Comparison of drought indices for appraisal of drought characteristics in the Ken River Basin

Vinit K. Jain a, Rajendra P. Pandey b, Manoj K. Jain c, Hi-Ryong Byun d

a Research Scholar, Department of Hydrology, Indian Institute of Technology, Roorkee, India
b National Institute of Hydrology, Roorkee, India
c Department of Hydrology, Indian Institute of Technology, Roorkee, India
d Department of Environmental Atmospheric Sciences, Pukyong National University, Korea

1. Introduction

The preparedness and planning to cope with adverse impacts of a drought event depend on the information about its areal extent, severity and duration. This information can be obtained through drought monitoring and forecasting that is usually done using drought indices which provide quantitative information to decision makers about drought characteristics (Dogan et al., 2012). Over the years, a number of indices have been proposed for drought characterization (e.g. Palmer Drought Severity Index, PDSI; Palmer, 1965), Deciles (Gibbs and Maher, 1967), Crop Moisture Index (CMI; Palmer, 1968), Bhalme and Mooley Drought Index (BMDI; Bhalme and Mooley, 1980), Surface Water Supply Index (SWSI; Shafer and Dezman, 1982), Standardized Precipitation Index (SPI; McKee et al., 1993), Effective Drought Index (EDI; Byun and Willhite, 1999), Soil Moisture Deficit Index (SMDI; Narasimhan and Srinivasan, 2005), Reconnaissance Drought Index (RDI; Dogan et al., 2012), and Rainfall Decile based Drought Index (RDDI; Narasimhan and Srinivasan, 2005). The study reveals that (1) 1-month time step in all DIs may produce erroneous estimates of drought duration. (2) The drought indices computed for 9-month time step are best correlated with each other. However, the drought duration and the drought frequencies estimated using RD and RDDI are in disagreement with other DIs, therefore, these are not suitable for this area where the summer concentration of precipitation is very high. (3) The DIs are highly correlated at same time steps and can alternatively be used. However, they are poorly correlated at dissimilar time steps, which makes it hard to assess whether the drought occurred or not. (4) Because there are no objective rules to select the appropriate time step, and the identified drought duration varies too much with different time steps, it is very hard again to assess when the drought occurred.

However, EDI, that has self-defined time step in itself, and free from time step problem, (1) is correlated better with other DIs for all time steps and effective on long and short drought together, with highest correlation at 9-month time steps, (2) identifies the drought condition earlier than any other indices, therefore, (3) is found to be more suitable drought index for the study basin. This is in agreement with the result of EDI application in Korea, Japan, Turkey, Australia and Iran though the methods of its testing are different.
(RDI; Tsakiris et al., 2007). All of these indices are normally continuous functions of any one or more hydro-meteorological variables, viz. precipitation, temperature, soil water, streamflow, groundwater, potential evapotranspiration etc. (WMO, 1975).

Most of the available drought indices are developed for specific regions and have the limitation of use under different climatic conditions because of the inherent complexity of drought phenomena. For example, PDSI (Palmer, 1965), is extensively used in the United States, the RDDI (Gibbs and Maher, 1967) is operational in Australia, the China Z-Index (CZI) is used by the National Meteorological Center in China (Wu et al., 2001) and SPI (Edwards and Mckee, 1997) is being used widely including India because of its adaptability to different time scales and climatic conditions. Several attempts have been made in the past to analyze the appropriateness in describing the droughts characteristics for a particular region using different indices (Keyantash and Dracup, 2002; Ntale and Gan, 2003; Morid et al., 2006; Barua et al., 2011; Dogan et al., 2012) using multiple criterions of tractability, transparency, and dimensionality for comparison of various drought indices. Smakhtin and Hughes (2007) developed Spatial and Time Series Information modeling (SPATSIM) software for automated estimation of drought severity using five different drought indices. Pandey et al. (2008) used SPATSIM for a drought study of Orissa, India and found that EDI performed better than other DIs. Dogan et al. (2012) compared six meteorological drought indices and indicated that each drought index identified the drought characteristics differently. They observed the variation in severity values and duration of a drought event computed using different indices. Further, they concluded that EDI performed better for monthly rainfall changes in semi-arid Kenya closed basin, and Turkey. Also, Dogan et al. (2012) suggested that application of multiple time steps has significant role in assessment of regional drought characteristics. If one is interested in short term rainfall anomalies near real time drought monitoring, the shorter time step (i.e., 1-month, 3-month) should be used. However, if one needs to study the regional drought characteristics and to formulate area specific mitigation plan, he must use longer time steps, i.e. 6-, or 12- month. Many times the 1-month time step may lead to erroneous assessment of drought severity, because monthly rainfall deficiencies are common feature of arid regions. The present study is undertaken in the Ken River Basin, a drought prone region of central India, where the summer concentration of rainfall is very high, to examine the applicability of various drought indices for assessment of meteorological drought characteristics. The specific objectives of this study are (1) to compute severity of past drought events using various meteorological drought indices (2) to compute correlation between estimated drought severity at multiple time steps and (3) comparing the quantitative values of drought attributes obtained using various meteorological drought indices.

2. Brief description of the study area and data used

The study has been carried out for the Ken River Basin, located in drought prone region of central India. The study basin lies between north latitudes of 23° 07' and 25° 30' and east longitudes of 78° 30' and 80° 40'. The river Ken originates at an altitude of 550.0 m above mean sea level (msl). The average elevation of the plain areas of the basin is about 328 m above msl. The study basin is situated in the semi-arid and dry sub-humid climatic region of India with a single rainy season (June-September) followed by dry winter, and then a very dry summer. The basin is fed by south-west monsoon which starts from middle of June and lasts till the end of September. The spatial distribution of rainfall in the basin is highly variable. The average annual areal rainfall in the basin varies from 1250 mm to 800 mm with an estimated basin averaged annual rainfall of about 1165 mm. Approximately 91% of the annual rainfall is received during monsoon months. Continuous monthly rainfall data of 13 districts in and around the study basin for a period of 102 years from 1901 to 2002 is obtained and used in the present analysis. The mean monthly, seasonal and annual rainfall of all districts is presented in Table 1. Fig. 1 shows the location of the Ken River Basin in India along with the demarcation of districts jurisdiction for which rainfall data has been utilized.

3. Selection of drought indices

In the present study long term area weighted rainfall data for the period from 1901 to 2002 for 13 districts obtained from India Water Portal website has been used for evaluating meteorological drought indices. Six meteorological drought indices have been applied for computation of severity and duration of drought events. These indices are Rainfall Departure (RD), Z-Score, CZI, SPI, EDI and RDDI. A brief description of above indices is given below:

3.1. Rainfall Departure from the mean or median (RD)

Rainfall Departure (RD) is a good indicator of dry/wet conditions for a given time over specified areas. It is calculated by subtracting the long term average rainfall from monthly rainfall and dividing the difference by the long term average rainfall. The

| District       | Geographic Location | Mean Monthly Rainfall of various districts (mm) | Annual | Seasonal (Jun–Sep) |
|----------------|---------------------|-----------------------------------------------|--------|--------------------|
|                | Longitude | Latitude | Jan      | Feb      | Mar      | Apr      | May      | Jun      | Jul      | Aug      | Sep      | Oct      | Nov      | Dec      |          |
| Banda          | 80.31     | 25.48     | 22       | 11       | 11       | 4        | 5        | 89       | 321      | 390      | 173      | 26       | 12       | 9        | 1073     | 973      |
| Chattarpur     | 79.59     | 24.92     | 22       | 13       | 10       | 4        | 5        | 106      | 352      | 396      | 182      | 26       | 16       | 9        | 1142     | 1036     |
| Damoh          | 79.45     | 23.84     | 18       | 17       | 12       | 6        | 7        | 135      | 356      | 399      | 192      | 32       | 16       | 10       | 1200     | 1081     |
| Fatehpur       | 80.82     | 25.93     | 20       | 11       | 10       | 4        | 5        | 87       | 295      | 348      | 164      | 30       | 9        | 8        | 990       | 893      |
| Hamirpur       | 80.15     | 25.95     | 19       | 10       | 7        | 4        | 5        | 81       | 306      | 347      | 171      | 24       | 12       | 8        | 992    | 905      |
| Jabalpur       | 79.93     | 23.17     | 19       | 23       | 19       | 7        | 12       | 162      | 354      | 381      | 193      | 40       | 17       | 12       | 1239     | 1090     |
| Karan          | 80.40     | 23.84     | 22       | 23       | 17       | 7        | 12       | 151      | 350      | 399      | 193      | 34       | 13       | 13       | 1234     | 1093     |
| Mahoba         | 79.87     | 25.29     | 21       | 11       | 8        | 4        | 5        | 90       | 335      | 369      | 177      | 23       | 16       | 9        | 1066     | 970      |
| Narasinghapur  | 79.19     | 22.44     | 14       | 15       | 15       | 7        | 10       | 138      | 352      | 353      | 213      | 35       | 22       | 9        | 1183     | 1056     |
| Panna          | 80.18     | 24.72     | 23       | 18       | 13       | 6        | 6        | 117      | 351      | 411      | 191      | 27       | 14       | 11       | 1188     | 1070     |
| Raisen         | 77.78     | 23.33     | 11       | 9        | 7        | 4        | 10       | 115      | 408      | 372      | 232      | 22       | 20       | 9        | 1218     | 1127     |
| Sagar          | 78.75     | 23.83     | 15       | 12       | 7        | 3        | 7        | 119      | 375      | 394      | 203      | 26       | 19       | 10       | 1191     | 1091     |
| Satna          | 80.83     | 24.58     | 26       | 20       | 16       | 5        | 8        | 113      | 336      | 400      | 184      | 26       | 13       | 10       | 1159     | 1034     |
| Ken River Basin as a whole | 20 | 15 | 11 | 5 | 6 | 116 | 352 | 395 | 190 | 28 | 16 | 10 | 1161 | 1052 |

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negative values represent the deficit and positive values represent
the excess rainfall with respect to corresponding average. It is a
straightforward measure of rainfall deviation from its long-term
mean or median or a pre-determined specification.

3.2. Standardized Precipitation Index (SPI)

The Standardized Precipitation Index (SPI) for any location is
calculated based on the long-term precipitation record for a de-
sired period. The available long-term rainfall data is fitted to
gamma probability distribution, which is then transformed to a
normal distribution so that the mean SPI for the location and
desired period is zero (Mckee et al., 1993). This transformed
probability is the SPI value, which varies between +2.0 and –2.0,
with extremes outside this range occurring at 5% of the time
(Edwards and Mckee, 1997).

The SPI is perhaps the most popularly used drought index.
Mckee et al. (1993) developed SPI to identify and monitor drought
events using monthly rainfall data. It is intended to identify
drought periods as well as the severity of droughts, at multiple
time steps, such as at 1, 3, 6, 9, 12 or 24-months. However, the
objective choice on the best time step may depend on the purpose
of drought analysis. Due to its reliability, and ability to address
drought at multiple time steps for a variety of climatic regions, SPI
has been used extensively in various parts of the world (e.g.
Guttman, 1999; Keyantash and Dracup, 2002; Ntale and Gan,
2003; Vicente-Serrano et al., 2004; Patel et al., 2007; Pandey et al.,
2008; Mishra and Singh, 2009; Edossa et al., 2010; Roudier and
Mahe, 2010; Stricic et al., 2011; Zhai et al., 2010; etc.). However,
continuous long term data of at least 30 years is required to
calculate SPI; it does not allow missing data. The complete pro-
cedure for estimation of SPI is available in Edwards and Mckee
(1997).

3.3. China Z-Index (CZI)

China Z-Index (CZI) is extensively used by National Climate
Centre (NCC) of China to monitor drought conditions throughout
the country (Wu et al., 2001; Dogan et al., 2012). CZI assumes
that precipitation data follow the Pearson Type III distribution and is
related to Wilson-Hilferty cube-root transformation (Wilson and
Hilferty, 1931) from chi-square variable to the Z-scale (Kendall
and Stuart, 1977). The value of CZI is calculated as

$$\text{CZI} = \frac{6}{C_r}\left(\frac{C_r}{2}Z\text{Score} + 1\right)^{1/3} - \frac{6}{C_r} + \frac{C_r}{6}$$

where, $C_r$ is coefficient of skewness for ‘t’ time step. ‘t’ can be
equal to 1-, 2-, 3- ....9-, 12-, 24 months etc. ZScore is the statistical
Z-score and will be computed for the same time step ‘t’. However,
NCC computes CZI only for 1-month time step. In the present
study CZI will be computed for five time steps i.e. 1-, 3-, 6-, 9- and
12-month time step.

Many studies comparing the CZI with that of SPI and Z-score
reported similar results (Wu et al., 2001; Morid et al., 2006).
Further, Wu et al. (2001) suggested that because of simplicity in
calculating drought severity at monthly time step using CZI, it can
be preferred over SPI, where rainfall data are often incomplete.

3.4. Statistical Z-Score (Z-Score)

This index is also as simple as RD and calculated by subtracting
the long term mean from an individual rainfall value and then
dividing the difference by the standard deviation. The Z-Score
does not require adjusting the data by fitting the data to the
Gamma or Pearson Type III distributions. Because of this, it is
speculated that Z-Score might not represent the shorter time
scales (Edwards and Mckee, 1997). Because of its simple calcula-
tion and effectiveness, Z-Score have been used in many drought
studies (Akhtari et al., 2009; Komuscu, 1999; Morid et al., 2006;
Patel et al., 2007; Tsakiris and Vangelis, 2004; Wu et al., 2001;
Dogan et al., 2012). Various researchers also acclaimed that it is as
good as SPI and can be calculated on multiple time steps. It can
also accommodate missing values in the data series like CZI.

3.5. Effective Drought Index (EDI)

The Effective Drought Index (EDI) was proposed by Byun and
Wilhite (1999) to monitor the duration and severity of drought.

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Byun and Wilhite (1999) used a new concept of effective precipitation (EP). They defined effective precipitation as a function of current month’s rainfall and weighted rainfall over a defined preceding period computed using a time dependent reduction function. They computed EDI as a function of the amount of precipitation required to return to normal (PRN). Where, PRN is calculated from monthly effective precipitation and its deviation from the mean for each month. Thus, first step in calculation of EDI is to calculate EP. If Pj is rainfall ‘m’ months before the current month and N is the duration of preceding period, then effective precipitation for the current month (EPj) is given as

\[ EP_j = \sum_{m=1}^{N} \left( \sum_{i=1}^{m} P_i \right) / m \]  

(2)

For example if \( N = 3 \) then \( EP_j = P_1 + (P_1 + P_2)/2 + (P_1 + P_2 + P_3)/3 \), where \( P_1, P_2 \) and \( P_3 \) are rainfall values during current month \( (j) \), previous month and 2 months before respectively. Then average and standard deviation of EP values for each month are calculated and the time series of EP values is converted to deviations from the mean (DEP):

\[ DEP_j = EP_j - \bar{EP} \]  

(3)

The PRN values are then calculated as follows:

\[ PRN_j = \frac{DEP_j}{\sum_{i=1}^{N} \left( \frac{1}{i} \right)} \]  

(4)

The summation term is the sum of the reciprocals of all the months in the duration \( N \) (i.e. for \( N = 3 \) months), this term will be equal to \( \frac{1}{1} + \frac{1}{2} + \frac{1}{3} \). Finally EDI is calculated as follows:

\[ EDI = PRN_j / \tilde{\sigma}_{PRN} \]  

(5)

where, \( \tilde{\sigma}_{PRN} \) is the standard deviation of the corresponding month’s PRN values.

Originally, EDI was developed to monitor drought condition on daily time step (Akhbari et al., 2009; Kalamaras et al., 2010; Kim and Byun, 2009; Kim et al., 2009; Morid et al., 2006; Roudier and Mahe, 2010; Lee et al., 2012). Subsequently, it was extended for monthly drought monitoring (Smakhtin and Hughes, 2004; Morid et al., 2007; Pandey et al., 2008; Deo and Byun, 2014). The EDI and SPI use similar classification of drought severity. The EDI is based on the concept of effective precipitation (EP) that is calculated by a time dependent reduction function on daily/monthly precipitation and requires specifying at least 30-years data for calculation of mean effective precipitation. For calculation of monthly EDI, time step is defined by the unit of time (originally daily, but monthly in this study), the rainfall for the current month is given more weight and the weights in decreasing order are given to each preceding month’s rainfall values. Using the concept of reduction function, the onset and end date of drought can be defined clearly. The software to calculate the EDI at monthly and daily time step is freely available at http://atmos.pknu.ac.kr/~intra2/.

### 3.6. Rainfall deciles based drought index (RDDI)

The RDDI was originally suggested by Gibbs and Maher (1967) for investigating rainfall deficiency as per criteria set by the Australian Bureau of Meteorology. Deciles are calculated from actual rainfall series. First, rainfall values of each calendar month (or sum of rainfall values for a group of months for multiple time step) are ranked from lowest to highest and a cumulative frequency distribution is constructed. The distribution is then split into 10 deciles (10% slices). The first decile that has the top rainfall values indicates wettest months in the series, the last decile indicates driest months in the series. Deciles have been used in many drought indices evaluation studies (e.g., Keyantash and Dracup, 2002; Morid et al., 2006; Smakhtin and Hughes, 2007; Mpelasoka et al., 2008; Pandey et al., 2008; Barua et al., 2011; Dogan et al., 2012). The use of decile is advantageous due to simplicity in its computation. However, Keyantash and Dracup (2002) noted that this simplicity may lead to conceptual difficulties. For example, it is reasonable for a drought to terminate when observed rainfall is close to or above normal conditions. However, minor amounts of precipitation during non-monsoon periods, during which little or no precipitation is common (e.g., summer along the West Coast) could activate the first stopping rule, even though the absolute quantity of precipitation is trivial and does not terminate the water deficit. Therefore, climates with highly seasonal precipitation may not be well suited to rainfall deciles.

### 4. Methodology

The present investigation is carried out to compare the six drought indices for applicability in the Ken River Basin. The common procedural steps followed for comparison of drought indices are as under:

#### 4.1. Calculation of drought indices

The drought severity is calculated using SPI, Z-Score, CZI, RD, RDDI for 1, 3, 6, 9, and 12-month time steps and monthly EDI. In this study, the application of five drought indices for five different time steps and one drought index (EDI) for self-defined single time step resulted in 26 drought index time series.

#### 4.2. Comparison of DI values using Pearson correlation coefficients

The Pearson Product-Moment Correlation Coefficient, commonly termed as correlation coefficient (\( r \)), is a measure of linearity between two arrays and most widely used test statistics. Correlation Coefficient is computed pair wise between all 26 time series for the entire period of record creating a cross correlation matrix. It is calculated using Eq. (6).

\[ r = \frac{1}{n} \sum_{i=1}^{n} \left( \frac{x_i - \bar{x}}{S_x} \right) \left( \frac{y_i - \bar{y}}{S_y} \right) \]  

(6)

where, \( x_i \) and \( y_i \) represent the values of arrays with ‘n’ number of elements being compared and \( x \) and \( y \) are the mean values of two arrays and \( S_x \) and \( S_y \) are the standard deviation of \( x_i \) and \( y_i \) respectively. The \( r \) measures the degree of similarity in variation about the means of two values.

#### 4.3. Comparison of the drought characteristics identified by each drought index

Various indices have been used to identify number of drought months (i.e. the number of months falling under moderate, severe and extreme dry categories for which value of drought index is –1 or less) and maximum duration of drought event (i.e. continuous period of such drought months) in the given district. Subsequently, the above drought attributes estimated using different indices for various districts have been compared.

#### 4.4. Comparison of drought indices during historical drought period

Drought severity values computed using various indices are plotted for the historical drought period and compared to assess the suitability of different indices in identifying the onset and...
5. Results and discussion

5.1. Category of drought severity

The SPI is most widely used drought index in various parts of the world and is found to be suitable for Asia region too (Smakhtin and Hughes, 2004). EDI is relatively new drought index and have not been tested extensively for its applicability in Indian region, however some studies (Moirid et al., 2006; Mishra and Singh, 2009, Dogan et al., 2012) reported that EDI is more responsive to the occurrence of monthly rainfall deficiency is common feature of climate and 1-month time step may not describe the drought situation appropriately. The drought index values computed using these indices help in understanding the level of severity of a drought event. The various DIs have different range of values for defining the severity of a drought event. Therefore, for inter comparison of various indices, droughts are generally categorized into moderate, severe or extreme category depending upon the estimated values of index. The range of values for each severity category of various indices is shown in Table 2.

5.2. Comparison of drought indices using drought severity values

The comparison of various drought indices has been made by comparing the computed values of drought indices. For this purpose the Pearson correlation coefficients between paired time series of the severity values estimated using all drought indices are computed. For example severity values estimated using EDI are paired with severity values estimated using SPI-1 and correlation coefficient (0.52) is computed for this pair to form one cell of the matrix. Likewise the severity values estimated using SPI-1 is paired with severity values estimated using other DIs for all time steps and so on. This created a cross correlation matrix of 26 rows and 26 columns (5 indices X time steps and EDI with single time step=26). The first drought severity value using various indices for

Table 2

| Category       | Range of drought index values | EDI | SPI | SPI-3 | Z-Score | RD | RDDI-9 |
|----------------|------------------------------|-----|-----|-------|---------|----|--------|
| Extremely dry  | ≤ -2.0                       | -2  | -2  | -2    | -2     | ≤ -60 | < 10   |
| Severely dry   | -1.99 to -2.0                | -1.99 to -2 | -1.99 to -2 | -1.99 to -2 | -60 to 10 | -20 |
| Moderately dry | -1.49 to -1.5                | -1.49 to -1.5 | -1.49 to -1.5 | -40 to -30 | -30 |
| Normal         | 0.99 to 0.00                 | -0.99 to -0.99 | -0.99 to -0.99 | -30 to 0 | 0 |
| Moderately wet | 1.0 to 1.49                  | 1.0 to 1.49 | 1.0 to 1.49 | 1.0 to 30 | 70-80 |
| Very wet       | 1.5 to 1.99                  | 1.5 to 1.99 | 1.5 to 1.99 | 1.5 to 80 | 90 |
| Extremely wet  | ≥ 2.0                        | ≥ 2.0 | ≥ 2.0 | ≥ 2.0 | ≥ 60 | ≥ 90 |

The average in column SPI-3 is computed from the average correlation of SPI-3 with 3-monthly time step of DIs such as SPI-3, Z-Score-3, SPI-6, RDDI-3, RDDI-6 and average in column RDDI-9 is computed from the average correlation of RDDI-9 with 9-monthly time step of DIs such as SPI-1, SPI-3, Z-Score-3, SPI-6, RDDI-3, RDDI-6. 1-, 3-, 6-, 9- and 12-month time steps are obtained from the months of January-1901, March-1901, June-1901, September-1901 and December-1901, respectively. Therefore, the correlation between index values of different time steps is computed from the month of Jan-1902 to December-2002, in order to maintain the equal number of data points for all time steps. The similar correlation matrices are prepared for all districts and correlation matrix for district Sagar is shown in Table 3, as illustration.

From Table 3 it can be noted that the values of correlation coefficients of EDI with other indices (column 2) are more than that of the values of correlation coefficient with SPI-1 (column 3), except correlation of SPI-1 with other DIs of 1-month time step. For instance, correlation of EDI with SPI-3 is equal to 0.64, whereas, correlation of SPI-1 with SPI-3 is equal to 0.51. Likewise, values of correlation coefficient of EDI (each row of column 2) with other indices are also higher than the correlation of SPI-3 with other indices (column 4), except correlation of SPI-3 with other DIs of 3-month time step. The similar results are seen with other indices too. It indicates that correlation coefficient of EDI paired with other indices is comparatively higher (except for 1-month time step of other DIs). Further it is interesting to see that, the correlation of EDI with other indices increases with the increase in their time step up to 9-month. The correlation coefficient of EDI with other indices is more than 0.8 for the 9-month time step. The EDI shows highest correlation coefficient of 0.93 with Z-Score-9 (values not shown in Table 3). The correlation coefficients of EDI with 12-month time step of other DIs varies from 0.78 to 0.88. The correlation coefficient of EDI paired with other DIs for selected five time steps are shown in Fig. 2.

The Fig. 2 clearly indicates that correlation of EDI with 9, and 12-month time steps of SPI, Z-Score, SPI-3, RD and RDDI is more than 0.7. Also, correlation of EDI with 1 and 3-month time steps of SPI, Z-Score, RD and RDDI is more than 0.5 and 0.6 respectively. This suggests that EDI is comparable with other DIs for detection of long and short term droughts, though it always uses more than 12 months duration for its computation (time dependent reduction function). However, correlation of EDI with RD and...
RDDI is comparatively less for lower time steps. This suggests that RD and RDDI are comparable with EDI for higher time steps only.

On the other hand, very high correlation coefficient is observed between the paired values of SPI-1 with Z-Score-1 (r = 0.92), CZI-1 (r = 0.97), RD-1 (r = 0.83) and RDDI-1 (r = 0.88). Similarly, correlation coefficient of SPI-3 with Z-Score-3 (r = 0.96), CZI-3 (r = 0.99), RD-3 (r = 0.88) and RDDI-3 (r = 0.91) are also very good. Other indices also exhibit high values of correlation coefficients paired with the estimated values of index for same time step. It indicates that for same time step most of the indices are better correlated (r > 0.8). However, the estimate of SPI-1 values does not show good correlation with that of 3-, 6-, 9- or 12-month time steps of different DIs. Similarly, SPI-3 does not show good correlation with 1-, 6- 9- or 12-month time steps of other DIs. Likewise, poor correlation has been observed between estimates of other DIs for dissimilar time steps. This revealed that the estimates obtained from various DIs may not be comparable for different time steps.

Further, row 27 in Table 3 presents the average correlation coefficients estimated among various DIs for different time steps. For instance, average of column 2 i.e. EDI (0.72) represents the average correlation of EDI, with different DIs for all time steps. Similarly, column 4 i.e. SPI-3 (0.59) represents the average correlation of SPI-3 with different DIs for all time steps and so on. This analysis indicated that the highest average correlation is obtained for EDI and this also confirms that EDI is comparatively better correlated with other DIs with time steps of 1-, 3-, 6-, 9- and 12-month.

Similarly, the average value of correlation coefficient of a DI for a given time step with different DIs is shown in row 28 in Table 3. For example, in the column 3 row 28 of Table 3, the value 0.92 is the average of paired correlations of SPI-1 and SPI-1, SPI-1 and Z-Score-1, SPI-1 and CZI-1, SPI-1 and RD-1, and SPI-1 and RDDI-1 (i.e. for 1-month time step). Similarly, column 25 row 28 of Table 3, the value 0.88 is obtained from the average correlation of RDDI-6 with 6-monthly time step of DIs i.e. SPI-6, Z-Score-6, CZI-6, RD-6 and RDDI-6. Likewise all other averages in row 28 of Table 3 are obtained from the correlations of same time steps. The high value of average correlation coefficient (in Row 28) indicated that most of the DIs are better correlated with the DIs of same time step. Further, it is seen that the value of average correlation is relatively higher in longer time steps.

The average values of correlation coefficient of a DI in 1-month time step of each index (i.e. column 3, 8, 13, 18 and 23 of row 27 in Table 3) are further averaged to represent the 1-month time step average correlation of DIs. Similarly, average values of correlation coefficients of DIs for 3-, 6-, 9- and 12-month time steps have been computed. These computed values of correlation coefficient of DIs for different time step are plotted for different districts in Fig. 3. Further, the mean value of correlation coefficient for each time step is shown as continuous thick blue line in Fig. 3.

It is evident from the Fig. 3 that the mean value of correlation coefficients of DIs is maximum for 9-month (0.64) time steps followed by 6 months (0.62) and 12 months (0.56). From this analysis, it may be concluded that the 9-month time step may be more appropriate for comparison of DIs. It appears to be justified because in major parts of India, once the monsoon season is over (in September) significant rainfall is received only after 9 months i.e. onset of next monsoon.

In the analysis, RDDI showed relatively poor relationship with other DIs even for same time steps. The similar results are obtained for other districts too. This suggests that the application of RDDI is not suitable for any of the district in study basin. On the other hand, EDI is better correlated with other DIs for all time steps and best correlation of EDI with other DIs was found for 9-month time step (Fig. 2).

5.3. Appraisal of drought characteristics

As stated earlier that droughts are characterised with their duration and severity. Therefore, the drought months are identified using various indices during period 1902–2002 and are presented in Table 4.

It is very interesting to note that number of identified drought months increased with the increase of time step for SPI, Z-Score and CZI, whereas, RD identified maximum number of drought months for 1-month time step and decreased considerably with the increase of time step. However, RDDI identified approximately equal number of drought months with each time step and estimated relatively more number of drought months as compared to other DIs. As discussed in preceding sections, most DIs are better correlated for 9-month time step. Also, it is found that the number of drought months identified using EDI and other DIs for 9-month time step (except RDDI) are nearly equal. The number of drought months obtained using different DIs for 9-month time step for various districts in the study basin are plotted in Fig. 4.

It is clear from Fig. 4 that drought months identified using various DIs for 9-month time step for different districts are within a close range except in case of Raisen district. It further supports the conclusion that 9-monthly time step provides reasonable estimates of drought severity and duration for comparative analysis of various indices in the Ken River Basin.

The identified drought months are segregated under different drought severity categories according to the severity value (mentioned in Table 2) of each index i.e. Moderate, Severe and Extreme for various districts in study basin. The plots of number of drought months identified under different severity classes using various indices for Sagar district are shown as percentage of period under consideration in Fig. 5(a–e).

It can be noted from Fig. 5(a–c) the drought months as percent of total number of months under consideration obtained using SPI, Z-Score and CZI for 6, 9, and 12-month time step are very close ranging from 15.01% to 16.58%. However, there are significant differences in number of drought months with moderate, severe and extreme severity categories even for higher time steps of DIs.

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Also, RDDI (Fig. 5d) identified approximately equal number of drought months under different severity categories for all time steps. On the other hand, RD identified more number of drought months at shorter time step and significantly less number of drought months under extreme category with increase in time step (Fig. 5e). The estimates of severity categories using RDDI and RD are significantly different from the estimates of drought months using SPI, CZI and Z-Score. This means that RD and RDDI are not suitable for the Ken River basin where summer concentration of precipitation is very high.

In addition to the number of total drought months, the maximum duration of a single drought event (continuous period of drought months) are also identified using various indices for all time steps. The maximum duration of identified drought event increases at higher time step. The analysis indicated that maximum duration of drought event varies for each district. Some of the districts with longer duration are more prone to drought as compared to other districts. Maximum duration of identified drought event using DIs for 9-month time step for various district are presented in Fig. 6.

Fig. 6 indicates that Satna district has faced drought event of maximum duration i.e. 32 months estimated using EDI. Also, Panna, Katni, Chattarpur and Damoh districts have faced drought events for maximum duration of continuous 23 months.

Estimates of drought duration obtained using EDI appears to be slightly more as compared to other DIs for most of the districts. However, these estimates from other DIs are within a close range of drought duration.

The scrutiny of estimates revealed that the reason of longer drought duration estimate by EDI is because of the early detection of the drought onset as compared to other DIs. Also, the drought is not terminated by EDI, until rainfall during non-monsoon months is sufficient high to meet the water deficiencies required for termination of drought. It is due to the reason that EDI considers the reduction of water with time passing. For example, the rainfall 9 month before is summed in SPI with same weight of it one month before. However, EDI considers it not with same weight but with reduced weight because water is diminished by evaporation, run-off etc for 8 months. Therefore EDI detects drought earlier than other DIs.

5.4. Comparative evaluation of drought indices in real case

Once a drought is triggered during the monsoon months, it is often continued till the arrival of next monsoon. It may also however terminate if significantly excess rainfall occurs during non-monsoon month of the year. It is simply because the rainfall deficiencies created during monsoon months are not usually met from rainfall during non-monsoon months. In order to establish the suitability of a particular DI and the time step in defining the

Table 4

| Drought Index | Banda | Chattarpur | Damoh | Fatehpur | Hamirpur | Jabalpur | Katni | Mahoba | Narsinghapat | Panna | Raisen | Sagar | Satna |
|---------------|-------|------------|-------|----------|----------|---------|-------|-------|-------------|-------|-------|-------|-------|
| EDI           | 201   | 224        | 214   | 172      | 205      | 190     | 196   | 225   | 201         | 206   | 202   | 206   | 187   |
| SPI-1         | 143   | 157        | 206   | 175      | 140      | 254     | 255   | 137   | 259         | 206   | 167   | 226   | 173   |
| Z-Score-1     | 83    | 69         | 71    | 81       | 87       | 73      | 98    | 85    | 73          | 69    | 61    | 61    | 83    |
| CZI-1         | 102   | 111        | 105   | 100      | 102      | 163     | 178   | 111   | 97          | 117   | 77    | 87    | 143   |
| RD-1          | 598   | 598        | 593   | 617      | 593      | 548     | 556   | 588   | 606         | 585   | 649   | 626   | 571   |
| RDDI-1        | 375   | 378        | 369   | 365      | 381      | 373     | 372   | 382   | 376         | 370   | 367   | 370   | 368   |
| SPI-3         | 192   | 202        | 195   | 183      | 190      | 186     | 182   | 200   | 189         | 193   | 181   | 195   | 184   |
| Z-Score-3     | 189   | 197        | 179   | 172      | 192      | 178     | 182   | 202   | 168         | 192   | 135   | 154   | 176   |
| CZI-3         | 200   | 209        | 193   | 190      | 207      | 194     | 192   | 213   | 190         | 202   | 178   | 189   | 193   |
| RD-3          | 432   | 431        | 422   | 421      | 413      | 366     | 390   | 413   | 438         | 409   | 469   | 427   | 0     |
| RDDI-3        | 367   | 367        | 367   | 366      | 365      | 368     | 366   | 366   | 367         | 367   | 367   | 367   | 366   |
| SPI-6         | 191   | 210        | 194   | 177      | 197      | 200     | 184   | 206   | 199         | 195   | 189   | 195   | 195   |
| Z-Score-6     | 196   | 212        | 190   | 188      | 203      | 198     | 187   | 217   | 190         | 204   | 172   | 183   | 198   |
| CZI-6         | 200   | 215        | 197   | 192      | 206      | 200     | 189   | 220   | 198         | 204   | 186   | 191   | 200   |
| RD-6          | 285   | 308        | 294   | 282      | 293      | 248     | 250   | 301   | 307         | 292   | 350   | 303   | 254   |
| RDDI-6        | 361   | 365        | 365   | 362      | 360      | 367     | 366   | 362   | 367         | 365   | 367   | 366   | 363   |
| SPI-9         | 193   | 208        | 199   | 177      | 194      | 185     | 181   | 209   | 171         | 196   | 191   | 198   | 191   |
| Z-Score-9     | 199   | 219        | 201   | 183      | 207      | 184     | 180   | 217   | 209         | 207   | 186   | 196   | 194   |
| CZI-9         | 201   | 219        | 202   | 185      | 207      | 189     | 181   | 218   | 215         | 208   | 190   | 198   | 195   |
| RD-9          | 209   | 220        | 194   | 215      | 209      | 152     | 147   | 212   | 204         | 207   | 261   | 199   | 167   |
| RDDI-9        | 361   | 362        | 364   | 361      | 360      | 364     | 363   | 361   | 364         | 362   | 364   | 364   | 362   |
| SPI-12        | 204   | 202        | 183   | 179      | 200      | 195     | 172   | 210   | 240         | 200   | 208   | 201   | 180   |
| Z-Score-12    | 209   | 211        | 183   | 189      | 210      | 190     | 177   | 214   | 227         | 208   | 199   | 198   | 182   |
| CZI-12        | 209   | 211        | 183   | 189      | 210      | 194     | 177   | 215   | 237         | 208   | 207   | 201   | 182   |
| RD-12         | 163   | 167        | 146   | 164      | 156      | 89      | 100   | 169   | 158         | 164   | 225   | 158   | 115   |
| RDDI-12       | 361   | 361        | 361   | 361      | 360      | 361     | 361   | 360   | 361         | 361   | 361   | 361   | 361   |

![Fig. 4. Comparison of number of drought months identified using EDI and 9-monthly time step of various indices for different districts.](https://dx.doi.org/10.1016/j.wace.2015.05.002)
onset, termination and severity quantification of drought event, the values of various indices are plotted for the drought years for various districts. The plots of comparison for EDI, SPI, CZI and Z-Score for 1-month and 9-month time steps for district Sagar are shown in Fig. 7(a) and (b) respectively. Also, analysis presented in preceding sections indicated that EDI provides relatively better assessment of drought for study area. Therefore, the performance of other DIs has been discussed in comparison to the values of EDI. Specific discussions are presented here for the occurrence of drought event during January-1991 to January-1994. The results are then validated based on the time series of monthly rainfall compared to monthly average rainfall for 1-month time step. Similarly, DIs with higher time steps are validated based on multi-monthly rainfall (obtained from sum of previous months rainfall depending upon the time step) compared to average of multi-monthly rainfall of the corresponding period (fixed for particular month). For example, for 6-month time step, the rainfall value of June month is the sum of five previous months’ rainfall plus June month rainfall and the multi-monthly average is the average of all June months in the 6-monthly time series. Similarly for 9-month time step the rainfall value of December month is sum of April–December months’ rainfall and the multi-monthly average is the average of all December months in the 9-monthly time series (Fig. 7b).

It can be seen from Fig. 7(a) that during July-1991 there had been significant rainfall deficit (~64%). The EDI, SPI, CZI and Z-

![Fig. 5. Comparison of percentage of drought severity categories identified using EDI and 1, 3, 6, 9 and 12-month time step of (a) SPI (b) Z-Score (c) CZI (d) RDDI and (e) RD for Sagar district.](image)

![Fig. 6. Comparison of the maximum duration of drought events identified using EDI and 9-month time step of various indices for different districts.](image)
Score represents drought situation appropriately. However, rainfall during the month of August-91 was slightly above the monthly average value (+16%). The SPI, Z-Score and Z-Score indicated this month as moderately wet (0.43–0.54), the termination of drought in August-91 and re-onset in September-91, while EDI identified it under normal range (−0.52). This is simply because the consideration of previous deficit accumulation is important and it is considered in case of EDI.

Subsequently, the period between September-1991 to April-1992 (except Dec–91) was again a deficit period and therefore, drought started in July-1991 is still continued in September-1991 and onward. Further the rainfall values for the month December-1991 is 12 mm against average of 10 mm. Since, this excess is insignificant and insufficient to terminate the drought; this situation is very well indicated by EDI which indicated this period as drought without terminating the on-going drought event. On the other hand, Z-Score-1, CZI-1 both in October-1991 and SPI-1 in November-1991 indicated the termination of drought.

Further, during January-1992 to April-1992, no significant rainfall has been received during this period, however, SPI-1, Z-Score-1 and CZI-1 indicated this period as normal, whereas, EDI rightly indicated this period under drought condition. In May-1992, only small surplus of precipitation made DIs to represent this month under wet category except EDI, because it is in dry season and this surplus was insufficient to fulfill previously accumulated deficit. Rainfall during the period June-1992 (89% deficit), July-1992 (84% deficit) to August-1992 (32% deficit) was again continuously less than average and SPI (−2.28) identified it as extreme drought during Jun-92. However, the same event (June-1992) is described under severe category by EDI (−1.55) because of less significant rainfall during June month and with increased severity during July-1992 (−2.28) and August-1992 (−2.0). During September-1992 (65% surplus), SPI-1, Z-Score-1 and CZI-1, terminated the drought and defined the event under wet category. However EDI indicated this month as temporary escape from drought situation, which is quite obvious because the surplus rainfall during September-1992 was still not sufficient to meet the previously accumulated deficit and to be indicated as wet month.

During period October-1992 to June-1993, the rainfall is again either below normal or insignificant and EDI appropriately detected this rainfall defining this period under drought. However, other indices detected this period as normal and the next onset of drought only during the month July-1993 (except SPI-1, which detected December-1992 also as drought month). Again, the rainfall during the period July-1993 to December-1993 is significantly below normal value and during the period January-1994 to May-1994 rainfall is more than average (non-significant in terms of its magnitude). During this period (July-1993 to May-1994) SPI-1, Z-Score-1, CZI-1 continue to define the combination of dry and wet events till the end of December-1994, while EDI continue to show the drought of moderate category till the end of May-1994 because of poor monsoon during the year 1993. The return to normal by EDI is shown at June-1994 with heavy rain. However in other indices that using 1-month time step, many normal conditions appeared during the drought period. Especially in May-92, where these DIs indicated the month as wet. In actual, EDI clearly showed the water deficit from July-1991 till May-1994, except temporal escape from drought situation (0.0 > EDI > −1.0), in August-1991, May-1992, September-1992 and June-1993 months, and indicated it as long duration of drought, that is terminated only in June-94.

Above discussion indicates that application of SPI, Z-Score and Z-Score for 1-month time step may lead to erroneous assessment of drought situation. Further, it can be concluded from above discussion that the EDI has captured the real essence of drought situation of study area.

For comparison of various indices at 9–monthly time step the index values plotted for the same historical drought period are

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shown in Fig. 7(b). It can be seen from Fig. 7(b), that EDI time series curve is close to that of SPI-9, CZI-9 and Z-Score-9.

During, January-1991 to May-1991, the 9-monthly rainfall is more than the corresponding normal values, therefore, this period is well indicated as non-drought period by all DIs. Further, the 9-month rainfall from June-1991 to April-1993 is continuously below the 9-monthly average rainfall. This period is indicated as drought period except few temporal escapes by SPI-9, CZI-9 and Z-Score-9 during the month April-1992 and by EDI during May-1992 and September-1992. During April-1992, the magnitude of 9-month rainfall deficit is less as compared to previous deficit during September-1991 to March-1992. Therefore, SPI-9, Z-Score-9 and CZI-9 indicated temporary escape from drought in April-1992. However, the EDI, which depends on the 12 months’ time dependent reduction function, indicated April-1992 as drought month because the effect of the surplus of rainfall at May-1991 has diminished due to the passing of time. At May-1992, EDI value shows slight increase because of surplus rainfall during this month and accumulated (but reduced on passing of time) effect of previous rainfall during the months from June-1991 to April-1992 (Fig. 7a). EDI considers the recent rainfall more important than the past rainfall because the major part of past rainfall might have diminished by evaporation, runoff and other losses. After May-1992, all indices indicated the similar pattern of increases and decreases of drought severity except for April-1993. In April-1993, small excess of rain made DIs above normal except EDI that show slight increase at June-1993.

The comparative analysis of various indices indicated that the period from June-1991 to May-1994 had been generally a drought period with one or two instances of above normal rainfall during this period. This period has been verified with the documented records of District Statistical Handbook. It is observed from the analysis that during the period of drought identified using EDI, the region suffered with huge crop loss. On the other hand, the wet periods identified using SPI, Z-Score and CZI did not help much in terminating the drought. It revealed that EDI seems to be more suitable in timely detection of long term as well as short term monthly rainfall deficiency as compared to other indices.

6. Conclusions

Following conclusions can be drawn from the study.
1. Comparison of EDI, SPI, Z-Score, CZI, RD and RDDI indicated that all these indices are highly correlated for same time steps and the correlation increases at higher time step with higher correlations at 9 and 12-month time steps. On the contrary, SPI, Z-Score, CZI, RD and RDDI are found to be poorly correlated with dissimilar time steps.
2. Historical drought analysis based on the EDI, SPI, Z-Score, CZI, RD and RDDI indicated that EDI showed the drought condition of the study basin more realistically than other DIs.
3. Selection of time step in identification of onset of any long term drought is very important. Drought indices compared at 1-month time step may lead to erroneous assessment of drought characteristics because sometimes a short term excess may terminate the long term drought and divide a prevailing drought event into two short events and this may not be appropriate. Therefore, while comparing drought indices, the drought severity should be computed using higher time step of the drought index. The time step should be chosen in such a way, that at least one significant rainfall month is included in the time step.
4. EDI is found to be better correlated with other DIs for all time steps (except same time step of various DIs). The best correlation of EDI was found to be with 9-month time step of other indices. This indicates that 9-month time step of DIs is a better choice to detect the drought intensity for study basin.
5. Overall EDI is found to be good choice for assessment of drought characteristics and monitoring of drought condition, because of its capability of timely detection of drought onset and realistic quantification of severity of drought events in study area.

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