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# A study on frequency of western disturbances and precipitation trends over Jammu & Kashmir, India : 1980-2019

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**सार** – 1980 से 2019 की अवधि के दौरान पश्चिमी विक्षोभ (डब्ल्यूडी) की आवृत्ति और जम्मू-कश्मीर में वर्षण की परिवर्तनशीलता पर एक अध्ययन किया गया है। अध्ययन अवधि के दौरान नवंबर से अप्रैल तक पश्चिमी विक्षोभ की आवृत्ति निर्धारित की गई और परिणामों से पता चला कि कुल 600 पश्चिमी विक्षोभ के मामले प्रेक्षित गए किए। पश्चिमी विक्षोभ आवृत्तियों ने नवंबर और मार्च के दौरान क्रमशः गिरावट -0.610 और -2.748 के साथ महत्वपूर्ण कमी की प्रवृत्ति r ($p<0.01$) तथा जनवरी (0.417) और फरवरी (2.795) मिमी/माह स्लोप वेल्यू ($p<0.01$) के दौरान वृद्धि की प्रवृत्ति का पता चला। मान-केंडल सांख्यिकीय परीक्षणों का उपयोग करते हुए वर्षा प्रवृत्तियों के परिणामों ने दिसंबर और मार्च के महीने में कुपवाड़ा और मार्च के महीने में गुलमर्ग के लिए क्रमशः -2.450 और -2.947 और -6.947 मिमी/माह के स्लोप वेल्यू के साथ महत्वपूर्ण कमी की प्रवृति का पता चला। अन्य स्टेशनों के लिए कोई महत्वपूर्ण प्रवृत्ति नहीं देखी गई। नवोन्मेषी प्रवृत्तिट विश्लेषण के परिणामों ने -0.288 (जम्मू) से -1.978 (श्रीनगर) मिमी/माह तक अधिकांश स्टेशनों में नवंबर और दिसंबर के महीने के लिए महत्वपूर्ण कमी की प्रवृत्ति देखी गई। गुलमर्ग, बटोट, बदरवाह और कटरा ने जनवरी के महीने के लिए क्रमशः -2.311, -1.221, -0.737 और -0.917 मिमी/माह के स्लोप मानों के साथ महत्वपूर्ण कमी की प्रवृत्ति 3 रही। फरवरी के महीने में कुकरनाग, कुपवाड़ा, श्रीनगर, बनिहाल, बटोटे और बदरवाह स्टेशनों के लिए क्रमशः 1.267, 1.958, 1.040, 2.231 और 1.058 मिमी/माह के साथ p मान <0.01 के साथ महत्वपूर्ण वृद्धि की प्रवृत्ती देखी गई। कुकरनाग (2.348 मिमी/माह) को छोड़कर, सभी स्टेशनों में अप्रैल माह मेंकमी की प्रवृत्ति का पता चला। पियर्सन सहसंबंध के परिणामों से पता चला है कि बदरवाह, कटरा, काजीगुंड और श्रीनगर स्टेशन का वर्षण (0.351, 0.370, 0.357, 0.369) दिसंबर की पश्चिमी विक्षोभ आवृत्ति पी <0.05 के साथ, जनवरी (0.436) के महीने के लिएकुपवाड़ा के साथ, और मार्च (0.363) के महीने के लिए बटोट के साथ सकारात्मक रूप से सहसंबद्ध है। सभी स्टेशनों की औसत वर्षण और कुल पश्चिमी विक्षोभ आवृत्ति के सहसंबंध की गणना की गई और परिणामों ने $R^2$ मान 0.55 के साथ वर्षा और पश्चिमी विक्षोभ आवृत्ति के बीच सकारात्मक सहसंबंध दिखाया।

**ABSTRACT.** A study has been conducted on frequency of western disturbances (WDs) and variability of precipitation over J&K during the period 1980 to 2019. The frequency of WD's from November to April during study period was determined and results showed that total 600 WD's cases were observed. The WD frequencies showed significant decreasing trend ($p<0.01$) during November and March with slope values -0.610 and -2.748 respectively and increasing trends during January (0.417) and February (2.795) mm/ month slope value ($p<0.01$). The results of precipitation trends using Mann-Kendall statistical tests showed significant decreasing trends for Kupwara in the month of December and March and Gulmarg in the month of March with a slope value of -2.450 & -2.947 and -6.947 mm/month respectively. No significant trends were observed for other stations. The results of Innovative trend analysis showed decreasing significant trends for the month of November and December for most of the stations with slope ranging from -0.288 (Jammu) to -1.978 (Srinagar) mm/month. Gulmarg, Batote, Baderwah, and Katra showed significant decreasing trends for the month of January with slope values -2.311, -1.221, -0.737 and -0.917 mm/month respectively. Significant increasing trends were observed in the month of February for the stations Kukernag, Kupwara, Srinagar, Banihal, Batote and Baderwah with slope values 1.267, 1.958, 1.040, 2.231 and 1.058 mm/month respectively with p value <0.01. Except Kukernag (2.348 mm/month), all the stations showed decreasing trend for the month of April. The results of Pearson correlation showed that Precipitation of Baderwah, Katra, Qazigund and Srinagar station is positively correlated (0.351, 0.370, 0.357, 0.369) with WD frequency of December with significant at $p<0.05$, Kupwara for the month of January (0.436) and Batote for the month of March (0.363). The correlation between average precipitation of all the stations and total WD frequency was computed and results showed positive correlation between precipitation and WD frequency with $R^2$ value 0.55.

**Key words** – Western disturbances, Jammu & Kashmir, Precipitation.

## 1. Introduction

Primary sources of precipitation over the north-west Himalayan (NWH) region and the plains of northern India during winter are the eastward-moving upper air troughs in the subtropical westerlies, commonly known as the western disturbances (WDs) in the Asian subcontinent (Dimri *et al*., 2015; Kumar *et al*., 2015). WDs yield winter precipitation, primarily, in solid form, *i.e*., snow, over the NWH and rainfall in the plains of northern India. Winter precipitation over northern India and the NWH plays a very important role in many sectors of the economy such as agriculture, horticulture, water resources, hydroelectricity and the daily water needs of millions of people dependent on the rivers originating from the Himalaya (Chand and Singh 2015; Kumar *et al*., 2016).

The origin and structure of western depressions over northwest India were initially described and classified as "weak" extratropical disturbances, traveling with the narrow but intense jet stream that flows around the southern rim of the Indian Himalayas [Mull and Desai, 1947; Riehl, 1962]. The moisture in these storms usually originates over the Mediterranean Sea and the Atlantic Ocean. Extratropical storms are global rather than a localized phenomenon with moisture usually carried in the upper atmosphere and localized behavior such as frontal systems. These are the extra tropical upper air troughs or cyclonic circulations (CCs) in mid-latitude westerlies that move west to east across the Himalayan region (Puranik and Karekar, 2009), CCs sometimes develop south of the system at lower levels, in which case they are known as induced CCs. Some WDs produce well-distributed and large amounts of precipitation along with heavy snowfall/rainfall, landslides, cloudbursts etc. over the Himalayan region, while others pass across this area without causing precipitation (Malurkar, 1947). Hence, studies related to WDs and their associated weather are essential to the NWH. The interplay of WDs with the topography of the western Himalayas determines the spatial and vertical distribution of precipitation.

The global hydrological cycle is expected to amplify in response to global climate change and variability (Zahn and Allan, 2013). It is expected that the regions where precipitation is strongly dependent on ocean moisture uptake will experience stronger precipitation events (Gimeno *et al*., 2013). The variability of mid latitude winter weather is strongly governed by extra tropical cyclones, although there is very little evidence that the frequency or wind speed of these cyclones will increase. However, more intense precipitation from the cyclones that carry WDs will have socioeconomic impacts over the western Himalayas, which remains an issue for further investigation in light of existing scientific knowledge and understanding. Observation-based studies concerning the changing nature of WDs are scarce. Cannon *et al*. (2014) investigated variations and changes in winter WD (WWD) activity from 1970 to 2010 for heavy precipitation events and found significant differences between the western Himalayas and central Himalayan (CH) regions. Yadav *et al*. (2010) proposed a physical mechanism explaining a potential intensification of WDs in a changing climate. This mechanism suggests a baroclinic response due to the Sverdrup balance related to a large-scale sinking motion over the western Pacific during the warm phase of ENSO. The cyclonic circulation anomaly intensifies the WD's passing over northwest India. With specific reference to the frequency of WDs, Ridley *et al*. (2013) provided a comprehensive overview on the projected increased frequency of WDs up to the year 2100. Madhura *et al*. (2014) also report an increase in WD frequency due to mid tropospheric warming trends observed in recent decades over west-central Asia. Such warming will increase the baroclinic instability of the mean westerly wind and could favor increased variability of the WDs and increased precipitation. Bhutiyani *et al*. (2010) also studied precipitation trends in the northwest Himalayas and did not found any trends in precipitation during the winter season. Kumar and Jain (2010) found decreasing trends in monsoon and winter rainy days over all the stations and a decreasing trend in annual rainfall over three stations in the Kashmir valley. However, there is hardly any study in literature related to frequency of WDs and variability of precipitation over the NWH with particular focus on Jammu & Kashmir (J&K). Therefore the present study has been conducted to analyze the trend of WD frequencies and associated precipitation using daily precipitation data for the period 1980 to 2019 over J&K.

## 2. Materials and method

### 2.1. *Study area and data collection*

In the present study we used daily precipitation data of 10 stations of J&K for the period 1980-2019 during the months, November to April from India Meteorological Department. Locations of the stations are given in Fig. 1.


**Fig. 1.** Map of study area and location of stations over Jammu & Kashmir

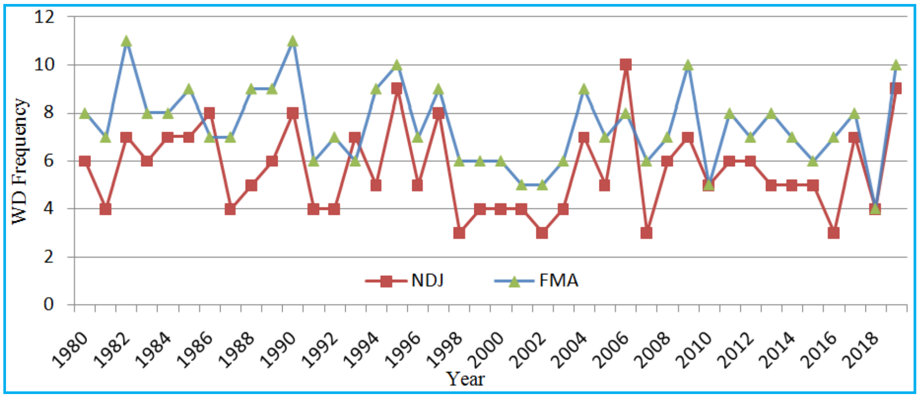


**Fig. 2.** Frequency of WD's during NDJ (November, December, January) and FMA (February, March and April) for the period 1980-2019 over J&K

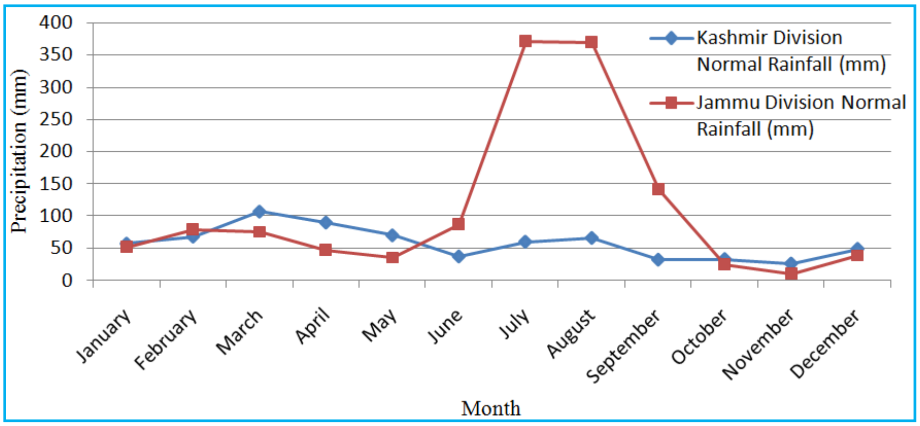


**Fig. 3.** Rainfall climatology of Kashmir and Jammu division

The frequency of WD during each month was determined by considering the precipitation event during the passage of WD over J&K. The monthly means of precipitation for Kashmir Division and Jammu Division are separately calculated during the study period. (Figs. 2&3).

2.2. *Statistical methods*

Many statistical techniques (parametric or non-parametric) have been developed to detect trends within time series such as linear regression, Spearman's Rho test, Mann-Kendall test and innovative trend analysis. In this study, the Mann-Kendall and Spearman's Rho tests were used to analyze the precipitation trends, while the linear regression was used to calculate magnitude of trends.

2.2.1. *Mann-Kendall trend test*

The Mann-Kendall test statistic S (Mann, 1945; Kendall, 1975) is calculated by using

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

where, $n$ is the number of data points, $xi$ and $xj$ are the data values in time series $i$ and $j$ ($j > i$), respectively and sgn ($xj$ $xi$) is the sign function determined as:

$$\operatorname{sgn}(xi - xj) = \begin{cases} 1 if\,(x_j - x_i) > 0 \\ 0\,(x_j - x_i) = 0 \\ -1\,(x_j - x_i) < 0 \end{cases}$$

The positive (negative) value of S indicates an increasing (decreasing) trend. If n is larger than 10 and time series has approximately normal distribution, then the variance of the slope value becomes :`

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

where, $p$ is the number of tied groups; $t_i$ is the number of ties of extent $i$. The standard normal test statistics $Z$ used for detecting a significant trend is expressed as:

$$Zs = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} if\ S > 0 \\ 0\ if \qquad S = 0 \\ \frac{S \mp 1}{\sqrt{Var(S)}} if\ S < 0 \end{cases}$$

Positive values of $Zs$ indicate increasing trends while the negative $Zs$ show decreasing trends.

2.2.2. *Linear regression method*

A linear regression method is one of methods which are used to estimate a slope. The slope indicates the mean temporal change of the studied variable. Positive values of the slope show increasing trends, while negative values of the slope indicate decreasing trends. A linear regression line has an equation of the form

$$y = a + bx$$

where, $x$ = the explanatory variable, $y$ = the dependent variable, $b$ = the slope of the line and $a$ = the intercept.

**TABLE 1**

**Latitude and Longitude of the stations**

| Location of station | Coordinates | |
|---|---|---|
| | Lat. (°N) | Long. (°E) |
| Srinagar | 34° 03' | 74° 48' |
| Qazigund | 33° 35' | 75° 09' |
| Kokernag | 33° 35' | 75° 18' |
| Kupwara | 34° 01' | 74° 15' |
| Gulmarg | 34° 03' | 74° 23' |
| Katra | 32° 58' | 74° 55' |
| Kathua | 32° 20' | 75° 30' |
| Banihal | 33° 25' | 75° 11' |
| Bhaderwah | 32° 58' | 75° 43' |
| Batote | 33° 06' | 75° 49' |

2.2.3. Spearman's Rho test Spearman's Rho test is non-parametric method commonly used to verify the absence of trends. Its statistic D and the standardized test statistic ZD are expressed as follows.

$$D = 1 - \frac{6\sum_{i=1}^{n}\left[R(X_i) - i\right]^2}{n(n^2 - 1)}$$

$$Z_d = D\frac{\sqrt{n-2}}{1 - D^2}$$

where, $R(X_i)$ is the rank of $i$th observation $X_j$ in the time series and n is the length of the time series. Positive values of $Z_d$ indicate increasing trends while negative $Z_d$ show decreasing trends.

## 3. Results and discussion

The frequency of WD's from November to April during study period was determined based on total WD's. It was found that total 600 WD's cases were observed

**TABLE 2**

**Trend of WDs during different months using Innovative trend analysis**

| Trend | Month | Trend Slope | Standard deviation | Correlation | Lower CL p<1.0 | Upper CL p<1.0 | Lower CL p<0.5 | Upper CL p<0.5 | Lower CL p<0.1 | Upper CL p<0.1 |
|---|---|---|---|---|---|---|---|---|---|---|
| WD | November | **-0.610** [a] | 0.164 | 0.964 | -0.270 | 0.270 | -0.322 | 0.322 | -0.423 | 0.423 |
| | December | -0.416 | 0.369 | 0.929 | -0.606 | 0.606 | -0.722 | 0.722 | -0.950 | 0.950 |
| | January | 0.417 | 0.293 | 0.966 | -0.483 | 0.483 | -0.575 | 0.575 | -0.756 | 0.756 |
| | February | **2.795** [a] | 0.467 | 0.938 | -0.769 | 0.769 | -0.916 | 0.916 | -1.204 | 1.204 |
| | March | **-2.748** [a] | 0.206 | 0.989 | -0.339 | 0.339 | -0.403 | 0.403 | -0.530 | 0.530 |
| | April | -0.017 | 0.161 | 0.974 | -0.266 | 0.266 | -0.316 | 0.316 | -0.416 | 0.416 |

**TABLE 3**

**Trend of WDs during different months using Mann-Kendall test**

| Trend | Test | November | December | January | February | March | April |
|---|---|---|---|---|---|---|---|
| WD | Zd | 0.920 | -0.944 | **-2.042** | -0.409 | -0.383 | 0.114 |
| | Zs | 0.870 | -0.927 | **-2.100** | -0.313 | -0.483 | 0.207 |
| | b (mm/year) | 0.011 | -0.010 | **-0.034** | -0.004 | -0.012 | 0.004 |

during the period 1980-2019. It has been observed that on an average, the frequency of WD's during the month of November, December and January was less as compared to February, March and April. It was also observed from the daily data of precipitation that WD's during November, December and January were less severe as compared to February, March and April respectively during the study period. (Fig. 2)

The climatological information for Kashmir and Jammu Division is separately carried out and results revealed that the contribution of WD's in annual precipitation is 60-65% in Kashmir Division. Hence most of the precipitation is observed during January-April in Kashmir Division. The impact of SW monsoon over Jammu Division is considerable and contributes 50-55% in annual precipitation. The precipitation caused due to WD's over Jammu Division during the months, January-April is important for Rabi crops and it contributes 30-35% of annual precipitation. Westerlies and southwest monsoon are the two main sources of precipitation in the study area. From June to September, the moisture across the Himalayas is brought by the southwest monsoons from the Indian Ocean across the Arabian Sea and the Bay of Bengal. From October to May, the mid-latitude westerlies dominate in the western Himalayas, which bring moisture from the Mediterranean Sea or the mid-west Atlantic Ocean. The westerlies are also active in the southwest monsoon period in the western Himalayas but with lower frequency. The Pir-Panjal mountain range is preventing the entry of Southwest monsoons into the valley. Thus Jammu Division receives ample rainfall during monsoon period as compared to Kashmir Division (Fig. 3). Hence annual precipitation received over Kashmir Division is less than Jammu Division.

*Western Disturbance (WD) trends* : Trends of WD over different months were analyzed using Innovative trend analysis, Mann-Kendall and linear regression analysis. The analysis showed that WD frequencies showed decreasing significant trend ($p < 0.01$) during November and March with slope values -0.610 and -2.748 respectively. The results also showed decreasing trends during the months of December and April but are non-significant. However increasing trends were observed during February with slope value 2.795 ($p < 0.01$) and January with slope value 0.417 but were non-significant (Table 2). The results observed from Mann-Kendall test and linear regression analyses were slightly different from Innovative trend analysis. The results showed decreasing

**TABLE 4**

**Precipitation trends for different months of stations using the Mann-Kendall test**

| Station | Test | Month | | | | | |
|---|---|---|---|---|---|---|---|
| | | November | December | January | February | March | April |
| Gulmarg | Zd | -0.817 | -1.731 | -0.368 | -1.185 | **-2.384** | -0.722 |
| | Zs | -0.903 | -1.624 | -0.652 | -1.218 | **-2.535** | -1.095 |
| | b (mm/year) | -0.636 | -2.124 | -1.104 | -1.895 | -6.618 | -1.544 |
| Kukernag | Zd | -0.286 | -0.068 | 0.232 | 0.422 | -1.212 | 0.831 |
| | Zs | -0.317 | -0.247 | 0.131 | 0.714 | -1.262 | 0.929 |
| | b (mm/year) | -0.209 | -1.106 | 0.800 | 0.605 | -1.649 | 2.576 |
| Kupwara | Zd | 0.286 | **-1.989** | 0.313 | 1.185 | **-2.302** | -1.294 |
| | Zs | 0.215 | **-2.008** | 0.186 | 1.366 | **-2.012** | -1.304 |
| | b (mm/year) | 0.218 | -2.450 | 0.336 | 1.390 | -2.947 | -1.193 |
| Qazigund | Zd | -0.382 | -1.160 | 0.014 | -0.627 | -1.294 | -0.313 |
| | Zs | -0.189 | -1.102 | 0.093 | -0.548 | -1.311 | -0.358 |
| | b (mm/year) | -0.405 | -2.364 | 0.717 | -0.587 | -2.741 | -0.125 |
| Srinagar | Zd | -0.178 | -1.091 | 0.981 | 1.063 | -1.022 | -0.041 |
| | Zs | -0.174 | -1.159 | 0.838 | 1.178 | -0.982 | -0.222 |
| | b (mm/year) | 0.029 | -2.338 | 0.802 | 0.741 | -1.556 | -0.254 |

**TABLE 5**

**Precipitation trends for different months of stations using the Mann-Kendall test**

| Station | Test | Month | | | | | |
|---|---|---|---|---|---|---|---|
| | | November | December | January | February | March | April |
| Banihal | Zd | -0.600 | 0.354 | 0.422 | 1.076 | -1.158 | 0.940 |
| | Zs | 0.382 | -0.148 | 0.397 | 0.918 | -1.227 | 0.870 |
| | b (mm/year) | 0.156 | -1.293 | 1.070 | 1.838 | -2.256 | 0.642 |
| Batote | Zd | 0.682 | -0.423 | -0.736 | 0.232 | -1.212 | -0.722 |
| | Zs | 0.566 | -0.555 | -0.811 | 0.257 | -1.221 | -0.740 |
| | b (mm/year) | 0.640 | -1.910 | -1.279 | 1.104 | -2.281 | -0.929 |
| Bhaderwah | Zd | 0.136 | -0.613 | -0.504 | 0.109 | -1.526 | -0.095 |
| | Zs | 0.144 | -0.772 | -0.378 | -0.063 | -1.428 | -0.271 |
| | b (mm/year) | -0.362 | -1.840 | 0.094 | 0.354 | -1.919 | -1.135 |
| Jammu | Zd | 0.536 | -0.710 | 0.272 | -0.313 | -0.885 | -0.191 |
| | Zs | 0.557 | -0.852 | 0.314 | -0.600 | -0.879 | -0.269 |
| | b (mm/year) | -0.235 | -1.055 | 0.341 | -0.376 | 0.600 | -0.366 |
| Katra | Zd | 0.164 | -0.587 | -0.232 | -0.232 | -0.749 | -0.858 |
| | Zs | 0.259 | -0.802 | -0.117 | -0.471 | -0.847 | -0.965 |
| | b (mm/year) | -0.317 | -2.094 | -0.173 | -0.382 | 0.158 | -1.634 |

**TABLE 6**

**Precipitation trends for different months of stations using Innovative trend analysis**

| Station | Month | Slope (s) | Standard deviation | Correlation | Lower CL | Upper CL | Lower CL | Upper CL | Lower CL | Upper CL |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | p<1.0 | | p<0.05 | | p<0.01 | |
| Gulmarg | November | **-0.939**[a] | 0.087 | 0.982 | -0.144 | 0.144 | -0.171 | 0.171 | -0.225 | 0.225 |
| | December | **-1.407**[a] | 0.208 | 0.955 | -0.343 | 0.343 | -0.409 | 0.409 | -0.537 | 0.537 |
| | January | **-2.311**[a] | 0.320 | 0.920 | -0.527 | 0.527 | -0.628 | 0.628 | -0.825 | 0.825 |
| | February | -1.413[b] | 0.683 | 0.853 | -1.123 | 1.123 | -1.338 | 1.338 | -1.759 | 1.759 |
| | March | **-7.806**[a] | 0.459 | 0.949 | -0.755 | 0.755 | -0.900 | 0.900 | -1.182 | 1.182 |
| | April | **-1.616**[a] | 0.252 | 0.950 | -0.414 | 0.414 | -0.494 | 0.494 | -0.649 | 0.649 |
| Kukernag | November | **-0.546**[a] | 0.061 | 0.987 | -0.100 | 0.100 | -0.119 | 0.119 | -0.157 | 0.157 |
| | December | **-0.864**[a] | 0.182 | 0.944 | -0.299 | 0.299 | -0.356 | 0.356 | -0.469 | 0.469 |
| | January | 0.046 | 0.063 | 0.994 | -0.103 | 0.103 | -0.123 | 0.123 | -0.161 | 0.161 |
| | February | **1.267**[a] | 0.152 | 0.969 | -0.251 | 0.251 | -0.299 | 0.299 | -0.393 | 0.393 |
| | March | **-1.748**[a] | 0.261 | 0.951 | -0.429 | 0.429 | -0.511 | 0.511 | -0.672 | 0.672 |
| | April | **2.348**[a] | 0.605 | 0.790 | -0.996 | 0.996 | -1.187 | 1.187 | -1.559 | 1.559 |
| Kupwara | November | **0.379**[a] | 0.099 | 0.970 | -0.163 | 0.163 | -0.194 | 0.194 | -0.255 | 0.255 |
| | December | **-1.764**[a] | 0.186 | 0.967 | -0.305 | 0.305 | -0.364 | 0.364 | -0.478 | 0.478 |
| | January | 0.354 | 0.182 | 0.949 | -0.299 | 0.299 | -0.356 | 0.356 | -0.468 | 0.468 |
| | February | **1.958**[a] | 0.222 | 0.955 | -0.366 | 0.366 | -0.436 | 0.436 | -0.573 | 0.573 |
| | March | **-4.116**[a] | 0.234 | 0.970 | -0.385 | 0.385 | -0.458 | 0.458 | -0.602 | 0.602 |
| | April | -1.038[b] | 0.220 | 0.955 | -0.362 | 0.362 | -0.431 | 0.431 | -0.567 | 0.567 |
| Qazigund | November | **-0.461**[a] | 0.080 | 0.982 | -0.131 | 0.131 | -0.156 | 0.156 | -0.205 | 0.205 |
| | December | **-1.764**[a] | 0.153 | 0.983 | -0.252 | 0.252 | -0.300 | 0.300 | -0.394 | 0.394 |
| | January | -0.073 | 0.132 | 0.985 | -0.217 | 0.217 | -0.258 | 0.258 | -0.339 | 0.339 |
| | February | -0.043 | 0.157 | 0.985 | -0.258 | 0.258 | -0.307 | 0.307 | -0.403 | 0.403 |
| | March | **-3.160**[a] | 0.236 | 0.979 | -0.389 | 0.389 | -0.463 | 0.463 | -0.608 | 0.608 |
| | April | -0.300 | 0.217 | 0.917 | -0.358 | 0.358 | -0.426 | 0.426 | -0.560 | 0.560 |
| Srinagar | November | -0.066 | 0.094 | 0.944 | -0.155 | 0.155 | -0.185 | 0.185 | -0.243 | 0.243 |
| | December | **-1.978**[a] | 0.225 | 0.931 | -0.371 | 0.371 | -0.442 | 0.442 | -0.581 | 0.581 |
| | January | **0.638**[a] | 0.084 | 0.969 | -0.139 | 0.139 | -0.166 | 0.166 | -0.218 | 0.218 |
| | February | **1.040**[a] | 0.150 | 0.918 | -0.246 | 0.246 | -0.293 | 0.293 | -0.385 | 0.385 |
| | March | **-1.568**[a] | 0.173 | 0.977 | -0.284 | 0.284 | -0.339 | 0.339 | -0.445 | 0.445 |
| | April | -0.288[b] | 0.133 | 0.958 | -0.220 | 0.220 | -0.262 | 0.262 | -0.344 | 0.344 |

(Bold figures marked with a is significant at p value<0.01 and figures marked with b is significant at p<0.05)

trends during the months December, January, February and March with significant values only for the month of January $p < 0.01$. Non-significant increasing trends were observed for the months of November and April (Table 3). Kumar *et al*., 2015 also found significantly decreasing trends in frequency of WD's during 1977-2007 over central parts of Himalayan region. Decreasing frequencies of WD during March to May over higher altitudes of Western Himalayan region were also observed by Das *et al*., 2002.

**TABLE 7**

**Precipitation trends for different months of stations using Innovative trend analysis**

| Station | Month | Trend Slope | Standard deviation | Correlation | Lower CL p<1.0 | Upper CL p<1.0 | Lower CL p<0.5 | Upper CL p<0.5 | Lower CL p<0.1 | Upper CL p<0.1 |
|---|---|---|---|---|---|---|---|---|---|---|
| Banihal | November | **-0.610** [a] | 0.164 | 0.964 | -0.270 | 0.270 | -0.322 | 0.322 | -0.423 | 0.423 |
| | December | -0.416 | 0.369 | 0.929 | -0.606 | 0.606 | -0.722 | 0.722 | -0.950 | 0.950 |
| | January | 0.417 | 0.293 | 0.966 | -0.483 | 0.483 | -0.575 | 0.575 | -0.756 | 0.756 |
| | February | **2.795** [a] | 0.467 | 0.938 | -0.769 | 0.769 | -0.916 | 0.916 | -1.204 | 1.204 |
| | March | **-2.748** [a] | 0.206 | 0.989 | -0.339 | 0.339 | -0.403 | 0.403 | -0.530 | 0.530 |
| | April | -0.017 | 0.161 | 0.974 | -0.266 | 0.266 | -0.316 | 0.316 | -0.416 | 0.416 |
| Batote | November | -0.018 | 0.177 | 0.955 | -0.292 | 0.292 | -0.347 | 0.347 | -0.457 | 0.457 |
| | December | **-1.130** [a] | 0.426 | 0.888 | -0.700 | 0.700 | -0.835 | 0.835 | -1.097 | 1.097 |
| | January | **-1.221** [a] | 0.265 | 0.971 | -0.437 | 0.437 | -0.520 | 0.520 | -0.684 | 0.684 |
| | February | **2.231** [a] | 0.412 | 0.940 | -0.678 | 0.678 | -0.808 | 0.808 | -1.062 | 1.062 |
| | March | **-3.310** [a] | 0.237 | 0.985 | -0.389 | 0.389 | -0.464 | 0.464 | -0.609 | 0.609 |
| | April | **-1.769** [a] | 0.164 | 0.974 | -0.270 | 0.270 | -0.322 | 0.322 | -0.423 | 0.423 |
| Baderwah | November | **-0.727** [a] | 0.106 | 0.960 | -0.175 | 0.175 | -0.209 | 0.209 | -0.274 | 0.274 |
| | December | **-1.532** [a] | 0.252 | 0.928 | -0.414 | 0.414 | -0.494 | 0.494 | -0.649 | 0.649 |
| | January | **-0.737** [a] | 0.204 | 0.963 | -0.336 | 0.336 | -0.400 | 0.400 | -0.526 | 0.526 |
| | February | **1.058** [a] | 0.212 | 0.972 | -0.349 | 0.349 | -0.416 | 0.416 | -0.547 | 0.547 |
| | March | **-1.941** [a] | 0.273 | 0.967 | -0.450 | 0.450 | -0.536 | 0.536 | -0.704 | 0.704 |
| | April | **-1.296** [a] | 0.238 | 0.941 | -0.392 | 0.392 | -0.467 | 0.467 | -0.614 | 0.614 |
| Jammu | November | **0.221** [a] | 0.110 | 0.945 | -0.180 | 0.180 | -0.215 | 0.215 | -0.282 | 0.282 |
| | December | **-0.288** [a] | 0.087 | 0.881 | -0.143 | 0.143 | -0.170 | 0.170 | -0.224 | 0.224 |
| | January | -0.157 | 0.170 | 0.927 | -0.280 | 0.280 | -0.333 | 0.333 | -0.438 | 0.438 |
| | February | **-0.752** [a] | 0.135 | 0.963 | -0.223 | 0.223 | -0.265 | 0.265 | -0.349 | 0.349 |
| | March | 0.548 | 0.354 | 0.900 | -0.582 | 0.582 | -0.693 | 0.693 | -0.911 | 0.911 |
| | April | **-0.498** [a] | 0.155 | 0.917 | -0.256 | 0.256 | -0.305 | 0.305 | -0.400 | 0.400 |
| Katra | November | **-0.517** [a] | 0.099 | 0.913 | -0.162 | 0.162 | -0.193 | 0.193 | -0.254 | 0.254 |
| | December | **-1.795** [a] | 0.200 | 0.959 | -0.329 | 0.329 | -0.392 | 0.392 | -0.515 | 0.515 |
| | January | **-0.917** [a] | 0.207 | 0.962 | -0.341 | 0.341 | -0.406 | 0.406 | -0.533 | 0.533 |
| | February | **-0.648** [a] | 0.210 | 0.970 | -0.345 | 0.345 | -0.411 | 0.411 | -0.541 | 0.541 |
| | March | -0.364 | 0.509 | 0.902 | -0.838 | 0.838 | -0.998 | 0.998 | -1.312 | 1.312 |
| | April | **-1.669** [a] | 0.227 | 0.940 | -0.374 | 0.374 | -0.445 | 0.445 | -0.585 | 0.585 |

(Bold figures marked with a is significant at p value <0.01 and figures marked with b is significant at p<0.05)

*Precipitation trends* : Precipitation trends for different months of all stations were analyzed using the Mann-Kendall test, the Spearman's Rho test and the linear regression. Trends of precipitation are considered statistically significant at $p < 0.01$ and $p < 0.05$. When a significant trend is identified by two statistical methods, the trend is presented in bold character in the table. The results of the statistical tests for the monthly precipitation series over the period 1980-2019 are summarized in (Tables 4&5). The results showed that slope (s) were

**TABLE 8**

**Correlation studies between Precipitation and WD frequency using Spearman's Rho test**

| Spearman's Rho | November WD | December WD | January WD | February WD | March WD | April WD | Total WD |
|---|---|---|---|---|---|---|---|
| Banihal | -0.005 | -0.149 | 0.097 | 0.086 | 0.089 | 0.087 | 0.014 |
| Batote | 0.129 | 0.003 | 0.223 | 0.147 | **0.350*** | 0.181 | 0.327 |
| Bhaderwah | -0.132 | **0.333*** | -0.025 | 0.102 | 0.096 | 0.084 | 0.121 |
| Gulmarg | -0.043 | 0.144 | 0.279 | 0.062 | 0.06 | 0.174 | 0.181 |
| Jammu | -0.062 | 0.316 | 0.07 | 0.099 | 0.175 | 0.189 | 0.247 |
| Katra | -0.01 | **0.365*** | 0.19 | 0.13 | 0.177 | 0.197 | **0.344*** |
| Kukernag | -0.019 | 0.248 | 0.086 | 0.135 | 0.073 | 0.227 | 0.211 |
| Kupwara | 0.121 | 0.327 | 0.3 | 0.083 | -0.018 | 0.184 | 0.304 |
| Qazigund | -0.066 | **0.338*** | 0.085 | -0.094 | -0.174 | 0.165 | 0.039 |
| Srinagar | -0.018 | **0.388*** | 0.037 | 0.004 | -0.017 | 0.198 | 0.179 |

**TABLE 9**

**Correlation studies between Precipitation and WD frequency using Pearson Correlation**

| Pearson Correlation | November WD | December WD | January WD | February WD | March WD | April WD | Total WD |
|---|---|---|---|---|---|---|---|
| Banihal | 0.01 | -0.167 | 0.112 | 0.128 | 0.121 | 0.11 | 0.125 |
| Batote | 0.075 | -0.023 | 0.219 | 0.215 | **0.363*** | 0.171 | **0.401*** |
| Bhaderwah | -0.075 | **0.351*** | 0.098 | 0.111 | 0.094 | 0.102 | 0.257 |
| Gulmarg | -0.043 | 0.159 | 0.315 | 0.15 | -0.012 | 0.144 | 0.269 |
| Jammu | 0.029 | 0.286 | 0.192 | 0.093 | 0.17 | 0.153 | **0.357*** |
| Katra | 0.048 | **0.370*** | 0.211 | 0.152 | 0.181 | 0.172 | **0.435**** |
| Kukernag | -0.012 | 0.144 | 0.146 | 0.097 | 0.074 | 0.207 | 0.253 |
| Kupwara | 0.029 | 0.285 | **0.436**** | 0.163 | 0.023 | 0.209 | **0.436**** |
| Qazigund | -0.042 | **0.357*** | 0.098 | -0.054 | -0.2 | 0.15 | 0.112 |
| Srinagar | -0.032 | **0.369*** | 0.139 | 0.024 | -0.031 | 0.143 | 0.231 |

dominated mostly by negative values with significant at $p < 0.01$ and $p < 0.05$. The results of the Mann-Kendall statistical tests for the monthly precipitation series over the period 1980-2019 showed significant decreasing trends for Kupwara in the month of December and March with a slope value of -2.450 and -2.947 mm/month respectively while Gulmarg station showed decreasing significant trends for the month of March with slope value of -6.947 mm/month (Tables 4&5). No significant trends were observed for other stations for different months although some stations showed increased trends while some showed decreasing trends.

The results of Innovative trend analysis showed decreasing significant trends for the month of November and December for most of the stations with slope ranging from -0.288 (Jammu) to -1.978 (Srinagar) mm/month. Gulmarg, Batote, Baderwah, and Katra showed significant decreasing trends for the month of January with slope values -2.311, -1.221, -0.737 and -0.917 mm/month respectively. Significant increasing trends were observed in the month of February for the stations Kukernag, Kupwara, Srinagar, Banihal, Batote and Baderwah with slope values 1.267, 1.958, 1.040, 2.231 and 1.058 mm/month respectively with p value <0.01.

**TABLE 10**

**Correlation studies between Precipitation and WD frequency using Mann–Kendall Test**

| Mann-Kendal test | November WD | December WD | January WD | February WD | March WD | April WD | Total WD |
|---|---|---|---|---|---|---|---|
| Banihal | 0.002 | -0.125 | 0.073 | 0.063 | 0.081 | 0.057 | -0.003 |
| Batote | 0.088 | -0.002 | 0.176 | 0.113 | **0.274*** | 0.145 | 0.233 |
| Bhaderwah | -0.103 | **0.259*** | -0.004 | 0.071 | 0.073 | 0.061 | 0.073 |
| Gulmarg | -0.035 | 0.121 | 0.22 | 0.048 | 0.048 | 0.12 | 0.107 |
| Jammu | -0.05 | 0.248 | 0.066 | 0.082 | 0.128 | 0.138 | 0.163 |
| Katra | -0.002 | **0.292*** | 0.141 | 0.107 | 0.136 | 0.155 | **0.242*** |
| Kukernag | -0.009 | 0.186 | 0.088 | 0.098 | 0.048 | 0.153 | 0.16 |
| Kupwara | 0.091 | 0.251 | 0.238 | 0.071 | -0.007 | 0.149 | 0.207 |
| Qazigund | -0.054 | **0.259*** | 0.073 | -0.063 | -0.124 | 0.131 | 0.037 |
| Srinagar | 0.002 | **0.294*** | 0.033 | 0.006 | -0.015 | 0.142 | 0.137 |

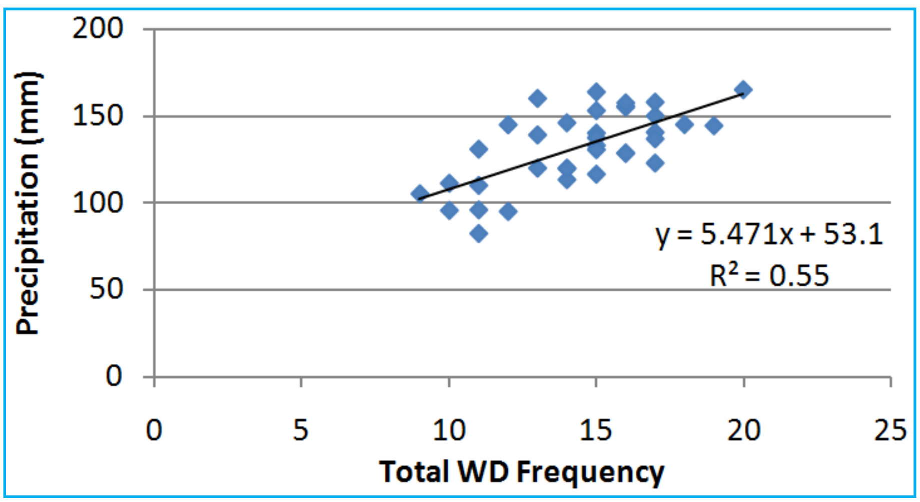


**Fig. 4.** Correlation between average precipitation of all the stations and total WD frequency

Except Kukernag (2.348 mm/month), all the stations showed decreasing trend for the month of April (Tables 6&7). Bhutiyani *et al*. (2010) also studied precipitation trends in the northwest Himalayas and did not found any trends in precipitation during the winter season. Similar results were observed by Kumar and Jain (2010) and they found decreasing trends in monsoon and winter rainy days over all the stations. Decreasing trends in winter precipitation were also observed by Kumar and Jain, 2010; Dimri and Dash, 2012. Decreasing precipitation trends during winter is due to decreasing WD frequencies over the region.

Correlations are computed between precipitation of Individual station and frequency of WD during a particular month using Mann-Kendall, Spearman's rho and Pearson correlation. The results of Pearson correlation (Table 9) showed that Precipitation of Baderwah, Katra, Qazigund and Srinagar station is positively correlated (0.351, 0.370, 0.357, 0.369) with WD frequency of December with significant at $p < 0.05$, Kupwara for the month of January (0.436), and Batote for the month of March (0.363). Similar results were also observed for all the stations using Mann-Kendall and Spearman's Rho test. No significant correlation was observed for the months of November, January (except Kupwara), February and April.Spearman's rho and Mann-Kendall correlation results (Tables 8 and 10) showed positively correlation of total WD frequency for Katra station (0.242 and 0.344) with significant at $p < 0.05$, while Pearson correlation showed positive correlation for Batote (0.401), Jammu (0.357) with significant at $p < 0.05$, Katra (0.435) and Kupwara (0.436) with significant at p value $p < 0.01$. The correlation between average precipitation of all the stations and total WD frequency was computed (Fig. 4) and results showed positive correlation between precipitation and WD frequency with $R^2$ value 0.55.

## 4. Conclusions

The following conclusions were drawn from the above study.

(*i*) The analysis showed significant decreasing trends of WD frequencies ($p < 0.01$) during November and March with slope values -0.610 and -2.748 respectively and increasing trends were observed during February with slope value 2.795 ($p < 0.01$) and January with slope value 0.417 but were non-significant.

(*ii*) The results of the Mann-Kendall statistical tests for the monthly precipitation series over the period 1980-2019 showed significant decreasing trends for Kupwara in the month of December and March with a slope value of -2.450 and -2.947 mm/month respectively while Gulmarg station showed decreasing significant trends for the month of March with slope value of -6.947 mm/month.

(*iii*) The results of Innovative trend analysis showed decreasing significant trends for the month of November, December, January, March and April by most of the stations. Significant increasing trends were observed in the month of February for the stations Kukernag, Kupwara, Srinagar, Banihal, Batote and Baderwah with slope values 1.267, 1.958, 1.040, 2.231 and 1.058 mm/month respectively with p value <0.01. Except Kukernag (2.348 mm/month), all the stations showed decreasing trend for the month of April.

(*iv*) The results of Pearson correlation showed that Precipitation of Baderwah, Katra, Qazigund and Srinagar station is positively correlated (0.351, 0.370, 0.357, 0.369) with WD frequency of December with significant at $p < 0.05$, Kupwara for the month of January (0.436) and Batote for the month of March (0.363).

(*v*) The correlation between average precipitation of all the stations and total WD frequency showed positive l correlation between precipitation and WD frequency with $R^2$ value 0.55.

(*vi*) Thus, it is concluded that frequency of WDs showed decreasing significant trends during onset of winter and spring (November and March) and increasing trends during peak winter months (January and February). The decreasing precipitation trends in the month of November and March is due to decreasing WD frequencies during these months.

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**References**

Bhutiyani, M. R., Kale, V. S. and Pawar, N. S., 2010, "Climate change and the precipitation variations in the NW Himalaya", *International Journal of Climatology*, **22**, 25-33.

Cannon, F., Carvalho, L. M. V., Jones, C. and Bookhagen, B., 2014, "Multi-annual variations in winter westerly disturbance activity affecting the Himalaya", *Climate Dynamics*, **44**, 441-455.

Chand, R. and Singh, C., 2015, "Movements of western disturbance and associated cloud convection", *Journal of Indian Geophysics Union*, **19,** 62-70.

Das, M. R., Mukhopadhyay, R. K., Dandekar, M. M. and Kshirsagar, S. R., 2002, "Pre-monsoon western disturbances in relation to monsoon rainfall, its advancement over NW India and their trends", *Current Science*, **82**, 1320-1321.

Dimri, A. P. and Dash, S. K., 2012, "Wintertime climate trends in the Western Himalayas", *Climatic Change*, **111**, 775-800.

Dimri, A. P., Niyogi, D., Barros, A. P., Ridley, J., Mohanty, U. C., Yasunari, T. and Sikka, D. R., 2015, "Western disturbances: A review", *Review Geophysics*, **53**, 225-246.

Gimeno, L. R., Nieto, R., Drumond, A., Castillo, R. and Trigo, R., 2013, "Influence of the intensification of the major oceanic moisture sources on continental precipitation", *Geophysics Research*, **40**, 1443-1450.

Kumar, N., Yadav, B. P., Gahlot, S. and Singh, M., 2015, "Winter frequency of western disturbances and precipitation indices over Himachal Pradesh, India : 1977-2007", *Atmosfera*, **28**, 63-70.

Kumar, V. and Jain, S. K., 2010, "Trends in seasonal and annual rainfall and rainy days in Kashmir Valley in the last century", *Quatern International*, **212**, 64-69.

Madhura, R. K., Krishnan, R., Revadekar, J. V., Mujumdar, M. and Goswami, B. N., 2014, "Changes in Western Disturbances over the western Himalayas in a warming environment", *Climate Dynamics*, **44**, 1157-1168.

Malurkar, S. L., 1947, "Abnormally dry and wet Western Disturbances over North India", *Current Science*, **16**, 5, 139-141.

Mull, S. and Desai, B. N., 1947, "The origin and structure of the winter depression of Northwest India", India Meteorological Department, Technical Note No. 25:18.

Puranik, D. M. and Karekar, R. N., 2009, "Western Disturbances seen with AMSU-B and infrared sensors", *Journal of Earth system science*, **118**, 1, 27-39.

Ridley, J., Wiltshire, A. and Mathison, C., 2013, "More frequent occurrence of westerly disturbances in Karakoram up to 2100", *Science of Total Environment*, doi : 10.1016/j.scitotenv.2013.03.074.

Riehl, H., 1962, "Jet streams of the atmosphere, Colorado State University", Technical Paper, 32.

Yadav, R. K., Yoo, J. H., Kucharski, F. and Abid, M. A., 2010, "Why is ENSO influencing northwest India winter precipitation in recent decades?", *Journal of Climatology*, **23**, 8, 1979-1993.

Zahn, M. and Allan, R. P., 2013, "Climate warming-related strengthening of the tropical hydrological cycle", *Journal of Climatology*, **26**, 562-574.