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Long-Term Spatio-Temporal Analysis of Rainfall Variability and Trends in Punjab, India (1901-2022): Implications for Agricultural Sustainability

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Abstract
Rainfall variability under arid and semi-arid climatic conditions has profound socio-economic implications for agricultural livelihoods. Understanding the spatial and temporal variability of rainfall is therefore essential for sustainable agricultural planning. The present study examines long-term rainfall variability and trends over a 122-year period (1901–2022) across 20 districts of Punjab, India, with the objective of identifying significant temporal patterns and providing insights for future agricultural sustainability. Descriptive statistical analyses combined with trend detection techniques, including the Mann–Kendall (MK) test and Sen's slope estimator, were employed to assess rainfall trends at multiple spatial and temporal scales. The results indicate that Pathankot, Hoshiarpur, and Shaheed Bhagat Singh Nagar received the highest average annual rainfall, while Fazilka, Sri Muktsar Sahib, and Bathinda recorded the lowest. The long-period average (LPA) rainfall for Punjab was estimated at 630.2 ± 154.9 mm. Among agro-climatic zones, the sub-mountain undulating plain zone (SMZ) exhibited the highest LPA rainfall (1039.4 mm), followed by the central plain zone (CPZ; 689.4 mm), undulating plain zone (UPZ; 663.5 mm), and western zone (WZ; 435.2 mm), whereas the western plain zone (WPZ) recorded the lowest LPA rainfall (385.6 mm). Decadal analysis revealed the highest rainfall intensity during 1951–1960 (722.7 ± 148.6 mm) and the lowest during 1921–1930 (542.7 ± 101.6 mm). Although an increasing rainfall trend was observed during the initial decade (1901–1910) and a declining trend during the most recent decade (2011–2022), the overall long-term rainfall trend was not statistically significant. The findings provide valuable insights for rainfall management, agricultural planning, and policy formulation aimed at enhancing resilience and ensuring food security, particularly in arid and semi-arid regions.

Keywords: Agro-climatic zone; MK-Test; Rainfall; Sen's slope; Trend; Variability

Introduction
The Indian state of Punjab, popularly known as the "Granary of India," plays a pivotal role in the nation's food security, contributing around 14% of India's total food grain production despite occupying only about 1.54 % (50,362 km²) of national land area. Geographically, Punjab extends between latitudes 29°30′N to 32°32′N and longitudes 73°55′E to 76°50′E, with elevations ranging from 180 to 300 m above mean sea level. It shares its boundaries with Himachal Pradesh to the northeast, Haryana to the southeast, Rajasthan to the southwest, the Union Territory of Chandigarh to the east, and Jammu and Kashmir to the north, while the international border with Pakistan lies to the west. The climate of Punjab is significantly influenced by its proximity to the Himalayan foothills and its geographical position along the Indo–Gangetic plains. Rainfall distribution across the state exhibits marked spatial variability, with the sub-mountainous regions receiving comparatively higher rainfall, whereas the southwestern parts experience scanty rainfall coupled

with higher temperatures. Punjab state derives its name from the five tributaries of the Indus River system—Sutlej, Beas, Ravi, Chenab, and Jhelum. However, at present, only the Sutlej, Beas, and Ravi flow through Indian Punjab, while the remaining rivers lie within the territory of Pakistan.

Punjab is administratively divided into 23 districts and ranks as the 16th most populous state in India, with a population of over 27 million (Jerath et al., 2014). Agriculture is the backbone of the state's economy and a primary source of livelihood. At national level, agriculture supports around 68.84% of Indian population (Chandramouli, 2011), while in Punjab, more than 65% of the state's total population is directly engaged in Agrarian sector (Singh et al., 2016). Given this heavy agriculture dependence, variation in climatic factors, particularly rainfall, exerts severe social and policy implications on the livelihood of farming communities, especially under arid and semi-arid climatic conditions (Banerjee, 2015; Mahdi et al., 2021, 2022). The Intergovernmental Panel on Climate Change (IPCC) reported that climate change has enormous inferences for the global rainfall pattern. Rainfall variability occurs not only over time (temporal variability) but also across locations (spatial variability) (Pai et al., 2014; Hoover et al., 2021). Temporal variability may range from short-term fluctuations at daily and seasonal scales to long-term changes spanning decades or even centuries, whereas spatial variability reflects differences in rainfall distribution across regions. Spatio-temporal rainfall variability thus refers to changes in both the magnitude and distribution of rainfall over space and time. Based on the time scale of analysis, the rainfall variability can further be categorized into long- and short-period variations. Long-period variability generally refers to changes occurring over decadal to centennial time scales and is influenced by factors such as ocean–atmosphere interactions, variations in sea surface temperatures, solar activity, and volcanic eruptions. In contrast, short-period rainfall variability typically operates at weekly, monthly, or interannual scales and is governed by atmospheric circulation patterns, moisture availability, and regional oceanic conditions. Both long- and short-period rainfall variability have significant implications for agricultural productivity, water resource availability, and ecosystem stability. Therefore, comprehensive understanding of these variations and their underlying causes is crucial for predicting future climatic changes and formulating effective strategies to mitigate their impact (Singh et al., 2021, 2022).

Cruz et al. (2007) reported declining trends in annual rainfall across northeastern and northern China, northeastern India, Indonesia, coastal Pakistan, and parts of the Philippines, while increasing trends were observed in Bangladesh, western and southeastern China, and western Philippines. The study also highlighted increased damage from intense cyclones across South and Southeast Asia, suggesting a rise in the frequency and intensity of extreme weather events. In India, about 70–80% of annual rainfall occurs during the southwest monsoon (SWM; June–September), with northeastern and southeastern regions receiving substantial rainfall during the monsoon withdrawal phase (Rajeevan et al., 2010). Several studies have reported no statistically significant long-term trends in annual rainfall over northeastern India (Goswami et al., 2010; Deka et al., 2013; Jain et al., 2013). During the SWM, rainfall is concentrated along the west coast and northeastern India, while the northwestern and southeastern regions receive comparatively low precipitation (Srinivasan et al., 1972). Climate projections indicate an increase of approximately 20% in All-India SWM rainfall, accompanied by higher rainfall intensity (1-4 mm day^{-1}), although a slight decrease (1mm day^{-1}) is projected over parts of northwestern India (IPCC, 2013). Furthermore, the total number of rainy days is projected to decline across most parts of India, with a pronounced reduction (>15 days) over the western and central regions. In contrast, an increase of 5–10 rainy days is expected near the Himalayan foothills and in northeastern India (Kumar et al., 2012). Overall, mean annual rainfall over India is projected to increase by about 10% by 2070 (Pathak et al., 2012).

The rainfall patterns in Punjab state vary considerably across agro-climatic zones (Gill et al., 2010) and are projected to become increasingly uneven and erratic under future climate scenarios. Such variability is expected to intensify social pressure on the water resources, leading to excessive extraction of already stressed groundwater reserves. Rainfall deficits exacerbate water scarcity by limiting recharge of groundwater and surface reservoirs, resulting in reduced flows in springs, streams, and rivers, particularly in arid and semi-arid regions (Asoka et al., 2018). Additionally, inadequate rainfall can degrade water quality by altering salinity, acidity, dissolved oxygen, and turbidity, thereby reducing soil biological productivity. Conversely, episodes of intense rainfall increase the risk of flash floods across various regions of India (Annamalai and Sperber, 2005), underscoring the dual challenges posed by both rainfall scarcity and extremes.

Rainfall variability in Punjab has significant implications for agriculture, which remains the state's primary source of livelihood. Erratic southwest monsoon activity during the *Kharif* season and variability in western disturbances during the *Rabi* season often result in contrasting hydrological extremes, including water stress and drought-like conditions in some areas and flooding or waterlogging in others. Such variability adversely affects crop productivity and leads to substantial economic losses for farming communities. Declining annual rainfall and a reduction in the number of rainy days further aggravate these challenges, underscoring the need for effective monitoring and management of the state's water resources. Empirical evidence highlights pronounced seasonal and spatial variability in rainfall across Punjab. Kingra et al. (2004) reported that the Ballowal Saunkhri region received 1009 mm of rainfall during the Kharif season but only 154 mm during the Rabi season, indicating substantial intra-annual variability. A decreasing trend in annual rainfall has also been observed at Ballowal Saunkhri and Bathinda (Gill et al., 2010). Furthermore, a decline in the number of rainy days across several locations in Punjab was reported during 2000–2009, with Ballowal Saunkhri recording the highest number and Bathinda the lowest. Such hydro-climatic changes can trigger cascading environmental, social, and economic impacts across the region. Long-term analysis of climatic variables is therefore essential for understanding and monitoring both regional and global climate change dynamics (Kumar et al., 2010). Changes in long-term rainfall patterns directly influence water availability, drought and flood occurrences, and the estimation of agricultural, industrial, and domestic water demands, making rainfall trend assessment a critical component of sustainable resource planning (Pal and Mishra, 2017).

Although numerous studies have examined trends in climatic variables at national (Athar, 2015; Fan and Chen, 2016; Szabó et al., 2019), regional (Duhan and Pandey, 2013; Duan et al., 2016), and station-specific scales (Sahu et al., 2016; Beyene, 2015), comprehensive documentation of long-term rainfall trends in Punjab spanning the last century remains limited. In view of this knowledge gap, the present study investigates the spatial and temporal variability of rainfall across different districts of Punjab over a 122-year period. The specific objectives are to (i) detect statistically significant trends in rainfall time series and (ii) analyze the occurrence and variability of rainfall patterns across spatial and temporal scales. The findings are expected to provide valuable insights for formulating future strategies related to climate change adaptation, sustainable water resource management, and mitigation of drought and flood risks.

Source of data

The rainfall data used in this study were obtained from the Climate Monitoring and Prediction Group of the India Meteorological Department (IMD), Pune, India, and are freely accessible. The dataset consists of daily gridded rainfall values provided on a regular rectangular latitude–longitude grid with a high spatial resolution of 0.25° × 0.25°, stored in gridded (*.grd) format (Pai et al., 2014). Daily rainfall data spanning 122 years (1901–2022) were downloaded for analysis. The complete dataset comprises 135 × 129 grid points, covering latitudinal extents from 6.5°N to 38.5°N and longitudinal extents from 67.5°E to 100.0°E. As the downloaded dataset encompassed the entire Indian region, grid points lying outside the geographical boundary of Indian Punjab were excluded during data preprocessing. Initial filtering was performed using a customized C++ program, followed by spatial verification and refinement using the Quantum Geographic Information System (QGIS) software to ensure accurate delineation of the Punjab boundary. The remaining grid points within the study area were retained for further analysis. In Fig. 1, blue markers indicate the pre-selected rainfall grid points, while yellow markers represent the final selected grids within Punjab. The geographical extent of each district and the corresponding number of rainfall grid points used in the analysis are summarized in Table 1.

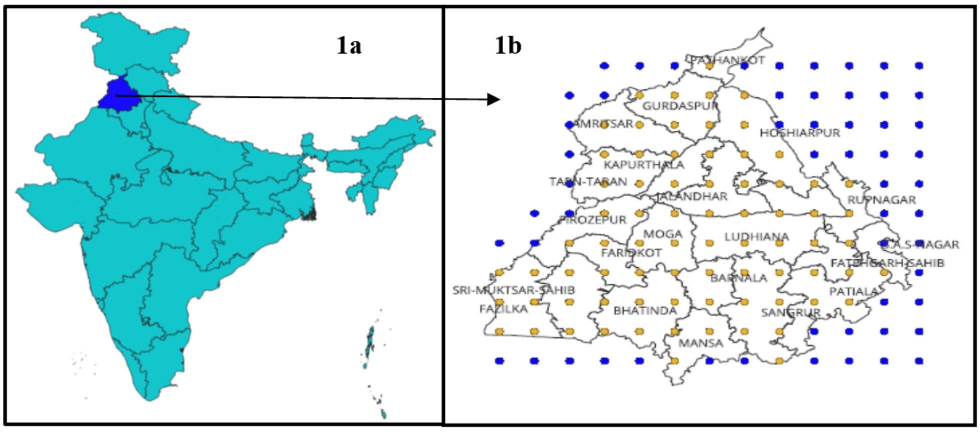

Fig. 1a. The shaded area in blue indicates the location of Punjab state on Indian map;
1b. Yellow markers indicate the grid points corresponding to rainfall in the Indian-Punjab region. Points lying out of the boundary (blue markers) are excluded from the study.

Materials and methods

Categorization of data

The entire Indian Punjab state was categorized into five agro-climatic zones—sub-mountain undulating plain zone (SMZ), undulating plain zone (UPZ), central plain zone (CPZ), western plain zone (WPZ), and western zone (WZ). The district-wise rainfall was computed by averaging the daily rainfall values of every grid point falling within the administrative boundary of each district. In the present study, the UPZ comprised two districts (Rupnagar and Shaheed Bhagat Singh Nagar), while the WPZ (Faridkot, Fazilka, and Ferozepur) and SMZ (Gurdaspur, Pathankot, and Hoshiarpur) each consisted of three districts. The CPZ included six districts (Amritsar, Tarn Taran, Kapurthala, Jalandhar, Ludhiana, and Patiala), and the WZ also comprised six districts (Moga, Bathinda, Mansa, Sri Muktsar Sahib, Sangrur, and Barnala). Out of the total 23 districts in Punjab, 20 districts were considered in this study, as no rainfall grid points fell within the districts of Fatehgarh Sahib and Sahibzada Ajit Singh Nagar (Mohali), necessitating their exclusion. Additionally, Malerkotla district, carved out of Sangrur district in 2021, was not considered due to the unavailability of separate long-term rainfall data.

For state-level analysis, rainfall values from a total of 75 grid points falling within the Punjab boundary were averaged annually to estimate mean rainfall for the entire state (Table 1). In addition to spatial categorization, the rainfall data were analyzed at annual and decadal temporal scales. Annual rainfall for each district was obtained by aggregating daily rainfall values for each calendar year. The complete 122-year dataset was further grouped into twelve decades: Decade 1 (1901–1910), Decade 2 (1911–1920), Decade 3 (1921–1930), Decade 4 (1931–1940), Decade 5 (1941–1950), Decade 6 (1951–1960), Decade 7 (1961–1970), Decade 8 (1971–1980), Decade 9 (1981–1990), Decade 10 (1991–2000), Decade 11 (2001–2010), and Decade 12 (2011–2022). The final decade comprised twelve years instead of ten due to asymmetry in the available data.

Table 1. Longitude, latitude and total rainfall grid points of various districts.

District	Longitude	Latitude	Number of grid points
Gurdaspur	75°-75.5° E	31.75°-32° N	5
Pathankot	75.5° E	32.25° N	1
Hoshiarpur	75.75°-76.25° E	31.25°-32° N	6
	Sub-mountain undulating zone (SMZ)		**12**
Rupnagar	76.5° E	30.75°-31.25° N	2
Shaheed Bhagat Singh Nagar	76°-76.5° E	31° N	3
	Undulating plain zone (UPZ)		**5**
Amritsar	74.75°-75.25° E	31.5°-31.75° N	3
Taran-Taran	74.75°-75° E	31.25°-31.5° N	4
Kapurthala	75.25°-75.5° E	31.25°-31.5° N	2
Jalandhar	75.5° E	31°-31.25° N	2
Ludhiana	75.5°-76.25° E	30.75°-31° N	5
Patiala	76.25°-76.75° E	30.25°-30.5° N	5
	Central plain zone (CPZ)		**21**
Faridkot	74.5°-74.75° E	30.5°-30.75° N	4
Fazilka	74°-74.25° E	30°-30.5° N	6
Ferozepur	74°.75-75° E	31° N	2
	Western plain zone (WPZ)		**12**
Moga	75°-75.25° E	30.5°-31° N	4
Bathinda	74.75°-75.25° E	30°-30.50° N	7
Mansa	75.25°-75.5° E	29.75°-30° N	2
Sri Mukatsar Sahib	74.5° E	30°-30.5° N	3
Sangrur	75.75°-76° E	29.75°-30.5° N	7
Barnala	75.5° E	30.25°-30.50° N	2
	Western zone (WZ)		**25**

Descriptive statistical analysis

Descriptive statistical measures, including minimum, maximum, mean, standard deviation (SD), coefficient of variation (CV), skewness, and kurtosis, were computed to characterize the rainfall data and assess its variability (Table 2). The mean, SD, and CV were used to quantify central tendency and dispersion, while skewness and kurtosis were employed to examine the shape of the rainfall distribution. Skewness describes the degree of asymmetry in a dataset around its mean, whereas kurtosis indicates whether the distribution is light-tailed or heavy-tailed relative to a normal distribution. These parameters were derived from the frequency distribution of rainfall data. Trend analysis describes the systematic change in a variable over time and represents the relationship between a dependent variable and its temporal scale (Hawkins and Webber, 1980). To assess monotonic trends in rainfall time series, non-parametric methods namely, the Mann–Kendall (MK) test (Mann, 1945; Kendall, 1975) and Sen's slope estimator, were applied. These methods are robust against non-normal data distributions and missing values and are widely used in hydro-climatic trend analysis. The procedures followed those described by Basistha et al. (2009), Yadav et al. (2014), and Oguntunde et al. (2012). The suitability of the MK test and Sen's slope estimator for detecting precipitation trends has been well documented in previous studies (Karabörk et al., 2007; Jiang et al., 2007; Liu et al., 2008).

Trend-free pre-whitening

Trend-free pre-whitening (TFPW) is a data pre-processing technique used to remove serial autocorrelation in time series data prior to trend analysis. Autocorrelation occurs when observations are correlated with their preceding values and can lead to biased trend estimates and misleading statistical significance levels. The TFPW procedure involves two main steps: (i) detrending the time series by removing any long-term trend and (ii) pre-whitening the detrended series to remove any autocorrelation. Typically, an autoregressive model is fitted to the detrended data, and the resulting residuals are treated as the pre-whitened data. Subsequently, trend analysis is performed on the pre-whitened data to obtain unbiased estimates of the underlying trend in the original time series (Hamed and Rao, 1998; Rao et al., 2003).

Mann–Kendall's test

The MK test is a widely used non-parametric statistical method for detecting monotonic trends in time series data. The test evaluates the presence of a trend by computing Kendall's rank correlation coefficient (also called Kendall's tau) between all possible pairs of data points in a time series. The sign of the coefficient indicates the direction of the trend, with positive values representing increasing trends and negative values indicating decreasing trends, while its magnitude reflects the strength of the trend. Statistical significance is assessed using the standard normal distribution. If the calculated p-value is less than the selected significance level (commonly p = 0.10, 0.05, or 0.01), the null hypothesis of no trend is rejected, indicating a statistically significant trend in time series data. Being a non-parametric method, the MK test does not require the data to follow a normal distribution and is relatively insensitive to outliers and abrupt breaks caused by inhomogeneities in the time series. In the present study, the MK test was implemented using the RStudio software environment. The null hypothesis (H_0) assumes no trend in the rainfall time series, whereas the alternative hypothesis (H_1) assumes the presence of a monotonic trend. For a time series, n observations (X_1, X_2, X_3, ..., X_n) are replaced by their relative ranks (R_1, R_2, R_3, ..., R_n). The MK test statistic (S) is computed as:

$$S = \sum_{i=1}^{n-1} \left\{ \sum_{j=i+1}^{n} sgn(R_j - R_i) \right\} \quad \text{......................} (1)$$

where the sign function sgn(x) is defined as:

$$sgn(x) = \begin{cases} +1, \text{if } x > 0; \\ 0, \text{if } x = 0; \\ -1, \text{if } x < 0. \end{cases}$$

A positive S value indicates an increasing trend, whereas a negative value indicates a decreasing trend. If the null hypothesis (H_o) is true, S is approximately normally distributed with μ = 0 (Equation 2).

$$Var(S) = n\frac{(n-1)(2n+5)}{18} \quad \text{....................} (2)$$

The standardized test statistic (*Z*) is computed as:xq

$$Z = \begin{cases} \frac{S-1}{\sqrt{var(S)}}, if\ S > 0 \\ 0, \quad if\ S = 0 \\ \frac{S+1}{\sqrt{var(S)}}, if\ S < 0 \end{cases} \quad \text{......................} (3)$$

The presence of a statistically significant trend is determined by comparing the absolute value of *Z* with the critical values of the standard normal distribution. The critical values at the 90%, 95%, and 99% confidence levels are 1.645, 1.96, and 2.576, respectively.

Sen's estimator

Sen's estimator is a robust non-parametric method used to estimate the slope of a monotonic trend in a time series (Sen, 1968). The method is based on calculating the median of slopes obtained from all possible pairs of observations in the dataset. In the present study, Sen's slope estimator was applied to quantify the magnitude of change in long-period average (1901–2022) and decadal rainfall series for each district using the RStudio software environment. Positive and negative values of Sen's slope indicate increasing and decreasing trends, respectively (Xu et al., 2010).

Sen's estimator is widely employed in hydro-meteorological trend analysis due to its robustness and reliability (Jayawardene et al., 2015; Martina et al., 2020; Patakamuri et al., 2020). In this approach, the slope for each pair of data points is calculated as per equation (4):

$$T_i = \frac{x_j - x_k}{j - k}, for\ i = 1,2,3 \dots .n \quad \text{........................} (4)$$

where T_i is the slope, and x_j and x_k are the data values at time steps j and k (j > k), respectively. Sen's slope estimator (Q_i) is then computed as the median of the n values of T_i using equation (5):

$$Q_{median} = \begin{cases} T_{(n+1)/2}, \quad if\ n\ is\ odd \\ \frac{1}{2}[(T_{n/2}) + T_{(n+2)/2}], \quad if\ n\ is\ even \end{cases} \quad \text{..................} (5)$$

Positive values of Q_{median} indicate an increasing trend, whereas negative values indicate a decreasing trend in the time series.

Results and Discussion

Spatio-temporal rainfall variability for LPA

A comprehensive assessment of rainfall variability across multiple spatial and temporal scales is essential for developing effective adaptation and mitigation strategies under future climate change scenarios (Addisu et al., 2015; Neil and Notodiputro, 2016; Gajbhiye et al., 2016). The descriptive statistical analysis of district-wise annual rainfall for the long-term period (1901–2022) is presented in Fig. 2 and Table 3. In the SMZ, the lowest annual rainfall was recorded at Gurdaspur (417.8 mm) and Pathankot (495.9 mm) during 2002, while Hoshiarpur received its lowest rainfall (493.5 mm) in 2018. Conversely, the maximum annual rainfall in these districts reached 1768.0 mm at Gurdaspur (1971), 2419.2 mm at Pathankot (1968), and 1985.4 mm at Hoshiarpur (1988). In the UPZ, rainfall at Rupnagar varied from a minimum of 52.7 mm in 1918 to a maximum of 1117.1 mm in 1973, whereas Shaheed Bhagat Singh Nagar (SBS Nagar) recorded annual rainfall ranging from 406.5 mm (1918) to 1797.2 mm (1988).

Within the CPZ, minimum rainfall was observed in different years across districts, including Amritsar (1965), Tarn Taran and Ludhiana (1974), Kapurthala (1972), Jalandhar (1905), and Patiala (1918). The highest rainfall values in CPZ districts were recorded during relatively recent decades, including 1306.4 mm at Kapurthala and 1379.5 mm at Ludhiana (1988), 1422.4 mm at Jalandhar (1995), 1556.1 mm at Patiala (2008), 1456.4 mm at Amritsar (2011), and 1333.4 mm at Tarn Taran (2012). In the WPZ, comparatively higher rainfall was recorded during earlier years, with maxima of 879.3 mm at Faridkot, 1090.8 mm at Ferozepur, and 873.4 mm at Fazilka. In contrast, markedly lower rainfall was observed during later years, with minimum values of 150.5 mm at Faridkot, 64.9 mm at Ferozepur, and 91.8 mm at Fazilka. Similarly, rainfall variability in the WZ was pronounced. Among the six districts, Mansa (137.8 mm) and Sangrur (276.2 mm) recorded their lowest rainfall in 2000, while Moga (148.8 mm) and Bathinda (119.2 mm) observed minimum rainfall in 1999. The lowest rainfall in Sri Muktsar Sahib and Barnala occurred earlier, during 1947 (134.6 mm) and 1943 (197.1 mm), respectively (Fig. 2; Table 3).

The LPA rainfall distribution exhibited distinct spatial variability across agro-climatic zones (Fig. 3). Among the districts, the highest LPA rainfall was observed in Pathankot (1204.5 mm), followed by Hoshiarpur (1059.7 mm) and SBS Nagar (889.0 mm). In contrast, Fazilka (307.2 mm), Sri Muktsar Sahib (368.1 mm), and Bathinda (374.2 mm) received the lowest LPA rainfall. Overall, the LPA rainfall across Punjab ranged from 355.1 to 1150.2 mm, with a state-wide mean of 630.2 ± 154.9 mm (Table 3). These results are consistent with the findings of Kumar et al. (2021), who reported substantial inter-annual and intra-seasonal rainfall variability across different regions of India.

However, in WPZ, older years recorded higher rainfall (i.e., 879.3 mm at Faridkot, 1090.8 mm at Ferozepur, and 873.4 mm at Fazilka). Albeit, lower rainfall was recorded during later years (91.8 mm at Fazilka, 150.5 mm at Faridkot, and 64.9 mm at Ferozepur). Out of six districts under WZ, only two districts recorded poor rainfall during 2000 (137.8 at Mansa and 276.2 mm at Sangrur) and another two districts during 1999 (148.8 mm at Moga and 119.2 mm at Bathinda). However, the lowest rainfall at Sri Muktsar Sahib and Barnala districts was 134.6 and 197.1 mm during 1947 and 1943, respectively (Table 3 and Fig. 2). The long-period average rainfall distribution exhibited distinct variation in various zones (Fig. 3). Among different districts, the highest LPA rainfall of 1204.5, 1059.7 and 889.0 mm was observed in Pathankot, Hoshiarpur and SBS Nagar, respectively. However, Fazilka, Sri Muktsar Sahib and Bathinda received poor LPA rainfall amounts of 307.2, 368.1 and 374.2 mm, respectively. Thus, ranging from 355.1 and 1150.2 mm, the LPA rainfall for the whole Punjab state was 630.2±154.9 mm (Table 3). These findings are well supported by the results of Kumar et al. (2021), who reported a significant variation in the pattern of inter-annual and intra-seasonal rainfall across different locations in India.

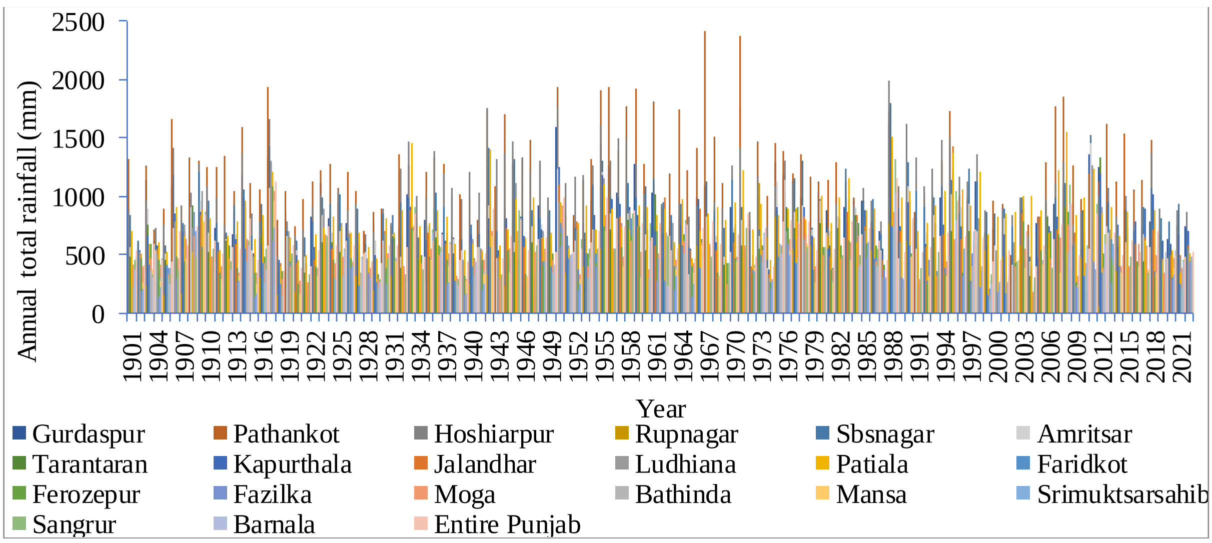

Fig. 2. Annual rainfall variation in different districts of Punjab during 1901-2022.

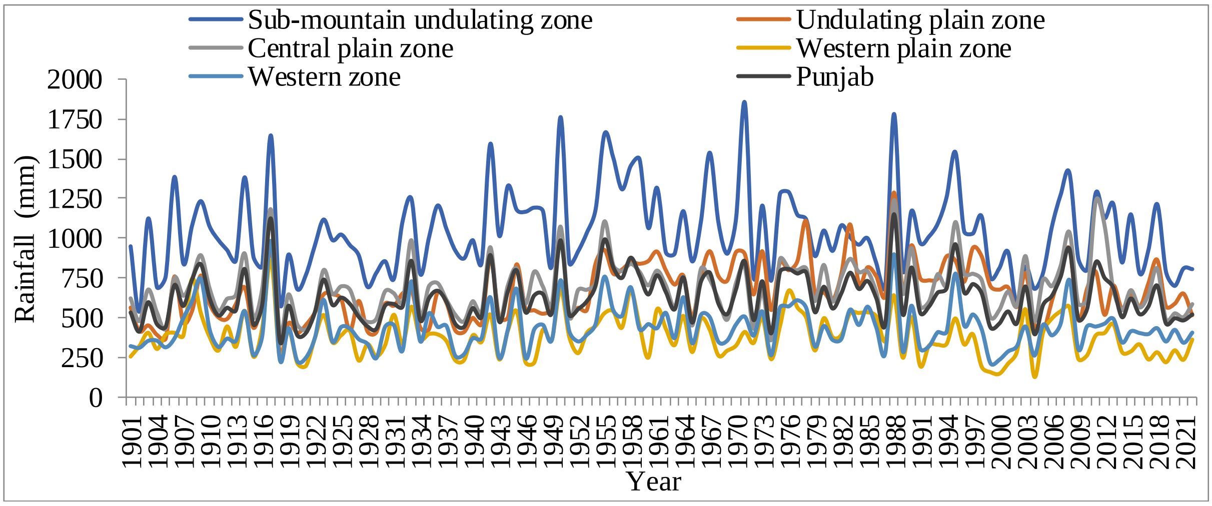

Fig. 3. Annual rainfall variation in different agroclimatic zones of Punjab during 1901-2022

Table 2. Formula used for computation of different statistical measures.

Eqn.	Statistical measures	Formula	Symbol used
1.	Arithmetic mean (X_{avg})	$\sum X_i/N$	X_i is rainfall in mm at the i_{th} observation and N is the sample size.
2.	Standard deviation (SD)	$[\sum (X_i - X_{avg})^2 / (N-1)]^{1/2}$	X_i is rainfall in mm, X_{avg} is the mean rainfall, and N is the sample size.
3.	Co-efficient of variation (CV)	$100 \times (\sigma / X_{avg})$	X_{avg} is mean rainfall and σ is standard deviation.
4.	Skewness (SKEW)	$\sum (X_i - X_{avg})^3 / (N-1) * \sigma^3$	X_i is the i^{th} observation, X_{avg} is the mean rainfall, N is the number of observations, and σ is standard deviation.
5.	Kurtosis (KURT)	$N * \Sigma(X_i - X_{avg})^4 / [\Sigma(X_i - X_{avg})^2]^2$	X_i is the i^{th} observation, X_{avg} is the mean rainfall, and N is the number of observations.

Results of descriptive statistical analysis (Table 3) revealed positive skewness and kurtosis values across all districts and agro-climatic zones. Positive skewness, which represents asymmetry of the frequency distribution around the mean, indicated that the annual rainfall distribution to be asymmetric during the LPA period was right-skewed, with a longer tail toward higher rainfall values. The positive kurtosis values further suggest a leptokurtic distribution, characterized by a higher frequency of extreme rainfall events.

Table 3. Descriptive statistics of long period (1901-2022) rainfall (mm) in different districts of Punjab

	Min	Max	Mean	SD	CV	Kurtosis	Skewness	Slope	intercept	R^2
Gurdaspur	417.8	1768.0	868.1	251.2	345.6	1.3	1.0	0.6	828.8	0.0083
Pathankot	495.9	2419.2	1204.5	369.1	326.4	0.8	0.8	0.1	1196.3	0.0002
Hoshiarpur	493.5	1985.4	1059.7	274.7	385.8	0.4	0.7	0.2	1045.2	0.0010
SMZ	**539.0**	**1852.5**	**1039.4**	**264.1**	**25.4**	**0.8**	**0.6**	**0.1**	**811.7**	**0.0002**
Rupnagar	52.7	1117.1	437.9	202.9	215.9	0.0	0.6	2.9	261.0	0.2598
SBS Nagar	406.5	1797.2	889.0	233.3	381.1	1.3	0.7	1.0	825.7	0.0251
UPZ	**281.3**	**1286.7**	**663.5**	**178.3**	**26.9**	**0.5**	**0.2**	**2.0**	**-3230.3**	**0.1550**
Amritsar	340.0	1456.4	710.6	209.0	340.0	1.1	0.9	1.1	645.6	0.0331
Taran-Taran	311.7	1333.4	602.8	192.0	314.0	1.4	1.0	1.0	541.9	0.0345
Kapurthala	289.8	1306.4	708.4	200.2	353.9	1.1	0.9	1.0	644.9	0.0344
Jalandhar	322.8	1422.4	653.7	188.8	346.3	2.2	1.1	0.5	622.1	0.0096
Ludhiana	300.5	1379.5	664.1	199.6	332.7	1.6	1.0	-0.1	672.0	0.0005
Patiala	346.2	1556.1	805.7	237.5	339.2	0.9	0.7	1.7	705.3	0.0610
CPZ	**359.5**	**1238.3**	**689.4**	**176.5**	**25.6**	**0.9**	**0.9**	**0.8**	**-828.2**	**0.0240**
Faridkot	150.5	879.3	395.9	144.2	274.5	0.7	0.8	-0.5	424.2	0.0132
Ferozepur	64.9	1090.8	459.8	179.1	256.7	0.6	0.4	-0.7	500.4	0.0176
Fazilka	91.8	873.4	307.2	130.8	234.8	1.7	1.0	0.0	308.4	0.0000
WPZ	**128.2**	**862.8**	**385.6**	**132.6**	**34.4**	**0.6**	**0.6**	**-0.5**	**1300.3**	**0.0155**
Moga	148.8	1046.8	469.4	157.5	298.0	1.1	0.7	-0.4	495.2	0.0092
Bathinda	119.2	946.7	374.2	143.1	261.6	1.7	1.1	-0.1	380.7	0.0007
Mansa	137.8	964.7	390.3	146.9	265.7	1.9	1.2	-0.1	395.4	0.0004
Srimuktsar Sahib	134.6	735.8	368.1	133.2	276.2	0.1	0.7	0.5	337.1	0.0185
Sangrur	276.2	1315.4	529.6	192.2	275.6	2.5	1.4	0.4	503.5	0.0063
Barnala	197.1	1098.0	479.9	180.8	265.4	1.2	1.1	0.2	467.5	0.0016
WZ	**213.1**	**982.3**	**435.2**	**141.6**	**32.5**	**1.2**	**1.9**	**0.1**	**262.2**	**0.0005**
Punjab	**355.1**	**1150.2**	**630.2**	**154.9**	**24.6**	**0.8**	**0.7**	**0.4**	**-209.8**	**0.0096**

Trend analysis showed that six out of the twenty districts exhibited a declining rainfall trend, ranging from −0.10 to −0.70 mm yr⁻¹, with the most pronounced decrease (~0.5 mm yr⁻¹) observed in the WPZ. In contrast, a strong increasing trend of 2.9 mm yr⁻¹ was recorded for Rupnagar over the long-term study period. At the zonal scale, the maximum LPA rainfall was observed in the SMZ (1039.4 mm), followed by the CPZ (689.4 mm) (Fig. 4). Conversely, the WPZ remained the driest region, with an LPA rainfall of 385.6 mm, followed by the WZ (435.2 mm) and the UPZ (663.5 mm). On both zonal and state-wide scales, a declining LPA rainfall trend was observed only in the WPZ, whereas all other agro-climatic zones exhibited an overall increasing rainfall tendency (Fig. 4).

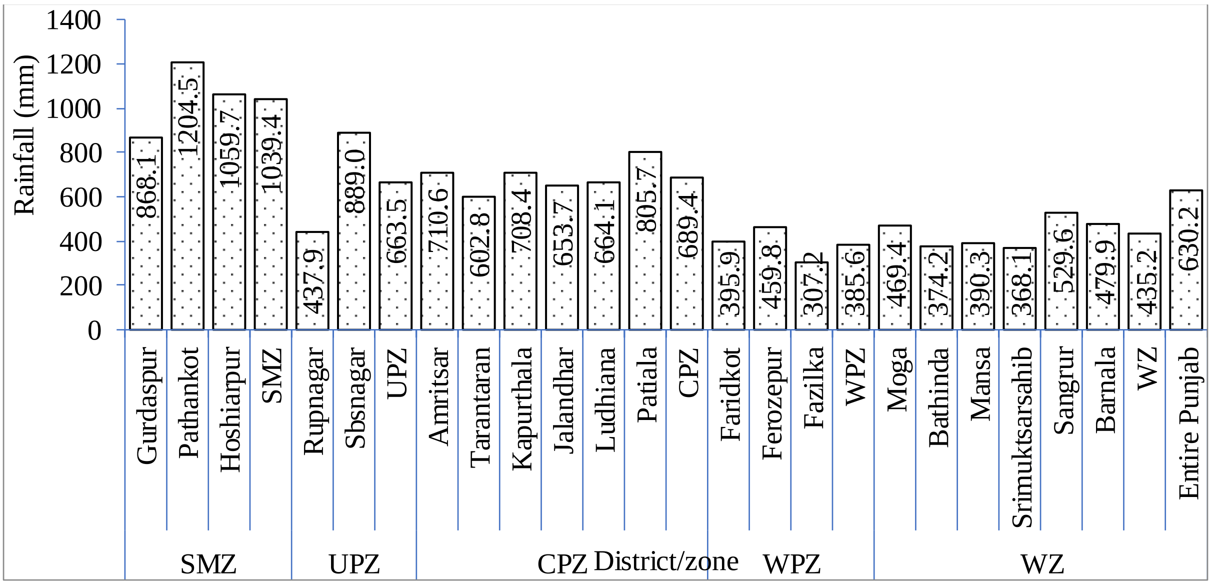

Fig. 4. Long period average (1901-2022) of rainfall at different districts of Punjab

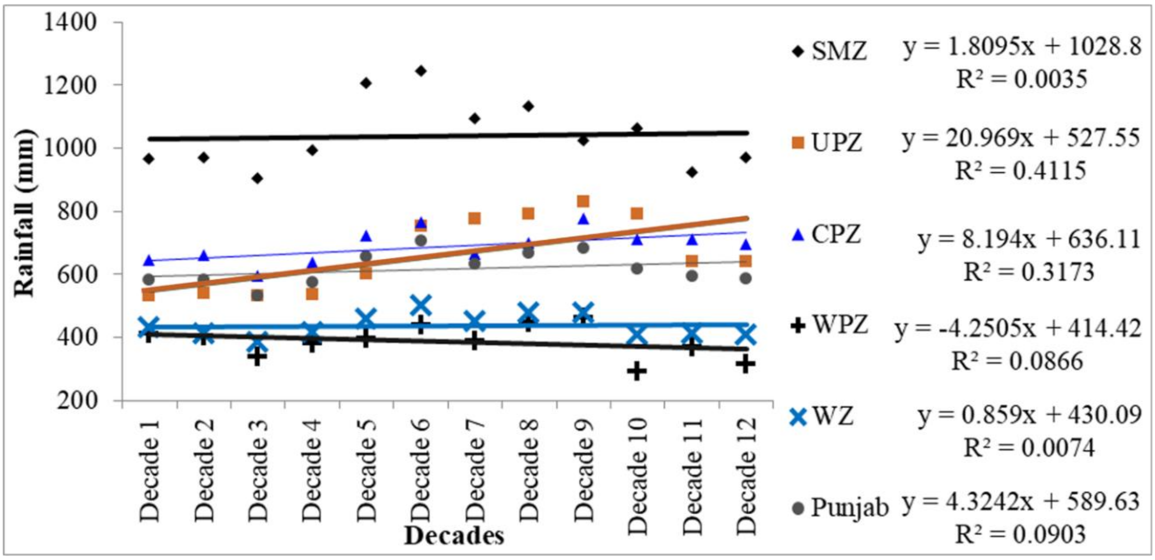

Fig. 5. Zone wise variation in decadal rainfall

Spatio-temporal rainfall variability for decades

The decadal rainfall patterns across different agro-climatic zones of Punjab (Table 4) indicate that the SMZ received the highest rainfall, followed by CPZ, UPZ, WZ, and WPZ. At the state level, the three wettest decades were the sixth decade (722.7 ± 148.6 mm), followed by the ninth (697.0 ± 195.3 mm) and eighth decades (685.1 ± 155.3 mm). In contrast, the lowest rainfall occurred during three consecutive decades, with mean rainfall values of 542.7 ± 101.6 mm in the third decade, 585.1 ± 119.9 mm in the fourth decade, and 591.0 ± 224.1 mm in the second decade. The coefficient of variation (CV), reflecting rainfall variability, ranged from 17.1% to 37.9% across decades, indicating substantial inter-decadal variability in rainfall. Among the agro-climatic regions, the lowest decadal average rainfall was observed during the third decade (1921–1930) in most zones, except for the UPZ and WPZ, which experienced minimum rainfall during the first (1901–1910) and tenth (2001–2010) decades, respectively. Conversely, the maximum rainfall in the SMZ and WZ occurred during the eighth (1971–1980) and second (1911–1920) decades, respectively, while the UPZ and CPZ recorded peak rainfall during the ninth decade (1981–1990). The WPZ experienced its maximum rainfall during the second decade (1911–1920). For the entire Punjab state, the highest and lowest decadal rainfall were observed during the sixth and third decades, respectively (Table 4).

Table 4. Descriptive statistics of the decadal rainfall in different agroclimatic zones of Punjab.

	SMZ	UPZ	CPZ	WPZ	WZ	Punjab	SMZ	UPZ	CPZ	WPZ	WZ	Punjab
	Decade 1: (1901-1910)						**Decade 2: (1911-1920)**					
Min	539.0	369.0	433.6	255.8	311.0	412.6	593.9	281.3	411.5	214.5	225.9	355.1
Max	1385.3	764.9	892.8	745.4	744.3	835.8	1644.7	918.5	1179.1	862.8	982.3	1122.2
Mean	967.4	531.5	645.1	412.6	429.6	592.0	968.0	539.2	658.9	404.2	410.9	591.0
SD±	260.6	141.5	137.5	138.0	144.6	137.6	316.1	176.1	229.2	192.9	222.3	224.1
CV%	26.9	26.6	21.3	33.4	33.7	23.3	32.7	32.7	34.8	47.7	54.1	37.9
Skewness	-0.10	0.75	0.10	1.72	1.44	0.40	1.32	0.95	1.46	1.61	2.19	1.67
Kurtosis	-0.66	-0.54	-0.12	3.65	1.33	-0.68	1.48	1.60	2.22	3.09	5.45	3.18
Slope	41.38	22.75	26.82	27.41	34.59	30.78	-21.72	-10.51	-4.51	-0.28	3.04	-5.53
Intercept	-77882	-42812	-50456	-51811	-65487	-58055	42568	20666	9305	937	-5422	11192
R^2	0.231	0.237	0.349	0.362	0.524	0.458	0.043	0.033	0.004	0.000	0.002	0.006
	Decade 3: (1921-1930)						**Decade 4: (1931-1940)**					
Min	693.6	407.6	425.2	198.7	245.4	405.3	743.6	409.7	476.6	232.2	260.3	442.0
Max	1117.1	647.2	799.5	516.6	612.6	739.5	1247.2	674.8	986.7	568.9	728.8	857.0
Mean	903.1	532.9	593.2	338.7	384.5	542.7	991.9	535.0	638.0	379.1	414.8	585.1
SD±	129.5	100.4	120.4	94.1	106.6	101.6	168.8	108.2	145.4	106.3	141.4	119.9
CV%	14.3	18.8	20.3	27.8	27.7	18.7	17.0	20.2	22.8	28.0	34.1	20.5
Skewness	-0.06	-0.21	0.23	0.29	0.81	0.44	0.02	0.10	1.59	0.37	1.17	1.20
Kurtosis	-0.60	-1.99	-1.06	0.16	1.48	0.12	-0.90	-1.97	3.45	0.10	1.74	2.29
Slope	-17.80	-7.11	-0.97	-5.34	-3.15	-5.82	-0.13	-17.98	-20.23	-21.85	-18.46	-16.43
Intercept	35185	14216	2467	10616	6445	11741	1247	35337	39795	42666	36146	32379
R^2	0.173	0.046	0.001	0.030	0.008	0.030	0.000	0.253	0.178	0.387	0.156	0.172
	Decade 5: (1941-1950)						**Decade 6: (1951-1960)**					
Min	827.6	459.7	486.1	217.2	248.0	476.2	844.5	506.8	506.9	248.8	350.5	518.3
Max	1761.0	876.4	1072.7	678.3	735.1	986.6	1654.4	926.5	1105.2	669.6	757.6	991.2
Mean	1207.6	603.0	720.7	396.9	457.6	667.4	1246.1	750.9	763.6	438.3	501.4	722.7
SD±	295.8	144.0	186.3	152.1	170.9	173.6	278.2	151.6	154.7	124.3	131.3	148.6
CV%	24.5	23.9	25.9	38.3	37.4	26.0	22.3	20.2	20.3	28.4	26.2	20.6
Skewness	0.64	1.28	0.68	0.46	0.48	0.79	-0.03	-0.82	0.83	0.21	1.10	0.36
Kurtosis	0.10	0.33	-0.22	-0.44	-0.95	-0.49	-1.46	-1.12	2.58	0.25	0.34	-0.46
Slope	19.59	-2.71	20.75	11.46	12.04	13.90	50.68	38.26	20.12	8.34	14.51	24.12
Intercept	-36912	5874	-39656	-21889	-22972	-26375	-97855	-74068	-38584	-15866	-27875	-46434
R^2	0.040	0.003	0.114	0.052	0.046	0.059	0.304	0.584	0.155	0.041	0.112	0.241
	Decade 7: (1961-1970)						**Decade 8: (1971-1980)**					
Min	853.9	503.6	450.6	261.7	339.5	468.9	732.3	548.1	359.5	239.3	263.3	401.1
Max	1537.5	917.9	806.5	553.0	628.7	783.4	1852.5	1106.9	866.7	669.6	609.5	853.8
Mean	1091.6	777.6	664.0	390.1	448.7	650.0	1130.8	793.1	699.5	445.8	476.7	685.1
SD±	215.3	124.6	126.9	105.5	96.5	111.3	323.5	167.2	179.8	129.3	118.0	155.3
CV%	19.7	16.0	19.1	27.0	21.5	17.1	28.6	21.1	25.7	29.0	24.8	22.7
Skewness	0.94	-0.95	-0.65	0.30	0.51	-0.37	1.03	0.34	-1.14	-0.02	-0.82	-0.92
Kurtosis	0.63	1.77	-1.00	-1.59	-0.60	-1.35	2.07	-0.19	-0.09	-0.28	-0.65	-0.61
Slope	3.07	3.04	-10.12	-20.62	-8.06	-7.51	-33.23	-1.83	20.21	9.97	0.93	2.02
Intercept	-4938	-5188	20562	40922	16293	15420	66772	4411	-39227	-19254	-1364	-3311
R^2	0.002	0.005	0.058	0.350	0.064	0.042	0.097	0.001	0.116	0.055	0.001	0.002
	Decade 9: (1981-1990)						**Decade 10: (1991-2000)**					
Min	694.4	607.9	461.1	248.7	275.0	457.5	751.0	676.2	503.0	147.0	213.1	438.7
Max	1780.5	1286.7	1238.3	640.6	898.6	1150.2	1540.4	939.0	1101.4	495.3	777.4	962.2
Mean	1025.0	831.6	775.2	461.1	477.2	697.0	1063.9	789.7	709.3	290.4	406.7	633.0
SD±	299.2	216.3	212.8	115.2	184.4	195.3	222.8	92.6	172.1	113.8	162.5	149.1
CV%	29.2	26.0	27.5	25.0	38.6	28.0	20.9	11.7	24.3	39.2	40.0	23.6
Skewness	2.0	1.2	0.9	-0.4	1.3	1.4	0.9	0.5	1.2	0.3	1.2	1.0
Kurtosis	5.0	0.9	1.8	-0.2	2.3	2.7	1.6	-1.5	2.3	-0.7	2.4	1.9
Slope	19.5	19.2	18.5	0.9	14.9	14.9	-25.5	-1.1	-7.3	-13.8	-7.8	-10.8
Intercept	-37768	-37240	-35896	-1244	-29193	-28925	52029	2933	15320	27911	15973	22152
R^2	0.039	0.072	0.069	0.001	0.060	0.053	0.120	0.001	0.017	0.136	0.021	0.048
	Decade 11: (2001-2010)						**Decade 10: (2011-2022)**					
Min	583.5	416.3	478.6	128.2	261.5	396.8	699.8	515.4	486.8	219.8	342.2	463.8
Max	1409.4	931.6	1036.9	566.4	737.1	932.5	1284.4	863.8	1233.0	459.4	493.1	848.1
Mean	921.4	640.6	710.9	368.8	410.5	605.1	970.2	641.1	694.2	315.5	409.5	597.3
SD±	258.6	165.6	166.8	162.2	138.0	157.6	210.5	109.8	236.3	74.7	47.0	123.7
CV%	28.1	25.9	23.5	44.0	33.6	26.0	21.7	17.1	34.0	23.7	11.5	20.7
Skewness	0.85	0.28	0.71	-0.03	1.48	0.91	0.31	0.79	1.56	0.57	0.00	0.84
Kurtosis	0.03	-0.74	0.17	-1.76	3.07	0.82	-1.79	-0.16	1.61	-0.55	-0.50	-0.38
Slope	36.57	7.86	8.43	9.56	19.97	16.12	-40.82	-6.16	-46.11	-11.83	-6.66	-25.38
Intercept	-72425	-15117	-16201	-18800	-39632	-31727	83279	13059	93677	24180	13847	51786
R^2	0.183	0.021	0.023	0.032	0.192	0.096	0.489	0.041	0.495	0.327	0.261	0.547

Trend analysis revealed an increasing decadal rainfall trend in all agro-climatic zones except the WPZ, although the magnitude varied among regions. The rate of increase was estimated at 1.8 mm decade^{-1} in the SMZ, 21.0 mm decade^{-1} in the UPZ, 8.2 mm decade^{-1} in the CPZ, 0.86 mm decade^{-1} in the WZ, and 4.3 mm decade^{-1} for the state. The corresponding coefficients of determination (R^2) were 0.0035, 0.41, 0.32, 0.007, and 0.09, respectively. In contrast, the WPZ exhibited a declining rainfall trend of −4.3 mm decade^{-1}, with an R^2 value of 0.09 (Fig. 5).

Trend analysis of rainfall for LPA

The MK test (z), Sen's slope estimator (S), and corresponding significance levels were applied to long-term rainfall time series to investigate rainfall trends across different agro-climatic zones of Punjab (Table 5). The LPA rainfall exhibited a decreasing trend in only five districts, namely Pathankot (-0.20 mm), Ludhiana (-0.30 mm), Faridkot (-1.10 mm), Ferozepur (-1.28 mm), and Moga (-0.68 mm). Among these, the rate of rainfall decline was comparatively higher in Ferozepur and Faridkot compared to Ludhiana, Pathankot, and Moga; however, the decreasing trends in all five districts were statistically non-significant. In contrast, the remaining districts displayed increasing rainfall trends. Statistically significant increasing trends were detected in Rupnagar (5.97 mm yr^{-1}; ***p = 0.001), Kapurthala (2.12 mm yr^{-1}; *p = 0.05), and Patiala (3.34 mm yr^{-1}; ***p = 0.001). These findings are consistent with Kumar et al. (2021), who reported increases in annual and monsoon precipitation over Punjab by 32.18 mm and 27.45 mm, respectively, when comparing the periods 1981–2010 and 1991–2020.

At the agro-climatic zone, only the WPZ exhibited a decreasing rainfall trend, although this trend was not statistically significant (z = −0.99). All other zones showed increasing rainfall trends, with the UPZ recording a statistically significant rise (z = 4.36***, p = 0.001). Overall, rainfall trends varied across the state, with certain regions experiencing increasing rainfall, while others showed stable or declining tendencies. It is noteworthy that, except for the UPZ, none of the agro-climatic zones exhibited a statistically significant increasing trend. Similarly, at the state level, Punjab showed an overall increasing rainfall trend, but the magnitude of change was not statistically significant. It is important to emphasize that a statistically non-significant trend does not imply the absence of change in the time series; rather, it indicates insufficient statistical evidence to conclusively establish a trend. The observed increase in rainfall across Punjab may therefore be influenced by random variability rather than a persistent long-term trend. Continued monitoring of rainfall patterns is essential to determine whether these trends persist and eventually attain statistical significance. Furthermore, investigating the role of large-scale climate drivers and regional climatic variability may help explain the observed variability in rainfall patterns. Similar observations have also been reported by Mahdi et al. (2022) for the Kashmir Valley, India.

Trend analysis of rainfall at the decadal scale

The decadal rainfall trends across different agro-climatic regions of Punjab, along with their corresponding z-statistics values (Fig. 6 and Table 6), indicate considerable spatial and temporal variability. Among the five agro-climatic regions analyzed (SMZ, UPZ, CPZ, WPZ, and WZ), rainfall exhibited an increasing trend in four decades in SMZ, five decades each in UPZ and WPZ, six decades in CPZ, and seven decades in WZ. Across all zones, the first decade (1901–1910) and the sixth decade (1951–1960) recorded the highest z-statistics values, suggesting strong positive rainfall trends during these periods. The WZ showed a statistically significant increasing trend, with a z-statistics value of 2.68* (p = 0.01). Additionally, the rainfall trend for the entire Punjab state was also found to be statistically significant, with a z-statistics value of 1.97* (p = 0.05).

Table 5. Man-Kendall and Sen's slope for annual long period average rainfall trend.

	z	n	p-value	S	varS	tau	S-slope	Trend
Gurdaspur	1.26	122	0.21	570	204207	0.08	0.72	+
Pathankot	-0.20	118	0.84	-87	184847	-0.01	-0.22	-
Hoshiarpur	0.24	122	0.81	111	204208	0.02	0.15	+
SMZ	0.16	122	0.88	72	204207	0.01	0.10	+
Rupnagar	5.97	122	0.00	2700	204205	0.37	2.98	+***
SBS Nagar	1.90	122	0.06	860	204207	0.12	1.11	+
UPZ	4.36	122	0.00	1973	204208	0.27	1.99	+***
Amritsar	1.8561	118	0.06	799	184847	0.12	1.04	+
Taran-Taran	1.7235	118	0.08	742	184846	0.11	0.90	+
Kapurthala	2.12	122	0.03	960	204207	0.13	0.99	+*
Jalandhar	1.00	122	0.32	452	204207	0.06	0.44	+
Ludhiana	-0.30	122	0.77	-136	204205	-0.02	-0.17	-
Patiala	3.34	122	0.00	1509	204204	0.20	1.96	+***
CPZ	1.59	122	0.11	719	204206	0.10	0.73	+
Faridkot	-1.10	122	0.27	-500	204205	-0.07	-0.39	-
Ferozepur	-1.277	118	0.20	-550	184846	-0.08	-0.66	+
Fazilka	0.31	122	0.75	143	204206	0.02	0.09	+
WPZ	-0.99	122	0.32	-448	204205	-0.06	-0.33	-
Moga	-0.68	122	0.50	-308	204207	-0.04	-0.26	-
Bathinda	0.16	122	0.87	73	204204	0.01	0.05	+
Mansa	0.42	122	0.67	191	204203	0.03	0.15	+
SrimuktsarSahib	1.80	122	0.07	813	204208	0.11	0.59	+
Sangrur	0.87	122	0.38	395	204208	0.05	0.31	+
Barnala	0.76	122	0.45	346	204205	0.05	0.35	+
WZ	0.87	122	0.38	395	204206	0.05	0.27	+
Punjab	1.15	122	0.25	520	204207	0.07	0.48	+

Note: '+' or '-' indicates increasing or decreasing trend at '*' (p=0.05), '**' (p=0.01) and, '***' (p=0.001) level of significance.

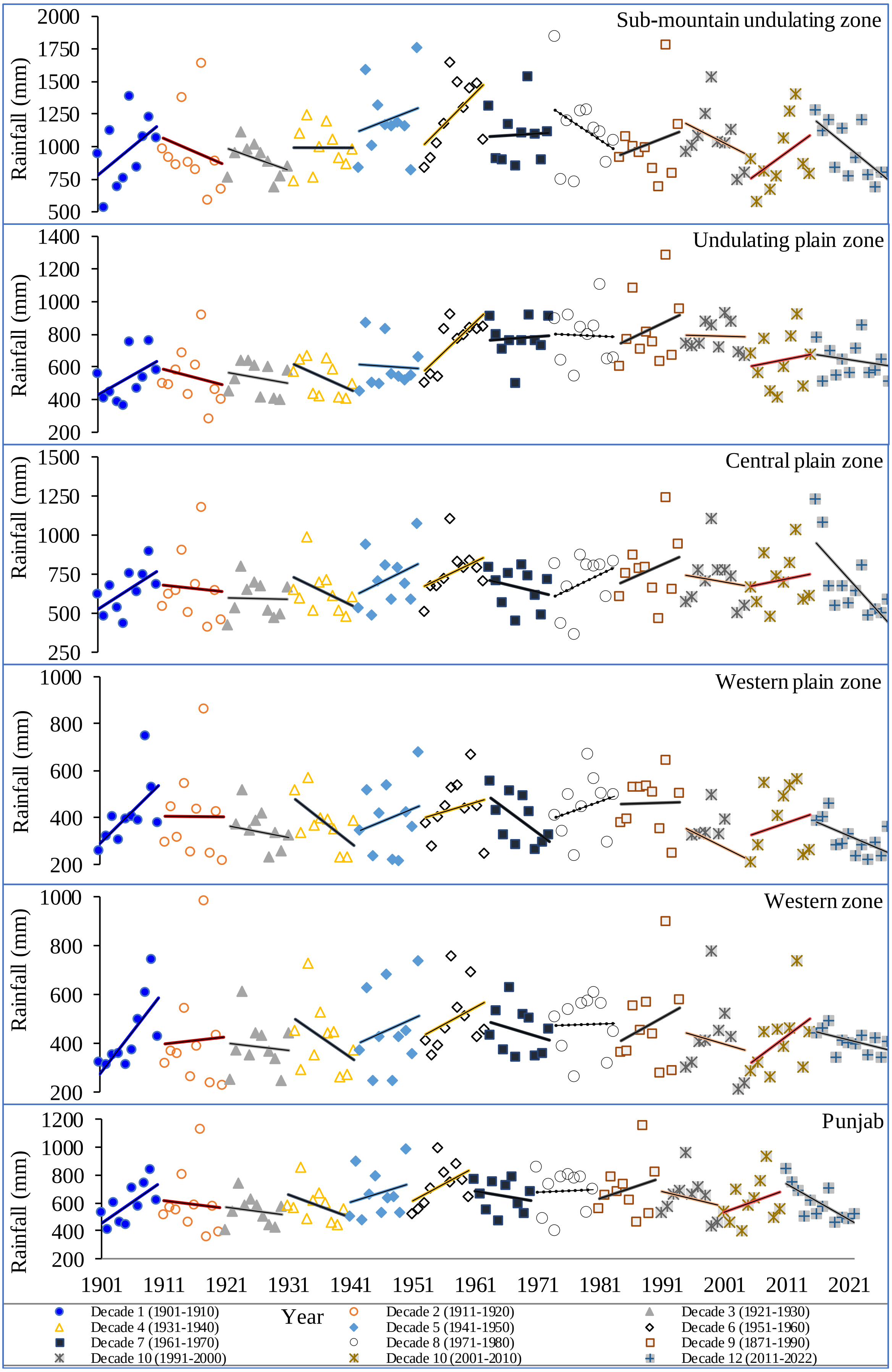

Fig. 6. Decade wise variation in annual rainfall in different agroclimatic zones of Punjab.

These findings are consistent with those of Kumar et al. (2010), who reported a significant increasing trend in long-term annual rainfall (1871–2005) for Punjab, Haryana, and Karnataka, while no significant trends were observed for most other Indian states over the 135-year period. In contrast, the remaining decades across the agro-climatic regions exhibited declining rainfall trends; however, these trends were statistically non-significant (Table 6). Notably, during the most recent period (2011–2022), a negative z-score was observed for the entire Punjab state, indicating a declining rainfall tendency in recent years. This reduction may help explain the observed decrease in rainfall when viewed in the context of long-term historical variability. Nevertheless, the statistically significant positive trend observed during the first decade (1901–1910; z = 1.97*, p = 0.05) highlights the pronounced inter-decadal variability in rainfall patterns.

Overall, the results demonstrate marked spatio-temporal heterogeneity in decadal rainfall trends across Punjab, underscoring the dynamic nature of regional rainfall variability over the past century.

Table 6. Man-Kendall and Sen's slope for decadal average rainfall trend.

	Decade 1	Decade 2	Decade 3	Decade 4	Decade 5	Decade 6	Decade 7	Decade 8	Decade 9	Decade 10	Decade 11	Decade 12
	Sub-mountain undulating zone											
z	1.252	-1.252	-1.073	-0.179	0.179	1.610	0.000	-0.894	-0.179	-0.358	1.073	-2.126
S	15	-15	-13	-3	3	19	-1	-11	-3	-5	13	-32
varS	125	125	125	125	125	125	125	125	125	125	125	213
tau	0.333	-0.333	-0.289	-0.067	0.067	0.422	-0.022	-0.244	-0.067	-0.111	0.289	-0.485
S-slope	62.5	-30.7	-24.7	-9.9	6.7	77.1	-1.4	-32.9	-13.6	-16.6	38.6	-37.7
Trend	+	-	-	-	+	+	-	-	-	-	+	-*
	Undulating plain zone											
z	1.252	-0.716	-1.073	-1.431	0.716	2.147	-0.179	0.000	0.537	-0.537	0.358	-0.343
S	15	-9	-13	-17	9	25	-3	-1	7	-7	5	-6
varS	125	125	125	125	125	125	125	125	125	125	125	213
tau	0.333	-0.200	-0.289	-0.378	0.200	0.556	-0.067	-0.022	0.156	-0.156	0.111	-0.091
S-slope	21.7	-10.9	-6.1	-12.1	9.3	38.8	-0.8	-7.4	19.5	-5.2	9.5	-5.7
Trend	+	-	-	-	+	+*	-	-	+	-	+	-
	Central plain zone											
z	1.610	0.000	-0.179	-1.073	0.537	1.431	-0.716	0.358	0.537	-0.179	0.358	-2.263
S	19	-1	-3	-13	7	17	-9	5	7	-3	5	-34
varS	125	125	125	125	125	125	125	125	125	125	125	213
tau	0.422	-0.022	-0.067	-0.289	0.156	0.378	-0.200	0.111	0.156	-0.067	0.111	-0.515
S-slope	25.8	-9.3	-2.4	-18.8	16.7	23.5	-9.4	10.2	11.4	-2.6	6.8	-30.5
Trend	+	-	-	-	+	+	-	+	+	-	+	-*
	Western plain zone											
z	1.431	-0.716	-0.537	-1.431	0.358	1.073	-1.789	0.537	0.000	-0.716	0.716	-1.577
S	17	-9	-7	-17	5	13	-21	7	1	-9	9	-24
varS	125	125	125	125	125	125	125	125	125	125	125	213
tau	0.378	-0.200	-0.156	-0.378	0.111	0.289	-0.467	0.156	0.022	-0.200	0.200	-0.364
S-slope	21.8	-6.3	-5.7	-24.7	6.8	12.8	-21.5	10.2	1.4	-10.6	22.4	-12.0
Trend	+	-	-	-	+	+	-	+	-	-	+	-
	Western zone											
z	2.683	-0.179	-0.179	-1.073	0.537	1.073	-0.716	0.358	0.716	0.179	1.252	-1.577
S	31	-3	-3	-13	7	13	-9	5	9	3	15	-24
varS	125	125	125	125	125	125	125	125	125	125	125	213
tau	0.689	-0.067	-0.067	-0.289	0.156	0.289	-0.200	0.111	0.200	0.067	0.333	-0.364
S-slope	29.2	-7.5	-1.6	-17.5	12.0	15.9	-9.1	7.8	9.2	3.5	17.2	-7.2
Trend	+**	-	-	-	+	+	-	+	+	+	+	-
	Entire Punjab											
z	1.968	-0.179	-0.537	-1.252	0.537	1.610	-0.537	-0.358	0.358	-0.179	0.894	-2.400
S	23	-3	-7	-15	7	19	-7	-5	5	-3	11	-36
varS	125	125	125	125	125	125	125	125	125	125	125	213
tau	0.511	-0.067	-0.156	-0.333	0.156	0.422	-0.156	-0.111	0.111	-0.067	0.244	-0.545
S-slope	32.2	-13.5	-10.2	-16.3	8.7	31.1	-9.8	-4.9	13.7	-3.1	19.4	-25.2
Trend	+*	-	-	-	+	+	-	-	+	-	+	-*

Note:'+' or '-' indicates increasing or decreasing trend at '*' (p=0.05), '**' (p=0.01) and, '***' (p=0.001) level of significance.

Conclusion

Understanding spatio-temporal rainfall variability is crucial for effective water resource management, mitigation of drought and flood impacts, and climate change adaptation under increasing climatic uncertainty. This study provides a comprehensive assessment of long-term rainfall variability across Punjab, India, over a 122-year period (1901–2022). The analysis revealed pronounced spatial heterogeneity in rainfall distribution among districts and agro-climatic zones, with substantially higher rainfall in the sub-mountain and central plain regions compared to the western and western plain zones. Decadal variability was evident, characterized by alternating periods of enhanced and reduced rainfall intensity. These findings underscore the importance of region-specific rainfall management and adaptive agricultural planning strategies to enhance resilience and ensure sustainable food security in the arid and semi-arid regions of Punjab. The site-specific insights derived from this study are valuable for anticipating future hydro-climatic risks and supporting evidence-based adaptation strategies.

References

Addisu S, Selassie YG, Fissha G, Gedif B (2015) Time series trend analysis of temperature and rainfall in lake Tana sub-basin, Ethiopia. Environmental Systems Research 4:25. https://doi.org/10.1186/s40068-015-0051-0.

Annamalai H, Sperber KR (2005) Regional heat sources and the active and break phases of boreal summer intraseasonal (30–50 day) variability. Journal of Atmospheric Sciences 62:2726-2748.

Asoka A, Wada Y, Fishman R, Mishra V (2018) Strong linkage between precipitation intensity and monsoon season groundwater recharge in India. Geophysical Research Letters 45:5536–5544. https://doi.org/10.1029/2018GL078466.

Athar H (2015) Teleconnections and variability in observed rainfall over Saudi Arabia during 1978-2010. Atmospheric Science Letters 16(3):373–379. https://doi.org/10.1002/asl2.570.

Banerjee RR (2015) Farmers' perception of climate change, impact and adaptation strategies: a case study of four villages in the semi-arid regions of India. Natural Hazards 75:2829-2845. https://doi.org/10.1007/s11069-014-1466-z.

Basistha A, Arya DS, Goel NK (2009) Analysis of historical changes in rainfall in the Indian Himalayas. International Journal of Climatology 29:555–557. https://doi.org/10.1002/joc.1706.

Beyene AN (2015) Precipitation and temperature trend analysis in Mekelle city, Northern Ethiopia, the case of Illala Meteorological station. Journal of Environment and Earth Science 5(19): 46–52.

Chandramouli C (2011) Census of India 2011: provisional population totals, paper 2, rural-urban distribution. New Delhi: Office of the Registrar General and Census Commissioner, India, p. 2.

Cruz RV, Harasawa H, Lal M, Wu S, Anokhin Y, Punsalmaa B, et al. (2007) Climate change, 2007, impacts, adaptation and vulnerability. In: Parry ML, CanzianioF, Palutikof JP, et al. (eds) Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 469–506.

Deka RL, Mahanta C, Pathak H, Nath KK, Das S (2013) Trends and fluctuations of rainfall regime in the Brahmaputra and Barak basins of Assam, India. Theoretical and Applied Climatology 114:61–71. https://doi.org/10.1007/s00704-012-0820-x.

Duan W, Bin H, Sahu, N, Pingping L, Daniel N, Maochuan H, Kaoru T (2016) Spatiotemporal variability of Hokkaido's seasonal precipitation in recent decades and connection to water vapor flux. International Journal of Climatology 37(9): 3660–3673. https://doi.org/10.1002/joc.4946.

Duhan D and Pandey A (2013) Statistical analysis of long term spatial and temporal trends of precipitation during 1901- 2002 at Madhya Pradesh, India. Atmospheric Research 122:136–149. https://doi.org/10.1016/j.atmosres.2012.10.010.

Fan L and Chen D (2016) Trends in extreme precipitation indices across China detected using quantile regression. Atmospheric Science Letters 17:400–406. https://doi.org/10.1002/asl.671.

Gajbhiye S, Meshram C, Singh SK Srivastava PK, Islam T (2016) Precipitation trend analysis of Sindh River basin, India, from 102-year record (1901-2002). Atmospheric Science Letters 17(1):71–77. https://doi.org/10.1002/asl.602.

Gill KK, Bains GS, Mukharjee J, Kingra PK, Bal SK (2010) Variability in Climate in three climatic regions of Punjab. Indian Journal of Ecology 37:33-39.

Goswami BB, Mukhopadhyay P, Mahanta R, Goswami BN (2010) Multiscale interaction with topography and extreme rainfall events in the northeast Indian region. Journal of Geophysical Research Atmospheres 115(D12): D12114. https://doi.org/10.1029/2009JD012275.

Hamed KH and Rao AR (1998) A modified Mann-Kendall trend test for autocorrelated data. Journal of Hydrology 204(1–4):182–196. https://doi.org/10.1016/S0022-1694(97)00125-X.

Hawkins CA and Webber JE (1980) Statistical Analysis: Applications to Business and Economics, Harper and Row, New York.

Hoover DL, Lauenroth WK, Milchunas DG, Porensky LM, Augustine DJ, Derner JD (2021) Sensitivity of productivity to precipitation amount and pattern varies by topographic position in a semiarid grassland. Ecosphere 12(2):e03376. https://doi.org/10.1002/ecs2.3376.

IPCC (2013) Climate Change 2013: The Physical Science Basis. In: Contribution of Working Group I to the 5th Assessment Report of Intergovernmental Panel on Climate Change (IPCC) Cambridge University Press, Cambridge, UK.

Jain SK, Kumar V, Saharia M (2013) Analysis of rainfall and temperature trends in northeast India. International Journal of Climatology 33:968-978. https://doi.org/10.1002/joc.3483.

Jayawardene H, Jayawarden D, Sonnadara D (2015) Interannual variability of precipitation in Sri Lanka. Journal of the National Science Foundation of Sri Lanka 43(1):75-82. https://doi.org/10.4038/jnsfsr.v43i1.7917.

Jerath N, Singh LS, Kaur S, Sharma V, Saile P, Tripathi P, Bhattacharya S, Parwana HK (2014) Punjab State Action Plan on Climate Change. Punjab State Council for Science and Technology and GIZ (Deutsche Gesellschaft for Internationale Zusarnmenarbeit GmbH - German International Cooperation, India), pp 329. https://moef.gov.in/wp-content/uploads/2017/09/Punjab.pdf.

Jiang T, Su B, Hartmann H (2007) Temporal and spatial trends of precipitation and river flow in the Yangtze River Basin, 1961–2000. Geomorphology 85(3-4):143-154. https://doi.org/10.1016/j.geomorph.2006.03.015.

Karabörk MÇ, Kahya E, Kömüşçü AÜ (2007) Analysis of Turkish precipitation data: homogeneity and the Southern Oscillation forcings on frequency distributions. Hydrological Processes 21(23):3203–3210. https://doi.org/10.1002/hyp.6524.

Kendall MG (1975) Rank Correlation Methods. 4th edition, Charles Griffin, London, UK.

Kingra PK, Mahi GS, Hundal SS (2004) Climatic water balance for different agroclimatic zones for contingent crop planning in Punjab. Journal of Agrometeorology 6:66-71.

Kumar A, Giri RK, Taloor AK, Singh AK (2021) Rainfall trend, variability and changes over the state of Punjab, India 1981–2020: A geospatial approach. Remote Sensing Applications: Society and Environment 23:100595. https://doi.org/10.1016/j.rsase.2021.100595.

Kumar DB, Surya TM, Phani K, Reddy SG, Kalyani G, Jogarao H, Prasanna KY (2012) Effect of Climatic Change on Indian Water Resources. International Conference on Control of Industrial Gaseous Emission (CIGE – 2012), Feb. 9-10, 2012.

Kumar V, Jain SK, Singh Y (2010) Analysis of long-term rainfall trends in India. Hydrological Sciences Journal 55(4):484–496. https://doi.org/10.1080/02626667.2010.481373.

Liu Q, Yang Z, Cui B (2008) Spatial and temporal variability of annual precipitation during 1961–2006 in Yellow River Basin, China. Journal of hydrology 361(3-4):330-338. https://doi.org/10.1016/j.jhydrol.2008.08.002.

Mahdi SS, Dhekale BS, Jan R, Bhat MA, Hussain A, Jehangir IA, Sofi NR, Ahmed L, Asif M. Qureshi I, Aezum AM, Bangroo SA, Wani OA, Bahar FA, Mishra, SK (2022) Analysis and farmers' perception of climate change in the Kashmir Valley, India. Theoretical and Applied Climatology 149(1-2): 727-741. https://doi.org/10.1007/s00704-022-04072-x.

Mahdi SS, Jan R, Jehangir IA, Hussain A, Bhat MA, Dhekale B, Ahmed L, Sofi NR, Bangroo SA, Qureshi AMI, Wani OA, and Bahar FA (2021) Farmer's perception of climate change and adaptation strategies under temperate environmental conditions of Kashmir, India. Journal of Agrometeorology 23(4):442–451. https://doi.org/10.54386/jam.v23i4.161.

Mann HB (1945) Non-parametric tests against trend. Econometrica 13:245–259. https://www.jstor.org/stable/1907187.

Martina Isabella M, Ambujam NK, Santhana Krishnan PT (2020) Trend analysis of stream flow and its relation to rainfall in the lower Tamiraparani sub-basin of Tamilnadu, India. Applied Ecology and Environmental Research 18(1):863-878. http://dx.doi.org/10.15666/aeer/1801_863878.

Neil MN and Notodiputro KA (2016) Trend and pattern classification of surface air temperature change in the Arctic region. Atmospheric Science Letters 17:378–383. https://doi.org/10.1002/asl.668.

Oguntunde PG, Abiodun BJ, Olukunle OJ, Olufayo AA (2012) Trends and variability in pan evaporation and other climatic variables at Ibadan, Nigeria, 1973–2008. Meteorological Applications, 19(4):464-472.

Pai DS, Sridhar L, Rajeevan M, Sreejith OP, Satbhai NS, Mukhopadhyay B (2014) Development of a new high spatial resolution (0.25× 0.25) long period (1901–2010) daily gridded rainfall data set over India and its comparison with existing data sets over the region. Mausam 65(1):1–8.

Pal AB, Khare D, Mishra PK, et al. (2017) Trend analysis of rainfall, temperature and runoff data: a case study of Rangoon watershed in Nepal. International Journal of Students' Research in Technology and Management 5(3):21–38. https://doi.org/10.18510/ijsrtm.2017.535.

Patakamuri SK, Muthiah K, Sridhar V (2020) Long-term homogeneity, trend, and change-point analysis of rainfall in the arid district of Ananthapuramu, Andhra Pradesh State, India. Water 12:211. https://doi.org/10.3390/w12010211.

Pathak H, Aggarwal PK, Singh SD (2012) Climate Change Impact, Adaptation and Mitigation in Agriculture: Methodology for Assessment and Applications. Indian Agricultural Research Institute, New Delhi.

Rajeevan M, Gadgil S, Bhate J (2010) Active and break spells of the Indian summer monsoon. Journal of Earth System Science 119:229–247. https://doi.org/10.1007/s12040-010-0019-4.

Rao AR, Hamed KH, Chen HL (2003) Nonstationarities in hydrologic and environmental time series (Vol. 45). Springer Science & Business Media. https://doi.org/10.1007/978-94-010-0117-5.

Sahu N, Robertson A, Boer R, Behera S, DeWitt DG, Kaoru T, Kumar M, Singh R B (2016) Probabilistic seasonal streamflow forecasts of the Citarum River, Indonesia, based on general circulation models. Stochastic Environmental Research Risk Assessment 31:1747–1758. https://doi.org/10.1007/s00477-016-1297-4.

Sen PK (1968) Estimates of the Regression Coefficient Based on Kendall's Tau. Journal of the American Statistical Association, 63:1379-1389.

https://doi.org/10.1080/01621459.1968.10480934.

Singh H, Mishra SK, Singh K, Singh K, Pal RK, Gill KK and Kingra PK (2021) Simulating the impact of climate change on sugarcane production in Punjab. Journal of Agrometeorology 23 (3):292-298.

Singh K, Mishra SK, Singh M, Singh K and Brar AS (2022) Water footprint assessment of surface and subsurface drip fertigated cotton-wheat cropping system – A case study under semi-arid environments of Indian Punjab. Journal of Cleaner Production 365:132735. https://doi.org/10.1016/j.jclepro.2022.132735.

Singh N, Malhotra P and Singh J (2016) Information needs and seeking behaviour of dairy farmers of Punjab. Indian Journal of Dairy Science 69(1):98-105.

Srinivasan V, Raman S, Mukherjee S (1972) Southwest monsoon - typical situations over West Bengal and Assam and adjacent states. IMD FMU Report number III 3.6:1-148.

Szabó S, Elemér L, Kovács Z, Püspöki Z, Kertész A, Singh SK, Balázs B (2019) NDVI dynamics as reflected in climatic variables: spatial and temporal trends – a case study of Hungary. GIScience and Remote Sensing 56(4):624–644. https://doi.org/10.1080/15481603.2018.1560686.

Xu Z, Liu Z, Fu G, Chen Y (2010) Trends of major hydro climatic variables in the Tarim River basin during the past 50 years. Journal of Arid Environments 74(2):256–267. https://doi.org/10.1016/j.jaridenv.2009.08.014.

Yadav R, Tripathi SK, Pranuthi G, Dubey SK (2014) Trend analysis by Mann-Kendall test for precipitation and temperature for thirteen districts of Uttarakhand. Journal of Agrometeorology 16(2):164-171. https://doi.org/10.54386/jam.v16i2.1507.

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Competing interest
The authors declare no competing interests.

Ethics approval

This study did not involve human participants or animals. Therefore, ethical approval was not required. No human subjects were involved or harmed during this research. The work presented in this manuscript is original and has not been submitted to or published in any other journal. All results are presented without fabrication, falsification, or inappropriate data manipulation, and no copyrighted material has been used without proper acknowledgment.

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