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Investigating Rainfall Trend and Monitoring Meteorological Drought in a Himalayan Watershed of India

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Abstract. Assessment of rainfall trend and monitoring meteorological drought and wet conditions are very important in dealing with agricultural planning and water resources management under the influence of changing climate in the Himalayan region. This study was conducted to assess rainfall trend and monitor the drought and wet pattern at four stations, namely Naula, Kedar, Chaukhutia and Mehalchauri, located in the upper Ramganga River catchment in Uttarakhand state of India in the central Himalayan region. Rainfall trend analysis at these stations was carried out using Mann-Kendall test and Sen's slope estimator. Standardized Precipitation Index (SPI) at multiple time scales of 1-, 3-, 6-, 9-, 12- and 24-months was used to assess meteorological drought and wet pattern at Naula station. Results have indicated a significantly downward trend in December and post-monsoon season and an upward trend in September at Naula station. Significantly downward trend was also observed in July, December and monsoon season at Kedar station, and in June, July, August, monsoon and annual data series at Chaukhutia station. No significant trend was observed at Mehalchauri station. Study also revealed that there are more chances of occurrences of mild drought and wet conditions and only meager chances of moderate drought and wet conditions during monsoon season. However, the chances of severe and extreme drought and wet conditions are almost negligible. Therefore, efforts must be made to harvest the excess water during the wet periods and utilize the same during the periods of mild and moderate drought for drinking, household activities and irrigation purposes.

Keywords: Trend analysis, deficit rainfall, drought and wet spell, SPI, Himalayan region.

1 Introduction

Drought is recognized as an environmental disaster and in recent times it has attracted the attention of environmentalists, ecologists, hydrologists, meteorologists, geologists and agricultural scientists. Drought occurs virtually in all climatic zones and is mostly related to the reduction of precipitation amount received over an extended period of time, usually a season or a year. Due to the growth of population and expansion of agricultural and industrial sectors, the demand for water has increased manifolds and the water scarcity has been occurring almost every year in many areas of the world.

Drought generally occurs when an area does not receive considerable amount of rainfall for a continuous period of time [1]. There are two main definitions of drought: conceptual and operational. Conceptual definition describes the drought in relative terms as a long dry period; whereas operational definition attempts to identify the onset, severity and duration of drought for a given return period [2]. The UN convention to combat drought and desertification [3] defined drought as the natural phenomenon that occurs when precipitation falls below normal recorded levels, which produces hydrological imbalances affecting the land resource production systems. Globally, drought (covering 7.5% land area) is the second most geographically extensive hazard after floods (11% of the earth's land area). The percentage of area affected by serious droughts has doubled from 1970 to the early 2000. The period of unusual dryness or drought is a normal feature of climate system in semi-arid and arid regions of the tropics of the world and it covers more than one-third of the land surface vulnerable to drought and desertification [4].

Meteorological drought is defined as the deficiency of precipitation from expected or normal levels over an extended period of time. India Meteorological Department (IMD) defines meteorological drought based on rainfall deficiency on sub-division basis. The meteorological droughts are classified into (a) moderate and (b) severe based on rainfall deficiency, i.e. 26 to 50% and more than 50%, respectively. It must be considered as specific to a region, since the atmospheric conditions that result in deficiencies of precipitation are highly variable from region to region. India is a home to extraordinary variety of climatic regions, ranging from tropical in the south to temperate and alpine in the Himalayan north. The rainfall over India has large spatial as well as temporal variability. The mean monthly rainfall during July is the highest with about one-fourth of the annual rainfall. Drought is a recurrent feature in India with about 28% of the geographical area being vulnerable to one or the other type of drought. There is hardly any decade when drought has not occurred at least once in two years in some areas of India. The preparedness and planning to cope with adverse impacts of a drought depends on the information about its areal extent, severity and duration. This information can be used to assess and monitor the drought events to provide information to decision makers about drought characteristics [5].

The Himalayan state of Uttarakhand in India is a disaster prone state with landslides, cloudbursts, and flashfloods being seasonal in nature. About 14% of the land is under cultivation and about 65% of the population depends on agriculture for their livelihood. The mean annual rainfall of the state is 1547 mm and more than 85% cultivable land is rain-fed. It is thus important to carry out drought studies so that the disaster may be monitored in a systematic manner and remedial measures could be made in time. Thus, there is a need to carry out drought monitoring plan and possible drought mitigation strategy in the region.

Various drought indices have been proposed in past few decades, among them some are region specific having limitations for use in other climatic conditions. These include Palmer drought severity index [6], the Decile Index [7], Bhalme and Mooley Drought Index [8], Surface Water Supply Index [9], Standardized Precipitation Index [10, 11, 12], Effective Drought Index [13], Reconnaissance Drought Index [14], Drought Severity Index [15]. [16] reviewed fourteen accepted drought indices that are used for assessing the severity of meteorological, hydrological and agricultural droughts. However, the Standard Precipitation Index (SPI) as recommended by [17] remains a preferred alternative among the researchers as a result of its simplicity, spatial consistency in interpretation, and probabilistic nature. Prediction of drought is helpful in early warning of drought occurrence and to reduce its impact.

Drought severity may vary from site to site under diverse climatic situation; hence, several applications of drought indices and their comparison are useful for specific regions. Drought identification and characterization in a given region allow water resources development and management for their rational use, particularly in the arid and semi-arid zones. It has been found that SPI is the best tool to monitor meteorological drought in India [18]. The SPI is widely used as a meteorological drought index to identify duration/severity of a drought [19]. [20] evaluated regional meteorological drought characteristics across the Pearl River basin in China by deriving severity-area-frequency curves based on SPI as a drought variable. Several studies were conducted on meteorological drought assessment in various parts of India [21, 22, 23, 24].

This study was conducted to assess the temporal trend in monthly, seasonal and annual rainfall series, and investigation of meteorological drought and wet conditions at four stations, namely Naula, Kedar, Chaukhutia and Mehalchauri, located in the upper Ramganga River catchment in Uttarakhand, India.

2 Materials and Methods

2.1 Study Area and Data Acquisition

The Ramganga River, one of the major tributaries of the Ganga River basin in northern India, originates in the outer Himalayas in Chamoli district of Uttarakhand and enters the plains near Kalagarh after traversing about 168 km in the hilly terrain with altitudes varying from 260m to 2950m above mean sea level. The raingauge stations of upper Ramganga catchment selected for this study are Naula, Kedar, Chaukhutia and Mehalchauri, as shown in Fig. 1. Naula, Kedar and Chaukhutia stations are located in the mid-Himalayan region, while Mehalchauri is located in high-Himalayan region.

The climate of the region varies from Himalayan subtropical to sub-temperate having a temperature variation from 30°C during summer to the minimum temperature of -2.9°C during winter. Most of the precipitation occurs in the form of rainfall from June 15 to September 15 along with occasional winter rains. The soils of this region are highly coarse textured varying from coarse sand to gritty sandy-loam, stony and highly erodible. The soils are mostly acidic in nature with the pH varying from 5.5 to 6.7. The soil depth at higher elevations is up to 22 cm with gravels and varies from 45 cm to 67 cm at middle altitudes and 45 cm to 135 cm at lower altitudes. The land-use pattern may be broadly classified as forest, pasture, cultivated and waste lands.

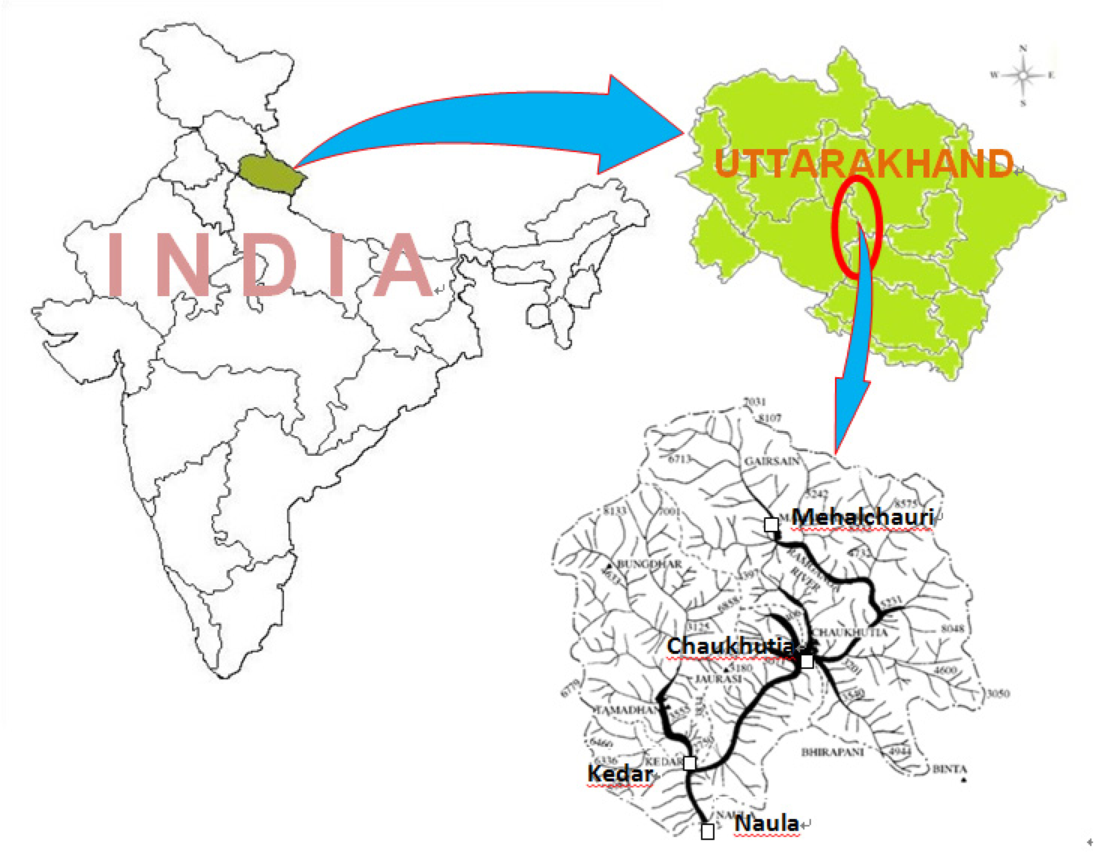

Figure 1. Study area with rain-gauge stations

The daily rainfall data at four stations (Table 1) were collected from the divisional office of the Forest and Soil Conservation Department, Ranikhet, Uttarakhand. Naula and Kedar stations had fairly long years of data, but Chaukhutia and Mahalchauri stations had short term data. The daily data were arranged into monthly, seasonal and annual datasets for detecting the presence of trend and analysis of meteorological drought and wet events.

Table 1. Location coordinates and availability of rainfall data at study stations

S. No.	Station	Longitude	Latitude	Availability of data (year)
1	Naula	70° 15´ 20´´ E	29° 4´ 20´´´N	1974 to 2011
2	Kedar	79° 14´ 12´´E	29° 47´ 36´´N	1974 to 2011
3	Chaukhutia	79° 21´ 50´´E	29° 53´ 25´´N	1974 to 1995
4	Mehalchauri	79° 19´ 24´´E	29° 58´ 12´´N	1974 to 1989

2.2 Trend Analysis

Testing the significance of observed trends in meteorological time series has received a greater attention recently, especially in connection with the assessment of observed changes in the natural and human environment due to global warming. Long term trend in observed rainfall time-series was analyzed on monthly, seasonal and annual basis. The existence or lack of trend was determined by the statistical tests and further rated as highly significant, significant and moderately significant at 0.01, 0.05 and 0.10 levels of significance, respectively. Determination of trends, its magnitude and statistical significance for all the stations was done by using non-parametric methods. Mann-Kendall trend test (Kendall, 1975), a non-parametric test which does not affect the results with outliers data, was used to identify the trend in a time series even if there is a seasonal component in the series. To analyze the magnitude of trend in the series, a non-parametric Sen's slope method [25] was used to quantitatively determine the rise or fall of the variable per unit of time.

Mann-Kendall Test

The Mann-Kendall (M-K) trend test is a rank correlated test between the rank of observations and their time order (Kendall, 1975). This method has been widely used to test randomness against trend detection in a time series. In this test, the null hypothesis (H_0) of no trend, i.e., the observations are randomly ordered in time, against the alternative hypothesis (H_1) with increasing or decreasing monotonic trend detection. The M-K test statistic S is calculated using the formula:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}\left(x_j - x_i\right) \tag{1}$$

where, x_i is the data time series ranked from i = 1, 2, ... n-1; and j = 2,3....n. Each of the data point x_i is taken as reference point, which is compared with the rest of the data points, x_j:

$$sgn(x_j - x_i) = \begin{cases} -1 & for\ x_j < x_i \\ 0 & for\ x_j = x_i \\ 1 & for\ x_j > x_i \end{cases}$$

A positive value of S indicates increasing trend, and a negative value indicates decreasing trend. It has been documented that when n $\geqslant$ 8, the statistic S is approximately normally distributed with the mean zero and variance computed as:

$$Var(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(t_i - 1)(2t_i + 5)}{18} \tag{2}$$

where, m is the number of tied groups and t_i is the number of ties in sample i. The normal test statistic Z_{MK} is computed as:

$$Z_{MK} = \begin{cases} \frac{S-1}{\sqrt{VAR(S)}}, if & S > 0 \\ 0, \quad if & S = 0 \\ \frac{S+1}{\sqrt{VAR\ (S)}}, if & S < 0 \end{cases} \tag{3}$$

The trend is said to be increasing, if Z_{MK} is positive and computed Z_{MK} statistic is greater than the Z_{MK} value corresponding to a desired level of significance (0.01, 0.05 or 0.10); and the trend is said to be decreasing, if Z_{MK} is negative and computed Z_{MK} statistic is greater than the Z_{MK} value corresponding to desired level of significance. The null hypothesis H_0 representing that no significant trend is present is accepted, if Z_{MK} is less than the Z_{MK} value.

Sen's slope estimator test

The Sen's slope estimator has been found to be a better and more power tool as compared to simple linear regression to detect the linear trend as it is unaffected by gross data errors and outliers. The Sen's slope is estimated as the median of all pair-wise slopes between each pair of points in the data set. The pair-wise slope T_i of all data points is computed as:

$$T_{ij} = \frac{x_j - x_i}{j-i} \tag{4}$$

where, x_j and x_j are data values at the times i and j (j >i), respectively. For n values in data set, there will be N= n(n-1)/2 number of slope estimates, and the median of these N values of T_{ij} is represented as Sen's estimator of slope (Q_i), which is calculated as:

$$Q_i = T_{(N+1)/2}, \text{ if N is odd} \tag{5}$$

and,

$$Q_i = 1/2\ (T_{N/2} + T_{(N+2)/2}), \text{ if N is even} \tag{6}$$

Positive value of Q_i indicates an increasing trend, while a negative value indicates a decreasing trend.

2.3 Standardized Precipitation Index (SPI)

Among various drought indices, SPI [26] is a probability index that considers only rainfall and requires long-term rainfall record for a desired period. Mathematically, it is based on the cumulative probability and the index is negative for drought and positive for wet condition. Due to its statistical consistency and intrinsic probabilistic nature, it describes the impact of both short-term and long-term drought. The SPI was used for temporal drought and wet analysis, to calculate drought severity and probability of occurrence of drought and wet condition as well as for analyzing fluctuation of rainfall pattern using monthly rainfall on multiple time-scales (1-, 3-, 6-, 9-, 12- and 24-months). Computation of the SPI values involves fitting a Gamma probability density function to a given time series of rainfall, whose probability density function is given as:

$$g\ (x) = \frac{1}{\beta^{\alpha}\ \Gamma(\alpha)} x^{\alpha-1}\, e^{-x/\beta} \text{ for x > 0} \tag{7}$$

where, α is a shape parameter, $\alpha > 0$; β is a scale parameter, $\beta > 0$; x is the amount of rainfall, $X > 0$; Γ (α) is the gamma function of α, expressed as $\int_0^{\infty} y^{\alpha-1}\, dy$. The cumulative probability is given as:

$$G\ (x) = \frac{1}{\Gamma(\alpha)} \int_0^{x} t^{\alpha-1}\, e^{-t}\, dt \tag{8}$$

As the Gamma distribution tends towards the normal as the shape parameter α tends to infinity, it is possible to use the normal probability distribution instead of Gamma, which is computationally easier and may be more accurate due of better fitting to the data. In this case, the SPI index is computed as:

$$SPI = (Z) = \frac{(x-\mu)}{\sigma} \tag{9}$$

where, μ and σ are the sample estimates of the population mean and standard deviation, respectively. On the basis of SPI values the wet and drought conditions existing at a place are categorized as presented in Table 2. Some researchers have classified the SPI values falling within ± 0.99 as near normal which indicates threshold values for drought (-0.99) and wet (+0.99) conditions [27].

Table 2. Classification of drought and wet conditions based on SPI value

SPI Value	Category	Symbol
SPI ⩾ 2	Extremely wet	D
1.50 ⩽ SPI ⩽ 1.99	Severely wet	C
1.00 ⩽ SPI ⩽ 1.49	Moderately wet	B
0.00 ⩽ SPI ⩽ 0.99	Mildly wet	A
-0.99 ⩽ SPI ⩽ 0	Mildly drought	1
-1.49 ⩽ SPI ⩽ -1.00	Moderately drought	2
-1.99 ⩽ SPI ⩽ -1.50	Severely drought	3
SPI ⩽ -2	Extremely drought	4

The SPI is computed by fitting a probability density function to the frequency distribution of rainfall summed over the time-scale of interest separately for each month. Each probability density function is then transformed into standardized normal distribution.

3 Results and Discussion

The statistical characteristics of monthly, seasonal and annual rainfall at Naula and Kedar, and Chaukhutia and Mehalchauri stations are given in Tables 3 and 4, respectively. The seasonal data were categorized as pre-monsoon season (February to May), monsoon season (June to September) and Post-monsoon (October to January). Statistical characteristics of the rainfall data series are better understood in terms of mean, standard deviation, skewness and kurtosis. Data with skewness close to zero indicate standard normal distribution, and with more positive (negative) values indicate positively (negatively) skewed distribution which explains that the data have mode<median<mean (mode>median>mean). Kurtosis indicates peakedness in the data such that the data with kurtosis equal to zero (meso-kurtic) follow standard normal distribution, while positive (negative) kurtosis indicates more peak or lepto-kurtic (flatness or platy-kurtic) nature. Station-wise statistical characteristics of rainfall pattern is described as follows.

3.1 Rainfall Pattern at Naula

The mean monthly rainfall of 444 months (1974-2011) at Naula station (Table 3) varied from the maximum of 184.33 mm (August) to the minimum of 7.07 mm (November). The monthly rainfall ranges from the minimum of zero (October to June) to the maximum of 507.10 mm (September). The standard deviation (SD), skewness and kurtosis ranged from 13.44 mm (November) to 107.95 mm (September), 0.33 (May) to 3.40 (April), and -0.61 (May) to 15.63 (April), respectively. On seasonal basis, the pre-monsoon season had the mean rainfall as 198.11 mm with the maximum as 418.9 mm (1982) and minimum as 30.20 mm (1998) having the SD, skewness and kurtosis as 86.31 mm, 0.55 and -0.17, respectively. The monsoon season had the mean rainfall as 563.06 mm with the maximum as 1194.73 mm (2009) and minimum as 301.6 mm (1980) having the SD, skewness and kurtosis as 207.06 mm,1.17 and 1.18, respectively. The post-monsoon season had the mean rainfall as 92.53 mm with the maximum as 316.24 mm (1984) and minimum as 6.0 mm (2011) having the SD, skewness and kurtosis as 71.66 mm, 1.23 and 1.69, respectively. The mean annual rainfall was 853.70 mm with the maximum of 1511.73 mm (1982) and the minimum of 134.80 mm (2011) having the SD, skewness and kurtosis as 270.16 mm, 0.48 and 0.97, respectively. The data generally showed positive skewness and lepto-kurtic nature of data (except for January, May, July, and pre-monsoon). The distribution of mean annual rainfall was during pre-monsoon (23.2%), monsoon (65.96%), and the post-monsoon (10.84%).

Table 3. Statistical characteristics of monthly, seasonal and annual rainfall data (1974-2011) at Naula and Kedar stations

Month/ Season/ Annual	Statistics of rainfall series at Naula						Statistics of rainfall series at Kedar					
	Mean (mm)	Max. (mm)	Min. (mm)	SD (mm)	Skew.	Kurt.	Mean (mm)	Max. (mm)	Min. (mm)	SD (mm)	Skew.	Kurt.
January	43.74	139.90	0.00	39.84	0.72	-0.58	37.62	139.20	0.00	34.58	1.06	0.60
February	60.20	179.84	0.00	49.45	0.81	0.07	63.09	330.80	0.00	62.25	2.34	8.59
March	48.31	181.80	0.00	46.25	1.13	0.83	46.79	162.02	0.00	45.79	1.10	0.39
April	38.29	237.00	0.00	40.76	3.40	15.63	30.97	158.94	0.00	30.12	2.41	8.38
May	51.31	126.60	0.00	32.77	0.33	-0.61	46.42	149.30	0.00	31.62	0.91	1.65
June	99.94	301.80	0.00	63.62	1.00	1.68	102.08	234.40	0.00	61.45	0.41	-0.67
July	170.82	383.20	43.00	90.08	0.79	-0.06	192.70	543.00	16.51	122.97	1.33	1.46
August	184.33	418.00	40.20	85.15	0.37	0.05	189.70	521.30	12.32	115.52	0.94	1.03
September	107.97	507.10	1.00	107.95	2.12	5.47	116.51	429.80	2.85	95.51	1.38	2.28
October	21.78	200.20	0.00	44.03	3.11	9.97	21.45	178.00	0.00	39.54	3.13	10.23
November	7.07	55.00	0.00	13.44	2.37	5.28	7.82	59.69	0.00	15.56	2.28	4.69
December	19.94	114.30	0.00	29.12	1.81	2.68	14.71	85.59	0.00	19.82	1.84	3.84
Pre-Mon.	198.11	418.90	30.20	86.31	0.55	-0.17	187.27	534.20	22.86	103.34	1.28	2.37
Monsoon	563.06	1194.73	301.60	207.06	1.17	1.18	600.99	1424.10	247.62	265.10	1.43	2.07
Post-Mon.	92.53	316.24	6.00	71.66	1.23	1.69	81.60	248.84	7.62	62.55	1.17	0.69
Annual	853.70	1511.73	134.80	270.16	0.48	0.97	869.86	2089.30	121.92	359.92	1.23	2.99

3.2 Rainfall Pattern at Kedar

The mean monthly rainfall of 444 months (1974-2011) at Kedar station (Table 3) varied from the minimum of 7.82 mm (November) to the maximum of 192.70 mm (July). The monthly rainfall varied from zero (October to May) to 543 mm (July). The SD, skewness and kurtosis varied from 15.56 mm (November) to 122.97 mm (July), 0.41 (June) to 3.13 (October) and -0.67(June) to 10.23 (October), respectively. On seasonal basis, the pre-monsoon season had the mean rainfall as 187.27 mm with the maximum as 534.20 mm (1989) and minimum as 22.86 mm (1998) having the SD, skewness and kurtosis as 103.34 mm, 1.28 and 2.37, respectively. The monsoon season had the mean rainfall as 600.99 mm with the maximum as 1424.10 mm (1989) and minimum as 247.62 mm (1985) having the SD, skewness and kurtosis as 265.10 mm, 1.43 and 2.07, respectively. The post-monsoon season had the mean rainfall as 81.60 mm with the maximum as 248.84 mm (1984) and minimum as 7.62 mm (2011) having the SD, skewness and kurtosis as 62.55 mm, 1.17 and 0.69, respectively. The mean annual rainfall was 869.86 mm with the maximum of 2098.30 mm (1989) and the minimum of 121.92 mm (2011) having the SD, skewness and kurtosis as 359.92 mm, 1.23 and 2.99, respectively. The data generally showed positive skewness and lepto-kurtic nature of data (except for June). The distribution of mean annual rainfall was during pre-monsoon (21.53%), monsoon (69.09%), and post-monsoon (9.38%).

3.3 Rainfall Pattern at Chaukhutia

The mean monthly rainfall of 259 months (1974-1995) at Chaukhutia station (Table 4) varied from 8.92 mm (November) to 337.57 mm (August). The monthly rainfall varied from zero (October to April) to 607.70 mm (July). The SD, skewness and kurtosis ranged from 14.92 mm (November) to 160.48 mm (August), -0.18 (August) to 2.81 (October) and -1.02 (January) to 9.30 (October). On seasonal basis, the pre-monsoon season had the mean rainfall as 217.03 mm with the maximum as 421.10 mm (1981) and minimum as 88.92 mm (1988) having the SD, skewness and kurtosis as 94.69 mm, 0.62 and -0.48, respectively. The monsoon season had the mean rainfall as 942.23 mm with the maximum as 1455.10 mm (1979) and minimum as 226.10 mm (1993) having the SD, skewness and kurtosis as 333.82 mm,-0.48 and -0.59, respectively. Post-monsoon period had the mean rainfall as 113.63mm with the maximum as 340.20 mm (1984) and minimum as 3.50 mm (1974) having the SD, skewness and kurtosis as 79.37 mm, 1.05 and 1.77, respectively. The annual rainfall was 1272.89 mm with the maximum of 1920.70 mm (1981) and the minimum of 379.40 mm (1998) having the SD, skewness and kurtosis as 421.96 mm, -0.23 and -0.55, respectively. The data generally showed positive skewness (except for August, Monsoon and annual) and lepto-kurtic nature of data (except for January, February, May, July, August, pre-monsoon, monsoon and annual). The distribution of the mean annual rainfall was during pre-monsoon (17.05%), monsoon (74.02%), and post-monsoon (8.93%).

Table 4. Statistical characteristics of monthly, seasonal and annual rainfall (1974-1995) at Chaukhutia and Mehalchauri stations

Month/ Season/ Annual	Statistics of rainfall series at Chaukhutia						Statistics of rainfall series at Mehalchauri					
	Mean (mm)	Max. (mm)	Min. (mm)	SD (mm)	Skew.	Kurt.	Mean (mm)	Max. (mm)	Min. (mm)	SD (mm)	Skew.	Kurt.
January	49.49	129.80	0.00	39.77	0.38	-1.02	42.51	108.50	0.00	37.46	0.43	-1.02
February	55.41	127.20	0.00	33.29	0.14	-0.12	58.86	147.00	4.70	41.76	0.61	-0.20
March	57.51	197.50	0.00	52.99	1.14	0.96	60.09	215.90	0.00	57.02	1.55	2.95
April	44.45	151.00	0.00	37.40	1.24	1.70	46.74	159.00	0.00	43.52	1.53	2.14
May	59.66	161.90	6.50	46.63	0.96	-0.06	86.22	214.00	2.50	62.19	0.59	-0.29
June	158.51	522.60	35.80	102.62	2.18	6.98	142.23	322.70	16.00	78.72	0.85	0.69
July	287.28	607.70	63.80	156.72	0.25	-0.99	285.54	580.70	122.00	132.19	0.73	-0.12
August	337.57	596.90	38.60	160.48	-0.18	-0.83	269.27	582.21	79.00	141.52	0.67	-0.05
September	158.87	412.50	18.90	102.35	0.96	0.97	127.50	275.40	4.00	82.35	0.27	-0.94
October	22.38	159.40	0.00	36.62	2.81	9.30	25.73	143.00	0.00	38.30	2.20	5.40
November	8.92	53.40	0.00	14.92	1.72	2.48	12.30	58.82	0.00	17.96	1.63	2.09
December	32.84	111.00	0.00	33.42	1.03	0.37	35.97	112.00	0.00	32.32	1.00	0.40
Pre-Mon.	217.03	421.10	88.92	94.69	0.62	-0.48	251.91	462.00	25.50	99.63	-0.40	1.94
Monsoon	942.23	1455.10	226.10	333.82	-0.48	-0.59	824.54	1450.70	364.00	316.67	0.82	0.03
Post-Mon.	113.63	340.20	3.50	79.37	1.05	1.77	116.51	318.50	10.00	78.48	0.93	1.76
Annual	1272.89	1920.70	379.40	421.96	-0.23	-0.55	1192.96	1875.30	681.91	365.32	0.67	-0.18

3.4 Rainfall Pattern at Mehalchauri

The mean monthly rainfall of 187 months (1974-1989) at Mehalchauri station (Table 4) varied from 12.30 mm (November) to 285.54 mm (July). The monthly rainfall varies from zero (October to January) to 582.21 mm (August). The SD, skewness and kurtosis varied from 17.96 mm (November) to 141.52 mm (August), 0.27 (September) to 2.20 (October) and -1.02 (January) to 5.40 (October). On seasonal basis, the pre-monsoon season had the mean rainfall as 251.91 mm with the maximum as 462.0 mm (1982) and minimum as 25.50 mm (1988) having the SD, skewness and kurtosis as 99.63 mm, -0.40 and 1.94, respectively. The monsoon season had the mean rainfall as 824.54 mm with the maximum as 1450.70 mm (1977) and the minimum as 364.0 mm (1986) having the SD, skewness and kurtosis as 316.67 mm, 0.82 and 0.03, respectively. The post-monsoon season had the mean rainfall as 113.86 mm with the maximum as 318.50 mm (1984) and minimum as 10.00 mm (1974) having the SD, skewness and kurtosis as 78.48 mm, 0.93 and 1.76, respectively. The mean annual rainfall was 1174.57 mm with the maximum of 1875.30 mm (1977) and the minimum of 681.91 mm (1986) having the SD, skewness and kurtosis as 365.32 mm, 0.67 and -0.18, respectively. The data generally showed positive skewness (except for pre-monsoon) and lepto-kurtic nature of data (except for January, February, May, July, August, September and annual). The distribution of mean annual rainfall was during the pre-monsoon (21.11%), monsoon (69.12%), and post-monsoon (9.77%).

3.5 Rainfall Trend Analysis

The existence of trend in rainfall data series of all months, seasons and annual for Naula, Kedar, Chaukhutia and Mehalchauri stations were computed. The Mann-Kendall test statistic (Z_{MK}) and Sen's slope estimator (Q) were used to identify the nature and magnitude of trend, respectively in the rainfall data series corresponding to various levels of significance for all stations (Table 5). Positive value of Z_{MK} and Q indicates an increasing trend and negative value indicates a decreasing trend. Station-wise analysis of trend in rainfall data series is given as follows.

Table 5. Mann-Kendall test statistic (Z_{MK}) and Sen's slope estimator (Q) for monthly, seasonal and annual rainfall data series for all stations

Period	Naula		Kedar		Chaukhutia		Mehalchauri	
	Z_{MK}	Q	Z_{MK}	Q	Z_{MK}	Q	Z_{MK}	Q
January	-1.0316	-0.4087	-0.8305	-0.3233	0.7357	1.0440	0.3638	2.2240
February	0.7168	0.4000	1.0064	0.7000	0.9595	1.0360	1.1256	0.3667
March	-1.0819	-0.4294	-0.3398	-0.1271	0.3667	0.2727	-0.2704	3.0000
April	0.8426	0.2844	0.8804	0.2822	-1.2430	-0.5000	-0.9915	-1.1470
May	-0.3143	-0.2500	-0.3774	-0.1786	-0.3384	-0.4909	-0.4052	-1.7400
June	0.6035	0.4688	-0.5407	-0.5173	-2.0303**	-5.0270	-1.1256	-4.7870
July	-1.5081	-2.1000	-2.3763*	-3.1040	-2.8198*	-14.740	-0.3152	-4.5540
August	-0.0754	-0.0714	-1.1819	-2.1170	-1.9739**	-13.560	-1.2156	-13.610
September	1.6598***	2.1510	0.7293	1.0230	-1.0151	-3.7500	-0.6753	-4.5310
October	0.0775	0.0000	0.1048	0.0000	-1.6364	-0.5905	-0.3180	-0.0962
November	-1.1377	0.0000	-0.8008	0.0000	-0.8662	0.0000	0.2417	0.0000
December	-2.5573*	-0.4577	-2.3775*	-0.2489	-0.3961	-0.3000	1.4857	2.2240
Pre-monsoon	-0.5281	-0.7837	-0.3018	-0.3877	-0.7332	-2.3750	-0.8554	-5.1790
Monsoon	1.1310	2.9290	-1.2075	-4.0690	-2.9326*	-35.230	-0.5853	-19.060
Post-monsoon	-2.0368**	-1.7930	-1.7225***	-1.3580	-0.5076	-1.7920	1.0355	4.1440
Annual	0.5029	1.3250	-0.9560	-4.3490	-2.6506*	-34.4100	-0.7654	-19.560

Significant at: 0.01 level (*); 0.05 level (**); and 0.10 level (***)

Trend analysis for Naula station (Table 5) revealed that there was significantly increasing trend for September at 10% level of significance, but significantly decreasing trends for December at 1% level and for post-monsoon season at 5% level. Rest of the months, seasons and annual data showed non-significantly increasing or decreasing trends as indicated by their Z_{MK} values.

Trend analysis for Kedar station (Table 5) revealed that there was significantly decreasing trends for July and December at 1% level, and for post-monsoon season at 10% level. Rest of the months, seasons and annual data showed non-significantly increasing or decreasing trends.

Trend analysis for Chaukhutia station (Table 5) revealed that there was significantly decreasing trends for July, monsoon season and annual data series at 1% level and for June and August at 5% level.

Rest of the months, seasons and annual data showed non-significantly increasing or decreasing trends. This indicates that the rainfall pattern at Chaukhutia station, which is located in mid-Himalayan region, is having a declining trend.

Trend analysis for Mahalchauri station (Table 5) revealed no trend even at 10% level of significance; however, the monthly, seasonal and annual data series showed non-significantly increasing or decreasing trends. This indicates that the rainfall pattern at Mehalchauri, which is located in upper-Himalayan region, is having no trend affected much by climate change.

3.6 Drought and Wet Analysis

The SPI was used to assess the meteorological drought and wet conditions on multi-temporal time-scales (1-, 3-, 6-, 9-, 12-, and 24-months) for Naula, Kedar, Chaukhutia and Mehalchauri stations under study. Station-wise results of the occurrence of drought and wet spells are described as follows.

Drought and Wet Pattern at Naula

Table 6(a). SPI-based drought pattern of rainfall series at Naula station

SPI category	Drought months	Drought incidents	Average duration (month)	Longest drought pattern			
				Duration (month)	Period	Severity	Average intensity
SPI-1	282	91	3.1	11	Feb 91 to Dec 91	-5.646	-0.513
SPI-3	254	53	4.8	13	Jan 98 to Jan 99;	-11.565	-0.890
					May 02 to May 03	-7.912	-0.609
SPI-6	247	36	6.9	22	Jul 78 to Apr 80	-14.061	-0.639
SPI-9	249	31	8.0	33	Aug 78 to Apr 81	-27.094	-0.821
SPI-12	263	23	11.4	41	Aug 78 to Dec 81	-31.159	-0.760
SPI-24	268	21	12.8	72	Jul 99 to Jun 05	-44.220	-0.614

Table 6(b). SPI-based wet pattern of rainfall series at Naula station

SPI category	Wet months	Wet incidents	Average duration (month)	Longest wet pattern			
				Duration (month)	Period	Severity	Average intensity
SPI-1	162	91	1.8	7	Mar 82 to Sep 82	9.807	1.401
SPI-3	188	53	3.6	15	Oct 96 to Dec 97	17.933	1.196
SPI-6	192	36	5.3	20	Aug 96 to Mar 98	20.953	1.048
SPI-9	186	31	6.0	26	Apr 92 to Apr 94	37.322	1.435
SPI-12	170	23	7.4	28	Mar 92 to Jun 94	41.194	1.471
SPI-24	153	21	7.3	23	Jun 93 to Apr 95	43.538	1.893

General pattern of drought and wet events for Naula station is given in Tables 6(a) and 6(b), respectively. It is evident from Table 6(a) that the total number of drought months reduced from 282 (SPI-1) to 247 (SPI-6), but increased to 268 (SPI-24). The number of drought incidents continuously decreased from 91 (SPI-1) to 21 (SPI-24); however, average duration of drought increased from 3.1 months (SPI-1) to 12.8 months (SPI-24). The longest duration of drought severity continuously increased from 11 months (SPI-1) to 72 months (SPI-24); however, its average intensity varied from -0.513 (SPI-1) to -0.890 (SPI-3) which fell under mild drought category. It indicates that mild drought incidents are expected to occur more frequently with short durations rather than that for long durations. It was also revealed that out of 444 months, the extreme drought occurred during 4 months (0.90%) only, one each on short term (SPI-3) and long term (SPI-12) basis, and twice on medium term (SPI-9) basis. The most extreme drought occurred in June, 1984 for SPI-12. However, the severe drought occurred during 44 months (9.9%) out of 444 months of record at Naula station. All other months had the mild and moderate droughts more frequently. This indicates very low frequency of extreme and severe drought conditions at Naula station.

Table 6(b) indicates that total number of wet months increased from 162 (SPI-1) to 192 (SPI-6), but decreased from 192 (SPI-6) to 153 (SPI-24). Just like drought events, the number of wet incidents also continuously decreased from 91 (SPI-1) to 21 (SPI-24); however, average duration of wet events increased from 1.8 months (SPI-1) to 7.4 months (SPI-12), but slightly decreased to 7.3 months for SPI-24. The longest duration of wet severity continuously increased from 7 months (SPI-1) to 28 months (SPI-12) and slightly decreased to 23 months (SPI-24); however, average wet intensity varied from 1.048 (SPI-6) to 1.893 (SPI-24) which fell under moderate and severe wet category. It was also revealed that out of 444 months of record, the extreme and severe wet conditions accounted for only 117 months (26.4%) and 118 months (26.6%), respectively, indicating no serious threat of drought or drainage problems, however rainwater harvesting should be encouraged in the region.

Drought and Wet Pattern at Kedar

Table 7(a). SPI-based drought pattern of rainfall series at Kedar station

SPI category	Drought months	Drought incidents	Average duration (month)	Longest drought pattern			
				Duration (month)	Period	Severity	Average intensity
SPI-1	293	84	3.5	11	Feb 91 to Dec 91	-9.054	-0.823
				11	Mar 02 to Mar 03	-8.808	-0.801
SPI-3	256	55	4.7	15	Jul 07 to Sep 08	-12.119	-0.808
SPI-6	251	27	9.3	30	Aug 06 to Jan 09	-22.487	-0.750
SPI-9	256	27	9.5	35	Jun 90 to Apr 93	-31.296	-0.894
SPI-12	255	18	14.2	48	Jun 00 to May 04	-33.676	-0.702
SPI-24	265	15	17.7	69	Sep 99 to May 05	-41.739	-0.605

Table 7(b). SPI-based wet pattern of rainfall series at Kedar station

SPI category	Wet months	Wet incidents	Average duration (month)	Longest wet pattern			
				Duration (month)	Period	Severity	Average intensity
SPI-1	151	84	1.8	7	Feb 87 to Aug 87	9.521	1.360
SPI-3	186	54	3.4	14	Nov 96 to Dec 97	15.145	1.082
SPI-6	188	27	7.0	46	May 86 to Feb 90	69.158	1.503
SPI-9	180	26	6.9	24	Jun 88 to May 90	48.692	2.029
SPI-12	178	18	9.9	48	Aug 86 to Jul 90	86.102	1.794
SPI-24	157	15	10.5	48	Jun 87 to Apr 91	93.785	1.954

The general pattern of drought and wet events for Kedar station is given in Tables 7(a) and (b), respectively. It is evident from Table 7(a) that the total number of drought months reduced from 293 (SPI-1) to 251 (SPI-6), but increased from 251 (SPI-6) to 265 (SPI-24). The number of drought incidents continuously decreased from 84 (SPI-1) to 15 (SPI-24); however, average duration of drought increased from 3.5 months (SPI-1) to 17.7 months (SPI-24). The longest duration of drought severity continuously increased from 11 months (SPI-1) to 69 months (SPI-24); however, average intensity varied from -0.894 (SPI-9) to -0.605 (SPI-24) which fell under mild drought category. It indicates that mild drought incidents are expected to occur more frequently with short durations rather than that for long durations. It was also revealed that there were no occurrences of extreme drought during 37 years (444 months) of rainfall data; however, there were only 30 months (6.8%) of severe drought.

Table 7(b) indicates that total number of wet months increased from 151 (SPI-1) to 188 (SPI-6), but decreased from 188 (SPI-6) to 157 (SPI-24). Just like drought events, the number of wet incidents also continuously decreased from 84 (SPI-1) to 15 (SPI-24); however, average duration increased from 1.8 (SPI-1) to 10.5 (SPI-24) months. It indicates that the wet incidents occur more frequently with short durations rather than that for long durations at Kedar station. The longest duration of wet severity continuously increased from 7 months (SPI-1) to 46 months (SPI-6); decreased to 24 (SPI-9); and increased to 48 (SPI- 12 and 24); however, its average intensity varied from 1.082 (SPI-3) as moderate wet to 2.029 (SPI-9) as extreme wet category. On the other hand, the extreme wet events were 136 (30.6%) and severe wet events were 91 (20.5%). This reveals that there are nearly 51% chances of serious wet conditions at Kedar station. Therefore, more efforts will be required to take precautionary measures for the control of floods and water logging in the low-lying areas in valleys along with rainwater harvesting.

Drought and Wet Pattern at Chaukhutia

Table 8(a). SPI-based drought pattern of rainfall series at Chaukhutia station

SPI category	Drought months	Drought incidents	Average Duration (month)	Longest drought pattern			
				Duration (month)	Period	Severity	Average intensity
SPI-1	158	58	2.7	23	Oct 92 to Aug 94	-20.314	-0.883
SPI-3	136	33	4.1	26	Dec 92 to Jan 95	-28.527	-1.097
SPI-6	131	25	5.2	34	Mar 93 to Dec 95	-43.390	-1.276
SPI-9	129	18	7.2	31	Jun 93 to Dec 95	-45.997	-1.484
SPI-12	129	17	7.6	90	Jul 88 to Dec 95	-91.863	-1.021
SPI-24	91	4	22.8	79	Jun 89 to Dec 95	-88.890	-1.125

Table 8(b). SPI-based wet pattern of rainfall series at Chaukhutia station

SPI category	Wet months	Wet incidents	Average duration (month)	Longest wet pattern			
				Duration (month)	Period	Severity	Average intensity
SPI-1	102	58	1.8	4	Apr 76 to Jul 76	7.331	1.833
				4	Jan 81 to Apr 81	4.882	1.221
				4	Jul 82 to Oct 82	4.229	1.057
				4	Jul 84 to Oct 84	5.738	1.434
				4	May 85 to Aug 85	3.516	0.879
				4	Feb 87 to May 87	3.734	0.933
SPI-3	121	33	3.7	25	Nov 80 to Nov 82	30.793	1.232
SPI-6	123	25	4.9	27	Dec 80 to Feb 83	36.691	1.359
SPI-9	122	18	6.8	33	Feb 81 to Oct 83	38.729	1.174
SPI-12	119	17	7.0	32	Feb 81 to Sep 83	37.845	1.183
SPI-24	144	4	36.0	110	Jul 79 to Aug 88	79.580	0.723

The general pattern of drought and wet events for Chaukhutia station is given in Tables 8(a) and 8(b), respectively. Table 8(a) reveals that the total number of drought months reduced from 158 (SPI-1) to 91 (SPI-24). The number of drought incidents continuously decreased from 58 (SPI-1) to 4 (SPI-24); however, average duration of drought increased from 2.7 (SPI-1) to 22.8 (SPI-24) months. It indicates that mild drought incidents are expected to occur more frequently with short durations rather than that for long durations. The longest duration of drought severity continuously increased from 23 months (SPI-1) to 34 months (SPI-6), but sharply increased from 31 (SPI-9) to 90 (SPI-12) and reduced to 79 (SPI-24); however, average intensity varied from -0.883 (SPI-1) as mild drought to -1.484 (SPI-9) as moderate drought. It was also indicated that out of 259 rainfall data, there were 26 (10%) events of extreme drought mostly at medium and long time scales; however, there were 46 months (17.8%) of severe drought and rest were mild and moderate drought. The most extreme drought occurred in May, 1994 for SPI-12.

Table 8(b) indicates that total number of wet months increased from 102 (SPI-1) to 123 (SPI-6), but decreased from 123 (SPI-6) to 119 (SPI-12) and further increased to 144 (SPI-24). Just like drought events, the number of wet incidents also continuously decreased from 58 (SPI-1) to 4 (SPI-24); however, average duration increased from 1.8 (SPI-1) to 36.0 (SPI-24) months. The longest duration of wet severity continuously increased from 4 months (SPI-1) to 33 months (SPI-9); decreased to 32 (SPI-12); and sharply increased to 110 (SPI-24); however, its average intensity varied from 1.833 (SPI-1) as severe wet to 0.723 (SPI-24) as mild wet category. Also, the extreme wet events were 24 (9.3%) and severe wet events were 59 (22.8%). This reveals that there are only 31.4% chances of serious wet conditions and most of the months had mild and moderate wet conditions at Chaukhutia station. It indicates that the wet incidents occur more frequently with short durations rather than that for long durations at Chaukhutia station. Therefore, more efforts will be required to take precautionary measures for the control of floods and water logging in the valleys along with rainwater harvesting.

Drought and Wet Pattern at Mehalchauri

Table 9(a). SPI-based drought pattern of rainfall series at Mehalchauri station

SPI category	Drought months	Drought incidents	Average duration (month)	Longest drought pattern			
				Duration (month)	Period	Severity	Average intensity
SPI-1	117	43	2.7	8	Jun 86 to Jan 87	-8.394	-1.049
SPI-3	101	27	3.7	11	Mar 88 to Jan 89	-9.920	-0.902
SPI-6	101	17	5.9	19	Mar 83 to Sep 84	-13.555	-0.713
SPI-9	104	11	9.5	37	Jun 86 to Jun 89	-31.192	-0.843
SPI-12	104	7	14.9	42	Jun 86 to Nov 89	-32.845	-0.782
SPI-24	103	4	25.8	43	Jun86 to Dec89	-32.322	-0.752

Table 9(b). SPI-based wet pattern of rainfall series at Mehalchauri station

SPI category	Wet months	Wet incidents	Average duration (month)	Longest wet pattern			
				Duration (month)	Period	Severity	Average intensity
SPI-1	70	43	1.6	6	Apr76 to Sep76	7.979	1.330
SPI-3	84	27	3.1	17	Feb77 to Jun78	18.312	1.077
SPI-6	81	17	4.8	27	May76 to Jul78	38.261	1.417
SPI-9	75	11	6.8	37	Jul 75 to Jul78	53.216	1.438
SPI-12	72	7	10.3	38	Jul75 to Aug78	56.939	1.498
SPI-24	61	4	15.3	39	May76 to Jul79	53.689	1.377

The general pattern of drought and wet events for Mehalchauri station is given in Tables 9(a) and 9(b), respectively. Table 9(a) reveals that total number of drought months reduced from 117 (SPI-1) to 101 (SPI-3 and -6); increased to 104 (SPI-12) and decreased to 103 (SPI-24). The number of drought incidents continuously decreased from 43 (SPI-1) to 4 (SPI-24); however, average duration of drought increased from 2.7 (SPI-1) to 25.8 (SPI-24) months. The longest duration of drought severity continuously increased from 8 months (SPI-1) to 43 months (SPI-24); however, average intensity varied from -0.713 (SPI-6) as mild drought to -1.049 (SPI-1) as moderate drought. It was also indicated that there were no occurrences of extreme drought out of 187 of rainfall data; however, there were 18 events (9.6%) of severe drought and rest of the events were of mild and moderate drought. It indicates that mild drought incidents are expected to occur more frequently with short durations rather than that for long durations.

Table 9(b) indicates that the total number of wet months increased from 70 (SPI-1) to 84 (SPI-3), but decreased to 61 (SPI-24). Just like drought events, the number of wet incidents also continuously decreased from 43 (SPI-1) to 4 (SPI-24); however, average duration increased from 1.6 (SPI-1) to 15.3 (SPI-24) months. The longest duration of wet severity continuously increased from 6 months (SPI-1) to 39 months (SPI-24); however, its average intensity varied from 1.077 (SPI-3) to 1.498 (SPI-12) as moderate wet category. The extreme wet months were 45 occurrences of serious wet conditions and most of the months had mild and moderate wet conditions at Mehalchauri station. It indicates that the wet incidents occur more frequently with short durations rather than that for long durations at Mehalchauri station. Therefore, precautionary measures should be taken for the control of floods and water logging in the valleys along with rainwater harvesting and storage for supplemental irrigation during the periods of drought in the region.

3.7 Prediction of Drought and Wet Events

Month-wise probability of occurrence of meteorological drought and wet events was determined at different time-scales for all the stations and the results are as follows.

The probability analysis of meteorological drought for Naula station revealed that mean monthly probability of occurrence of mild and moderate droughts across all months varied from 0.40 to 0.51 and 0.09 to 0.14, respectively. However, probability for severe drought varied from 0.01 to 0.03, which is almost negligible; and the extreme drought was non-existent. Analysis of drought on seasonal basis indicated that the probability of mild-drought was 0.52 for the post-monsoon (October to January), followed by 0.47 for monsoon (June to September) and 0.40 for pre-monsoon (February to May) seasons. However, the probability of moderate drought was merely 0.14 for pre-monsoon, followed by 0.12 for post-monsoon and 0.09 for monsoon seasons. Probability of severe and extreme droughts was nearly zero.

The mean monthly probability of occurrence of wet events varied from 0.40 to 0.51 and 0.11 to 0.14 for mild and moderate, respectively. It varied merely from 0.03 to 0.07 and 0.04 to 0.06, for severe and extreme wet events, respectively. On seasonal basis, the probability of mild-wet events was 0.28 for the pre-monsoon and monsoon seasons, followed by 0.21 for post-monsoon season. However, the mean probability of moderate wet events was only 0.08 for pre-monsoon, followed by 0.05 each for monsoon and post-monsoon seasons. Probabilities for pre-monsoon, monsoon and post-monsoon seasons were 0.04, 0.03, 0.06 and 0.04, 0.05, 0.05 for severe and extreme wet events, respectively.

Nearly, the similar pattern was obtained for Kedar, Chaukhutia and Mehalchauri stations also. The results of this analysis have clearly indicated that severe and extreme drought and wet events are not a serious problem at these stations; however, there are more chances of mild and moderate drought and wet events. During wet events, the surplus water must be collected and stored by adopting appropriate rainwater harvesting and moisture conservation measures such as farm ponds, mulching, contour cultivation etc. to tackle the occasional threats of drought even during monsoon season.

4 Conclusions

Significantly downward trend for December and post-monsoon season and an upward trend for September were observed at Naula station. Significantly downward trend was also observed in July, December and monsoon season at Kedar station, and in June, July, August, monsoon and annual data series at Chaukhutia station. No significant trend was observed at Mehalchauri station. In general, mid-Himalayan region (Kedar and Chaukhutia) showed declining trend in rainfall, while the high-Himalayan region (Mehalchauri) showed no effect in rainfall trend. SPI-based drought analysis revealed that there are negligible chances of severe and extreme droughts at these stations, but more chances of mild and moderate droughts, which may be taken care of by adopting appropriate water and moisture conservation measures such as rainwater harvesting, mulching, contour cultivation etc.

References

1. S.T. Chen, C.C. Kuo and P.S. Yu, "Historical trends and variability of meteorological droughts in Taiwan," *Hydrol Sci J 54*(3): 430-441. 2009.
2. A.K. Mishra, V.P. Singh and V.R. Desai, "Drought Characterization: a probabilistic approach", *Stoch Environ Res Risk 23*(1): 41-55. 2009.
3. UN Secretariat General, "United Nations Convention to Combat Drought and Desertification in Countries Experiencing Serious Droughts and/or Desertification, Particularly in Africa, Paris. 1994.
4. R. Nagarajan, "*Drought Assessment*", Centre of Studies in Resources Engineering, Indian Institute of Technology, Bombay, India. 2009.

5. S. Dogan, A. Berktay and V.P. Singh, "Comparison of multi-monthly rainfall-based drought severity indices, with application to semi-arid Konya closed basin", *Turkey J Hydrol., 470*: 255-268. 2012.
6. W.C. Palmer, "Meteorological droughts", US Department of Commerce, *Weather Bureau. Research* Paper No. 45: 58. 1965.
7. W.J. Gibbs and J.V. Maher, "Rainfall deciles as drought indicators. *Bureau of Meteorology Bulletin 48*, Commonwealth of Australia, Melbourne, Australia. 1967.
8. H.N. Bhalme and D.A. Mooley, "Large-scale droughts/floods and monsoon circulation," *Monthly Weather Review, 108*(8): 1197-1211. 1980.
9. B.A. Shafer and L.E. Dezman, "Development of a Surface Water Supply Index (SWSI) to assess the severity of drought conditions in snowpack runoff areas". In Proceedings of the western snow conference, Fort Collins, CO: Colorado State University, Vol. 50: 164-175. 1982.
10. T.B. McKee, N.J. Doeskin and J. Kleist, "The relationship of drought frequency and duration to time scales". Proceedings of the eighth conference on applied climatology, Vol. 17. *Am Meteorol Soc*, Boston, MA, USA, No. 22:179-184. 1993.
11. A. Tabrizi A., D. Khalili, A.A. Kamgar-Haghighi and S. Zand-Pars, "Utilization of Time-Based Meteorological Droughts to Investigate Occurrence of Streamflow Droughts". *Water Resour Manage,* 24: 4287–4306. 2010.
12. J.F. Santos, M.M. Portela and I. Pulido-Calvo, "Regional frequency analysis of droughts in Portugal", *Water Resour Manage*, 25: 3537–3558. 2011.
13. H.R. Byun and D.A. Wilhite, "Objective quantification of drought severity and duration," *J Climate 12*: 2747-2756. 1999.
14. G. Tsakiris, D. Pangalou, and H. Vangelis, "Regional drought assessment based on the Reconnaissance Drought Index (RDI)". *Water Resour Manage 21*(5):821-833. 2007.
15. R.P. Pandey, S.K. Mishra, R. Singh and K.S Ramasastri, "Stream flow drought severity analysis of Betwa River System (India)". *Water Resour Manage, 22*:1127-1141. 2008.
16. J. Keyantash and J.A. Dracup, "The quantification of drought: an evaluation of drought indices", The drought monitor. *Bull Am Meteorol Soc 83*(8): 1167–1180. 2002.
17. N.B. Guttman, "Comparing the Palmer drought index and the Standardized Precipitation Index", *J Am Water Resour Assoc 34*(1):113-121. 1998.
18. D.S. Pai, S. Latha, G. Pulak and H.R. Hatwar, "District-wide drought climatology of the southwest monsoon season over India based on standardized precipitation index (SPI)", *Nat Hazards*, 59: 1797–1813. 2011.
19. P. Angelidis, F. Maris, N. Kotsovinos and V. Hrissanthou, "Computation of Drought Index SPI with Alternative Distribution Functions," *Water Resources Management,* 26: 2453-2473. 2012.
20. Qiang Zhang, Xiao Mingzhing and Chen Xiaohong, "Regional evaluations of meteorological drought characteristics across the Pearl River basin, China". *Am. J. Climate Change, 1*: 48-55. 2012.
21. Palchaudhuri and Biswas, "Analysis of Meteorological Drought Using Standardized Precipitation Index – A Case Study of Puruliya District, West Bengal, India", *International Journal of Environmental and Ecological Engineering*, Vol. 7, No. 3: 167-174. 2013.
22. S. Sachan, T. Thomas and R. M. Singh, "Meteorological and hydrological drought characteristics in Bearma basin of Bundelkhand region in Madhya Pradesh", Indian Journal of Soil Conservation, Vol. 42, No. 2, pp 235-242. 2014.
23. Anil Kumar, "Characterizing meteorological drought using standardized precipitation index for Dehradun, Uttarakhand. Ind. J. Soil Cons., Vol. 44(2): 157-162. 2016.
24. M. Bhushan, A. Raj and L.B. Roy, "Drought and their analysis for Amritsar district in Punjab", J. Indian Water Res. Soc., Vol. 37 (3): 1-6. 2017.
25. M.G. Kendall, "*Rank Correlation Methods*", Charles Griffin, London. 1975.
26. P.K. Sen, "Estimates of the regression coefficient based on Kendall's tau", *J Am Stat Assoc, 63* (324): 1379-1389. 1968.
27. N.L. Adhyani, T. June, and A. Sopaheluwakan, "Exposure to drought: Duration, severity, intensity" (Java, Bali Nusa Tenggara), *IOP Conf. Ser.: Earth Environ. Sci.* 58: 012-040. 2017.

