Drought Evaluation of Tiruchirapalli City, India, Using Three Meteorological Indices

K. Sasireka and C. R. Suribabu

Abstract Large communities of people worldwide are affected by droughts, causing major economic losses, environmental harm, and social deprivation. The characteristics of the drought are hard to define, detect and monitor. Drought events are quantified by several indices when there is no real ground-level assessment system available. The drought indexes such as Standardized Precipitation Index (SPI), Statistical Z score (SZs) and China-Z Index (CZI) that can provide a direct, simple and quantitative evaluation of the key characteristics of intensity, duration of drought, and spatial extent. This article analyzes the SPI, statistical Z score and CZI on different time scales such as annual and seasonal (North–East, South–West Winter and Summer) by taking Tiruchirapalli as a study area using 25 years (1981–2005) of monthly rainfall data. In this analysis, the implementation of each index is compared and the study results suggest that the CZI and SZs can provide similar results and shows the minor deviation to the SPI for all time scales, and that the CZI and SZs computations are comparatively easy compared to the SPI.

Keywords Rainfall · Drought · SPI · China-Z index · Statistical Z score

1 Introduction

The main disasters namely floods and drought have been taken into account while formulating any development plans in any region. The execution of any development plan mainly depends upon the occurrence, intensity and distribution of these two extreme events. Among the different types of drought the most important drought is Meteorological drought. It identifies stages of drought on the basis of the number of days with precipitation below certain specified threshold [3]. The length of prolonged

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C. M. Rao et al. (eds.), *Advanced Modelling and Innovations in Water Resources Engineering*, Lecture Notes in Civil Engineering 176,
https://doi.org/10.1007/978-981-16-4629-4_3

and severe drought cycles can have important consequences for conditions in agriculture, socio-economic and the climate. Comprehensive and adequate knowledge on past drought variations will allow adequate management of future drought risks [13]. Appropriate assessment of the drought characteristics is therefore critical for ensuring the effective use of water resources, agricultural and power productions. Many of the indices considered in the existing literature when evaluating meteorological drought use rainfall as the only input parameter or in conjunction with other meteorological elements.

Among the different type of drought indices, such as Palmer [8], Deciles, the China-Z index (CZI; Wu et al. [12]), and the Reconnaissance Drought Index [11] the choice of selection of the indices are based on its quality and availability of the data. Many of these indices are determined based on meteorological factors such as temperature and rainfall. In this paper CZI developed in China, the Z score Index and SPI were chosen due to their applicability to different time scales and climatic conditions. The SPI developed by McKee et al. [7] is based solely on rainfall data and is generally used for assessing and quantifying drought [6]. Suribabu and Evangelin Ramani [10] used SPI, CZI and SZs indices to find the landslide triggering factor based on the moisture level in Coonoor Hill Station. SPI's popularity is based primarily on its suitability for various time scales and its ease in testing without needing any statistical constraints.

2 Study Area

Tiruchirapalli district covers 4404 km^2 of which 1852 km^2 (about 42%) is agricultural land. Figure 1 shows the study area and it is situated in central Tamil Nadu and lies in the state's most fertile area of the Kaveri delta zone. Despite receiving most of its rainfall from the North-East (NE) Monsoon, Tamil Nadu receives adequate rainfall from both Monsoon seasons, making it predominant for agriculture. The annual Normal 760 mm rainfall is slightly less than the 945.00 mm state average. The 25-year daily Rainfall data from the IMD for the period 1981 to 2005 is used in this paper. Even though Meteorological department is able to consistently provide forecasts with good accuracy for a short span of time, the daily rainfall data is utilized to forecast for a long term, to plan cultivation of long-term crops by stochastic methods.

Rainfall time series of Tiruchirapalli city for various time scales is shown in Fig. 2. Figure 2 shows the maximum annual rainfall of about 1200 mm has occurred in the year 1983 and 2005 at a time interval of 22 years. From Fig. 2, it has been concluded that the NE rainfall time series pattern is similar to the annual rainfall pattern and it depicts that more contribution of NE rainfall than SW rainfall. The Tiruchirapalli city gains very meager quantity of rainfall from winter season compared to summer rainfall. Table 1 shows the average rainfall, standard deviation of different time scale as well as skewness of rainfall data. The winter rainfall shows the lowest standard deviation of 45.29 mm and it depicts that the rainfall distribution is very close to the mean rainfall and the annual rainfall shows the highest standard deviation of

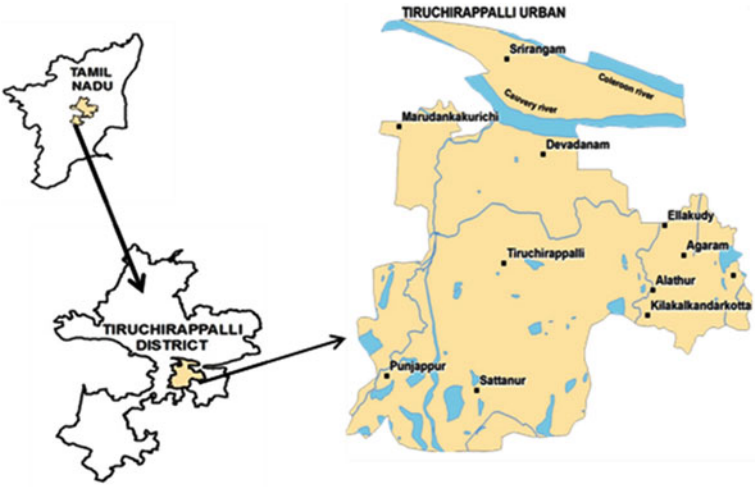

Fig. 1 Study area

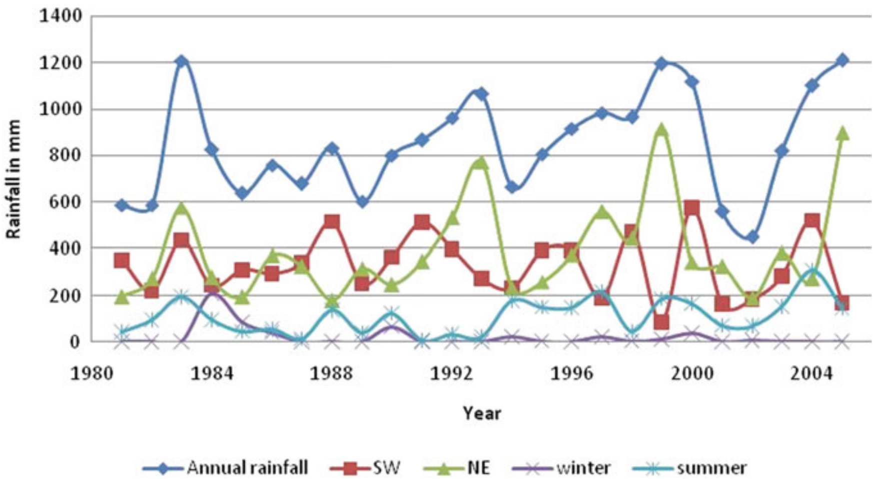

Fig. 2 Rainfall time series of Trichy city in different time scale

Table 1 Rainfall statistics of the study area

Rainfall time scale	Mean (mm)	Standard deviation	Skewness
Annual	849.29	221.46	0.1209
SW	326.80	130.27	0.1908
NE	392.02	209.40	1.4502
Winter	20.54	45.29	3.3985
Summer	109.92	75.56	0.6722

221.46 mm and this reflects the rainfall values being distributed far away from the mean annual rainfall. The positive value of the skewness represents the rainfall data are skewed right, and if the skewness value is greater than one it represents the data are highly skewed. It can be shown from Table 1 that the winter rainfall data is highly skewed than the other time scale data.

3 Methodology

Three Drought indices have been used to classify the historic data into seven categories moisture condition of the city ranging from Extremely Wet (EW) to Extremely Dry (ED). Twenty-five years of daily rainfall collected from IMD for the years 1981–2005 has been used to assess severity of drought occurrence in those periods. To assess the drought characteristics of the city, three indices namely SPI, CZI and SZs are selected as these three indices has a common classification and range of values for each classification. For example, if any the index value for a particular month falls between -0.99 and 0.99 it is classified as Normal.

3.1 Statistical Z score (SZs)

It has been used in many researches because of a simple calculation [1, 2]. The SZs index is a dimensionless quantity widely used in statistics. It is given by

$$Z = ((x - \mu))/\sigma \tag{1}$$

where x = individual rainfall value, μ = long-term mean, σ = standard deviation.

3.2 China-Z Index (CZI)

The CZI is related to cube-root transformation of Wilson–Hilferty [5]. Assuming the precipitation data are in line with Pearson Type III distribution.

$$\mathrm{CZI} = \frac{6}{C}\left(\frac{C}{2}Z + 1\right)^{\frac{1}{3}} - \left(\frac{6}{C}\right) + \left(\frac{C}{6}\right) \tag{2}$$

$$C = \frac{\sum_{i=1}^{n}(x_i - \mu)^3}{n\sigma^3} \tag{3}$$

where C = coefficient of skewness, x = precipitation for period i, and Z = Statistical Z index.

3.3 Standard Precipitation Index (SPI)

SPI is used in this study due to its advantages discussed below by [4].

1. Rainfall data alone sufficient for the assessment of drought using SPI.
2. The topography also doesn't significantly affect the SPI.
3. The various time scales described by the SPI help to characterize the drought conditions that are useful for hydrological and agricultural applications.
4. Another advantage lies in its standardization, which guarantees consistent frequencies of extreme events irrespective of the place and time.

In essence, computation of SPI starts with constructing a frequency distribution for a given time span from precipitation data at a site. In this method, the data is fitted with gamma probability and then fitted to normal distribution such that the SPI of a location has a zero mean [7].

The cumulative likelihood using the Gamma distribution is as follows:

$$G(x) = \frac{1}{\beta^{\alpha}\tau(\alpha)}\int_0^x x^{\alpha-1}\mathrm{e}^{-x/\beta}\mathrm{d}x \text{ for } x > 0 \tag{4}$$

where $x =$ the precipitation value, $\alpha =$ the shape parameter, $\beta =$ the scale parameter, and $\tau(\alpha) =$ Gamma function.

It can be easily calculated using built in function available in MS-Excel function as given below:

$$\text{SPI} = \text{NORMSINV}(\text{GAMMADIST}(\mu, \alpha, \beta, \text{TRUE})) \tag{5}$$

The α and β value can be determined using maximum likelihood method as follows:

$$\propto = \frac{1}{4A}\left(1 + \sqrt{1 + \frac{4A}{3}}\right) \tag{6}$$

$$\beta = \frac{\mu}{\alpha} \tag{7}$$

$$A = \ln(\mu) - \frac{\sum \ln(x)}{n} \tag{8}$$

where $\mu =$ mean value of precipitation, $x =$ precipitation and $n =$ rainfall observations in numbers.

4 Results and Discussion

The given period was classified into seven types based on the indices calculated. Table 2 shows the range of drought indices for SPI, CZI and statistical Z score. All three indices gave coherent results with regard to the classification.

The 25 years of daily rainfall data had been used in this analysis to compute the value of drought indices for various time scales such as monthly, annual, seasonal (NE, SW, and Winter) to evaluate the wet and dry periods of the Trichirapalli city. The calculation of three drought indices was carried out using Ms-Excel software. Zero monthly rainfall is considered to be 0.01 mm in order to calculate the SPI value as it is obtained by Gamma distribution. It should be noted that the distribution of Gamma is not defined for zero value. Considering zero precipitation months as 0.01 mm, the calculation of standard deviation and long-term mean value is not affected. The α and β values are calculated on the basis of Eqs. 6, 7 and 8. The built-up function represented by Eq. 5 is employed to determine the SPI value for each month, annual and seasonal value directly. Monthly drought indices are initially computed for each year. The rainfall values for the NE monsoon period (October, November and December), SW monsoon period (June–September), Winter (January and February) and Summer (March–May) are aggregated for each year to assess indices for different time scale. The deviation of SPI values was analyzed by comparing its value with SZs and CZI value.

Table 2 Different types of drought indices based on index value

SPI, CZI and Z score	Class	Symbol
≥2	Extremely wet	EW
1.5 to 1.99	Severely wet	SW
1 to 1.49	Moderately wet	MW
−0.99 to 0.99	Normal	N
−1 to −1.49	Moderately dry	MD
−1.5 to −1.99	Very dry	VD
≤−2	Extremely dry	ED

Table 3 Status of moisture level in recent 20 years (1991–2010)

Rainfall time scale	EW			VW			MW			N		
	SPI	SZs	CZI	SPI	SZs	CZI	SPI	SZs	CZI	SPI	SZs	CZI
Annual	0	0	0	2	3	3	4	2	2	14	15	15
SW	0	0	0	1	1	1	4	4	4	15	15	15
NE	2	2	0	1	1	3	1	0	0	17	21	18
Winter	1	1	1	1	0	0	2	2	2	9	22	22
Summer	0	1	1	1	0	0	3	3	3	17	17	17

Table 4 Status of moisture level in recent 20 years (1991–2010)

Rainfall time scale	MD			VD			ED		
	SPI	SZs	CZI	SPI	SZs	CZI	SPI	SZs	CZI
Annual	4	4	4	0	1	1	1	0	0
SW	4	4	4	0	1	1	1	0	0
NE	4	1	4	0	0	0	0	0	0
Winter	12	0	0	0	0	0	0	0	0
Summer	2	4	3	1	0	1	1	0	0

Tables 3 and 4 give moisture category based on SPI, CZI and SZs for various time scales. It can be seen from Table 3 that EW moisture categorization for NE and winter season is similar for both SPI and SZs method and for same moisture category all three indices shows the similar result for annual and SW season. For ED moisture category, the similar results are observed for both SZs and CZI for all the time scale. For normal moisture category, there is no deviation between CZI and SZs for all time scale except NE season. For MW category, both the method CZI and SZs show similar results for all time scale. By considering all the moisture category and different time scale, the CZI and SZs provided a similar result and it shows only minor deviation from results of SPI.

Table 5 shows the values of regression coefficient and corresponding equation between the (i) SPI and SZs, (ii) SPI and CZI, and (iii) SZs and CZI, for annual and seasonal rainfall. By considering above all three cases the range of regression coefficient varies from maximum of 0.999 to 0.643. The regression coefficient results show that for annual and SW season SZs versus CZI gives best fit than SPI. The lowest value of R^2 values such as 0.643, 0.853 and 0.904 indentified for winter season for all three cases respectively.

From Table 5, it has been concluded that the R^2 value obtained between SZs versus CZI is maximum for all time scale compared to other two cases.

Figure 3a–d shows the linear regression plot between the values of SPI and SZs for historical year 1981–2005. This means that for all the time period, except for the winter season, the SPI normally has a strong relationship. This is because that SZs shows the moderate dry condition and at the same year SPI shows the normal conditions, so that most of the points are far away from the regression line. The above said trend but better relationship is observed in the case of regression plot between SPI and CZI which is shown in Fig. 4a–e. Figure 5a–e shows the regression plot between SZs vs. China-Z Index shows the better relationship between these drought indices which is concluded from the regression coefficient is above 0.9 for all the time scale. By considering all the regression plots, SZs vs CZI shows better relationships for all the time scale except NE values. But regression plot between SPI versus SZs and SPI versus CZI Fig. 3b and Fig. 4b respectively show high relationship in NE season.

Table 5 Regression equation and its coefficient for different indices

Rainfall time scale	Linear equation			Regression coefficient (R^2)		
	SPI versus SZs	SPI versus CZI	SZs versus CZI	SPI versus SZs	SPI versus CZI	SZs versus CZI
Annual	$y = 0.975x$	$y = 0.976x$	$y = 0.999x$	0.991	0.994	0.999
SW	$y = 0.964x - 0.001$	$y = 0.967x$	$y = 0.997x + 0.001$	0.969	0.978	0.999
NE	$y = 0.968x + 0.005$	$y = 0.877x + 0.045$	$y = 0.879x + 0.041$	0.975	0.998	0.964
Winter	$y = 0.773x + 0.115$	$y = 0.568x + 0.348$	$y = 0.606x + 0.263$	0.643	0.853	0.904
Summer	$y = 0.935x - 0.004$	$y = 0.939x + 0.002$	$y = 0.975y + 0.006$	0.916	0.959	0.989

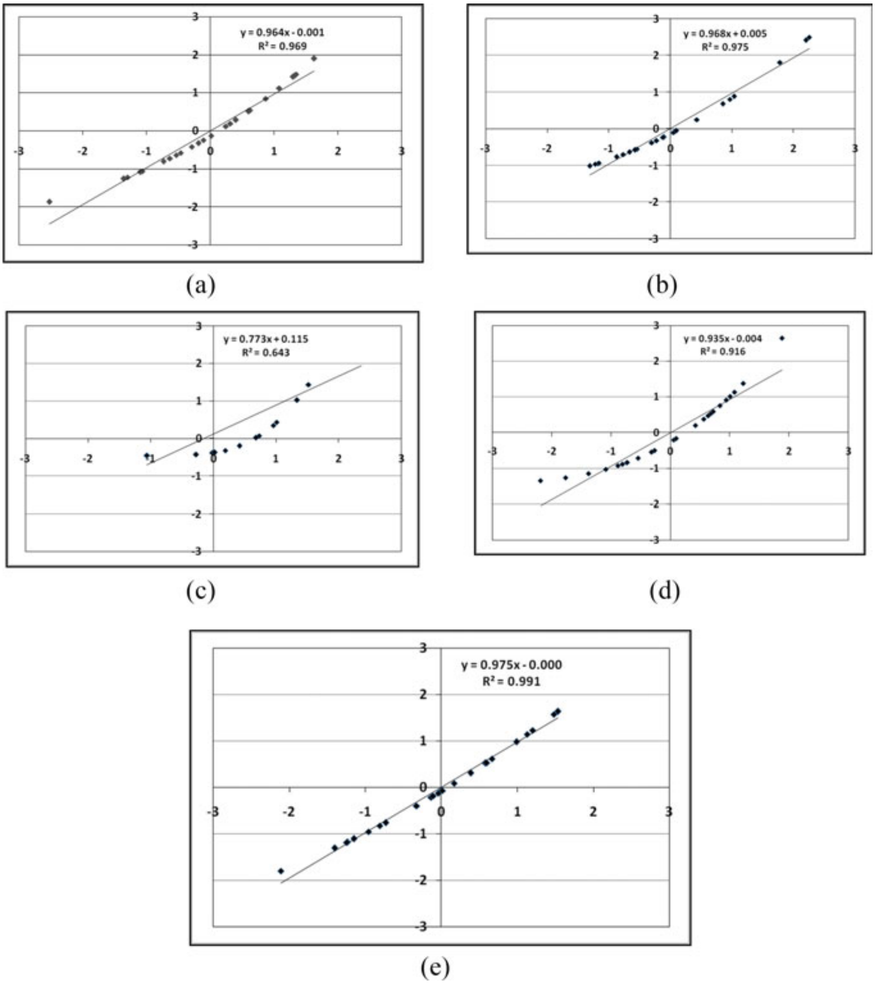

Fig. 3 Linear regression plot of SPI versus SZs for different times scale. **a** SW, **b** NE, **c** winter, **d** summer and **e** annual rainfall

5 Conclusion

Based on the findings on the Trichirappali city using monthly precipitation from the current drought analysis, the following conclusions can be drawn. This paper shows that SPI, CZI and SZs are effective tools for identifying, detecting and tracking flood and drought. The flexibility of the above methods enables checking of water supplies or fluctuations in precipitation at various timescales. In contrast, since it is derived solely from rainfall data, they are simpler than PDSI. With various time scales the CZI and SZs are very similar to the SPI. Suribabu and Neelakantan [9] concluded that there is fair agreement between three indicators for the annual moisture classification

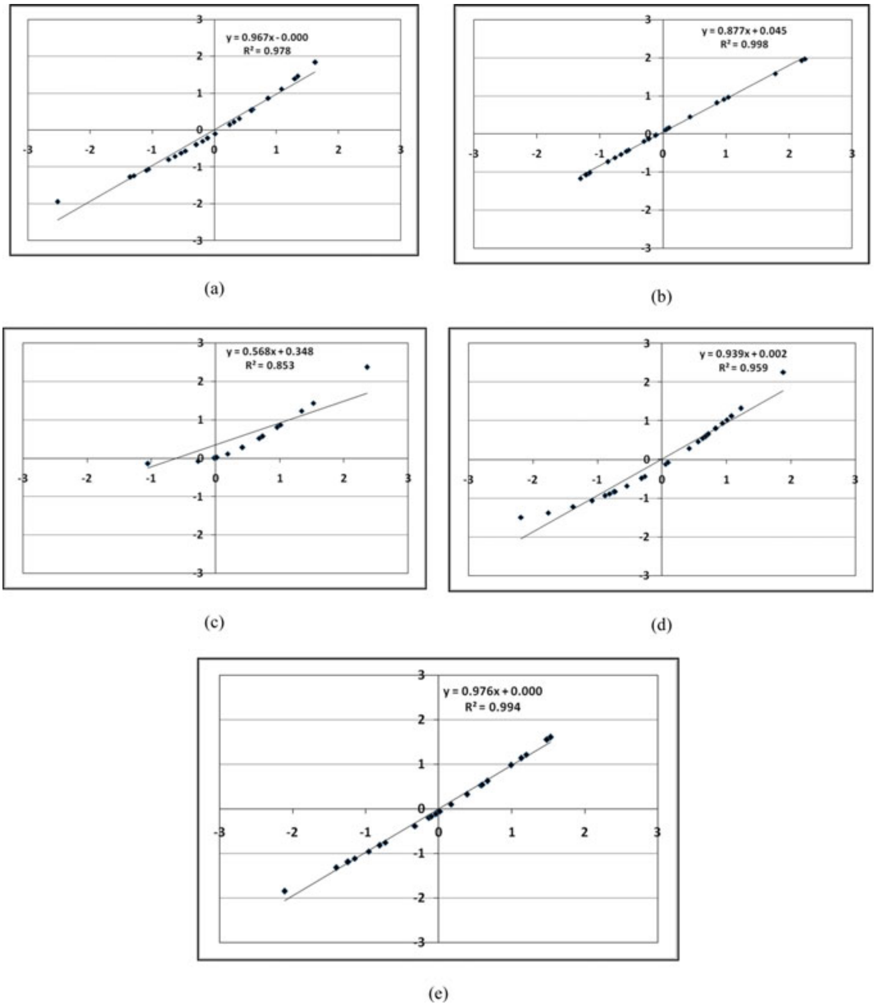

Fig. 4 Linear regression plot of SPI versus CZI for different times scale. **a** SW, **b** NE, **c** winter, **d** summer and **e** annual rainfall

and disagreement for the monthly moisture classification. In this paper, the findings show that the results of three indices for annual and monthly time series are identical for Normal moisture category. The main advantages of the CZI and SZs indices are that the computations of these two indices are simpler, and both indices allow missing data. This versatility is especially important for the areas where weather information is frequently incomplete. The study results using 25 years of rainfall data reveals that there is no extreme climatic conditions either severe dry or wet. Most of the year rainfall was close to be normal. This shows a favorable trend for farmers as the

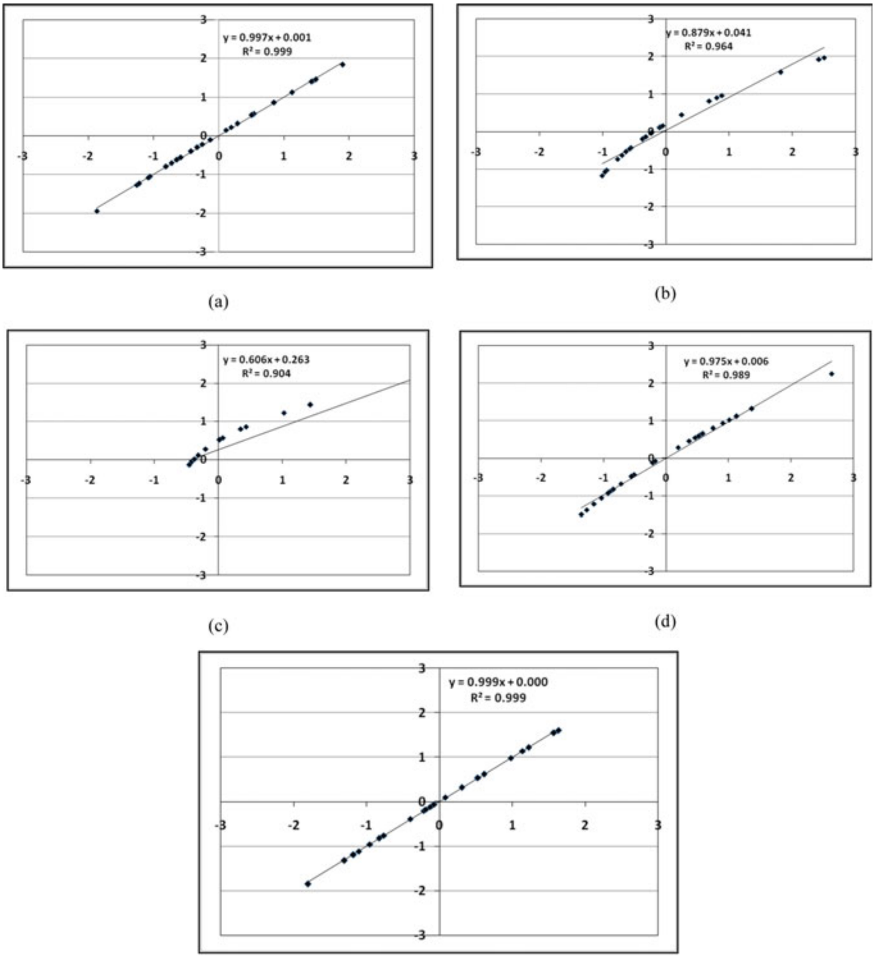

Fig. 5 Linear regression plot of SZs versus CZI for different times scale. **a** SW, **b** NE, **c** winter, **d** summer and **e** annual rainfall

chances of normal rainfall are fairly stable across different methods corresponding to the selected years for analysis.

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