



Long-term Spatio-temporal Variation of Meteorological Drought in Northwest India

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Abstract: This study focuses on the spatial and temporal patterns of meteorological drought by analyzing the monthly distribution of rainfall and temperature across Punjab and Haryana in Northwest India. The rainfall and temperature analysis was done from 1966 to 2017. The trend change was assessed using the Mann-Kendall test. Standardized potential evapotranspiration index (SPEI) was used to estimate the wetness and dryness for different months and seasons, with special reference to rice (SPEI-5 June-October) and wheat (SPEI-5 November-March) growing seasons during the study period. The analysis shows that Punjab has a significant increasing trend of meteorological drought. It was reported in the Gurdaspur (SPEI-5 October) and the South-western districts of Ferozepur and Bathinda (SPEI-5 March). In Haryana, significant increasing trends of meteorological drought were observed in Ambala, Gurgaon, Karnal, and Rohtak during (SPEI-5 October) and, Hisar and Rohtak in (SPEI-5 March). A comprehensive understanding of precipitation and temperature variability, trends, and change points is of unprecedented interest to a researcher because it is required for developing better contingency plans to mitigate the effects of climate change and increase future resilience.

Keywords: SPEI, Mann-Kendall, Temperature, Rainfall, Spatial, Temporal

Climate change increases the magnitude and frequency of rainfall extremes, posing a greater risk of drought and flooding (Chen et al 2014). It is a continuous process that has occurred in the past, is happening now, and will continue in the future. As observed in other parts of the country, the climate in northwestern India has changed dramatically. Spatial and temporal changes in the weather variables affect the climate and the hydrological cycle, with agronomic and environmental consequences (Kang and Banga 2013, Jalota et al 2013). Punjab and Haryana, located in Northwest India, experience a semi-arid and tropical climate. Punjab is divided into five agro-climatic zones; the sub-mountain undulating region, undulating plain region, central plain region, western plain region, and the western region whereas Haryana has two agro-climatic zones; the southwestern zone and the north-eastern zone. The complex topography of this region leads to significant spatial and temporal variations in rainfall. These states experience monsoon-dominated rainfall, with Punjab receiving 200-1000 mm annually and Haryana receiving 300-1000 mm, depending on location. Both states also receive some rainfall from western disturbances throughout the year. In Punjab, the rainy season lasts from June to September, with rainfall ranging from 200 to 1000 mm. In Haryana, annual rainfall ranges from 300 mm in the southwest to 1000 mm in the Shivalik hills region. Around 75% of the rainfall occurs during the monsoon, with the remaining 25% spread throughout the year.

Droughts are severe and frequent in India's northwestern region, which is arid and semiarid. Meteorological drought occurs once every three years in all districts in Punjab where it occurs once every four years, and droughts have taken place once every three years in nearly half of Haryana's districts, with the remaining experiencing droughts once every four years. As a result, the high and low rainfall anomalies can cause economic and humanitarian crises (World Bank 2006). Understanding the spatial and temporal variability of rainfall and temperature, therefore, becomes critical for predicting and mitigating the impact of droughts. This study seeks to assess the long-term spatial and temporal changes in meteorological droughts across Northwest India, with a focus on the states of Punjab and Haryana. By analyzing historical trends in rainfall and temperature using gridded data and robust statistical methods, the study seeks to provide insights into regional climate dynamics and support the development of effective strategies for drought mitigation and climate resilience.

MATERIAL AND METHODS

Study area: The study is conducted in the Punjab and Haryana. The research is based on gridded precipitation and temperature data sourced from the India Meteorological Department, Pune (https://www.imdpune.gov.in/Clim_Pred_LRF_New/Gridded_Data_Download.html) at the district level for 52 years (1966-2017). Gridded rainfall and

temperature data sets have been used in numerous hydrological and climatological studies (Tozer et al 2012). Daily grid data of rainfall (0.25° x 0.25°) and maximum and minimum temperature (1°x1°) were extracted using the QGIS (3.22) python console. Since the gridded temperature data is 1°x1°, some districts do not have gridded data points. So, the study employed a commonly used interpolation technique, Inverse Distance Weighting (IDW) (Burroughs 1986, Schut 1976), which is based on the assumption that the variables at a projected point are similar to the values at adjacent observation points (ESRI 1992). Using ArcGIS 10.4, temperature (maximum and minimum) data were interpolated to 0.25°x 0.25° grids. The daily average of the gridded temperature and rainfall data was calculated for each district, which was then aggregated monthly.

Analytical Framework

Standardized precipitation and evapotranspiration index (SPEI): The SPEI is a drought index based on the climatic water balance (CWB) approach, which combines precipitation and potential evapotranspiration (PET) (Serrano 2010) as input values, wherein CWB is defined as follows;

$$CWB_i = R_i - PET_i$$

R denotes rainfall and i denotes the monthly counter, which delivers a monthly water excess or shortage measure. The use of PET methods significantly impacts the calculation of the drought index. The SPEI index was computed using the Hargreaves method (Beguria et al 2013). The SPEI effectively identified significant historical droughts and is regarded as a reliable index for detecting drought events (Table 1). The negative SPEI value signifies a drought period, while a positive value represents a period of increased precipitation.

Spatial-temporal trend analysis: Hydro-meteorological data is typically non-parametric statistical tools. Therefore, the Mann-Kendall test and Sen's slope method were applied to assess the direction and magnitude of trends (Kendall 1975, Sen 1968 and Mann 1945).

Total drought duration frequency: To analyze drought sensitivity, drought frequency was identified for all drought

events with SPEI less than zero over the entire study period Ni (Wang et al 2014).

$$Drought\ frequency = \frac{n_i}{N_i} \times 100$$

where n_i is the number of drought events and N_i is the total number of months in the time series (1966-2017). The frequency results for various drought classes were assessed with varying intensities based on Table 1.

RESULTS AND DISCUSSION

Spatio-temporal pattern of rainfall: Rainfall in Punjab showed a high variation over the years with a decreasing trend in the last decade (Fig. 1). Hoshiarpur (1017.22 mm) and Gurdaspur (957.86 mm) recorded the highest average annual rainfall between 1966 and 2017, while Ferozepur (371.52 mm) and Bathinda received the least (395.23 mm) respectively. The average monthly rainfall follows a similar pattern throughout the year. Hoshiarpur shows the highest monthly average rainfall in July and August, followed by Gurdaspur in July and August, and Rupnagar had higher rainfall in June and October. The monthly average rainfall in Ferozepur and Bathinda was lowest in November, July and August received the most rainfall, while November and October received the least in Punjab. There has been no consistent rainfall over the last five decades. Kingra et al (2017) found a similar result.

Table 1. Classification of drought by SPEI values

SPEI	Interpretation
≥ 1.00	Severe wet
0.5 to 1.0	Moderately wet
0 to 0.5	Near normal
-0.5 to 0	Light drought
-1.00 to -0.5	Moderate drought
< -1.0	Severe drought

Source: Serrano et al 2010

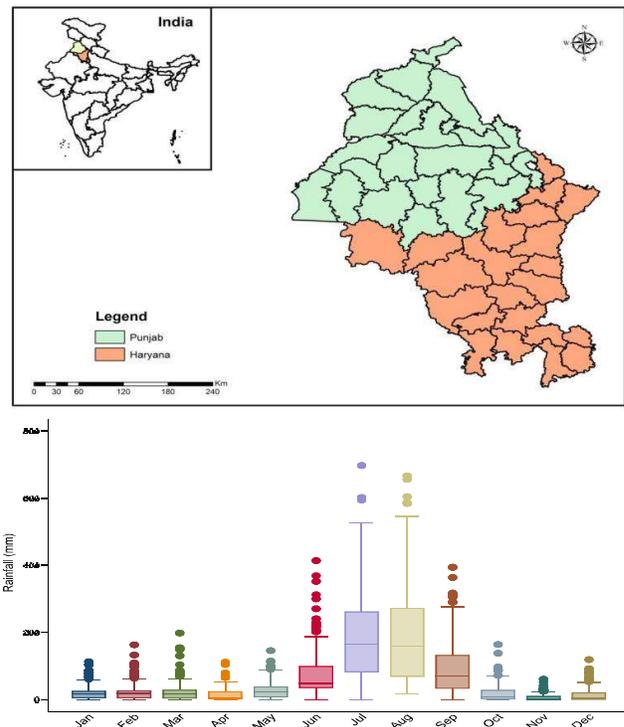


Fig. 1. Box plot of monthly rainfall in Punjab

During the growing period of rice (June-October), Hoshiarpur received the most rainfall (805.03 mm), followed by Gurdaspur, while Ferozepur Bathinda received the least rain. During this season, the state received 555.56 mm of rain. Ferozepur district exhibited a declining trend in annual rainfall, with a similar pattern observed in Gurdaspur for June-October rainfall. Significant monthly decreases in rainfall were also recorded in July for four districts in Punjab (Bathinda, Ferozepur, Gurdaspur and Sangrur) and in August for three districts (Amritsar, Bathinda and Ferozepur). The highest significant increasing trend was observed during April, where seven districts namely Amritsar, Bathinda, Hoshiarpur, Jalandhar, Kapurthala, Ludhiana, and Patiala show an increasing trend. Saxena and Mathur (2017) observed a non-significant decrease in monsoon rainfall and an increase in post-monsoon rainfall in North West India. This trend raises concerns for Kharif and rainfed Rabi crops that depend on stored soil moisture. A similar finding was observed by Chauhan et al (2022).

During the growing period of wheat (November-March), Gurdaspur received the most rainfall (170.02 mm), followed by Hoshiarpur. The district of Ferozepur received the least rainfall (48.2 mm), followed by Bathinda and the state received rainfall of (102.11 mm). No significant trends were observed for rainfall in all months except April, July and August. The monthly, seasonal, and annual precipitation patterns analysis revealed that significant changes were largely concentrated in Amritsar, Bathinda, Ferozepur, and Gurdaspur districts. Kumar and Sidana (2019) reported a decline in rainfall across all agroclimatic zones of Punjab. Their study highlighted that between 1986 and 2016, rainfall during the rice-growing season decreased by 208 mm, indicating a substantial reduction of 6.92% annually. In contrast, rainfall during the wheat-growing season saw a smaller, non-significant decline of 20 mm or 0.68% per year. Krishan et al (2015) observed an overall increase in annual and growing season rainfall across all districts, except during the winter season in Hoshiarpur, Kapurthala, Amritsar, Gurdaspur, Jalandhar, Ludhiana, Rupnagar, and Patiala. However, the extent of these trends varied from district to district. Consistent results show that in Bathinda, both the annual and monsoon rainfall have exhibited a decreasing trend, whereas, in Ludhiana, the yearly and monsoon rainfall have shown an increasing trend (Gill and Kukal 2017). Rainfall in Haryana also showed a similar trend of high variation over the years with a decreasing trend in the last decade (Fig. 2). Results revealed that the average annual rainfall received in the districts of Ambala (1146.9 mm) and Karnal (672.31 mm) was the highest, while Hisar (387.68 mm) and Mahendragarh received the least (536.69 mm).

Ambala had the highest monthly average rainfall in August and July, followed by Karnal in August and July. Mahendragarh received higher rainfall after Ambala in May. The monthly average rainfall in Mahendragarh and Hisar was lowest in November. August and July received the most rainfall, while November and December received the least in Haryana.

During the growing period of rice (June-October), Ambala received the most rainfall (953.39 mm), followed by Karnal (563.82 mm), while Hisar (319.11 mm) and Jind (411.98 mm) received the least rain. During this season, the state received 520.2 mm of rain. Furthermore, the study revealed that during the wheat growing period (November- March), Ambala received the most rainfall, followed by Jind while, the district of Gurgaon received the least rainfall, followed by Mahendragarh, and the state received rainfall of 63.75 mm. Abhilash et al (2020) also found that all locations have shown a general decreasing trend in rainfall behavior in recent times, with the variability of rainfall being greater in western Haryana than in eastern Haryana.

Trend of changes in temperature: The temperature (maximum, minimum, and average) trend of June-October and November-March in both states showed a similar trend. Significant monthly decreasing trends in maximum temperature were observed in all the districts of Punjab except Amritsar and Gurdaspur in January. No significant trend was detected in other months and seasons except in January. Singh et al (2022) also reported no significant trend in maximum temperature. The average minimum temperatures during the monthly and crop-growing seasons exhibited an upward trend across all districts of Punjab in January, February, March, July, August, September, October, November, and December. Significant increasing trends in monthly average minimum temperature were also observed in two districts (Bathinda and Ferozepur) in April and eight districts (Bathinda, Ferozepur, Hoshiarpur, Jalandhar, Ludhiana, Patiala, Rupnagar, and Sangrur) in May. No significant trend was detected in June in all the districts.

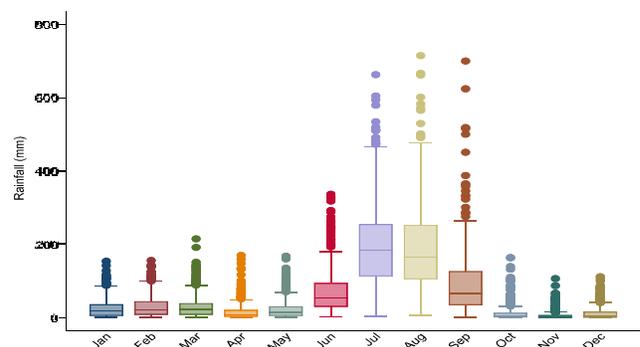


Fig. 2. Box plot of monthly rainfall in Haryana

Singh (2018) also reported that a decade-wise analysis using the Mann-Kendall test and Sen's slope estimator revealed a significant increase in all regions, with the rate of increase in the three regions of the state being approximately 0.05°C per year. The study observed that the minimum temperature during June–October and November–March in both states showed an increasing trend over the years.

In January, the average monthly maximum temperature showed a significant decreasing trend across all districts of Haryana. Conversely, a significant increasing trend was observed in five districts (Ambala, Gurgaon, Karnal, Mahendragarh, and Rohtak) during August. No significant trends were identified for the other months and growing seasons, except for January and August. Meanwhile, the average minimum temperatures in both monthly and crop-growing seasons showed an increasing trend in all districts of Haryana for February, March, May, August, September, November, and December. Significant increasing trends in monthly average minimum temperature were also observed in January in all the districts except Mahendragarh. Furthermore, the Mahendragarh district showed no significant trend in April, July, and October while other districts showed an increasingly significant trend. However, Mahendragarh is the only district exhibiting a significant

increasing trend in June, while no significant trends were found in the other districts. Umer et al (2014) observed that there has been an increase in the variation of maximum and minimum temperatures, along with a decrease in the number of rainy days, which has impacted wheat production in Haryana. Shalo et al (2016) also found a consistent result in the case of trend analysis of average minimum temperature showing a significant increasing trend with a 95% confidence level between 1969 and 2010 in Rohtak.

M-K test and Sen's slope of district-wise drought : Timescales usually vary from 1-48 months. Longer timescales (from 12 to 48 months) reflect the drought index for hydrology, whereas shorter timescales (from 1 to 6 months) indicate the drought index for agricultural practices. SPEI was calculated at 1, 5, and 12 months to examine the consistency of moisture conditions across all districts. The region's growing season for rice is SPEI-5 October, while that of wheat is SPEI-5 March. Additionally, a time scale of 1 month (SPEI 1) was estimated to correlate the drought with the crop's critical water requirement stage. December 12 months' (SPEI 12) timescale was also estimated to track drought at a year (Table 2).

Punjab experienced the most severe drought in 1987, 2002, and 2016. The monthly SPEI-1 (Table 2) shows a

Table 2. M-K test and Sen's slope of district-wise drought (SPEI) of Punjab

District	Test	SPEI-1			SPEI-5			SPEI-1			SPEI-5	SPEI-12		
		June	July	August	September	October	October	November	December	January	February	March	March	December
Amritsar	Z	1.15	-0.84	-1.88*	0.52	-1.05	-0.52	-2.30**	-1.05	0.73	0.42	-1.05	-0.52	-1.47
	Slope	0.01	-0.01	-0.01	0.01	-0.01	0.00	-0.02	-0.01	0.01	0.00	-0.01	-0.01	-0.01
Bathinda	Z	1.05	-2.09**	-1.99**	0.52	-3.14***	-1.47	-3.14***	-1.15	1.05	-1.05	-1.36	-1.78*	-2.41**
	Slope	0.01	-0.02	-0.02	0.00	-0.03	-0.01	-0.03	0.00	0.01	-0.01	-0.01	-0.02	-0.02
Ferozepur	Z	0.84	-2.09**	-1.99**	0.00	-1.99**	-1.67*	-3.14***	-1.05	0.52	-0.11	-1.36	-1.99**	-2.51**
	Slope	0.01	-0.02	-0.02	0.00	-0.02	-0.02	-0.03	-0.01	0.01	-0.01	-0.01	-0.02	-0.03
Gurdaspur	Z	-0.31	-2.19**	-1.15	0.31	-0.73	-1.88*	-2.62***	-0.73	0.00	0.31	-1.05	-1.05	-1.67*
	Slope	0.00	-0.02	-0.01	0.00	-0.01	-0.02	-0.02	-0.01	0.00	0.01	-0.01	-0.01	-0.02
Hoshiarpur	Z	0.31	-1.36	-1.05	-0.11	-0.94	-1.26	-2.83***	-0.52	-0.21	0.11	-0.42	-1.05	-1.36
	Slope	0.00	-0.01	-0.01	0.00	-0.01	-0.01	0.00	0.00	0.00	0.00	-0.01	-0.01	-0.01
Jalandhar	Z	0.73	-0.21	-1.05	1.05	-0.94	0.00	-3.14***	-0.52	1.05	0.00	-0.84	-0.84	-0.52
	Slope	0.01	0.00	0.00	0.01	-0.01	0.00	-0.03	0.00	0.01	0.00	0.00	-0.01	-0.01
Kapurthala	Z	1.05	0.31	-0.52	1.05	-0.63	0.42	-3.14***	-0.52	0.84	0.42	-0.73	-0.31	0.21
	Slope	0.01	0.00	0.00	0.01	-0.01	0.01	-0.03	0.00	0.01	0.01	0.00	0.00	0.00
Ludhiana	Z	0.31	-0.21	-0.73	-0.73	-1.05	-0.31	-3.14***	-0.73	0.73	-0.31	-0.73	-1.05	-0.52
	Slope	0.01	0.00	-0.01	-0.01	-0.01	0.00	-0.03	0.00	0.01	0.00	-0.01	-0.01	-0.01
Patiala	Z	0.84	-1.05	-0.84	1.05	-1.47	-0.31	-2.93***	-1.05	0.84	-0.11	-0.42	-0.73	-0.73
	Slope	0.01	-0.01	-0.01	0.01	-0.01	0.00	-0.02	0.00	0.01	0.00	0.00	-0.01	-0.01
Rupnagar	Z	0.52	0.52	-0.63	1.05	-0.31	0.11	-3.14***	-0.21	0.73	0.52	-0.52	-0.42	-0.11
	Slope	0.00	0.01	0.00	0.01	0.00	0.00	-0.02	0.00	0.01	0.00	0.00	0.00	-0.01
Sangrur	Z	0.84	-1.78*	-1.67*	0.84	-1.78*	-1.15	-3.45***	-0.31	0.84	-0.31	-1.05	-1.57	-1.78*
	Slope	0.01	-0.02	-0.02	0.01	-0.01	-0.01	-0.03	0.00	0.01	0.00	-0.01	-0.02	-0.01

***, ** and * indicate significance at the 1%, 5% and 10%, respectively

significant decreasing trend in the districts of Amritsar (August), Bathinda (July, August, and October), Ferozepur (July and August), Gurdaspur (July), Sangrur (July and August), and November showed a decreasing trend in all the districts of Punjab. SPEI-5 October also showed a significantly decreasing trend in the Gurdaspur district, while the rest of the districts showed no significant trend. Moreover, Bathinda and Ferozepur are the only districts that showed a significantly decreasing trend for SPEI-5 March. SPEI-12 values dropped in Patiala, Gurdaspur, and Ludhiana in Punjab.

The decreasing trend was observed in SPEI-1 in all the districts of Haryana (Table 3). Ambala (October), Gurgaon (August and October), Hisar (July and October), Jind (July), Karnal (July, August, and October), Mahendragarh (August and October) and Rohtak (July, August, and October), and all the districts in November showed a decreasing trend. SPEI-5 October shows a significant decreasing trend in Ambala,

Gurgaon, Karnal, and Rohtak, and SPEI-5 March in Hisar and Rohtak. Haryana also experienced the most severe droughts in 1987, 2002, and 2016 with SPEI-12 December values dropped in Gurgaon, Jind, and Rohtak in 1987, in Gurgaon, Hisar, and Mahendragarh in 2002, and Karnal in 2016. Gupta et al (2022) reported that drought has recently intensified in several regions of the northern Indian plains, raising worries about its effects on agricultural productivity, particularly crop yields.

Spatial pattern of frequency and severity of drought: SPEI-5 October drought occurrence showed a frequency of about 28-38% of moderate and severe drought combined in Punjab (Table 4). Ferozepur experienced the highest frequency of severe drought, accounting for 21.15%, and SPEI-5 October had a frequency of about 32-38% of moderate and severe drought combined. SPEI-5 March drought occurrence showed a frequency of about 26-36% of moderate and severe drought combined (Table 6). Ludhiana

Table 3. M-K test and Sen's slope of district-wise drought (SPEI) of Haryana

District	Test	SPEI-1				SPEI-5				SPEI-1			SPEI-5	SPEI-12
		June	July	August	September	October	October	November	December	January	February	March	March	December
Ambala	Z	-1.26	-0.84	-1.47	0.73	-1.99***	-1.88*	-2.93***	-1.36	0.31	-0.11	-0.42	-1.15	-2.09**
	Slope	-0.01	-0.01	-0.01	0.01	-0.02	-0.02	-0.03	-0.01	0.00	0.00	0.00	-0.01	-0.02
Gurgaon	Z	0.11	-1.05	-2.09**	0.21	-2.19**	-2.09**	-2.30**	-1.88*	0.63	-0.11	-1.05	-1.57	-2.72***
	Slope	0.00	-0.01	-0.02	0.00	-0.02	-0.02	-0.02	-0.01	0.01	0.00	-0.01	-0.01	-0.02
Hisar	Z	0.63	-1.78*	-1.57	0.42	-2.83***	-1.26	-2.93***	-1.57	0.31	-0.63	-0.94	-2.09**	-2.09**
	Slope	0.01	-0.02	-0.02	0.00	-0.02	-0.01	-0.03	-0.01	0.00	-0.01	-0.01	-0.02	-0.02
Jind	Z	0.52	-1.67*	-1.36	0.63	-1.47	-0.94	-2.72***	-1.47	1.15	0.11	-1.05	-1.26	-1.47
	Slope	0.01	-0.02	-0.02	0.01	-0.01	-0.01	-0.02	-0.01	0.01	0.00	-0.01	-0.01	-0.01
Karnal	Z	0.42	-2.51**	-2.62**	0.63	-1.88*	-2.93***	-2.93***	-2.09*	0.84	-0.11	-0.84	-1.05	-3.14***
	Slope	0.01	-0.02	-0.02	0.01	-0.02	-0.03	-0.02	-0.01	0.01	0.00	-0.01	-0.01	-0.03
Mahendra garh	Z	0.63	-1.67	-1.88*	-0.11	-2.30**	-1.36	-2.19**	-1.57	-0.11	0.63	-0.84	-0.84	-1.88*
	Slope	0.01	-0.02	-0.02	0.00	-0.02	-0.01	-0.02	-0.01	0.00	0.01	-0.01	-0.01	-0.02
Rohtak	Z	0.11	-2.30**	-2.51**	0.00	-2.41**	-2.83***	-2.62***	-1.78*	-0.11	-0.21	-1.05	-1.78*	-3.14***
	Slope	0.00	-0.02	-0.03	0.00	-0.02	-0.03	-0.02	-0.01	0.00	0.00	-0.01	-0.02	-0.03

***, ** and * indicate significance at the 1%, 5% and 10%, respectively

Table 4. Drought frequency of SPEI-5 October in Punjab

SPEI value	Interpretation	Amritsar	Bathinda	Ferozepur	Gurdaspur	Hoshiarpur	Jalandhar	Kapurthala	Ludhiana	Patiala	Rupnagar	Sangrur
1.0+	Severe wet	19.23	17.31	23.08	13.46	15.38	15.38	17.31	7.69	11.54	19.23	17.31
0.5 to 1.0	Moderately wet	15.38	13.46	15.38	23.08	19.23	15.38	13.46	26.92	15.38	11.54	15.38
0 to 0.5	Near normal	15.38	21.15	11.54	17.31	15.38	21.15	21.15	19.23	23.08	19.23	21.15
-0.5 to 0	Light drought	13.46	19.23	13.46	7.69	15.38	19.23	17.31	15.38	19.23	13.46	7.69
-1.0 to -0.5	Moderate drought	21.15	11.54	15.38	19.23	17.31	9.62	15.38	15.38	15.38	19.23	26.92
< -1.0	Severe drought	15.38	17.31	21.15	19.23	17.31	19.23	15.38	15.38	15.38	17.31	11.54

Table 5. Drought frequency of SPEI-5 October of Haryana

SPEI value	Interpretation	Ambala	Gurgaon	Hissar	Jind	Karnal	Mahendragarh	Rohtak
1.0+	Severe wet	19.23	15.38	17.31	13.46	11.54	15.38	21.15
0.5 to 1.0	Moderately wet	11.54	17.31	17.31	17.31	26.92	13.46	9.62
0 to 0.5	Near normal	23.08	17.31	11.54	21.15	13.46	23.08	17.31
-0.5 to 0	Light drought	9.62	15.38	21.15	15.38	9.62	13.46	21.15
-1.0 to -0.5	Moderate drought	21.15	21.15	17.31	19.23	23.08	17.31	17.31
< -1.0	Severe drought	15.38	13.46	15.38	13.46	15.38	17.31	13.46

Table 6. Drought frequency timescale SPEI-5 March of Punjab

SPEI value	Interpretation	Amritsar	Bathinda	Ferozepur	Gurdaspur	Hoshiarpur	Jalandhar	Kapurthala	Ludhiana	Patiala	Rupnagar	Sangrur
1.0+	Severe wet	19.23	21.15	17.31	19.23	25	23.08	23.08	15.38	17.31	15.38	19.23
0.5 to 1.0	Moderately wet	15.38	11.54	17.31	17.31	7.69	5.77	5.77	13.46	13.46	9.62	11.54
0 to 0.5	Near normal	15.38	17.31	15.38	9.62	15.38	15.38	17.31	25	17.31	28.85	15.38
-0.5 to 0	Light drought	13.46	23.08	15.38	19.23	19.23	25	21.15	15.38	19.23	19.23	21.15
-1.0 to -0.5	Moderate drought	21.15	11.54	17.31	19.23	11.54	13.46	17.31	7.69	19.23	5.77	17.31
< -1.0	Severe drought	15.38	15.38	17.31	15.38	21.15	17.31	15.38	23.08	13.46	21.15	15.38

Table 7. Drought frequency of SPEI-5 March of Haryana

SPEI value	Interpretation	Ambala	Gurgaon	Hissar	Jind	Karnal	Mahendragarh	Rohtak
1.0+	Severe wet	23.08	17.31	19.23	19.23	19.23	17.31	15.38
0.5 to 1.0	Moderately wet	7.69	11.54	15.38	11.54	13.46	19.23	17.31
0 to 0.5	Near Normal	17.31	23.08	13.46	15.38	13.46	9.62	17.31
-0.5 to 0	Light drought	15.38	19.23	23.08	25	21.15	25	21.15
-1.0 to -0.5	Moderate drought	21.15	15.38	13.46	13.46	15.38	9.62	11.54
< -1.0	Severe drought	15.38	13.46	15.38	15.38	17.31	19.23	17.31

recorded the highest frequency of severe drought, at approximately 23%. SPEI-5 March showed a frequency of about 28-36% of moderate to severe drought combined. While in Haryana, extreme dryness was observed in Mahendragarh district with 5.77% (Table 5) and SPEI-5 October a frequency of about 32-38% of moderate and severe drought combined. SPEI-5 March showed a frequency of about 28-36% of moderate to severe drought combined (Table 7).

CONCLUSIONS

The study provides a comprehensive assessment of drought characteristics using standardized drought indices, employing the SPEI across various monthly timescales in Punjab and Haryana. Significant monthly decreasing trends of rainfall were observed in four districts of Punjab (Bathinda, Ferozepur, Gurdaspur, and Sangrur) in July, and three districts (Amritsar, Bathinda, and Ferozepur) in August. Significant monthly decreasing rainfall trends were also observed in five districts of Haryana (Gurgaon, Jind, Karnal,

Mahendragarh, and Rohtak) in July, three districts (Gurgaon, Mahendragarh, and Rohtak) in August. The study observed that the minimum temperature during June-October and November-March in both states showed an increasing trend over the years. The highest frequency of severe drought was observed in Ludhiana and Mahendragarh. This research provides valuable insights for agricultural researchers, policymakers, and planners to create various irrigation and water management strategies suited to various climate change scenarios in the region. Policymakers must make efforts to adopt sustainable approaches that maximize the efficiency of water delivery and usage, such as rainwater harvesting, wastewater management, drip irrigation, and the use of recycled water.

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