	0.64	0.66	0.66	0.66	0.69	0.86	0.90	1.10	1.14
MBE	0.01	0.04	0.04	0.02	0.01	0.04	0.04	- 0.63	- 0.45	0.04	0.04
MAE	0.37	0.47	0.51	0.52	0.52	0.51	0.55	0.72	0.74	0.78	0.92
SEE	0.46	0.61	0.65	0.68	0.67	0.67	0.70	0.88	0.91	1.11	1.16
SEM	0.11	0.13	0.12	0.12	0.13	0.13	0.13	0.06	0.10	0.12	0.20
RE (%)	- 0.40	0.02	- 1.56	- 0.85	- 0.44	- 1.56	- 1.56	22.23	15.98	0.02	- 1.56
CRM	0.26	1.00	1.00	0.55	0.28	1.00	1.00	- 14.22	- 10.23	1.00	1.00
CA	1.06	0.84	0.86	0.93	0.86	0.86	0.86	1.37	0.94	0.86	0.35
r	0.74	0.00	0.00	0.45	0.72	0.00	0.00	15.22	11.23	0.00	0.00
D	0.93	0.89	0.87	0.86	0.87	0.86	0.85	0.70	0.73	0.57	0.76
C	0.82	0.72	0.68	0.64	0.66	0.66	0.64	0.58	0.45	0.20	0.52
r	0.88	0.81	0.78	0.75	0.76	0.76	0.75	0.82	0.61	0.34	0.69
EF	0.76	0.57	0.51	0.48	0.48	0.48	0.44	0.12	0.05	- 0.43	- 0.54

Fig. 9 Drought indices during long episode of drought (1999–2002) across Pakistan



the time period prolong. Almost all the indices show that drought slowly and gradually progresses and strengthen with the passage of time, except SSMAI, showing weakening (Fig. 9). The onset of drought was reported in 1999, but we may see that most of the drought indices (RVI, Z-score, MCZI, CZI, RDI and WASPI) were not able to capture this drought commencement. The identification of drought (onset and retrieve) makes it the most complex hydro-meteorological disasters among all the natural disasters. The deciles, PAWD and PCN also identify the same drought period mentioned above. The deciles gradually reduced from 4 to 1, PAWD from -20.7 to -49.3% and PCN from 72.4 to 47.9% during 1999 to 2002 (Fig. 10). All the indices indicate that 2002 was the most severe drought in Pakistan.

4 Conclusions

This study evaluated the drought conditions by using 15 drought indices in Pakistan. The performance of precipitation based drought indices (MCZI, Z-score, CZI, WASPI and RVI) is similar to SPI, however their

intensities are different. The SPTI, SSMAI and Sc-PDSI indicate high variation towards negative values, whereas the CI did not show variation. The deciles are more sensitive to drought conditions in terms of intensity, whereas PAWD and PCN showed insignificant drought intensity. The performance based statistical analysis show that SPEI and RDI are the best drought indices as these two use evapotranspiration and precipitation data, which enable them to depict a more real picture of drought conditions. The trend analysis shows that almost all drought indices are significantly increasing towards the positive side, resulting in more wetness than dryness. All the drought indices efficiently captured the longest episode of drought 1999–2002. In the light of above results, it is recommended to use the SPI, SPEI and RDI to monitor drought conditions in Pakistan and surrounding region. However, the development of new composite drought index comprising rainfall, temperature, and remote sensing index is needed which could be an advantage to monitor and identify the drought conditions in the region.

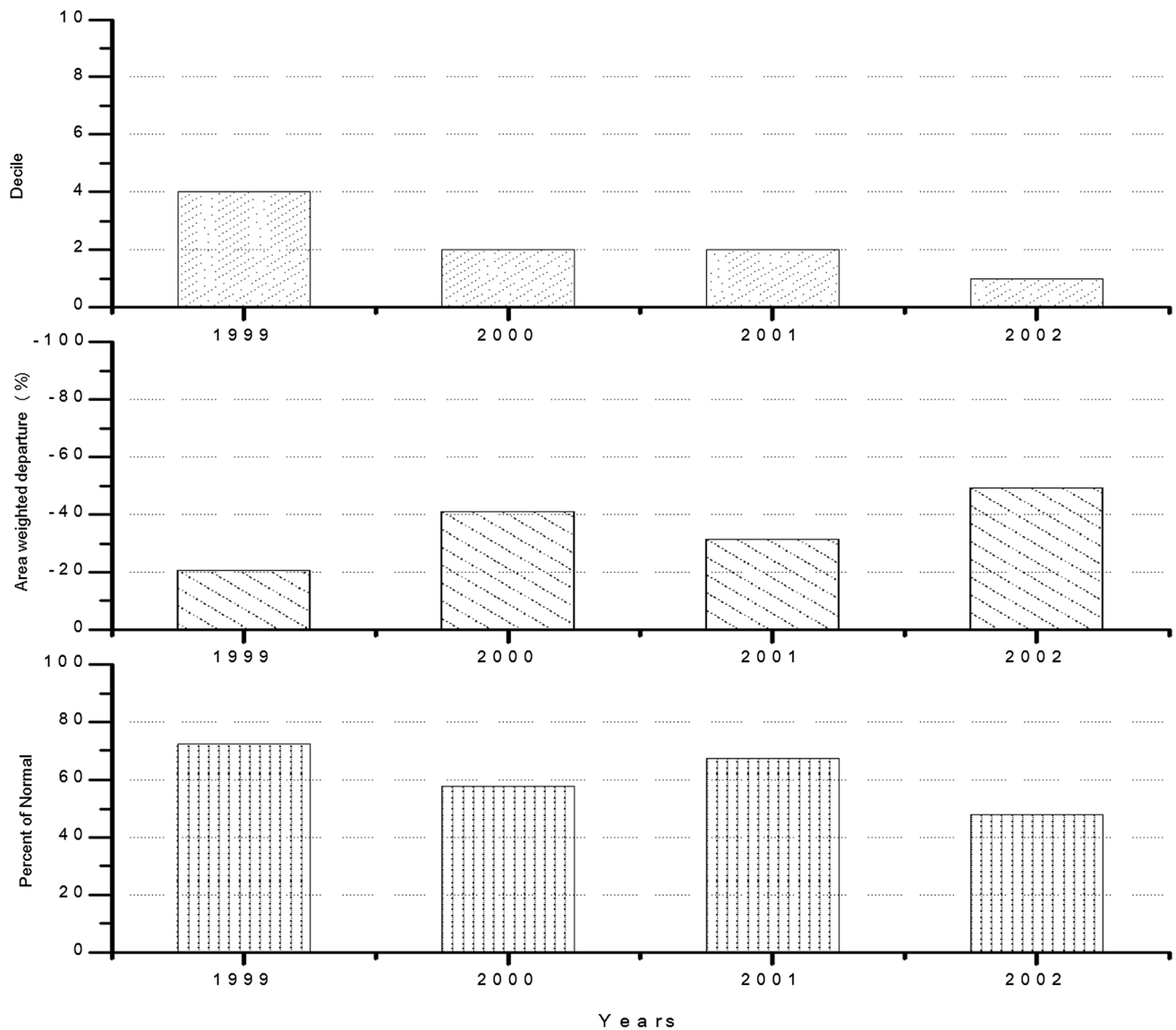


Fig. 10 Performance of decile, AWD (%) and percent of normal during 1999–2002 across Pakistan

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Appendix: A description of drought indices

Standardized precipitation index (SPI)

SPI is calculated by fitting the long term precipitation data to the probability distribution (e.g., gamma distribution), which is then transformed to normal distribution to get the

zero values for SPI mean (McKee et al. 1993; Edwards and McKee 1997). The SPI can be calculated at different time scales like 1-month, 3-months, 6-months, 12-months and so on. The SPI is not suitable at longer time scale as it reduces the sample size, even in the presence of long data (Guttman 1998). However, the SPI calculates the precipitation deficit at different time scales (i.e. 1–12) that may be helpful to identify drought conditions (e.g., soil moisture deficiency, reservoir storage, ground water and stream flow) over a region. Positive and negative values show above and below than the mean precipitation. SPI values show both dry and wet conditions. SPI drought part is randomly split into four classes, mild (-0.49 to -0.99), moderate (-1.0 to -1.49), severe (-1.50 to -1.99), and extreme ($SPI < -2.0$) conditions. A drought event starts when SPI reaches to -0.0 and

ends when SPI become positive. This index is widely used throughout the world (WMO 2012). SPI shows a better performance to monitor drought in China and Iran by Wu et al. (2001) and Ansari (2003) respectively.

Standardized precipitation evapotranspiration index (SPEI)

SPEI calculation procedure is same as SPI. SPI uses the precipitation data only, whereas SPEI uses both rainfall and reference evapotranspiration (ET₀) (Vicente-Serrano et al. 2010) which helps to identify the drought types, severity and impacts over a region (Vicente-Serrano et al. 2013). The water balance (the difference of precipitation and potential evapotranspiration) is calculated (Thornthwaite 1948) at different time scales to get SPEI values. The Penmen Monteith (PM) equation is used to calculate PET (Allen et al. 1998) as follows;

$$ET_0 = \frac{0.408 \Delta (R_n - G) + \gamma \left[\frac{900}{T+273} \right] u_2 (e_s - e_a)}{\Delta + \gamma (1 + 0.34u_2)}, \tag{6}$$

where ET₀ represents evapotranspiration (mm/day); Δ = saturated vapor pressure slope (kPa/°C); G = heat flux density of soil (MJ/m²/day); R_n = net radiation (MJ/m² per day); T = mean temperature (°C); u₂ = average daily speed of wind (m/s); e_s - e_a = deficit of vapor pressure; γ = psychrometric constant (kPa/°C).

The main advantage of SPEI is that it takes the PET data on a different time scales to monitor the drought conditions. These timescales are very useful to calculate the drought conditions in different hydrological sub-systems. SPEI is a standard variable and its average value is 0 and deviation is 1. According to Abramowitz and Stegun (1965), the classical approximation is used in the formula of SPEI as follows;

$$SPEI = W - \frac{C_0 + C_1 W + C_2 W^2}{1 + d_1 W + d_2 W^2 + d_3 W^3} \tag{7}$$

where W = -2ln(Q) for Q ≤ 0.5, Q is the probability of exceedance = 1 - F(x) if Q > 0.5, Q is replaced by 1 - Q and the resultant SPEI symbol is reversed. The C₀, C₁, C₂, d₁, d₂ and d₃ are constants.

Standardized precipitation temperature index (SPTI) or S-index

Standardized precipitation temperature index (SPTI) or dryness index (Si) jointly considers the precipitation and temperature as proposed by Ped (1975).

$$S_i = \frac{DS}{V_{DT}} - \frac{DQ}{V_{DQ}} \tag{8}$$

where ΔT and ΔP are the anomalies, σ_{ΔT} and σ_{ΔP} are the respective standard deviations at the station, calculated from long term data series of precipitation and temperature respectively. The values of the index range from very dry to very wet conditions.

Weighted anomaly standardized precipitation index (WASPI)

Lyon (2004) developed weighted anomaly standardized precipitation index (WASPI) to monitor the precipitation in tropical region. The monthly and annual precipitation data are used to calculate WASP. The values range from most severe (- 2.0) to severe wetness (2.0), which is well correlated with other drought indices. Basically, drought is termed as moisture deficit, therefore, generally 6 or 12 months’ rainfall accumulation is used.

$$WASP_N = \frac{1}{\sigma_{WASP_N}} \cdot \sum_{i=1}^N \left(\frac{P_i - \bar{P}_l}{\sigma_i} \cdot \frac{\bar{P}_l}{\bar{P}_A} \right) \tag{9}$$

where P_i, P_A is the monthly and annual rainfall, \bar{P}_l and \bar{P}_A is the monthly and annual rainfall climatology, σ_i is the standard deviation of monthly rainfall where σ_{WASP_N} is the standard deviation of WASP, which is 0.44 for Pakistan.

Rainfall variability index (RVI)

It is the ratio between anomalies over the standard deviation of long period of rainfall data. According to Gocic and Trajkovic (2013), the following equation is used to determine RVI

$$\delta_i = (P_i - \mu) / \sigma \tag{10}$$

where δ_i represents RVI, P_i is annual rainfall for *i*th year, μ and σ are the annual mean and standard deviation of rainfall. Time series of rainfall are classified into different climatic regimes. In case, if δ is negative, then the year is known as drought year. The World Meteorological Organization (WMO 1975), classify the rainfall, according to their climate zones.

$$\left. \begin{array}{l} P < \mu - 2 \cdot \sigma \quad \text{extreme dry} \\ \mu - 2 \cdot \sigma < P < \mu - \sigma \quad \text{dry} \\ \mu - \sigma < P < \mu + \sigma \quad \text{normal} \\ P > \mu + \sigma \quad \text{wet} \end{array} \right\} \tag{11}$$

Standardized soil moisture anomaly index (SSMAI)

Monthly soil moisture data (1951–2014) produced by Leaky Bucket model at a horizontal resolution (0.5° × 0.5°) is used to calculate SSMAI. It is reasonably

performed well against the limited observation in a different region with a spatial resolution ($0.5^\circ \times 0.5^\circ$) from 1948 to-date (Fan and Dool 2004, 2008). A strong correlation is noted between the annual rainfall departure with 12-SPI ($r=0.97$), rainfall departure with soil moisture ($r=0.80$) and soil moisture with SPI ($r=0.77$). Soil moisture anomaly index (SMAI) was developed by Bergman et al. (1988) in mid1980, a way to access global drought conditions in United States. Here a slight modification is incorporated to obtain standardized data. So, it could be easy to compare it with other drought indices.

$$\phi_j = \frac{X_j - \bar{X}}{\sigma} \tag{12}$$

where X_j is the precipitation of j th month is, \bar{X} is the mean precipitation and σ is the standard deviation.

China Z-index (CZI)

Wilson-Hilferty cube root transformation is used to calculate CZI (Kendall and Stuart 1977). CZI formula is as follows;

$$CZI_j = \frac{6}{C_s} \left(\frac{C_s}{2} + 1 \right)^{1/3} - \frac{6}{C_s} + \frac{C_s}{6} \tag{13}$$

$$C_s = \frac{\sum_{j=1}^n (X_j - \bar{X})^3}{n \times \sigma^3} \tag{14}$$

$$\phi_j = \frac{X_j - \bar{X}}{\sigma} \tag{15}$$

where j is the current month, C_s is the coefficient of skewness, n is the total number of months in the record, σ is the standard variant also called Z-Index and x_j is precipitation of j month.

Modified CZI (MCZI)

To calculate MCZI, Wu et al. (2001) used a median of precipitation instead of mean precipitation. This attempt minimized the difference between MCZI and SPI.

Z-Score

According to Triola (1995a), the equation of CZI is used to calculate Z-Score. Furthermore, the data fitting adjustment Pearson type III or Gamma distribution is not requiring by Z-Score and it might not be represented in shorter duration as well as the SPI (Edwards and McKee 1997).

The decile index (DI)

The decile index is widely used in Australia to monitor drought (Coughlan 1987). Long term monthly precipitation data is ranked in descending order to make cumulative frequency distribution (Gibbs and Maher 1967). The distribution depicts decile index. The first decile precipitation amount should not exceed by the lowest 10% of the total. The second decile is the amount between 10 and 20% of the total and so on. The severity of the drought can be assessed by comparing the amount of precipitation in a month or over a period of several months with the cumulative distribution of precipitation over a long term period. The 20% of lowest precipitation falls is termed to be much below normal (decile 1 and 2). Decile 3 and 4 (20–40%) shows below normal, decile 5 and 6 (40–60%) indicate near normal and so on. The Box-Cox transformation is used to normalize the monthly rainfall time series (McMahon 1986).

Percent of normal precipitation index (PNPI)

Morid et al. (2006) and Masoudi and Hakimi (2014) used the following equation to monitor drought in the region.

$$PNPI = \frac{P_i}{P} \times 100 \tag{16}$$

where P_i is the total precipitation of each year, P is the average climatology for a period from 1951 to2014.

Palmer drought severity index (PDSI)

It is the most significant meteorological index used in the United States to monitor drought (Heim 2002). Palmer (1965) considers precipitation, temperature and soil water content to calculate PDSI. Several studies (e.g., Karl 1986; Alley 1984; Zoljoodi and Didevarasl 2013) described the calculation procedure of this index. The final equation of PDSI is as follows;

$$PDSI_i = 0.897PDSI_{i-1} + \frac{1}{3}Z_i \tag{17}$$

where PDSI is dry and wet period of initial month, Z anomaly of the Palmer moisture index. The constant values of 0.987 and $1/3$ are derived from the linear slope of line accessed from the extreme droughts. According to Wells et al. (2004), the development of Sc-PDSI resolved many deficiencies experienced earlier in PDSI and its data is freely available on the Koninklijk Netherlands Meteorological Institute (KNMI) website of Climate Research Unit (CRU) (<http://climexp.knmi.nl/select.cgi>). The data set has been calculated globally for a period more than 110 years (1901–2012) with the horizontal resolution of $0.5^\circ \times 0.5^\circ$ on monthly basis.

Composite index (CI)

Zhang et al. (2006) developed this index to monitor the drought in China. The same index was employed to analyze the spatial and temporal characteristics of drought in Pakistan at annual basis. CI uses the data of standardized precipitation index (Z) and relative moisture index (M) as follows;

$$CI = aZ_{30} + bZ_{90} + cM_{30} \tag{18}$$

where Z_{30} and Z_{90} indicates the SPI index for the 1-month and 3-months, respectively, M_{30} shows the monthly moisture index and a, b, c are the coefficients, whose values are 0.47, 0.36, and 0.96 respectively.

$$M_{30} = \frac{P - PE}{PE} \tag{19}$$

Here, P is the precipitation, and PE is the potential evapotranspiration on monthly basis. The potential evapotranspiration was calculated by the Food and Agriculture Organization (FAO)-Penman–Monteith method (Allen et al. 1998).

Percentage area weighted departure (PAWD)

According to Rhynsburger (1973), it is commonly used in the fields of meteorology and hydrology. The PAWD is a very good tool to monitor drought conditions in Sindh province of Pakistan and its adjoining region. Thiessen Polygon Method (1911) is used to determine the area factor of precipitation in Pakistan. First the area factor is multiplied by the monthly or annual rainfall then the following method is used to calculate PAWD.

$$PAWD = \left[\frac{(X_i - \bar{X})}{\bar{X}} \right] \times 100 \tag{20}$$

where x_i is the precipitation of i th month, \bar{X} is the normal precipitation.

Reconnaissance drought index (RDI)

Reconnaissance drought index (RDI) is a meteorological index that is used for drought assessment. It is expressed as initial, normalized and standardized values (Eq. 21). The initial value (α_k) is based on the ratio between precipitation and potential evapotranspiration (PET). The PET is very helpful for identification and assessment of drought events. RDI does not depend upon the PET calculation method (Vangelis et al. 2013). The normalized RDI_n is the arithmetic mean of α_k values, whereas the standard RDI_{st} uses the assumption that α_k values follow the log normal distribution. So, RDI is computed by using the following equations as suggested by Tsakiris and Vangelis (2005).

Table 2 Different statistical error and performance test name along with their equations where x_i and y_i shows the values of SPI and the other indices respectively, \bar{X} and \bar{Y} shows the long-term data average

Name	Equations
Standard deviation	$St_{obn} = \sqrt{\frac{\sum_{i=1}^n (x_i - \bar{X})^2}{n-1}}$
Root mean square error	$RMSE = \sqrt{\frac{\sum_{i=1}^n (y_i - x_i)^2}{n}}$
Mean bias error	$MBE = \frac{\sum_{i=1}^n (y_i - x_i)}{n}$
Mean absolute error	$MAE = \frac{\sum_{i=1}^n y_i - x_i }{n}$
Standard error of estimate	$SEE = \sqrt{\frac{\sum_{i=1}^n (x_i - y_i)^2}{n-2}}$
Standard error of mean	$SEM = \frac{St_{dev}}{\sqrt{n}}$
Relative error (%)	$RE(\%) = \frac{MBE}{\bar{X}} \times 100$
Coefficient of residual mass	$CRM = \frac{\sum_{i=1}^n x_i - \sum_{i=1}^n y_i}{\sum_{i=1}^n x_i}$
Coefficient of adjustment	$CA = \frac{\sum_{i=1}^n (x_i - \bar{X})^2}{\sum_{i=1}^n (y_i - \bar{X})^2}$
Ratio	$r = \frac{y_{avg}}{x_{avg}}$
Concordance index	$D = 1 - \frac{\sum_{i=1}^n (y_i - x_i)^2}{\sum_{i=1}^n [y_i - \bar{X} + x_i - \bar{X}]^2}$
Confidence level	$C = R \times D$
Correlation coefficient	$r = \frac{\sum_{i=1}^n (x_i - \bar{X})(y_i - \bar{Y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{X})^2 \sum_{i=1}^n (y_i - \bar{Y})^2}}$
Efficiency	$EF = \frac{\sum_{i=1}^n (x_i - \bar{X})^2 - \sum_{i=1}^n (y_i - \bar{Y})^2}{\sum_{i=1}^n (x_i - \bar{X})^2}$

$$\alpha_k^{(i)} = \frac{\sum_{j=1}^k P_{ij}}{\sum_{j=1}^k PET_{ij}}, \quad i = 1 \text{ to } N$$

$$RDI_n^{(i)} = \frac{\alpha_k^i}{\bar{\alpha}_k} - 1$$

$$RDI_{st}^{(i)} = \frac{y_k - \bar{y}_k}{\alpha_{y_k}} \tag{21}$$

where P_{ij} and PET_{ij} are the precipitation and potential evapotranspiration of the j th month of the i th year, N is the total number of years, $\bar{\alpha}_k$ is the arithmetic mean of α_k^i . y_k is the $\ln(\alpha_k^{(i)})$, \bar{y}_k is arithmetic mean and σ_{y_k} is standard deviation (see Table 2).

The CZI, the SPEI, the MCZI, the Z-Score, the S Index, the RVI, the WASPI, the SSMAI and the SPI have similar numerical value range (Table 3). Therefore, it is easy to compare these items. However, the range of Decile (DI),

Table 3 Drought indices values and their classes

Class	SPI, SPEI, RDI, PDSI values	DI	AWD (%)	CI	PNPI
Extremely wet	≥ 2.0	≥ 90	> 80		
Severe wet	1.50 to 1.99	80 to 90	50 to 80		
Moderate wet	1.00 to 1.49	70 to 80	20 to 50		
Mild wet	0.50 to 0.99	60 to 70	10 to 20		> 110
Normal	0.49 to -0.49	40 to 60	-10 to 10	-0.6	$90-110$
Mild drought	-0.50 to -0.99	30 to 40	-10 to -20	-1.2 to -0.6	$80-90$
Moderate drought	-1.00 to -1.49	20 to 30	-20 to -30	-1.8 to -1.2	$70-80$
Severe drought	-1.50 to -1.99	10 to 20	-30 to -40	-2.4 to -1.8	$60-70$
Extremely drought	≤ -2.00	≤ 10	< -40	≤ -2.4	< 60

PNPI and %AWD values has been categorized into similar classes (Table 3). Here, the DI classes of 5 to 6 is classified as normal 4–5 slightly below normal, 3–4 below normal, 2–3 is much below normal, 1–2 very much below normal. The value excess of 90% is considered as normal period, the value less than 60% is considered as very much below normal, 70% much below normal, 80% below normal, 90% slightly below normal.

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