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Research paper

Spatio-Temporal Variation and Seasonal Rainfall Trends Across Agro-Climatic Zones of Himachal Pradesh (1981–2024) and Their Implications for Maize and Wheat Yields

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ABSTRACT

Understanding long-term precipitation variability and its agricultural implications is essential for climate-sensitive mountain regions. This study investigates spatial and seasonal precipitation trends across the agro-climatic zones of Himachal Pradesh using long-term gridded rainfall data from the NASA POWER database (1981–2024). Monthly precipitation was aggregated into annual and seasonal series (winter, pre-monsoon, monsoon, and post-monsoon). Trends were detected using the Modified Mann–Kendall test and Sen's slope estimator, while spatial patterns were represented using Inverse Distance Weighting interpolation. The results indicate a consistent increasing trend of precipitation across the state, with monsoon rainfall contributing the largest share of the observed increase. The winter precipitation also showed rising trend in higher elevation regions influenced by Western Disturbances. To evaluate agricultural implications, maize (*kharif*) and wheat (*rabi*) yields were analysed in relation to seasonal rainfall using Pearson correlation. The results reveal that maize productivity is more responsive to monsoon rainfall, whereas wheat yield shows stronger dependence on winter precipitation. These findings highlight spatially differentiated climate sensitivity of crops and provide insights for climate-responsive agricultural planning in the western Himalayan region.

Keywords: Agro-climatic zone, Himachal Himalaya, Modified Mann Kendall (MMK), Trend Analysis, Inverse Distance Weighting (IDW), Pearson Correlation.

Himachal Pradesh, located in the northwestern Himalaya, exhibits strong spatial variability in precipitation due to its complex topography and large altitudinal range. Orographic effects and seasonal atmospheric circulation produce marked differences in rainfall across the region. Areas exposed to the southwest monsoon receive relatively high precipitation, whereas interior districts such as Lahaul–Spiti and parts of Kinnaur lie in the rain-shadow zone and receive comparatively low rainfall. Seasonal precipitation in the western Himalaya is mainly controlled by the southwest monsoon during June–September and by winter Western Disturbances that bring rainfall and snowfall to higher elevations Dimri *et al.,* (2015); Hunt *et al.,* (2018).

Recent studies report increasing precipitation trends in several parts of the western Himalaya, including the Gangotri and Lahaul–Spiti regions Bansal and Talukdar (2024); Kumar *et al.,* (2025). Such changes may influence hydrological processes and agricultural productivity in mountain environments. Agriculture in Himachal Pradesh is largely rain-fed, with maize grown during the monsoon (*kharif*) season and wheat during the winter (*rabi*) season, making crop production highly sensitive to seasonal rainfall variability Poudel *et al.,* (2016); Vaidya *et al.,* (2018); Batool *et al.,* (2019).

Despite increasing research on Himalayan climate variability, integrated assessments linking long-term precipitation trends with crop productivity across the agro-climatic zones of Himachal Pradesh remain limited. Therefore, this study analyses long-term precipitation variability using NASA POWER rainfall data (1981–2024) and evaluates its relationship with maize and wheat productivity across different agro-climatic zones. Rainfall trends were analysed using the Modified Mann–Kendall test and

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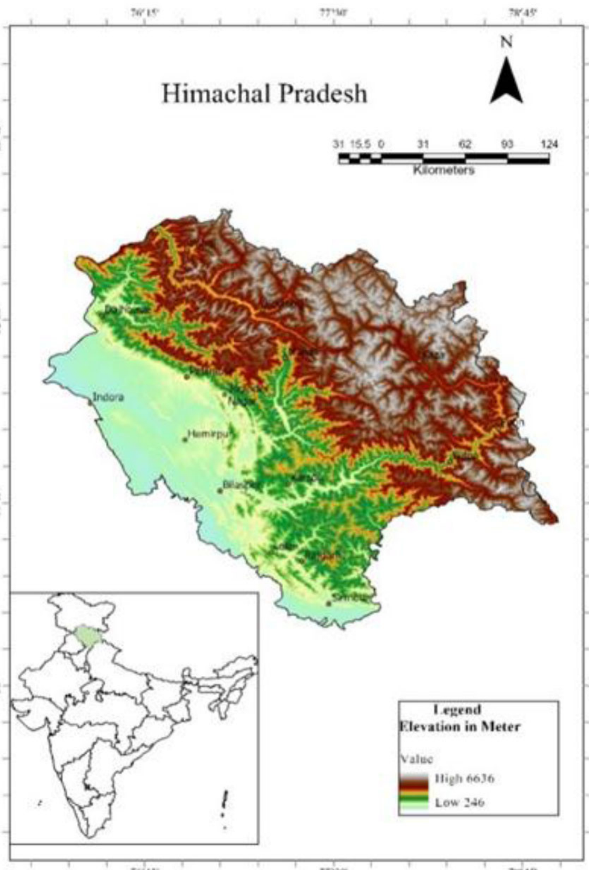

Fig. 1: Topography of the study area

Sen's slope estimator, spatial patterns were mapped through Inverse Distance Weighting interpolation, and rainfall–crop relationships were examined using Pearson correlation analysis.

STUDY AREA

Himachal Pradesh is located in the northwestern Himalayan region of India between 30°22′–33°12′ N latitude and 75°47′–79°04′ E longitude, covering an area of approximately 55,673 km². The state is characterized by complex mountainous terrain with elevations ranging from about 350 m in the Shivalik foothills to more than 6000 m in the Greater Himalaya, producing pronounced climatic and ecological gradients across the region.

Based on physiographic and climatic characteristics, the state is broadly divided into four agro-climatic zones: subtropical low hills (Zone I), mid-hill humid region (Zone II), high-hill temperate region (Zone III), and cold arid region of the trans-Himalaya (Zone IV). Precipitation exhibits strong spatial and seasonal variability, largely influenced by altitude, orographic effects, and atmospheric circulation systems.

Rainfall is primarily concentrated during the southwest monsoon months (June–September), which contribute the largest share of annual precipitation. Winter precipitation (January–February) occurs mainly due to Western Disturbances, while the pre-monsoon period (March–May) receives occasional convective rainfall and post-monsoon precipitation (October–December) remains relatively limited. This seasonal rainfall distribution plays an important role in shaping regional climate variability and agricultural practices.

Agriculture in the state is largely rain-fed, with maize cultivated during the monsoon (*kharif*) season and wheat during the winter (*rabi*) season, both highly dependent on seasonal rainfall availability. To analyse precipitation variability and its influence on crop productivity, rainfall data from sixteen representative stations distributed across the four agro-climatic zones were used in the present study (Fig. 1).

MATERIAL AND METHODOLOGY

Data collection and processing

This study uses long-term precipitation data derived from the NASA POWER (Prediction of Worldwide Energy Resources) database at a spatial resolution of 0.5° × 0.5°. Monthly rainfall records for 16 geographically representative stations across Himachal Pradesh were extracted for the 44-year period 1981–2024. These stations represent all four agro-climatic zones, enabling detailed spatial assessment of rainfall behaviour. Monthly rainfall totals were reorganised into four climatic seasons following Indian Meteorological Department classification: pre-monsoon (March–May), monsoon (June–September), post-monsoon (October–December), and winter (January–February). Annual rainfall was computed by summing all monthly values in each hydrological year.

Assessment of Serial Dependency

Lag-1 autocorrelation was calculated to examine serial dependence in the time series. Series showing significant autocorrelation at the 95% confidence level were analyzed using the Modified Mann–Kendall (MMK) test.

Modified Mann–Kendall Test (MMK)

The MMK procedure Hamed and Rao, (1998) was used to detect monotonic trends while accounting for autocorrelation. The test statistic is defined as:

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

where:

$$\operatorname{sign}\left(x_j - x_i\right) = \begin{cases} 1 & x_j - x_i > 0, \\ 0 & x_j - x_i = 0, \\ -1 & x_j - x_i < 0. \end{cases}$$

The variance of was adjusted to account for autocorrelation:

$$\operatorname{Var}^*(S) = \operatorname{Var}(S)[1 + \frac{2}{n(n-1)(n-2)} \sum_{i=1}^{n-1} (n-i)(n-i-1)(n-i-2)\rho_i]$$

where ρi is the autocorrelation at lag i.

The standardised statistic is then computed as:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\mathrm{Var}^*(S)}} & S > 0 \\ 0 & S = 0 \\ \frac{S+1}{\sqrt{\mathrm{Var}^*(S)}} & S < 0 \end{cases}$$

The positive or negative denotes an increasing or decreasing trend resprectively. Significance was evaluated at P = 0.001, 0.01, 0.05 and 0.10.

Sen's Slope Estimator

Trend magnitude is calculated using Sen's slope method Sen, (1968), which calculates the median of all pairwise slopes between data points.

$$Q = \mathrm{median}\{\frac{x_j - x_i}{j - i} \mid i < j\}$$

A positive slope indicates an increasing trend, while a negative slope indicates a decreasing trend.

Spatial Interpolation

To visualise spatial rainfall variation and trend magnitude, Inverse Distance Weighting (IDW) interpolation was conducted in ArcGIS 10.8. IDW assigns higher weight to values closer to the target location, making it well suited to mountainous regions where climatic conditions vary sharply across short distances.

Pearson correlation analysis

Crop yield data for maize (*Kharif*) and wheat (*Rabi*) for the period 1998–2022 were obtained from the Directorate of Economics and Statistics, Government of Himachal Pradesh. Pearson correlation analysis was used to examine the sensitivity of crop yields to seasonal rainfall, with monsoon rainfall correlated with maize yields and winter rainfall correlated with wheat yields.

RESULTS AND DISCUSSION

Annual rainfall distribution and trend pattern

Annual precipitation in Himachal Pradesh shows strong spatial variability (Fig. 1a) primarily controlled by altitude, orography and monsoonal circulation (Table 1). Mean annual rainfall ranges from 408 mm at Pooh (Zone IV) to 1228 mm at Sirmaur (Zone I), indicating a difference of more than 800 mm between the driest and wettest locations. This pattern reflects the pronounced rain-shadow effect in the trans-Himalayan region compared with the monsoon-exposed lower hills.

The coefficient of variation (CV) also highlights this contrast. Stations in the relatively wetter Zones I–III show moderate variability (29–35 %), whereas the high-altitude stations of Zone IV exhibit much higher variability, reaching 51 % at Keylong. Such variability suggests strong dependence on episodic synoptic systems, particularly Western Disturbances, which significantly influence precipitation in the inner Himalayan valleys (Dar, 2023; Kumar *et al.,* 2025).

Rainfall distribution across stations shows generally positive skewness, while several sites exhibit higher kurtosis values, indicating that annual totals are often influenced by occasional high-intensity rainfall or snowfall events rather than frequent moderate precipitation. This pattern is typical of monsoon-dominated mountain climates where extreme events contribute disproportionately to annual totals Bansal & Talukdar (2024).

Trend analysis using the Modified Mann–Kendall test indicates an overall increasing precipitation tendency across all stations during 1981–2024 (Table 1). Several stations display highly significant positive trends, while the remaining stations show

Table 1: Sen's slope estimate of seasonal and annual rainfall trend of different rainfall stations.

Station	Zone	Annual Q/Sig	Pre-monsoon Q/Sig	Monsoon Q/Sig	Post-monsoon Q/Sig	Winter Q/Sig
Bilaspur	1	16.21***	2.77**	9.78***	0.695*	1.39**
Hamirpur	1	14.44***	0.94ns	13.14***	0.400ns	0.94*
Sirmaur	1	12.91***	1.54*	10.19***	0.45**	0.653*
Indora	1	16.23**	0.39ns	13.98***	0.24ns	0.80ns
Palampur	2	20.75**	1.35ns	14.86***	0.45ns	1.32*
Solan	2	14.37***	1.94**	10.87***	0.53**	1.04*
Rajgarh	2	5.05**	1.99*	8.04**	0.62***	1.24*
Joginder nagar	2	10.3***	2.42**	4.96*	1.04/ns	1.63**
Dalhousie	3	20.52*	0.85ns	13.83***	0.65ns	1.65*
Manali	3	10.16***	2.44***	4.63ns	0.68*	1.44**
Karsog	3	10.3**	2.61**	5.21*	0.73***	1.31**
Keylong	4	17.49***	1.89ns	9.50***	0.71*	1.56**
Kaza	4	16.66**	2.17**	9.01***	0.82*	1.59***
Kalpa	4	20.26***	2.61**	12.57***	0.81*	1.70***
Pooh	4	4.35***	1.35**	1.08ns	0.50**	0.75**
Pangi	4	15.6*	0.91ns	8.80***	0.77ns	1.88**

Q: Sen's slope (mm/year), Sig = significance level: *** = 99.9%, ** = 95%, * = 90%, ns = not significant

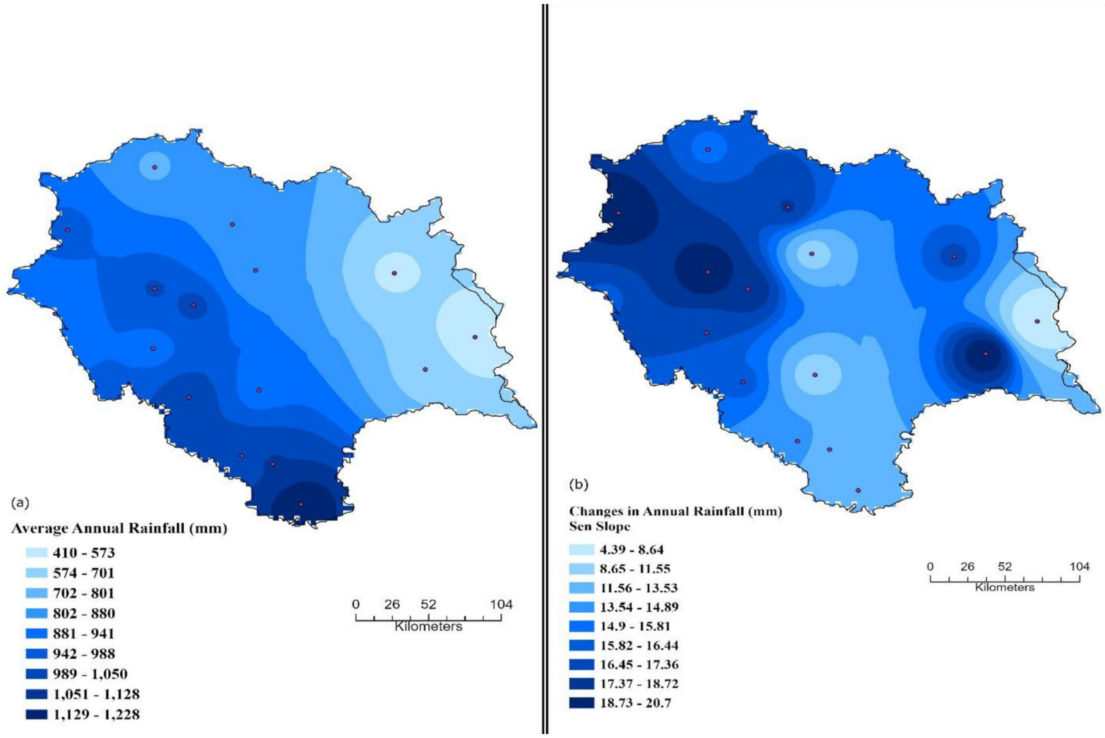

Fig. 2: (a) Annual Average rainfall (mm) (b) Annual rainfall trend Sen Slope (mm/yr)

positive trends at varying significance levels (Fig. 1b). Importantly, no station records a decreasing annual rainfall trend, suggesting a consistent wetting signal across Himachal Pradesh. The magnitude of change estimated by Sen's slope varies from 4.35 mm yr^{-1} at Pooh to 20.75 mm yr^{-1} at Palampur. Zone-averaged slopes are strongest in the low- and mid-hill zones (≈15–18 mm yr^{-1}) and slightly lower in the dry high-altitude Zone IV. These consistent positive trends across zones indicate a coherent regional climatic signal rather than localized variability.

Similar increasing precipitation tendencies have been reported in other Himalayan regions. Bansal & Talukdar (2024) documented rising precipitation in the Gangotri region, while Kumar *et al.,* (2025) observed increasing annual and winter precipitation in Lahaul–Spiti. Such increases are often attributed to enhanced atmospheric moisture availability and changes in regional monsoon circulation under warming conditions Hunt *et al.,* (2025).

While increased precipitation may improve water availability and groundwater recharge, it also raises the likelihood of floods, landslides, and soil erosion in steep Himalayan terrain. The July 2023 extreme rainfall events in Himachal Pradesh, where precipitation exceeded normal levels several times, illustrate the potential impacts of an intensifying hydro-climatic regime.

SEASONAL RAINFALL VARIABILITY

The spatial variability of seasonal rainfall are shown in Fig. 3a, 3b, 3c and 3d and the rainfall trend during last 44 years (1981 to 2024) during pre-monoon, monsoon, post monsoon and winter season are shown in Fig. 4a, 4b, 4c and 4d respectively.

Pre-monsoon (March–May)

The pre-monsoon season represents a transition from winter to the onset of the southwest monsoon. Most stations receive 150–200 mm of rainfall during this period. Despite relatively low totals, 10 of 16 stations (62 %) show increasing trends, with nine stations significant at the 90–95 % confidence level (Table 1).

Sen's slope values range from 0.39 to 2.77 mm yr^{-1}, indicating modest increases in early-season precipitation. These increases may reflect enhanced convective activity or occasional extension of Western Disturbance influence into early spring. Similar pre-monsoon rainfall increases have been observed in the western Himalaya, where extended Western Disturbance activity has been linked to higher March–April precipitation (Dar, 2023). Although relatively small, such increases may contribute to soil-moisture recharge before the main cropping season.

Monsoon rainfall

The southwest monsoon contributes approximately 65–70 % of annual precipitation in Himachal Pradesh and therefore dominates the regional hydrological cycle. Trend analysis indicates a clear intensification of monsoon rainfall across the study area. All stations show positive monsoon trend, with eleven stations significant at $p < 0.01$ (Table 1).

Sen's slope values range from 1.08 mm yr^{-1} to 14.86 mm yr^{-1}, while zone-average slopes remain between 8 and 11 mm yr^{-1}. The strengthening of monsoon rainfall is likely associated with enhanced moisture transport from the Arabian Sea branch of the southwest monsoon combined with strong orographic uplift along

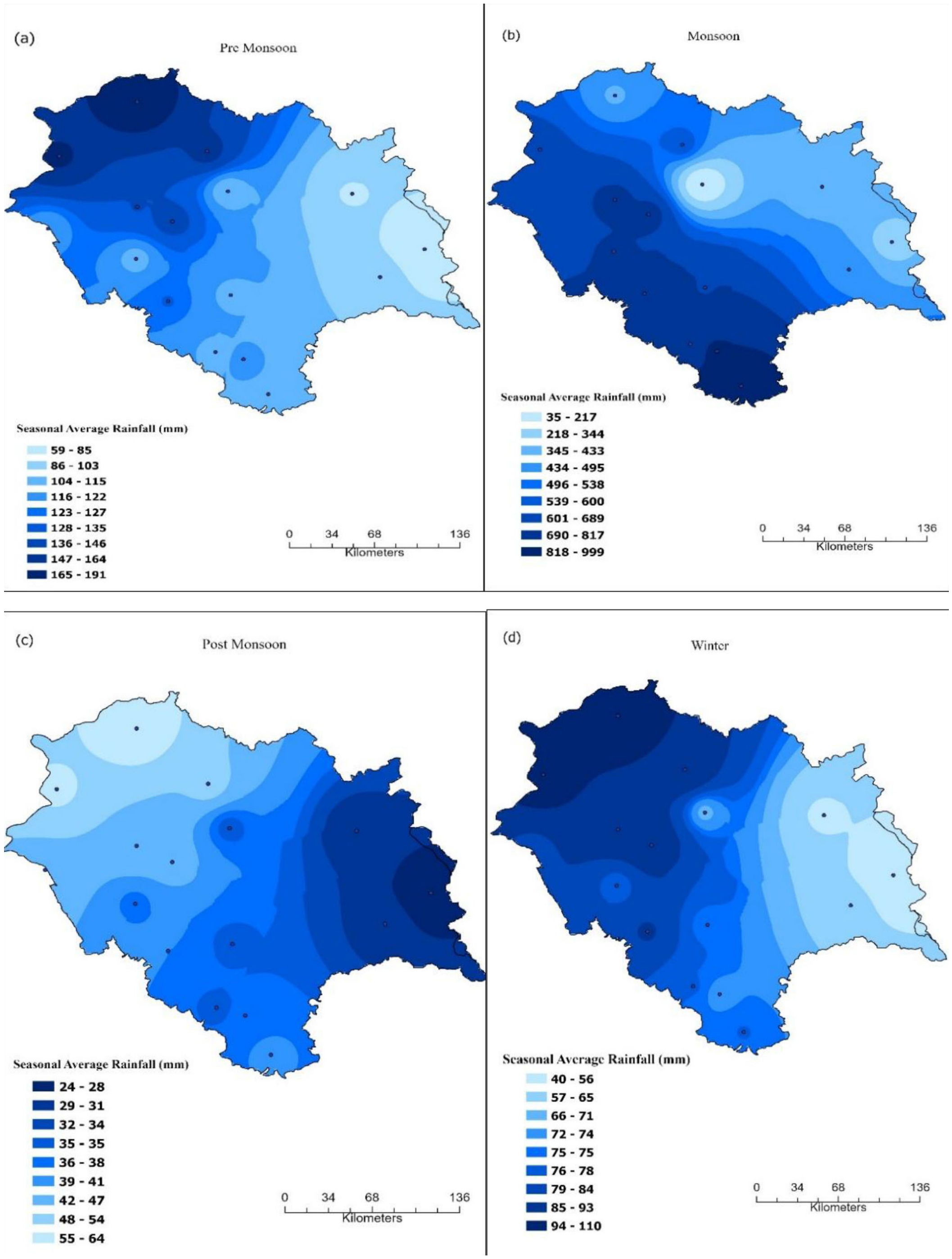

Fig. 3: Seasonal Average Rainfall: a) Pre-monsoon b) Monsoon c) Post monsoon d) Winter

Himalayan slopes.

Comparable increases in monsoon rainfall intensity have been reported across the western Himalaya Bansal & Talukdar (2024); Hunt *et al.,* (2025). However, spatial variability remains evident due to differences in topography and interactions between monsoon circulation and Western Disturbances Ahmed *et al.,* (2024).

Although increased monsoon rainfall may improve agricultural water availability and groundwater recharge, it also increases the risk of runoff, erosion, and landslides, particularly in cultivated slopes of districts such as Kangra, Mandi, and Solan.

Post-monsoon (October–December)

Post-monsoon rainfall is relatively low, generally ranging between 50 and 150 mm, and is mainly associated with residual

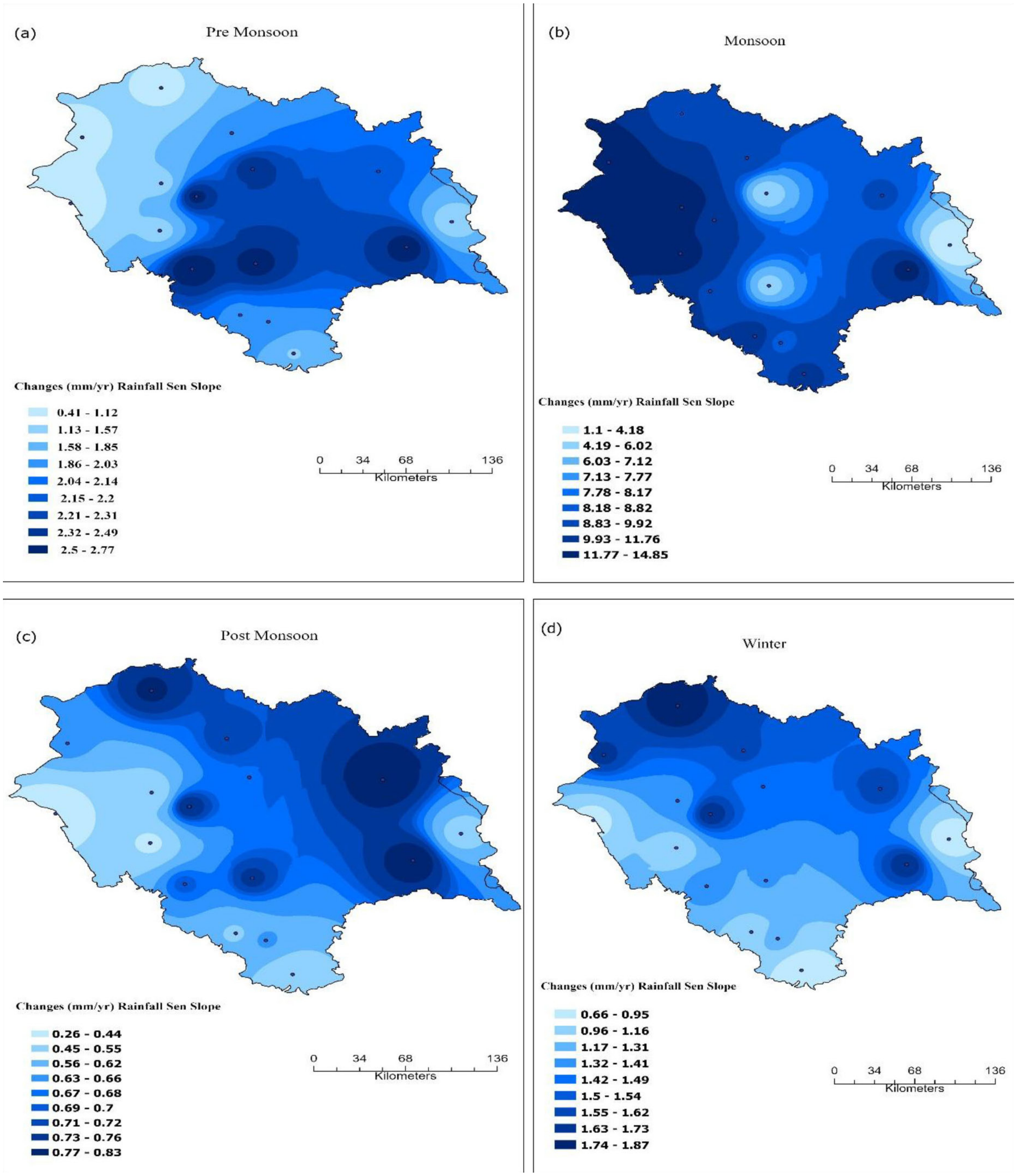

Fig. 4: Seasonal trend of Rainfall (Sen Slope, mm/yr: a) Pre-monsoon b) Monsoon c) Post monsoon d) Winter

cyclonic systems or occasional Western Disturbances. Trend results indicate relatively weak and inconsistent changes across stations.

Most stations show noticeable positive trends of varying significance levels, while six stations exhibit non-significant trends (Table 1). Sen's slope values remain small, approximately 0.2–1.04 mm yr^{-1}, indicating that post-monsoon precipitation has undergone minimal long-term change. This weak signal suggests that rainfall during this period remains largely controlled by episodic synoptic systems rather than systematic climatic shifts.

Winter rainfall

Winter precipitation in Himachal Pradesh is primarily associated with Western Disturbances, which produce snowfall and rainfall across the western Himalaya. Although seasonal totals are relatively low (20–80 mm), winter trends show noticeable increases at many stations.

Table 2: Station-wise correlation between seasonal rainfall and crop yield

Station	Wheat (Winter)	Maize (Monsoon)
Bilaspur	0.45*	0.24
Hamirpur	0.58**	0.36
Sirmaur	0.30	0.11
Palampur	0.55**	0.48*
Dalhousie	0.49*	0.41*
Manali	0.15	0.32
Keylong	0.15	0.58**
Kalpa	-0.06	0.62**
Joginder Nagar	0.47*	-0.09
Rajgarh	0.16	0.36
Solan	0.27	-0.08
Una	0.35	0.52**

Significance level *P < 0.05; **P< 0.01

Approximately 94 % of stations exhibit increasing winter precipitation, with several stations showing statistical significance (Table 1). Higher-altitude locations such as Kaza and Kalpa display comparatively stronger increases, indicating intensified Western Disturbance activity in the upper Himalayan region.

Similar winter precipitation increases have been reported in the western Himalaya Dar, (2023); Hunt *et al.,* (2025). Enhanced winter snowfall can improve spring meltwater availability but may also increase the risk of avalanches and flash floods, particularly during rapid warming events**.**

Rainfall–Crop Yield Relationships

Rainfall–crop yield correlations provide critical insights into agricultural sensitivity to climatic variability. Using Pearson correlation for 1998–2022, distinct response patterns emerge for maize and wheat across agro-climatic zones.

(A) Station-wise relationship

Station-level analysis reveals heterogeneous crop sensitivity across the state (Table 2). Wheat yield shows significant positive association with winter rainfall in several mid- and high-hill stations, including Bilaspur, Hamirpur, Palampur, Dalhousie and Joginder Nagar. These stations are predominantly rain-fed, and winter precipitation plays a critical role in soil-moisture recharge during tillering and grain formation stages.

In contrast, wheat–rainfall relationships in Kalpa, Manali, and Keylong are weak or statistically insignificant, suggesting that temperature constraints, shorter growing seasons, or non-climatic factors limit rainfall influence in higher altitudes.

Maize yield demonstrates stronger dependence on monsoon rainfall in moisture-limited and elevated stations such as Keylong, Kalpa, and Una. In lower elevation stations (e.g., Bilaspur and Solan), the relationship is comparatively weaker, likely due to better baseline moisture conditions and management practices.

These findings indicate that crop sensitivity to rainfall varies substantially across physiographic gradients.

CONCLUSION

The study evaluated long-term precipitation variability and its influence on crop productivity across the agro-climatic zones of Himachal Pradesh using NASA POWER rainfall data (1981–2024) and crop yield statistics for the period 1998–2022. The results indicate a general increasing tendency in annual precipitation across most stations of the state. Zonal analysis shows relatively stronger rainfall increases in the subtropical and mid-hill zones (Zones I and II)**,** while the high-hill (Zone III) and cold-arid trans-Himalayan region (Zone IV) also exhibit positive trends, though with comparatively smaller magnitudes. Seasonal analysis highlights that the monsoon period contributes the largest share of rainfall increase, whereas winter precipitation also shows increasing tendencies in higher elevation regions influenced by Western Disturbances.

The rainfall–crop relationship analysis reveals that maize productivity is positively associated with monsoon rainfall in several stations, while wheat yield shows stronger dependence on winter precipitation in the mid-hill regions**.** These results indicate that crop productivity in Himachal Pradesh is closely linked to seasonal rainfall variability across agro-climatic zones. By integrating precipitation trend analysis with crop-yield responses, the study provides a comprehensive understanding of climate–agriculture interactions in the western Himalayan region, offering useful insights for climate-resilient agricultural planning and regional water resource management.

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