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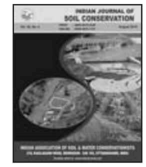

Characterizing meteorological drought using standardized precipitation index for Dehradun, Uttarakhand

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ABSTRACT

Standardized Precipitation Index (SPI) is based on the probability of precipitation for any time scale and it requires less input data and calculation efforts than other methods. The SPI is simply the transformation of the precipitation time series into a standardized normal distribution (z-distribution). Among the several proposed drought monitoring indices, the SPI has found a widespread application for describing and comparing droughts at different time periods and regions with different climatic conditions. This paper characterizes the meteorological drought using SPI for Dehradun area located at the foothills of Garhwal Himalayas in Uttarakhand state of India. Monthly SPI values were calculated at the time scales of 1-, 4-, 6-, and 12 months based on the daily rainfall data of 60 years. In monthly analysis, the negative z-values of 2009 indicated that though July and August contributed more in total annual rainfall, they received less rainfall than their average. However, June and September were near normal. On the basis of seasonal and annual rainfalls, 2009 was a severely dry year with z-values -1.84 and -1.826, respectively. As the high rainfall is received in monsoon season (June to September), rain water harvesting and utilization is a way to mitigate drought effect. High water requiring crops can be replaced with low water requiring crops which are efficient to utilize soil moisture through crop replacement practices. The results clearly indicated that there is a need to make and adopt proper drought management plans to mitigate the effect of seasonal and annual drought by way of rainwater harvesting and cultivating low water requiring crops in drought prone areas at watershed scale.

Key words :
Dehradun,
Drought mitigation,
Gamma distribution,
Meteorological drought,
Rainfall analysis,
SPI,
Uttarakhand

1. INTRODUCTION

Drought is a temporary reduction in water or moisture availability significantly below the normal or expected amount for a specific period. Drought events evolve slowly in time and their impacts generally last a long period of time. This condition occurs either due to inadequacy of rainfall or lack of irrigation facilities for meeting the normal crop water requirements in the context of the agro-climatic conditions prevailing in a particular area. Unlike other natural disasters, drought events evolve slowly in time and their impacts generally last for a long period of time.

The understanding that a deficit of precipitation has different impacts on groundwater, reservoir storage, soil moisture, snowpack and stream flow, led to the development of the SPI (McKee *et al.,* 1993). SPI is based on the probability of precipitation for any time scale and it requires less input data and calculation efforts than other methods. The SPI is simply the transformation of the precipitation time series into a standardized normal distribution (z-distribution). Among the several proposed drought monitoring indices, the SPI has found a widespread application for describing and comparing droughts at different time periods and regions with different climatic conditions.

Guttman (1998) and Hayes *et al.* (1999) compared SPI with Palmer Drought Severity Index (PDSI) and concluded that the SPI has advantages of statistical consistency, and the ability to describe both short-term and long-term drought impacts through different time scales of precipitation anomalies. Also, due to its intrinsic probabilistic nature, SPI is the ideal candidate for carrying out drought risk analysis. The SPI is based solely on rainfall and requires only the computation of two parameters, compared with the 68 computational terms needed to describe the PDSI. By avoiding dependence on soil moisture conditions, the SPI can be used effectively in both summer and winter. The SPI is also not affected adversely by topography. The SPI has variable time scale, which allows it to describe drought conditions important for a range of meteorological, agricultural, and hydrological applications. This temporal versatility is also helpful for the analysis of drought dynamics, especially the determination of onset and cessation, which have always been difficult to track with other indices.

A one-month SPI index is very similar to the percent of normal precipitation for a month. It is actually a more accurate representation of monthly precipitation due to the normalized distribution. As one month SPI reflects relatively short-term conditions, its application can be related closely with short-term soil moisture and may approximate the conditions represented by the Crop Moisture Index (CMI). The 3-month SPI provides a comparison of the precipitation over a specific 3-month period with the precipitation totals from the same 3-month period for all the years included in previous records. It reflects short- and medium-term moisture conditions and provides a seasonal estimation of precipitation. In Indian context a 4-month SPI was taken because of heavy rainfall during four months of monsoon season (June to September) and accordingly one can study the changing behavior of SPI in pre-monsoon, monsoon and post-monsoon seasons. The 6-month SPI compares the precipitation for that period with the same 6-month period over the previous records. But when compared with one year SPI, the graphs of both indices show an approximate overlapping situation. Therefore, one year SPI is preferred as it is less sensitive than a 6-month SPI and gives more accurate scale of drought. The SPI at one year time scale reflects long-term precipitation patterns. A 12-month SPI is a comparison of the precipitations for 12 consecutive months with the same period during previous years of available data.

Szalai and Szinell (2000) assessed the utility of the SPI for describing drought in Hungary and concluded that SPI was suitable for quantifying most types of drought event. Stream flow was described best by SPI with time scales of 2- to 6-months; strong relationships to ground water level were found at time scales of 5- to 24-months; and agricultural drought was replicated best by the SPI on the scale of 2- to 3-months. Kar *et al.* (2004) analyzed the drought in Orissa from 1960 to 2003 and concluded that the SPI of July and September was significantly correlated with the yield of monsoon rice and drought conditions can be mitigated by adopting contingent crop planning and rainwater harvesting strategies. Smakhtin and Hughes (2007) described a new software package for automated estimation, display and analyses of various drought indices a continuous functions of precipitation that allow quantitative assessment of meteorological drought events to be made. The software at present allows up to five different drought indices to be estimated. They include the Decline Index (DI), the Effective Drought Index (EDI), the SPI and deviations from the long-term mean and median value. Each index can be estimated from point and spatially averaged rainfall data and a number of options are provided for months' selection and the type of the analysis, including a running mean, single value or multiple annual values.

Various drought indices were tested and modified in different parts of the world by number of researchers (Pashiardis and Michaelides, 2008; Raziei *et al.,* 2009; Pandey *et al.,* 2010; Tabrizi *et al.,* 2010; Karavitis *et al.,* 2011; Pai *et al.,* 2011; Santos *et al.,* 2011; Angelidis *et al.,* 2012; Bonsal *et al.,* 2012; Dogan *et al.,* 2012; Zin *et al.,* 2012). In view of the above studies, the rainfall data for 60 years were used for estimating the SPI values to analyze the meteorological drought on different time scales (1-month, 4-month, 6-month, and 12-month), and to propose a drought mitigation and management plan for Dehradun, Uttarakhand, India.

2. MATERIALS AND METHODS

The study area lies in Doon valley, 230 km north of New Delhi and surrounded by the Himalayas in the north, Sivaliks in the south, river Ganga in the east, and river Yamuna in the west. It is located at $78^{0}4^{'}$E longitude and $30^{0}19^{'}$N latitude with an altitude of 670.5 m amsl. Dehradun has a sub-tropical climate with cold winters, warm and crisp springs, hot summers and a strong monsoon. The rainy season generally starts from the 2nd week of June and continues up to September having the maximum rainfall in July. During the summer, the temperature ranges between 36° to 16.7°C. In winters, the temperature lies in between 23.4° to 5.2°C. The relative humidity ranges from 49% in May to 92% in January. The rainfall data of Dehradun for 60 years (1950 to 2009) were collected from the India Meteorological Department (IMD) office at Dehradun. The monthly rainfall data were arranged for various time scales as seasonal (4-monthly), 6-monthly and annual (12-monthly) to determine corresponding SPI values. The annual, seasonal and monthly variation in rainfall pattern is shown in Fig. 1 to Fig. 3, respectively.

Standardized Precipitation Index (SPI)

The SPI is computed by fitting a probability density function to the frequency distribution of precipitation summed over the time scale of interest. Each probability density function is then transformed into the standardized normal distribution. Once standardized, the strength of the anomaly is classified to define drought intensities resulting from estimates of the SPI as presented in Table 1. The table also contains the corresponding probabilities of occurrence of each severity arising naturally from the normal probability density function. Thus, at a given location for an individual month, moderate droughts (SPI ≤ -1) have an occurrence probability of 15.9%, whereas extreme droughts (-1 $\geq$ SPI ≤ -2) have an event probability of 2.3%. Extreme values in the SPI will, by definition, occur with the same frequency at all locations.

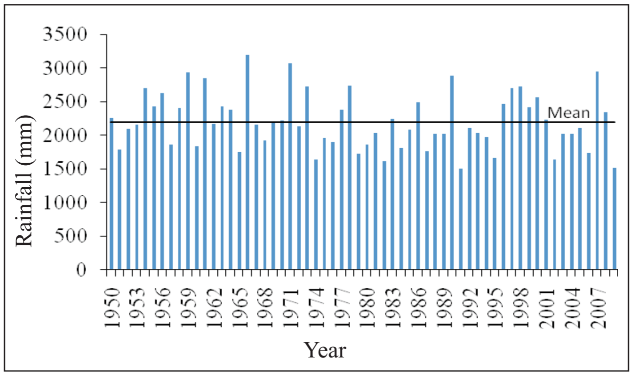

Fig. 1. Variation in annual rainfall data at Dehradun, UK

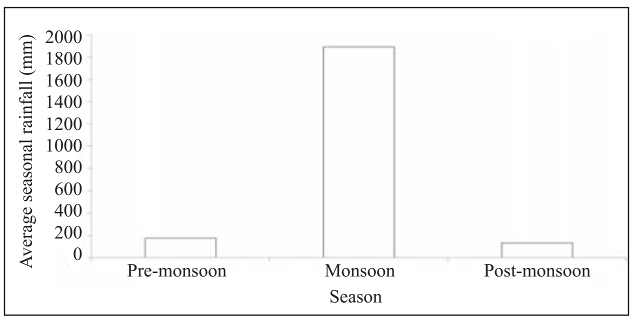

Fig. 2. Variation in average seasonal rainfall at Dehradun

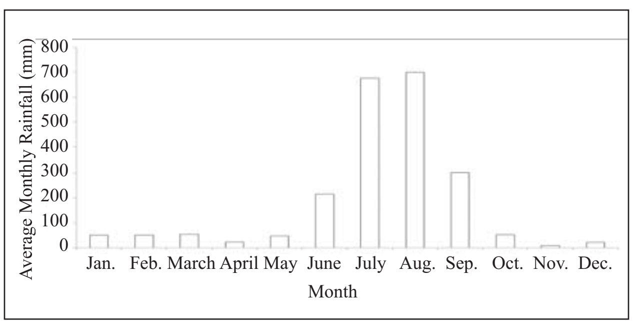

Fig. 3. Variation in average monthly rainfall at Dehradun

Table: 1
Drought classification by SPI value and corresponding event probability

Category	SPI values	Probability (%)
Extremely wet	2 and above	2.3
Severely wet	1.5 to 1.99	4.4
Moderately wet	1.0 to 1.49	9.2
Mildly wet	0.0 to 0.99	34.1
Mildly dry	-0.99 to 0.0	34.1
Moderately dry	-1 to -1.49	9.2
Severely dry	-1.5 to -1.99	4.4
Extremely dry	-2 and below	2.3

The SPI gives better representation of wetness and dryness than other previous methods which can be computed at different time scales, such as 1-, 3-, 4-, 6-, 12-, 24-, and 48-months. In this study, only 1-, 4-, 6-, and 12-month time scales are considered. The SPI calculation for a desired period at any location is based on the long term precipitation record (30 years or more). The positive SPI values show greater than median precipitation, while a negative SPI value indicates less than median precipitation. It was found that the Gamma distribution fits the precipitation time series very well. The Gamma distribution is defined by its frequency or probability density function as:

$$g(X) = \frac{1}{\beta^{\alpha} * \Gamma\alpha} x^{\alpha-1} e^{-x/\beta} \quad ...(1)$$

Where, α = shape parameter (α > 0), β = scale parameter $(\beta > 0)$, x = precipitation amount in mm ($x > 0$), and Γ(α) = a gamma function of α, expressed as:

$$\Gamma(\alpha) = \int_0^{\infty} y^{\alpha-1} e^{-y} dy \quad ...(2)$$

Computation of the SPI involves fitting a gamma probability density function to a given frequency distribution of precipitation totals of a time scale for a station. The parameters α and β of the gamma probability density function were estimated for each time scale of interest. The maximum likelihood solutions are used to optimally estimate α and β as follows:

$$\breve{a} = \frac{1}{4A} \left(1 + \sqrt{(1 + \frac{4A}{3}}\right) \quad ...(3)$$

$$\hat{\beta} = \frac{\overline{x}}{\alpha} \quad ...(4)$$

$$\text{Where, } A = \ln(\overline{x}) - \frac{\sum \ln(x)}{n} \quad ...(5)$$

Where, $\overline{x}$ = average rainfall in mm of all previous data of same event and n = number of precipitation observations.

After calculating the values of α, β and A, the cumulative probability of an observed precipitation event for a given time scale can be computed as:

$$G(X) = \int_0^x g(X)\,dx \text{ , or} \quad ...(6)$$

$$G(X) = \frac{1}{\hat{\beta}^{\hat{\alpha}} * \Gamma(\hat{\alpha})} \int_0^x x^{\hat{\alpha}-1} e^{-x/\hat{\beta}} dx \quad ...(7)$$

Since the gamma function is undefined for $x = 0$ and a precipitation distribution may contain zeros, the cumulative probability becomes,

$$H(X) = q + (1 - q)\, G(X) \quad ...(8)$$

Where, q = probability of a zero event. If m is the number of zeros in a precipitation time series, q can be estimated as m/n.

The cumulative probability $H(X)$ is then transformed to the standard normal random variate Z with zero mean and unit variance, which is the value of the SPI. This is an equi-probability transformation, which has the essential features of transforming a variate from one distribution (*G*amma) to a variate with a distribution of prescribed form (standard normal) such that the probability of being less than a given value of the variate shall be the same as the probability of being less than the corresponding value of the transformed variate.

The SPI value (Z) is more easily obtained computationally using an approximation suggested by Abramowitz and Stegun (1970) that converts cumulative probability to the standard normal random variable Z:

$$Z = SPI = -\left(t - \frac{(C_o + C_1 t + C_2 t^2)}{(1 + d_1 t + d_2 t^2 + d_3 t^3)}\right) \text{ for } 0 < H(X) \leq 0.5 \quad ...(9)$$

$$Z = SPI = +\left(t - \frac{(C_o + C_1 t + C_2 t^2)}{(1 + d_1 t + d_2 t^2 + d_3 t^3)}\right) \text{ for } 0.5 < H(X) \leq 1.0 \quad ...(10)$$

$$\text{Where, } t = \sqrt{\left(In \frac{1}{(H(X))^2}\right)} \text{ for } 0 < H(X) \leq 0.5 \quad ...(11)$$

$$t = \sqrt{\left(In \frac{1}{(1 - H(X))^2}\right)} \text{ for } 0.5 < H(X) \leq 1.0 \quad ...(12)$$

The coefficients are: $C_o = 2.515517$, $C_1 = 0.802853$, $C_2 = 0.010328$, $d_1 = 1.432788$, $d_2 = 0.189269$ and $d_3 = 0.001308$.

SPI is calculated for any month in the record for the previous *i* months, where *i* = 1, 2, 3, … 6, …9, …12, …24, ... 48, *etc.* depending upon the time scale of interest. In this study, 1- and 4-month SPI is used as a short-term or seasonal drought index which is generally used for monitoring the meteorological drought, whereas a 6- and 12-month SPI could be used for an intermediate-term hydrological drought index.

3. RESULTS AND DISCUSSION

The rainfall data were analyzed for meteorological drought monitoring on the basis of SPI at different time scales of 12-month (annual), 6-month, 4-month (seasonal), and 1-month as follows:

Annual Rainfall Data

The SPI at annual (12-month) time scale reflects long-term precipitation patterns indicating a comparison of the precipitation for 12 consecutive months with the same 12 consecutive months during all the previous years of available data. The average annual rainfall of Dehradun for the years 1950 to 2009 was 2202.1 mm. The SPI (Z value) of past years is calculated (Fig. 4) and according to the nomenclature of SPI value and the type of drought, it was found that there are 10 mildly dry years (33.33%), 6 moderately dry years (20%), 3 severely dry years (10%), 7 mildly wet years (23.33%), 2 moderately wet years (6.67%), and 2 Severely wet years (6.67%) (Table 2). The year 2009 was the severely dry year with the rainfall of 1518.9 mm. The worst dry conditions occurred in the year 1991 having 1498.4 mm rainfall and the worst wet condition occurred in year 2007 having 2940.50 mm rainfall during past 30 years. Overall, it was estimated that annually the chances of facing the dry conditions in the area are to the extent of 63.33%, which require adequate planning and adoption of appropriate measures such as rainwater harvesting, mulching, deep tillage, contour cultivation, *etc.* to mitigate the effect of drought in the area. The annual SPI values indicate that after every severely dry condition there is a mildly dry condition; therefore, on the basis of

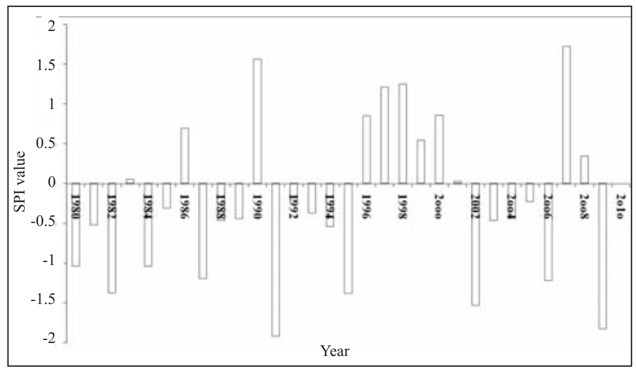

Fig. 4. Year-wise distribution of SPI values for Dehradun

Table: 2
Annual SPI values and corresponding inferences drawn thereon

Years	SPI (Z value)	Inference
1980	-1.036	Moderately dry
1981	-0.523	Mildly dry
1982	-1.378	Moderately dry
1983	0.054	Mildly wet
1984	-1.04	Moderately dry
1985	-0.31	Mildly dry
1986	0.693	Mildly wet
1987	-1.195	Moderately dry
1988	-0.467	Mildly dry
1989	-0.439	Mildly dry
1990	1.566	Severely wet
1991	-1.916	Severely dry
1992	-0.209	Mildly dry
1993	-0.369	Mildly dry
1994	-0.541	Mildly dry
1995	-1.384	Moderately dry
1996	0.849	Mildly wet
1997	1.216	Moderately wet
1998	1.254	Moderately wet
1999	0.547	Mildly wet
2000	0.857	Mildly wet
2001	0.030	Mildly wet
2002	-1.531	Severely dry
2003	-0.464	Mildly dry
2004	-0.437	Mildly dry
2005	-0.230	Mildly dry
2006	-1.221	Moderately dry
2007	1.727	Severely wet
2008	0.346	Mildly wet
2009	-1.827	Severely dry

this pattern, it can be predicted that probably there will be mildly dry condition next year (2010). The percentage of occurrence of various drought events indicates that the condition of occurrence of mildly dry events is the maximum (33.33%).

Six-monthly Rainfall Data

The six-monthly time scale reflects medium term trend in precipitation-time. For 6-month analysis, a year was divided into two groups each consisting of six months *i.e.,* January to June and July to December. The average rainfall of 6 months from January to June is 442.34 mm and from July to December is 1759.74 mm. Because of larger variations between the averages of these 6 monthly rainfalls, the SPI value will be reflected more by latter as it has higher rainfall magnitude. In the first 6-monthly period (January-June), the probability of occurrence of mildly-dry and mildly-wet conditions is 33.33%, moderately-wet 20%, and severely-dry 10%; while during the second 6-monthly period, the probability of occurrence of mildly-dry are 40%, mildly-wet 20%, moderately dry 20%, severely-dry 10%, and extremely-wet 10%. Therefore, the SPI pattern of 6-monthly data indicates the prediction of wet conditions in January-June period and dry conditions during July-December period, though the latter has about four times more average rainfall than the former.

Seasonal Rainfall Data

The seasonal rainfall (4-monthly) data were used for computing SPI on the basis of pre-monsoon, monsoon and post-monsoon basis so that drought management strategies could be made accordingly.

Pre-monsoon Rainfall Data

The minimum average rainfall during the 4-month pre-monsoon period (February to May) is 177.0 mm. The SPI of pre-monsoon season and the percentage of occurrence of different drought conditions reveal that there were 45% mildly-dry, 25% moderately-dry as well as moderately-wet conditions, and 5% as the extremely-dry conditions of pre-monsoon seasonal rainfall. Overall, it is estimated that the pre-monsoon season will face the dry conditions to the extent of 75%, which will require adequate measures such as rainwater harvesting, mulching *etc.* to mitigate the effect of drought in the area. On the basis of these probabilities, it can be predicted that the pre-monsoon season in 2010 is likely to receive mildly-dry conditions.

Monsoon Rainfall Data

The SPI of monsoon season (June to September) and the percentage of occurrence of different conditions indicate that the probability of occurrence of mildly-wet condition in monsoon season is maximum at 45%, mildly-dry at 20%, severely-dry at 15%, whereas severely-wet and moderately-dry having 10% of chances. Overall, it is estimated that the monsoon season will face the dry conditions to the extent of 45%, which requires adequate measures such as rainwater harvesting, mulching, *etc.* to mitigate the effect of drought in the area. On this basis, it may be predicted that the monsoon season during 2010 would be likely to have mildly-wet conditions with occasional dry spells.

Post-monsoon Rainfall Data

The 4-month post-monsoon period (October to January) has the minimum average rainfall of 132.8 mm. The SPI of post-monsoon season and the percentage of occurrence of different conditions indicate that the mildly-dry condition got the maximum probability of occurrence at 50%, moderately-dry at 15%, mildly-wet at 25%, whereas moderately-wet and extremely-dry conditions having only 5% chances. Overall, it is estimated that the post-monsoon season will face dry conditions to the extent of 70%. Therefore, based on the given dataset, it may be predicted that the post-monsoon season in the year 2010 will be mildly-dry.

Monthly Rainfall Data

A one-month SPI is very similar to the percent of normal precipitation for a month. It is actually a more accurate representation of monthly precipitation because the distribution has been normalized. Since the 1-month SPI reflects relatively short-term conditions, its application can be related closely with short-term soil moisture and crop stress, especially during the growing season. The monthly SPI may approximate the conditions represented by the crop moisture index. The SPI-based analysis indicates June and December as mildly-dry, April and July moderately-dry, August severely-dry and March extremely-dry months; while February, May, September and November as mildly-wet, January and October as moderately-wet months. Though October (moderately-wet) received much less rainfall of 168.4 mm than the August (severely-dry) 453.9 mm, it can be affirmed that the SPI does not depend on the average values of that month, but its variations from the long-term average and it is actually a more accurate representation of monthly precipitation. However, such interpretations need more analytical processes to arrive at any conclusion.

Drought Mitigation Planning

Drought mitigation planning focuses on enhancing our abilities to monitor drought, understand drought vulnerabilities, and mitigate drought. By proactively planning for drought, the society will be better prepared to deal with the damaging effects of drought in the most efficient manner. Though the prediction of onset and termination of drought are difficult to determine, one can identify various indicators of drought and by tracking them the crucial means of monitoring drought can be provided. To overcome rainfall deficits and encounter with the droughts in the region, contingent crop planning is needed to ensure stable productivity and appropriate strategies can be adopted to overcome drought problems in Dehradun area.

Rainwater management during excess rainfall periods and its multiple uses through farm diversification must be encouraged for increasing the productivity and sustainability in the drought-affected areas. Year 2009 being a severely dry year, a proper rainwater management program would be an appropriate option. On the contrary, the year 2008 having heavy rainfall during monsoon months (2174 mm) showed a very-wet condition but later a low rainfall from October 2008 to June 2009 (227.4 mm) having a severely-dry condition, indicated the need of rainwater harvesting during monsoon and its utilization during subsequent dry periods. In delayed monsoon conditions, the drought-resistant crop varieties of short duration can be promoted in the area.

4. CONCLUSIONS

The SPI is a drought index based on the probability of an observed precipitation deficit occurring over a given time period. The assessment periods considered range from 1 to 36 months. The variable time scale allows the SPI to describe drought conditions important for a range of meteorological, agricultural, and hydrological applications. For example, soil moisture conditions respond to precipitation deficits occurring on a relatively short time scales of 1 to 3 months, whereas groundwater, stream flow and reservoir storage respond to the precipitation deficits arising over 6 or more months.

The rainfall amount and distribution at Dehradun in Uttarakhand state, being erratic and uneven, are responsible for frequent drought spells throughout the year. Out of various methodologies available for studying the meteorological drought, the standardized precipitation index (SPI) at various time scales can be accepted and practiced for drought monitoring in this region. Estimation of annual, 6-monthly, seasonal and monthly rainfall at various probability levels can be used to determine expected periods of rainfall deficit or surplus as a guiding tool for drought management. The mildly-wet and mildly-dry conditions with 65% probability and z-value ranging from -0.99 to 0.99 requires proper water management planning activities in drought-prone and rainfed areas. This analysis shows that there is a need to adopt proper drought management planning to mitigate the effect of seasonal and annual drought. The rainwater harvesting techniques during rainy season should be carried out to mitigate the effects of drought during water scarcity periods. Also, the high water-requiring crops can be replaced by low water-requiring crops which are efficient to utilize soil moisture through crop replacement practices.

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