Trend analysis of western disturbance and associated precipitation during winter season using a non-parametric approach: empirical evidence from the Kashmir valley, northwestern India

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Abstract

The variability in western disturbance activity poses serious challenges to the fragile mountainous ecosystem of the Kashmir valley. However, limited research has been conducted on variability in western disturbance activity along northwestern India. The present study aims to analyse the trend and characteristics of western disturbance activity in the Kashmir Valley from 1991 to 2023. Mann-Kendall trend was utilised to quantify the trend of western disturbances and associated precipitation, while Sens slope estimator was used to assess its rate of change, respectively. The results reveal an insignificant decreasing trend of western disturbance activity (-0.024 mm/year) during November to April, while the associated rainfall also reveals a decreasing trend of (-4.25 mm/year), which is also not statistically significant. Results from individual stations reveal that Gulmarg is showing a statistically significant decreasing trend of -13.83 mm/year in rainfall associated with WD activity.

Keywords: *Trend analysis, Mann-Kendall, western disturbances, climatic variability, rainfall.*

Introduction

Western disturbances are eastward-moving extratropical meteorological phenomena embedded within the subtropical westerly jet stream. These storms originate primarily over the Mediterranean Sea and pick up moisture, carrying it towards the upper atmosphere during their journey and bringing winter precipitation in the form of rainfall and snowfall to northwestern India (Dimri & Dash, 2012; Yadav et al., 2012). They traverse across West Asia—including Iran, Afghanistan, and Pakistan—before reaching the northwestern parts of the Indian subcontinent. During winter, WDs follow their southernmost tracks and act as the principal source of non-monsoonal precipitation over the North-Western Himalaya (NWH) and adjoining plains of northern India (Dimri et al., 2015). These meteorological disturbances are important for the winter agriculture, especially wheat yield in Punjab and Haryana. Besides agriculture, they also play a crucial role in regional hydrology, hydroelectricity, landslides, and cloudbursts, and therefore their study is important in the northwestern Himalayas.

Western Disturbances are generally more intense and frequent during the winter months, and they contribute significantly to the hydrological and glacial development over the Himalayan region. However, their frequency typically declines after the winter season. During the winter season from December to April, on average, 6-7 WDs per month are experienced over the northwest Himalayas (Hunt et al., 2018). The interaction between WDs and the complex topography of the western Himalayas plays a crucial role in determining the spatial distribution, intensity, and vertical structure of precipitation.

Considering the increasing global surface temperatures, seasonal precipitation patterns are undergoing noticeable alterations. Climate change is expected to impact mountainous regions disproportionately due to their fragile ecosystems and sensitivity to meteorological variability. Large-scale changes in atmospheric circulation and jet stream dynamics may influence the frequency, intensity, and tracks of Western Disturbances, thereby affecting hydro-meteorological parameters over the NWH region.

Despite their significance, observational studies examining long-term changes in WD activity remain limited. Previous investigations have reported mixed findings. For instance, (Cannon et al., 2015) identified significant regional differences in heavy precipitation events associated with winter WDs between the western and central Himalayas. (Hunt et al., 2019) analysed WD data along the northwest

Himalayas from 1979-2024 and reported a 15% drop in WD tracking, linking it to upper-tropospheric warming. (Ahmed et al., 2022; N. Kumar et al., 2015) have observed a declining pattern in both the frequency of WD and associated precipitation trends during winter season over J&K and Himachal Pradesh, respectively. (Midhuna et al., 2023) have also identified a decline in WD frequency in winters, and it becomes far more common during the non-winter months. Conversely, (Dar, 2023) recorded a non-significant decreasing trend of winter precipitation along the Kashmir Himalayas, while (Bhutiyani et al., 2010) reported an increasing statistically insignificant trend in winter precipitation over the northwestern Himalayas.

However, there remains a scarcity of comprehensive studies focusing specifically on the frequency of WD and associated precipitation variability over the Kashmir valley. Winter precipitation in this region is critically important, as it contributes substantially to glacier mass accumulation and sustains regional livelihood through supporting agricultural development. Therefore, the present study aims to analyze trends in WD frequency and associated precipitation over the Kashmir valley. To identify spatial and temporal trends in WD and associated precipitation, non-parametric statistical techniques such as the Mann–Kendall (MK) test and the Theil–Sen estimator are employed. Several studies have incorporated these tests to detect monotonic trends and determine the true slope in hydro-meteorological time series due to their robustness against non-normal data distributions and missing values (Shafiq et al., 2018; Hussain et al., 2015).

Study Area:

The valley of Kashmir is under the fringes of Northwest Himalayas, covering 32 ° 22' to 34 ° 43' N latitude to 73 ° 52' to 75 ° 42' E longitudes. It represents a distinct meso-geographical region with an area of 15,000 km² and supporting a population of about 13.64 million. The valley forms an elliptical, bowl-shaped intermontane basin, enclosed by the Pir Panjal Range to the south and southwest, and the Great Himalayan Range to the north and east. This unique topographic configuration significantly influences regional climate dynamics, particularly winter precipitation associated with Western Disturbances. Physiographically, the valley can be divided into four broad units:

1. The surrounding mountain ranges
2. The foothill zones
3. The Karewas (lacustrine terrace deposits)
4. The central valley floor

Climatically, the region falls under a dry to semi-moist temperate regime, strongly influenced by altitude and seasonal precipitation variability. Temperatures range from nearly −9°C during severe winter months to about 38°C during peak summer. Winters (December–February) are particularly harsh and marked by frequent snowfall, primarily influenced by Western Disturbances. The region records an average annual mean maximum temperature of 19.27°C and a mean minimum temperature of 7.29°C, with an average annual precipitation of about 84 cm, a significant portion of which occurs during winter and early spring due to Western Disturbances.

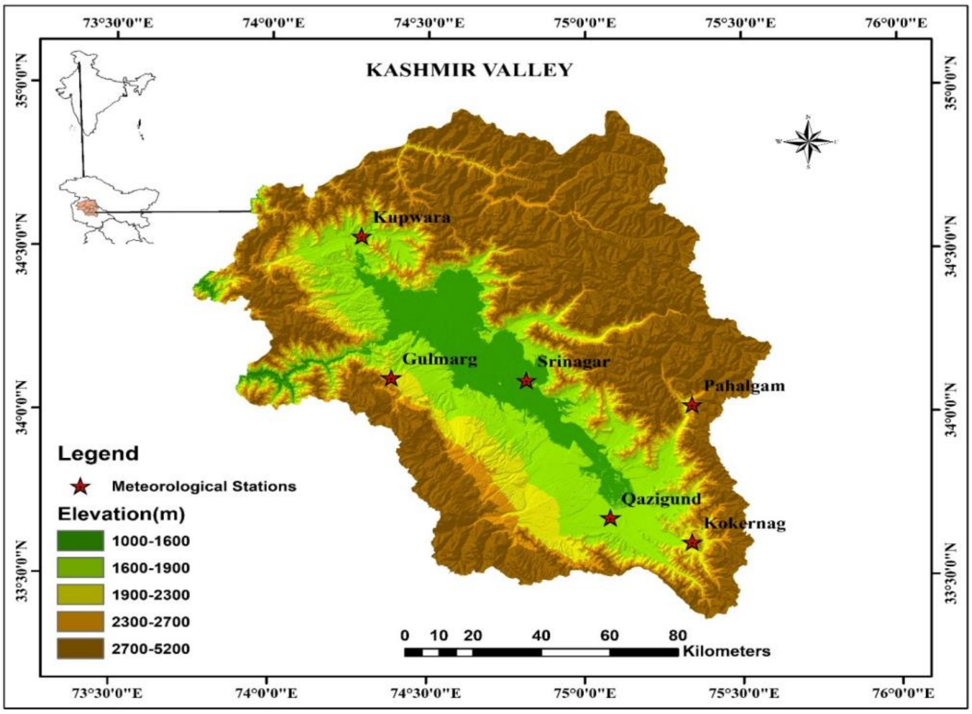

Fig.1: Study region (map generated by author).

S.no	Station	Latitude (North)	Longitude (East)	Elevation (mts)	Physiography
1	Qazigund	33° 57'	75° 17'	1690	Foot hills
2	Kokernag	33° 59'	75° 30'	1910	Karewas
3	Pahalgam	34° 02'	75° 33'	2310	Mountain
4	Srinagar	34° 05'	74° 80'	1588	Flood Plain
5	Gulmarg	34° 06'	74° 39'	2705	Mountain
6	Kupwara	34° 53'	74° 27'	1609	Karewas

Table 1: Meteorological stations in the study region.

Methodology:

Daily rainfall data for a period of thirty-three years (1991–2023) were obtained from six meteorological stations located within the Kashmir Valley. The data were collected from the India Meteorological Department and cover the winter season months from November to April, which correspond to the active period of Western Disturbance (WD) activity over the Kashmir valley. The locational and elevational data of the meteorological stations are presented in Table 1. These stations represent different physiographic units of the valley, enabling a comprehensive assessment of spatial variability in WD-associated precipitation. The monthly frequency of Western Disturbances was determined based on precipitation events recorded during their passage over the study region. A daily rainfall threshold of ≥ 2.5 mm was considered indicative of a WD spell. The identification of WD spells from precipitation records was carried out following the methodology proposed by (Dadial et al., 2024), which links precipitation occurrence during synoptic WD activity to quantify event frequency.

Statistical methods

Trend detection in hydro-meteorological time series is commonly carried out using both parametric and non-parametric statistical techniques. However, these time series data often violate assumptions of normality and are sensitive to outliers. Therefore, in the present study, non-parametric methods were applied to analyze trends in WD frequency and associated precipitation using Mann- Kendall test (Mann, 1945) and Sen's slope estimator test (Sen, 1968).

The Mann–Kendall rank-based test is considered an effective method for identifying monotonic trends and abrupt time series changes. It is a statistical approach primarily used to evaluate the null hypothesis of no trend versus the alternative hypothesis indicating a monotonic upward or downward trend in time series data. The non-parametric Mann-Kendall test is well suited for analyzing data series that exhibit a monotonic trend. Depending on the sample size, two types of statistics are applied: the S–statistic is used when the number of observations is less than 10, whereas the Z-statistic is employed when the number of observations is 10 or more (Hussain et al., 2015).
The test statistic S is calculated by

$$S = \sum_{i=1}^{n-1} \sum_{k=i+1}^{n} sgn(xk - xi)$$

Where xk and xi are the sequential data values in the time series, n is the number of data points, and sgn (xk-xi) is calculated using the equation.

$$sgn(\theta) = \begin{cases} +1, & \theta > 0 \\ 0, & \theta = 0 \\ -1, & \theta < 0 \end{cases}$$

A positive or negative value of S indicates an upward (increasing) or downward (decreasing) trend, respectively. When the number of observations is 10 or greater, the statistic S approximates a normal distribution, and the standardised test statistic Z is computed. The significance of the detected trend is evaluated using the corresponding Z-value at a confidence level of 95%.
While the Mann–Kendall test determines the presence of a trend, it does not quantify its magnitude. Therefore, the non-parametric Sen's slope estimator, introduced by Theil (1950) and Sen (1968), was used to calculate the true slope of the hydro-meteorological time series data. It uses a linear model to calculate trend analysis, and the slope (Qi) between two data points is calculated as:

$$Q_i = Median\left(\frac{x_i - x_k}{j - k}\right) \bigvee k < j$$

Where *xj* and *xk* represent the data values at times *j* and *k* (*j* > *k*), respectively. All possible slope estimates (Qi) are computed, and the median of these N slope values is taken as Sen's slope (Qmed). If N is odd, then Sen's estimator is computed by

$$Q_{med} = Q\left(\frac{N+1}{2}\right)$$

and if N is even, then Sen's estimator is computed by

$$Q_{med} = \left[Q\frac{N}{2} + Q\frac{(N+2)}{2}\right]/2$$

A positive Sen's slope indicates an increasing trend, while a negative slope indicates a decreasing trend. The statistical significance of the estimated slope is evaluated using a two-sided test at a 100(1 – α) % confidence interval (typically 95%).

Results And Discussion

Trend analysis by Mann-Kendall test statistics

The Mann-Kendall and Sen's slope estimator were applied to observe the trend and slope of western disturbances that occur from November to April over the last 33 years, that is, from 1991-2023. Time series analysis of WD and associated rainfall of study area is presented in Figures 2 and 3.

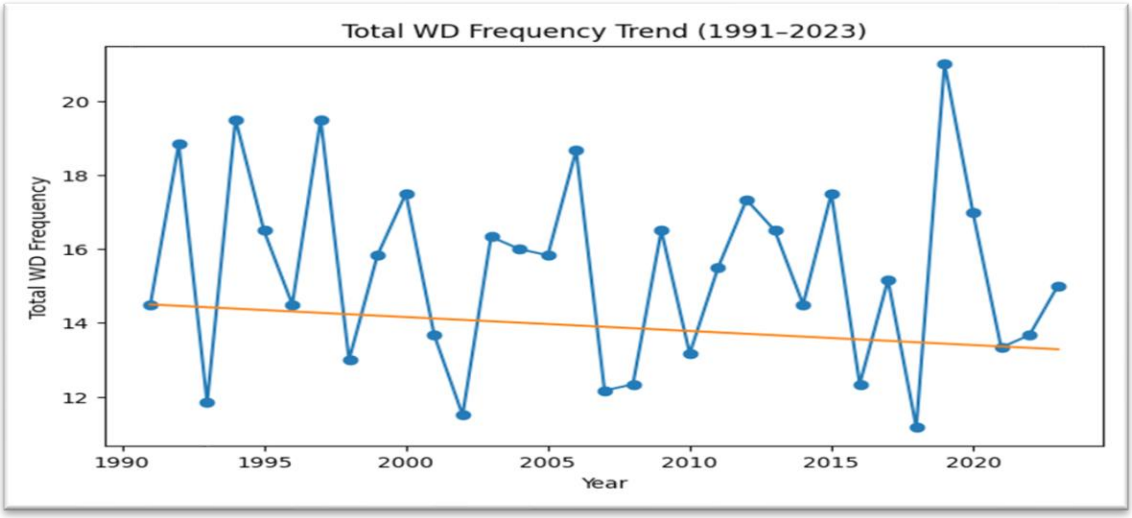

Figure 2: Time series analysis of winter western disturbances in Kashmir valley from 1991-2023.

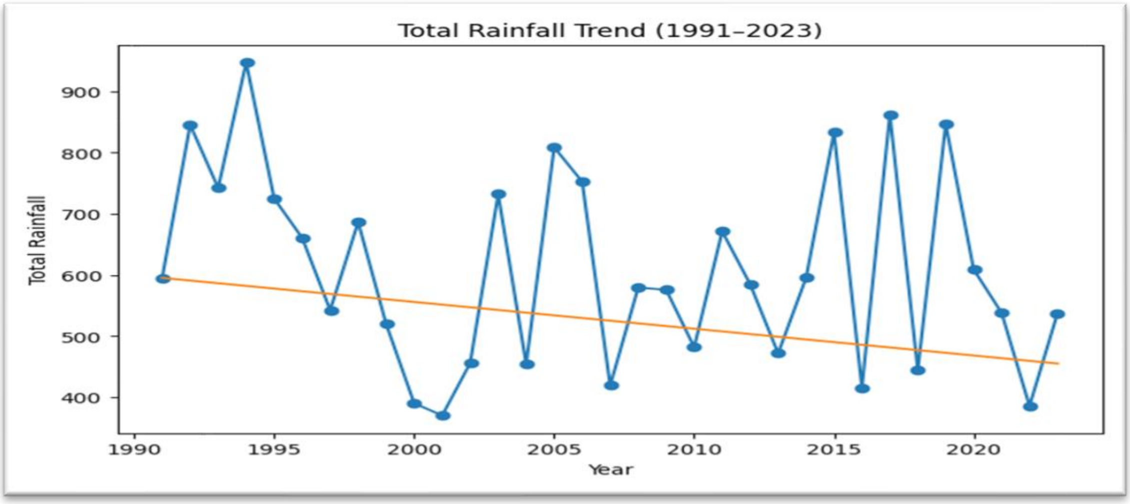

Figure 3: Time series analysis of winter rainfall data in Kashmir valley from 1991-2023.

Data on western disturbances and associated rainfall were collected from six meteorological stations in the Kashmir Valley. The result of the test statistics is presented in Tables 2 and 3.

The Mann–Kendall test revealed no statistically significant trend in winter WD frequency. Although minor increasing and decreasing tendencies are observed in certain months, none of the Z-values exceeds the critical threshold (±1.96) at the 95% confidence level. The results show that WD frequency does not exhibit any statistically significant trend during the study period. However, WD-induced rainfall during March shows a significant decreasing trend ($Z = -2.03$, $p < 0.05$) with a Sen's slope of −2.61 mm per year.

Results also reveal that the frequency of WD during the winter season has decreased by -0.024 mm/year. The associated precipitation also reveals a declining tendency of -4.25 mm/year, as indicated by Sen's slope estimator with an MK value of -0.34. These results are supported by Shafiq et al. (2018) and (V. Kumar & Jain, 2010), who also concluded that the winter precipitation in the Kashmir valley is exhibiting a declining trend.

Table 2: Monthly Statistical Summary of western disturbances in Kashmir valley from 1991-2023.

Variable	Mean	SD (σ)	CV (%)	Z-value	Sen's Slope	Trend
January	2.63	1.02	38.87	0.466	0.0099	No trend
February	2.95	0.69	23.29	-0.468	0.0000	No trend
March	3.34	0.77	23.07	-1.628	-0.0222	No trend
April	3.25	0.86	26.48	-0.610	0.0000	No trend
November	1.30	0.94	72.41	1.047	0.0195	No trend
December	1.71	1.08	63.30	-1.075	-0.0222	No trend
Total Winter WD	**15.16**	**2.48**	**16.37**	**-0.341**	**-0.0245**	**No trend**

Table 3: Monthly Statistical Summary of rainfall associated with WDs in the Kashmir valley from 1991-2023.

Variable	Mean (mm)	SD (σ)	CV (%)	Z-value	Sen's Slope (mm/year)	Trend
January	113.14	69.74	61.64	0.170	0.226	No trend
February	133.28	75.00	56.27	-1.503	-1.583	No trend
March	139.24	81.31	58.39	**-2.030**	**-2.605**	**Decreasing**
April	121.98	57.20	46.89	0.356	0.481	No trend
November	42.91	47.25	110.11	0.202	0.056	No trend
December	48.40	55.61	114.91	0.264	0.029	No trend
Total Rainfall	**598.76**	**161.06**	**26.90**	**-1.317**	**-4.253**	**No trend**

Station-wise analysis of WD activity.

The Kashmir Valley is located in the north-western Himalayas. Due to its location, the valley is frequently affected by Western Disturbances during the winter season, extending from November to April. In the present study, six meteorological stations of the valley were chosen to ensure diverse topographic features, including mountains, foothills, Karewas, and plains.

The Mann–Kendall test revealed no statistically significant trends in WD frequency across all six stations during 1991–2023. Sen's slope estimates indicated marginal declining tendencies at Pahalgam (−0.105 events/year) and Qazigund (−0.061 events/year), although these trends were not significant at the 95% confidence level. The statistical analysis has been presented in Table 4. Three meteorological stations viz: Kokernag, Pahalgam and Qazigund have registered a decreasing trend in WDs, which were all statistically insignificant. Kupwara and Srinagar registered a stable trend, while Gulmarg station shows an insignificant increasing trend. The range of trend magnitude through Sen's slope in WDs season varies from -0.10 to 0 mm/season per year.

Similarly, winter rainfall associated with WDs exhibited spatial heterogeneity. A statistically significant decreasing trend was observed at Gulmarg station ($Z = -2.402$, $p < 0.05$), with a Sen's slope of −13.83 mm/year. Other stations did not show significant rainfall trends. These results suggest that while WD frequency remains relatively stable, precipitation amounts, particularly in high-altitude regions, may be declining. Among six meteorological stations, four stations, viz. Gulmarg, Pahalgam, Qazigund, and Srinagar have registered a negative trend in precipitation, which are all statistically insignificant, except Gulmarg, which is Significant with ($p < 0.05$). On the other hand, Kupwara is showing a slight increasing trend, while Kokernag is showing no trend. The sens slope analysis for winter precipitation reveals that Gulmarg is showing a decreasing rainfall of -13.82 mm/season per year. **The statistical analysis has been presented in Table 5.**

Station	Z-value	Sen's Slope (Q)	Trend Direction	Significance
Gulmarg	0.109	0.000	Slight Increasing	Not Significant
Kokernag	-0.845	-0.041	Decreasing	Not Significant
Kupwara	0.110	0.000	Stable	Not Significant
Pahalgam	-1.561	-0.105	Decreasing	Not Significant
Qazigund	-1.188	-0.061	Decreasing	Not Significant
Srinagar	-0.016	0.000	Stable	Not Significant

Table 4: Trend analysis of WD activity at different stations in Kashmir Valley.

Table 5: trend analysis of WD-associated precipitation at different stations in Kashmir Valley.

Station	Z-value	Sen's Slope (mm/year)	Trend Direction	Significance
Gulmarg	-2.402	-13.83	Decreasing	**Significant ($p < 0.05$)**
Kokernag	0.015	0.04	Stable	Not Significant
Kupwara	0.232	1.11	Increasing	Not Significant
Pahalgam	-0.511	-1.61	Decreasing	Not Significant
Qazigund	-1.441	-4.71	Decreasing	Not Significant
Srinagar	-0.263	-0.68	Decreasing	Not Significant

Z: Statistics for MK test, Q: Slope of Theil-Sen approach (mm/season)

Correlation was computed between the frequency of WDs and precipitation at individual stations using Pearson correlation. The results of the correlation analysis have been presented in Table 6. The results reveal a positive association between WD frequency and rainfall across most stations in the valley. The average correlation of the study area was strong and highly significant ($r = 0.522$, $p < 0.01$), indicating that interannual variability in winter precipitation is substantially governed by WD activity. Significant positive correlations were observed at Kupwara ($r = 0.516$), Qazigund ($r = 0.460$), and Kokernag ($r = 0.451$). Moderate but significant relationships were found at Pahalgam and Srinagar. while Gulmarg exhibited a weaker and statistically non-significant relationship ($r = 0.321$).

Station	Correlation (r)	Significance Level
Gulmarg	0.321	Not Significant
Kokernag	0.451	**$p < 0.01$**
Kupwara	0.516	**$p < 0.01$**
Pahalgam	0.357	**$p < 0.05$**
Qazigund	0.460	**$p < 0.01$**
Srinagar	0.358	**$p < 0.05$**
Valley Average	0.522	**$p < 0.01$**

Table 6: Correlation analysis between WD activity and associated rainfall in the study area.

Conclusions

This study analyses the variability in western disturbances and associated rainfall during the winter season over the Kashmir valley from 1991 to 2023. The trend statistics in the winter WD activity and associated precipitation were analysed using the non-parametric Mann-Kendall test and the slope of the trend with Sen's slope estimator. WD activity has shown an insignificant decreasing trend of (-0.024 mm/year). while winter precipitation shows a consistent decrease at a rate of -4.25 mm/year, which is also statistically insignificant. The analysis, when carried out on an individual station basis, showed that Gulmarg is showing a statistically significant trend at 95% confidence interval in winter rainfall declining at the rate of -13.83 mm/year. Pahalgam, Qazigund and Srinagar also show a decreasing trend, but they were statistically insignificant. Overall, the study region exhibits a slight increase in WD activity with a decrease in its associated precipitation. This decrease in winter precipitation will have negative implications for the fragile ecosystem of Kashmir Valley.

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Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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