



# Assessing the Long-Term Changes in Potential Evapotranspiration and Its Impact on Agriculture in Lahaul and Spiti, Himachal Pradesh

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## ABSTRACT

Long-term variations in Potential Evapotranspiration (PET) are important for evaluating climate changes that affect agriculture in sensitive high-altitude regions. This study examined PET temporal trends from 1951 to 2022 and assessed the agricultural implications for the cold desert district of Lahaul and Spiti in the Indian State of Himachal Pradesh. Monthly PET data were obtained from the CRU TS v4.07 dataset and computed using the FAO Penman-Monteith method. Non-parametric statistical tests used to detect seasonal and annual trends were the Mann-Kendall (MK) test, the Modified Mann-Kendall (m-MK) test, and the Innovative Trend Analysis method. Increases and decreases across all seasons were statistically significant, with the strongest negative trend observed during the agricultural season (April–October), with MK Z-values ranging from  $-6.47$  to  $-2.92$  and m-MK values from  $-12.16$  to  $-2.14$ . The annual PET declined at a rate of  $-0.0030$  mm/year at Grid Point 1 ( $Z = -7.04$ ). These results suggest that declining atmospheric moisture demand may reduce crop irrigation requirements. However, changes in evapotranspiration, cropping intensity, and protected cultivation systems might also increase disease susceptibility. The study stresses the need to plan adaptive water and crop management strategies that align with the changing PET scenario.

## INTRODUCTION

Potential Evapotranspiration (PET) is the atmospheric demand for moisture, which is the quantity of water that would evaporate and transpire from a surface if water were not limited (Allen et al. 1998). As a diagnostic entity in the hydrological cycle, PET induces losses through actual evapotranspiration, fluctuations in soil moisture, and irrigation needs. It is of utmost importance for planning water-related agricultural production, as its changes will be adapted to the water demands of the crops, drought frequencies, and yield capacities. Variations in PET analytes can significantly disrupt the agroecological balance, particularly in agroecosystems that are predominantly rainfed or depend on glacial meltwater. This makes the long-term trend analysis of PET an important parameter for studying the impacts of climate change on agricultural sustainability.

Over the past few decades, global climate change has altered the climatic variables that govern PET, including air temperature, wind speed, solar radiation, and humidity (Donohue et al. 2010). PET trends, primarily linked to global warming and atmospheric stability, have been reported in studies across Europe, Asia, and North America. These changes have made hydrological modeling and agricultural forecasting more complex, particularly in arid and mountainous regions, where small changes in evapotranspiration can have outsized effects on water availability (Sheffield et al. 2012). In agricultural systems, PET is a measure of evaporative demand and an indicator of crop stress, irrigation scheduling, and the length of growing seasons (Fisher et al. 2011). Higher PET can cause water shortages, reduced soil moisture, and lower productivity, especially when precipitation does

not increase proportionally, particularly for water-intensive crops. Recent investigations have revealed the influence of seasonal precipitation regimes on PET, surface water, and vegetation dynamics in Baghdad's urban ecosystem (Abd Al Rukabie et al. 2024).

PET patterns in India have exhibited substantial spatial variability, with large increments observed in the north-western Himalayan belt, semi-arid areas, and Indo-Gangetic plains (Kumar et al. 2010, Mall et al. 2011). There is a concern with the Himalayan region primarily because of the critical source of major flowage, glacial water storage, and agroecosystems to climate fluctuations. National studies have shown increasing temperature trends and changing precipitation regimes. However, few region-specific studies on PET variation exist, especially in high-altitude cold desert zones. This implies a significant gap in understanding how atmospheric water demand changes over time in vulnerable mountain ecosystems and what this means for food and water security.

Across the wider Indian Himalayan region, Potential Evapotranspiration (PET) trends show considerable variability across altitudinal gradients, seasonal radiation fluxes, and changing snowfall amounts. Eastern Himalayan states such as Sikkim and Arunachal Pradesh have witnessed upward PET trends due to warming and a shortening of the snow period. In contrast, the western Himalayas exhibit more complex patterns, often shaped by topographic heterogeneity and changing monsoon behavior (Dimri et al. 2022, Kalubarme & Sharma 2006). Previous studies by Kumar et al. (2023) and Mall et al. (2011) reported increases in PET for the northwestern Himalaya; however, these studies have often overlooked sub-district-level areas or cold desert ecosystems. Region-specific investigations are largely temperature-oriented and therefore provide little insight into the seasonal variability of PET under changing atmospheric demands. This highlights a crucial research gap: climatic studies on PET trends in high-altitude cold deserts are relatively few and far between, given their susceptibility to moisture fluxes and climate variability.

In the northwestern Himalayas of Himachal Pradesh, Lahaul and Spiti constitute a cold desert agroecological zone owing to their distinctive topography and climate. An extremely low precipitation regime (less than 200 mm per year), high solar radiation, and seasonal glacial meltwater define the climate-sensitive agriculture in this region (Negi & Joshi 2004). The growing season is short, typically from May to September, and irrigation relies on snowmelt sources. The region is highly sensitive to increases in PET. Higher PET intensifies crop water stress, hindering sowing and harvesting operations and increasing the incidence of

agricultural droughts. Under warming phases with aberrant precipitation regimes and diminishing glacier reserves, these impacts are expected to be magnified (Shrestha et al. 2012, Immerzeel et al. 2010). Despite these risks, empirical studies on long-term PET trends in Lahaul and Spiti are scarce. Most studies in the Himalayan region have focused on temperature and precipitation trends or have provided only regional-level forecasts without local calibration. Furthermore, only a handful of studies have systematically quantified PET trends using suitable statistical methods that account for autocorrelation, data distribution, and nonlinear trends. Given the strategic importance of this district for food security and ecological equilibrium, this gap must be filled on a priority basis.

This study addresses this gap through a detailed temporal analysis of PET trends in Lahaul and Spiti over 72 years (1951-2022). PET values were computed using the FAO Penman-Monteith method, the most accurate and standardized approach for assessing evapotranspiration under various climatic conditions (Allen et al. 1998). For trend detection and interpretation, the study relied on three non-parametric statistical techniques: the Mann-Kendall (MK) test (Hirsch et al. 1982), the Modified Mann-Kendall (m-MK) test, which corrects for serial correlation (Hamed & Rao, 1998), and Innovative Trend Analysis (ITA), which is more sensitive to nonlinear and segmented trends (Şen 2012). Individually, these techniques can detect trends in long climatic datasets. In addition to trend detection, this study investigated the interplay between PET and agriculture in Lahaul and Spiti, focusing on crop water requirements, seasonal moisture balance, and potential changes in cropping patterns. By integrating meteorological data with agricultural indicators, this study aims to provide actionable outputs for local policymakers, agricultural planners, and climate adaptation agencies. The study's findings will then be used to develop irrigation strategies, cropping calendars, and resource allocation frameworks for the mountain region, moving from climate stress toward resilience.

Hence, this study aims to assess long-term spatiotemporal trends in PET across the Lahaul and Spiti districts over 72 years (1951–2022). The investigation is based on three principal research objectives: first, to determine seasonal and annual trends in PET using robust nonparametric statistical methods, second, to assess the spatial heterogeneity of these trends across the district, and third, to examine the possible agronomic implications of PET dynamics, crop water balance, and agricultural vulnerability in a high-altitude cold desert environment. Thus, by integrating climatological trend analysis with its agricultural context, this investigation aims to generate empirical insights into adaptive water

management and climate-resilient agricultural planning for fragile mountain ecosystems.

## MATERIALS AND METHODS

### Study Area

The Lahaul and Spiti district is the largest in Himachal Pradesh, with Keylong as its headquarter. With a geographical area of approximately 13,833 square kilometres, it is located in the northeastern part of the state between latitude  $31^{\circ}44'57''\text{N}$  and  $32^{\circ}59'57''\text{N}$  and longitude  $76^{\circ}46'29''\text{E}$  and  $78^{\circ}41'34''\text{E}$  (Fig. 1). It shares districts of Kullu on the southern side, Kangra on the south-western side, Chamba on the western side, and Jammu, the Union Territory, on

the northern side, with the north of the east set away by the Tibetan Autonomous Region. Administratively, the district is subdivided into three subdivisions, Udaipur, Lahaul, and Spiti, which are administered from Udaipur, Keylong, and Kaza, respectively (Kumar et al. 2023a).

Recognized as a tribal region, Lahaul and Spiti fall under the Integrated Tribal Development Programme. According to the 2011 Census, it is one of the state's least densely populated districts, with a population of just 31,528. The local economy is predominantly agrarian, with nearly 80% of residents working in agriculture and allied activities. The main agricultural outputs are high-value crops such as potatoes, green peas, hops, and seabuckthorn. Lahaul and Spiti's agricultural profile includes irrigated cultivation

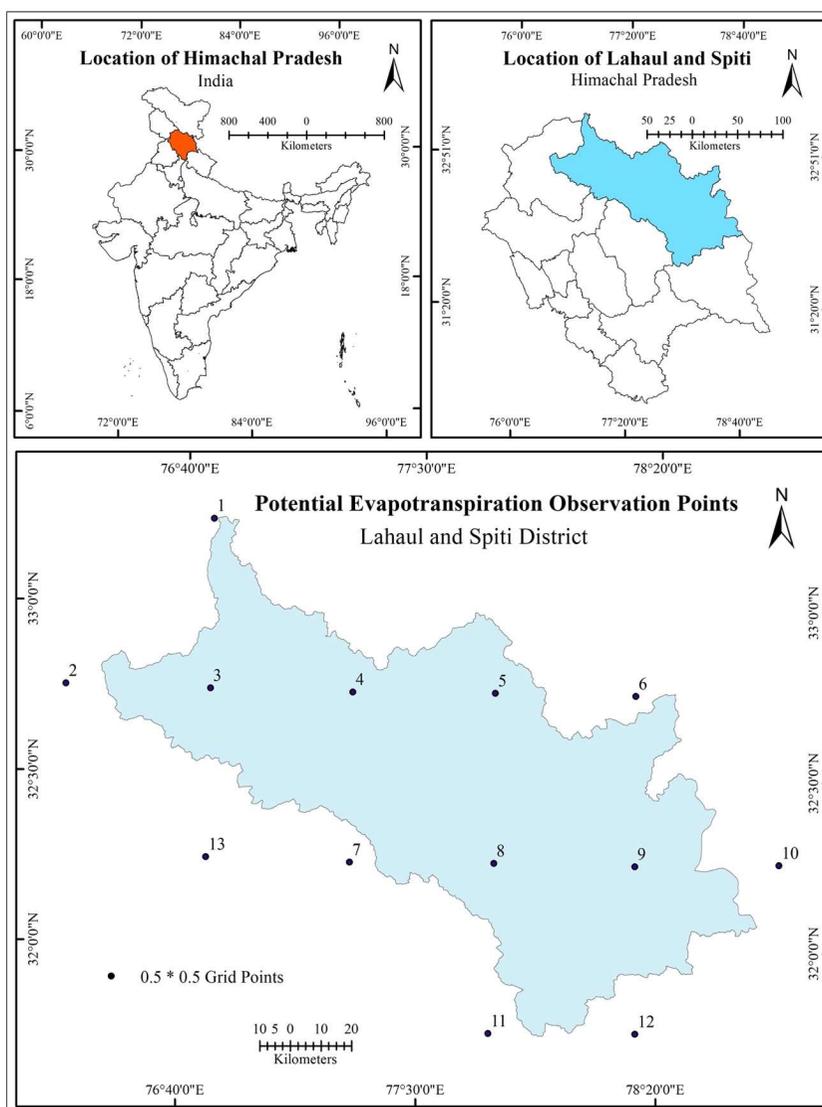


Fig. 1: Location and observation points of potential evapotranspiration.

of temperate crops, such as peas on 1,069 ha, producing 117,590 quintals, potatoes on 680 ha, producing 108,800 quintals, and cauliflower on 839 ha, producing 208,880 quintals. High yields are obtained in vegetables, whereas cereals such as wheat and barley are cultivated only in smaller areas, totaling 150 ha and producing 3,450 quintals (KVK 2021). Apart from agriculture, livestock rearing also plays a vital ancillary role in keeping rural livelihoods viable. The region has a dry temperate climate with extensive snow cover from November to April, which promotes the cultivation of temperate fruits, dry fruits, and specialty crops like hops. Owing to its remoteness, rugged terrain, and dependence on agriculture, the district still ranks as one of the least industrialized areas of Himachal Pradesh.

### Data Source

The dataset used for Potential Evapotranspiration (PET) analysis was obtained from the Climatic Research Unit (CRU) Time-Series (TS) Version 4.07, made available by the University of East Anglia. The CRU TS dataset provides gridded monthly climatic variables at a relatively high spatial resolution of  $0.5^\circ \times 0.5^\circ$  latitude–longitude from 1901 (Harris et al. 2020). This dataset is considered the best among others because it is consistent, has global coverage, and is thoroughly validated; hence, it was used for the analyses of long-term climate trends. In the present study, PET values were extracted for 1951–2022 using latitude–longitude coordinates that define the spatial extent of the Lahaul and Spiti District.

The CRU PET data were calculated using the FAO Penman-Monteith equation (Allen et al. 1998) from temperature, vapor pressure, cloud cover, and sunshine duration to maximize the physical basis for evapotranspiration in high-altitude arid terrains. The CRU dataset was chosen for its good temporal coverage and reliability, allowing for a consistent assessment of trends in PET over seven decades. The datasets were retrieved through the Centre for Environmental Data Analysis (CEDA) platform and then processed using Python-based climate data tools for statistical analysis.

### Methodology

The Mann-Kendall test is widely used to detect trends in time series of hydrologic and meteorological data, to name a few. In common usage, a test for statistical significance of trends in time series data was formally introduced by Mann in 1945 and subsequently by Kendall in 1948. Other forms of the Mann-Kendall test, such as the modified Mann-Kendall test and other new trend analysis methods, are also becoming popular. Many researchers prefer to use Sen's

Slope Estimator, developed by Sen in 1968, with the MK test to establish the magnitude of a trend, if any. This allows for a better determination of the direction and rate of change within seasonal or time-dependent datasets.

### Mann-Kendall Trend (MK-Test)

The Mann-Kendall (MK) test is a globally recognized non-parametric statistical approach for analysing hydro-climatological time series of various variables, for instance, precipitation, temperature, and streamflow. Thus, the method is mainly applied to detect monotonic increases and decreases in given data without assuming any distribution for the variable. Second, the relevant data series under analysis are assumed to be free of serial dependence. Serial correlation can be quite deceptive in detecting trends, to the extent that an apparent trend could be detected and concluded to exist when, in reality, there is none. To circumvent this drawback, one could engage in pre-whitening or use the Modified Mann-Kendall (m-MK) test. Both approaches ensure that the problem of serial correlation is refocused, analyzing the trends more quickly and accurately.

The test statistic  $S$  is determined using this procedure:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^n \text{sgn}(x_j - x_k) \quad \dots(1)$$

Where  $n$  is the length of the data, and  $x_i$  and  $x_j$  indicate data values at  $i$  and  $j$  times, respectively.

$$\text{sgn}(x_j - x_k) = \begin{cases} +1 & \text{if } (x_j > x_k) \\ 0 & \text{if } (x_j = x_k) \\ -1 & \text{if } (x_j < x_k) \end{cases} \quad \dots(2)$$

$$\text{Var}(S) = [n(n-1)(2n+5) - \sum_{i=1}^p t_i(t_i-1)(2t_i+5)]/18 \quad \dots(3)$$

In Equation (3),  $p$  indicates the number of tied groups, and  $t_i$  indicates how many times a datum repeats. In test statistics ( $S$ ), a positive  $S$  value means the trend is increasing, and a negative  $S$  value means the trend is decreasing.

The  $Z$  score value is obtained by using Equation (4)

$$Z_{\text{Mk}} = \begin{cases} \frac{S-1}{\sqrt{V(S)}} & \text{for } S > 0 \\ 0 & \text{for } 0 \\ \frac{S+1}{\sqrt{V(S)}} & \text{for } S < 0 \end{cases} \quad \dots(4)$$

### Modified-Mann Kendall Trend (m-MK-Test)

The adjusted variance formula is given by  $S$ , as required in the m-MK statistical test, to minimize the impact of autocorrelation coefficients on a time series. This was outlined by Hamed and Rao in 1998. The adjusted spatial and temporal variance formula of  $\text{Var}(S)$  is given as follows:

$$\text{Var}(S) = \text{Var}(S) \times \frac{n}{n^*} \quad \dots(5)$$

$\frac{n}{n^*}$  represents the modified coefficient of autocorrelated data, Equation (6), and  $r_k$  represents the autocorrelation coefficient of  $k_{th}$  Equation (7).

$$\frac{n}{n^*} = 1 + \frac{2}{n(n-1)(n-2)} \times \sum_{k=1}^{n-1} (n-k)(n-k-1)(n-k-2)r_k \quad \dots(6)$$

$$r_k = \frac{\frac{1}{n-k}}{\frac{1}{n}} \times \frac{\sum_{i=1}^{n-k} (x_i - x^-)(x_{i+k} - x^-)}{\sum_{i=1}^n (x_i - x^-)^2} \quad \dots(7)$$

### Sen's Slope Estimator

Sen's method was first advocated to study the length and direction of linear trends in long-term observational data series. Known as Sen's slope estimator, this method is best for detecting consistent linear changes over time because it operates well even in the presence of outliers and extreme values that would typically interfere with conventional methods (Kumar et al. 2023b). These features make the method ideal for analyzing environmental and climatic datasets, which are generally highly variable and contain anomalies. It has been widely used to assess trends in climatic variables, such as temperature and precipitation. In this method, the slopes  $Q_i$  are computed for all possible pairs of points in time within the time series of the observation data. These slope values provide information on the speed and direction of the change over time. Each  $Q_i$  is calculated from a simple, valuable formula for verifying trends of an environmental variable over time.

$$Q_i = \frac{Y_j - Y_i}{j - i} \quad \dots(9)$$

Where  $i = 1$  to  $n - 1$ ,  $j = 2$  to  $n$ ,  $Y_j$  and  $Y_i$  are data values at time  $j$  and  $i$  ( $j > i$ ), respectively. If, in the time series, there are  $n$  values of  $Y_j$ , estimates of the slope will be  $N = n(n - 2)/2$ . The slope of the Sen estimator is the mean slope of such slopes'  $N$  values. The Sen's slope is:

$$Q_{ij} = f(x) = \begin{cases} \frac{Y_j - Y_i}{j - i}, & \text{if } n \text{ is odd} \\ \frac{1}{2} \left( Q \frac{N}{2} + Q \left[ \frac{N+2}{2} \right] \right), & \text{if } n \text{ is even} \end{cases} \quad \dots(10)$$

A positive  $Q_i$  value ( $Q_i$ ) signifies an upward shift in the trend, while negative  $Q_i$  scores indicate a decline in the trend in the temporal data.

### Innovative Trend Analysis

Innovative Trend Analysis (ITA) has gained practicality and popularity in hydro-meteorological research for analyzing

trends within time series data over the last few years. Refined over time, ITA has addressed many of the drawbacks of standard statistical methods (Sen 2012). Trends in time series were accepted under conditions including data normality, independence of observations, and length of the dataset. However, one distinct advantage of the ITA is that it works well even in the presence of a serial correlation, which occurs so often in environmental time series data that other methods are almost unreliable. ITA also helps analyze trends graphically, leaving no room for skewness in the trend due to extreme data points. It involves simple steps: the dataset is divided into two halves of equal size. The first observation is discarded if an odd number of observations is present. Each half was then sorted in ascending order. Next, the scatter diagram was plotted, with the first half treated as the x-coordinate and the second half as the y-coordinate. Next, a 1:1 reference line was drawn along the plot as a benchmark. Points that appear higher than this line will be taken as an indication of upward trends, while points appearing lower will indicate downward trends. A clear visual interpretation makes the ITA a highly effective and user-Santo friendly tool for recognizing complex trend patterns in hydrological and climatological datasets.

## RESULTS AND DISCUSSION

The results of the analysis were generated at both annual and seasonal scales. The classifications were given by the India Meteorological Department, namely: winter (January–February), pre-monsoon (March–April–May), monsoon (June–July–August–September), and post-monsoon (October–November–December) (IMD 2022). In addition, a single growing season was observed in the high-altitude cold desert regions of Lahaul and Spiti. The duration of the study extended from April to October (Spehia et al. 2024). The MK and m-MK trend analyses showed confidence levels of 95% ( $p < 0.05$ ) and 99% ( $p < 0.01$ ), respectively.

### Mann-Kendall Trend Analysis

The Mann-Kendall test indicates a significant decreasing trend during all the seasons. During Winter, PET showed a definite decreasing trend, with Z-values between -3.42 and -0.62. The declining trend indicates that lower evaporation rates during winter could be due to decreasing temperatures or more cloud cover, reducing water loss from soil and vegetation (Fig. 2a). The pre-monsoon period followed a distinct decreasing trend, with the respective Z-values varying from -4.59 to -2.33 (Fig. 2b). Similar trends emerged during the monsoon season, with Z-values between -4.66 and -1.73. The decrease in PET during the monsoon may be due to increased cloud cover and rainfall, with decreased

evaporation despite rising temperatures (Fig. 2c). Throughout the post-monsoon period, a significant reduction in PET was indicated with Z values between -6.69 and -3.50, suggesting

that atmospheric water demand decreased consistently in the latter part of the year (Fig. 2d). The annual trend in PET indicates a long-term decreasing trend, with Z-values within

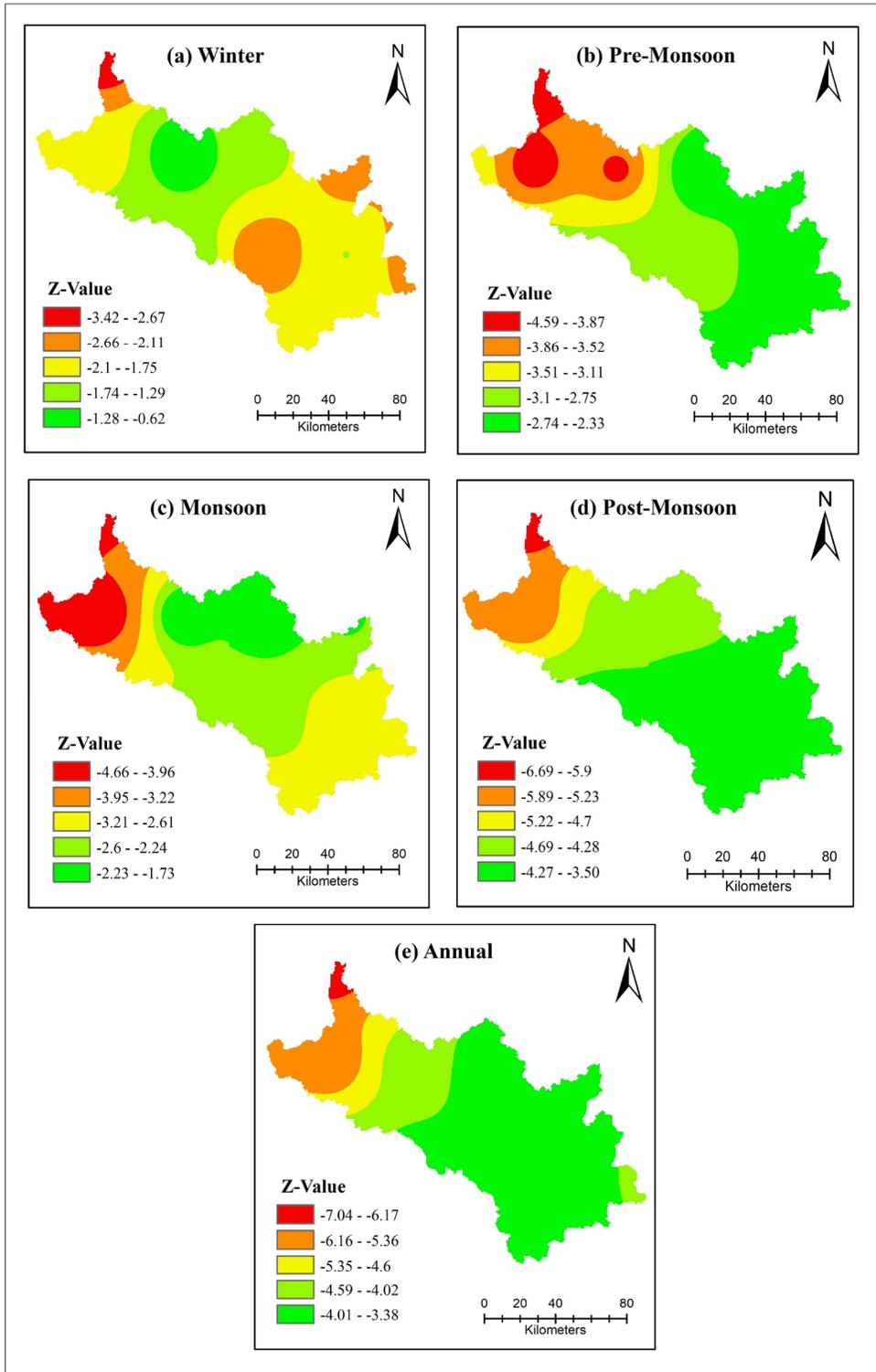


Fig. 2: Seasonal and annual spatial distribution of PET  $Z_{mk}$  values from 1951 to 2022.

Table 1: Seasonal and annual values of Mann-Kendall and Modified Mann-Kendall for potential evapotranspiration.

Grid Points	Latitude	Longitude	Mann-Kendall ( $Z_{mk}$ )		Modified Mann Kendall ( $Z_{mmk}$ )									
			Winter	Pre-Monsoon	Monsoon	Post-Monsoon	Agriculture	Annual	Winter	Pre-Monsoon	Monsoon	Post-Monsoon	Agriculture	Annual
1	33.25	76.75	-3.42**	-4.59**	-4.28**	-6.69**	-6.47**	-7.04**	-7.17**	-10.45**	-9.70**	-18.11**	-12.16**	-13.08**
2	32.75	76.25	-1.81	-2.96**	-4.62**	-5.35**	-5.24**	-5.65**	-2.14*	-11.13**	-12.48**	-6.38**	-10.55**	-11.61**
3	32.75	76.75	-1.98*	-4.09**	-4.66**	-5.80**	-6.03**	-6.14**	-1.86	-7.20**	-9.24**	-6.60**	-7.55**	-7.06**
4	32.75	77.25	-0.62	-3.96**	-1.73	-4.59**	-4.24**	-4.20**	-0.94	-7.72**	-2.24*	-5.58**	-4.72**	-4.53**
5	32.75	77.75	-1.61	-2.33*	-1.76	-4.32**	-3.11**	-3.47**	-1.72	-2.81**	-1.59	-5.05**	-2.54*	-2.97**
6	32.75	78.25	-2.45*	-2.55*	-2.18*	-4.25**	-2.92**	-3.38**	-1.95	-2.85**	-1.62	-5.70**	-2.14*	-2.61**
7	32.25	77.25	-1.34	-2.75**	-2.46*	-3.83**	-3.53**	-3.65**	-1.41	-3.17**	-2.66**	-4.21**	-2.99**	-3.20**
8	32.25	77.75	-2.56*	-3.03**	-2.33*	-4.06**	-3.10**	-3.59**	-3.74**	-2.67**	-1.72	-4.58**	-2.18*	-2.54*
9	32.25	78.25	-1.75	-2.50*	-2.93**	-4.11**	-3.56**	-3.81**	-1.58	-2.14*	-2.31*	-5.25**	-2.57*	-2.79**
10	32.25	78.75	-2.56*	-2.59**	-2.96**	-4.18**	-3.47**	-4.36**	-1.87	-2.33*	-2.24*	-5.55**	-2.46*	-3.10**
11	31.75	77.75	-1.90	-2.38*	-3.07**	-3.50**	-3.67**	-3.99**	-1.73	-2.06*	-2.45*	-4.23**	-2.72**	-3.01**
12	31.75	78.25	-1.78	-2.33*	-2.59**	-3.88**	-3.33**	-3.87**	-1.77	-2.00*	-2.05*	-4.71**	-2.43*	-2.80**
13	32.25	76.75	-1.57	-2.43**	-3.23**	-3.65**	-3.78**	-3.95**	-2.24*	-6.00**	-5.50**	-4.89**	-5.30**	-5.62**

\* Significant at 95% confidence interval, \*\* Significant at 99% confidence interval

the interval of -7.04 to -3.38, indicating that there have been marked declines in the evapotranspiration rates over the decades (Fig. 2e). During the agricultural period, one of the strongest decreasing trends appeared with Z-values ranging from -6.47 to -2.92, indicating that evapotranspiration rates during the growing season have significantly decreased, which could affect water management for crops and irrigation (Fig. 3a).

The MK test showed a statistically significant declining trend in PET across all seasons. The Winter season displayed a drastic and significant downward trend in PET at various grid points. The top decreasing PET is Grid Point 1, near Chimrat Panchayat in Lahaul block, where  $Z = -3.42$ , with a significance level of 99% (magnitude = -0.0012 mm/year), thus signifying that PET across various sites during the winter season is declining. During the Pre-Monsoon season, consistent and significant decreases in PET were observed at seven grid points at 99% and six grid points at 95%. The most pronounced fall comes from Grid Point 1, near Chimrat panchayat in Lahaul block ( $Z = -4.59$ , magnitude = 0.0033 mm/year), followed by Grid Point 9, near Tabo panchayat in Spiti block ( $Z = -3.03$ , magnitude = -0.00208 mm/year), and 8, near Hull panchayat in Spiti block ( $Z = -2.75$ ). PET also exhibited a decreasing trend during the monsoon season, notably at Grid Point 3, near Udaipur in the Lahaul block ( $Z = -4.66$ , magnitude = -0.0024 mm/year), with eight grid points significant at 99% and three at 95%. In the post-monsoon season, all grid points were statistically significant, with a 99% decrease in PET trend. The most significant decline can be observed at Grid Point 1, near Chimrat Panchayat in the Lahaul block ( $Z = -6.69$ , magnitude = -0.0026 mm/year), followed closely by Grid Point 3, near Udaipur in the Lahaul block ( $Z = -5.80$ ), and Grid Point 2, near Tindi Panchayat in the Lahaul block ( $Z = -5.35$ ). These strong trends indicate a considerable reduction in PET over time. The Agricultural season also shows a significant decrease in PET, and sizable decreases are observed at all grid points at 99% significance. The most significant decreasing trend was noted in Grid Point 1 ( $Z = -6.47$ , magnitude = -0.0025 mm/year), Grid Point 8, near Hull Panchayat in Spiti block ( $Z = -3.53$ ), and Grid Point 9 ( $Z = -3.56$ ). These decreases in PET during this season may indicate possible changes in the crop water requirements. Annual PET trends confirm a steady and statistically significant decline across all studied grid points, with the most substantial reductions at Grid Point 1 ( $Z = -7.04$ , magnitude = -0.0030 mm/year), Grid Point 11, near Sagnam in Spiti block ( $Z = -4.36$ , magnitude = -0.0018 mm/year), Grid Point 10, near Giu panchayat in Spiti block ( $Z = -3.81$ ), and Grid Point 8, near Hull panchayat in Spiti block ( $Z = -3.6$ ) (Table 1).

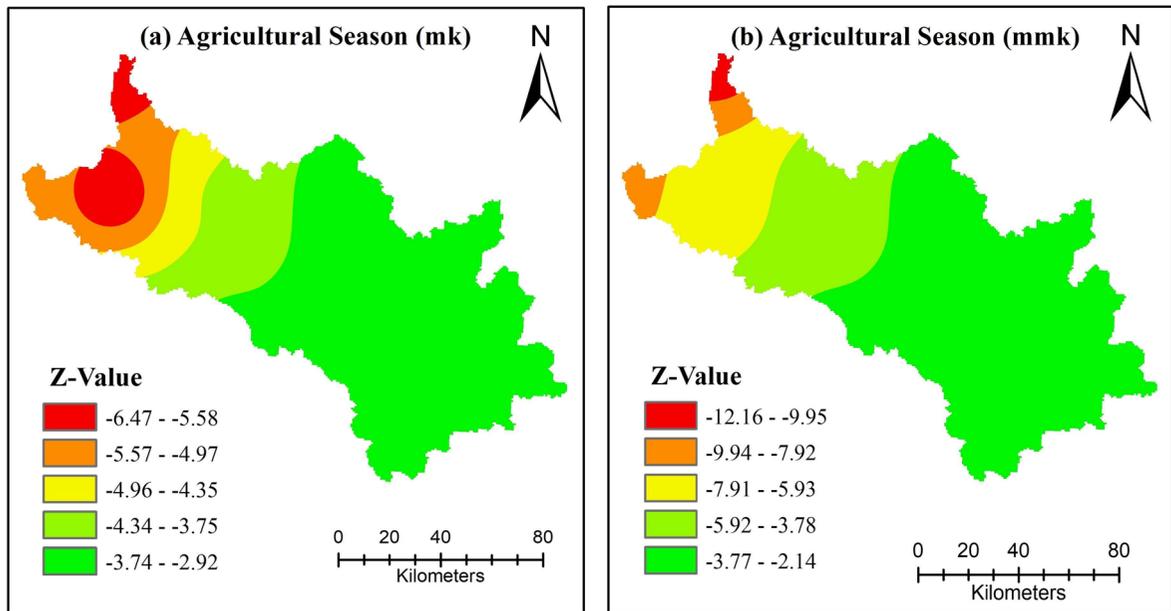


Fig. 3: Spatial distribution of agricultural season (a) Mann-Kendall (b) Modified Mann-Kendall.

### Modified Mann-Kendall Trend Analysis

The m-MK test showed a remarkable decreasing trend for all seasons, indicating a decreasing atmospheric moisture demand over time. A substantial decline in PET was noted during the winter months, with Z-values ranging from -7.17 to -0.94, suggesting that the rates of winter evaporation and transpiration have been decreasing (Fig. 4a). The other significant decline in PET was observed during the pre-monsoon periods, reflected in Z-values from -11.13 to -2.00 (Fig. 4b). Monsoon PET followed the same trend, with Z values ranging from -12.48 to -1.59, suggesting a decline in PET owing to increased humidity and higher rainfall during the wet season, which would lower direct evaporation from the land surface (Fig. 4c). During the post-monsoon season, one of the periods with maximum decreasing trend characteristics was observed with Z-values ranging from -18.11 to -4.21. The significance of this reduction indicates the extraordinary rapidity of the declining trend in post-monsoon evapotranspiration, which might indicate the retention of moisture in soils for a long time and lesser drying effects in the atmosphere (Fig. 4d). The annual trend thus confirms a long-standing decrease with Z values from -13.08 to -2.54, showing a continuous decreasing trend in evapotranspiration rates over decades (Fig. 4e). Concerned about the agricultural season, an appreciable decline has also been observed in the PET values, which range from -12.16 to -2.14, implying diminished PET rates through the growing season (Fig. 3b).

In Winter, most grid points showed a significant decreasing trend in PET, whereas two grid points (99%)

and two grid points (95%) displayed high significance. The most profound decline was observed at Grid Point 1 ( $Z = -7.17$ , magnitude =  $-0.0012$  mm/year), indicating a significant reduction in the evaporative demand. Declines were also observed for Grid Points 3, 4, and 5; however, these trends were not statistically significant. Evapotranspiration rates experienced a pronounced and broad decline, and pre-monsoon season PET followed a similar, albeit less intense, pattern. In this, nine grid points are significant at the 99% level and the remaining at the 95% level. An extreme decrease was recorded at Grid Point 2 ( $Z = -11.13$ , magnitude =  $-0.0023$  mm/year), affirming intense alterations in pre-monsoonal moisture dynamics, and at Grid Point 1, which covers Chimrat panchayat and Tingrit panchayat of Lahaul block ( $Z = -10.45$ , magnitude =  $-0.0033$  mm/year), indicating a significant reduction in evaporative losses. During the monsoon season, PET trends decreased over all grid points, and five grid points were statistically significant at 99% confidence. The highest decrease in PET was observed for Grid Point 2, near the Tindi panchayat in the Lahaul block ( $Z = -12.48$ , magnitude =  $-0.0028$  mm/year). The Post-Monsoon season had the steepest decrease in PET of all seasons at 99% statistically significant, with an extreme drop of 2.6 mm/year among all seasons occurring across grid point 1 ( $Z = -18.11$ ). The Agricultural season also exhibited a statistically significant decrease in PET, with the most considerable reductions at Grid Point 1 ( $Z = -12.16$ , magnitude =  $-0.0030$  mm/year) and Grid Point 2 ( $Z = -10.54$ , magnitude =  $-0.0027$  mm/year). This suggests a potential progressive decline in crop water demand, necessitating the

adaptation of irrigation strategies to improve water usage while maintaining soil moisture levels. The trend analysis for PET on an annual basis confirmed a decline over the long

term at all grid points, with the most significant reductions occurring at Grid Point 1, near Chimrat panchayat in Lahaul block ( $Z = -13.08$ , magnitude =  $-0.0025$  mm/year).

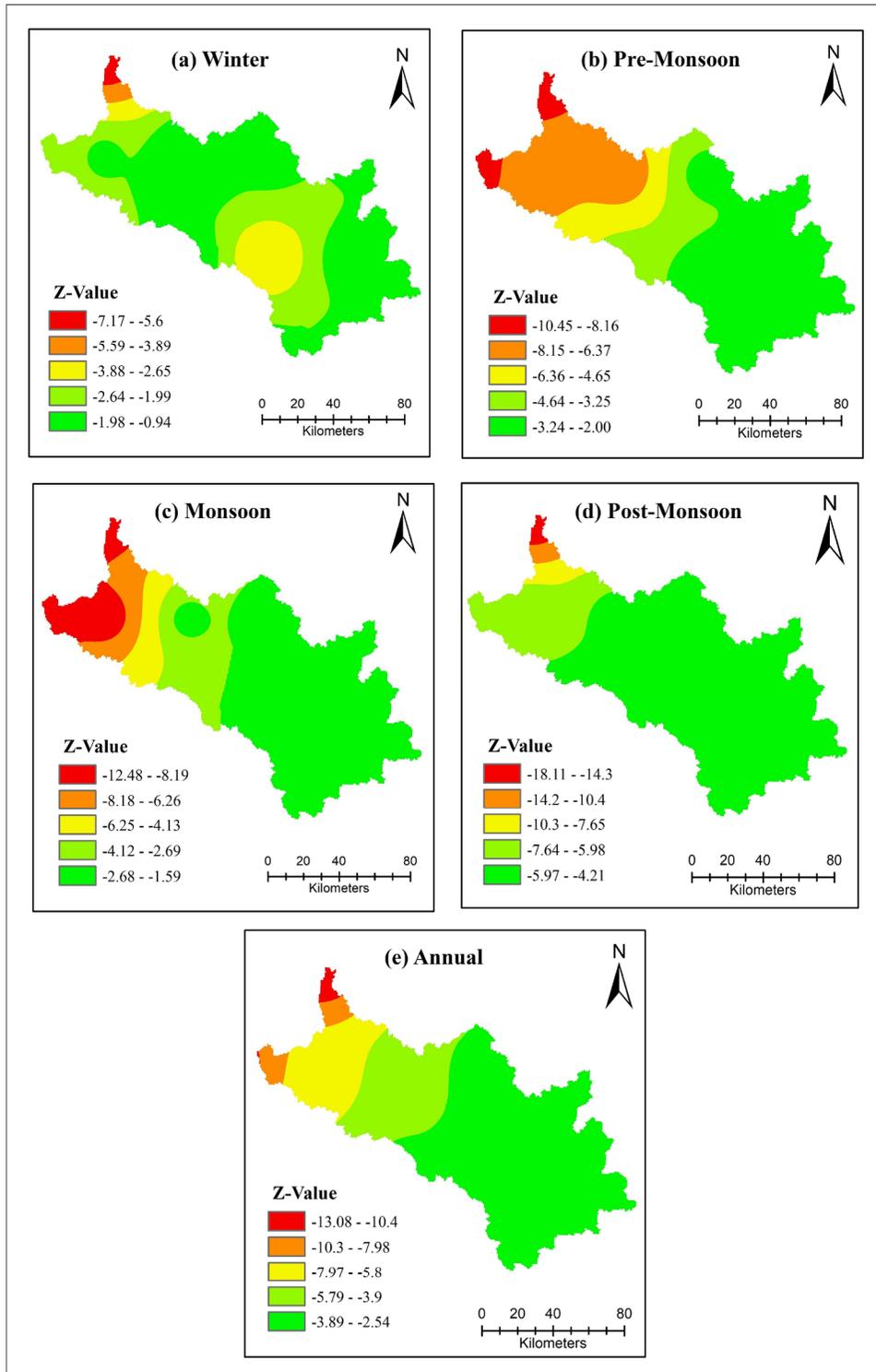


Fig. 4: Seasonal and annual spatial distribution of PET  $Z_{mmk}$  values from 1951 to 2022.

The sustained trend of decline in annual PET may signal a shift in the net evaporative dynamics related to large-scale climate variability, decreasing solar radiation, and altered atmospheric moisture columns (Table 1).

The decadal trend in annual PET (Fig. 5) reveals a marked increase from the 1950s to the 1980s, especially during 1971–80. A steady decline in potential evapotranspiration values was observed from 1991 onward, with the lowest PET values observed in the current decade of 2010–22. This trend corresponds to a gradual decrease in the atmosphere's capacity to evaporate, thus agreeing with the trends predicted by the Mann-Kendall and m-MK methods, indicating evolving hydro-climatic scenarios in the Lahaul and Spiti regions.

### Innovative Trend Analysis

Innovative Trend Analysis (ITA) of PET from 1951 to 2022 indicates a decreasing trend for all seasons, indicating temporal variation in atmospheric moisture demand. The ITA compares PET for the two study periods, 1951–86 (first half) and 1987–2022 (second half), with a 1:1 reference line denoting an unchanged or no trend condition. Values below the line imply a reduction in PET, and above, an increase. Most of the data points in all six panels (Winter, Pre-Monsoon, Monsoon, Post-Monsoon, Agricultural, and Annual PET) clustered in a supposedly decreasing triangle, clearly marking declining PET trends. The decline in winter PET could have been due to less solar radiation or cooling temperatures, with respective influences declining the evaporation rate.

A similar situation was observed in the historical decline of pre-monsoon and monsoon PET, indicating a lesser

atmospheric demand for moisture within these vital periods owing to temperature reduction and increased humidity. Another downward trend in the post-monsoon season, which further confirms the gradual weakening of evaporative demand, was observed. For the agricultural season, PET, a similar downward trend indicates less demand for irrigation water owing to reduced atmospheric moisture loss from the soil and crops. The annual PET trends further show the continuity of this downtrend, suggesting that long-term evaporation and transpiration potential have decreased in Lahaul and Spiti over the decades (Fig. 6).

### Impacts of Potential Evapotranspiration on Agriculture

A thorough analysis of long-term Potential Evapotranspiration (PET) in the Lahaul and Spiti region, for 1951–2022, established a statistically significant and seasonally decreasing trend. The trend was determined using three non-parametric tests: Mann-Kendall (MK), Modified Mann-Kendall (m-MK), and Innovative Trend Analysis (ITA). Considering PET as a term denoting moisture demand from the atmosphere, such a continuous decrease from April to October, which is agriculturally important, will affect mountain farming in this cold desert.

Agriculture in Lahaul and Spiti is vertically oriented toward high-value crops, such as potatoes, green peas, barley, and buckwheat (Negi & Joshi 2004). The growing season is short, and irrigation remains dependent on glacial and snowmelt water. A rapid agro-economic transformation has occurred in the region, driven by infrastructural development, including the Atal Tunnel, which has improved connectivity and market access (Sherup 2023, Kumar et al. 2023a). This

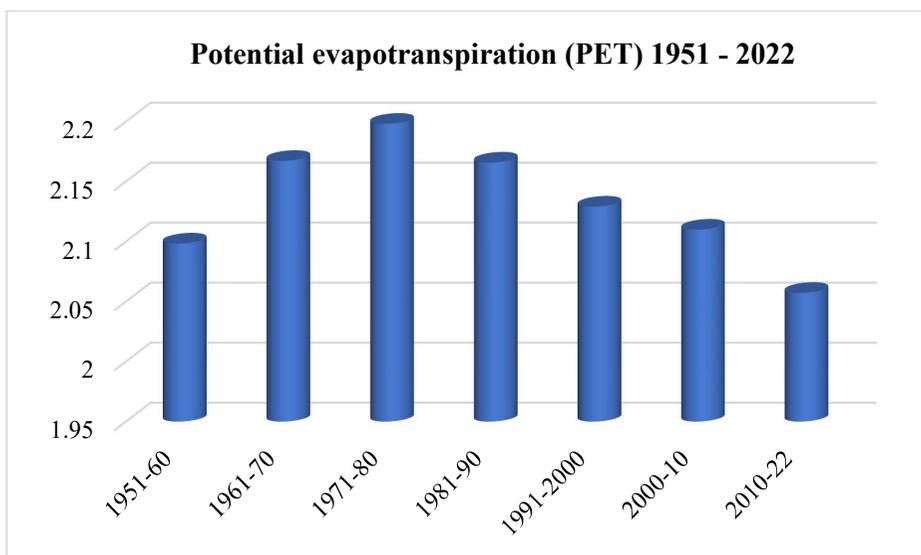


Fig. 5: Decadal variation in annual potential evapotranspiration across Lahaul and Spiti from 1951 to 2022.

has also led to expanded cultivated areas and mechanization, shifting toward polyhouse cultivation on a broader scale of intensification. Assuming that the lowering of PET is evidenced by Zmk values between -6.47 and -2.92 and Zmmk values between -12.16 and -2.14, it indicates that the moisture demand of the atmosphere dwindled.

An agricultural household survey of 295 farmers conducted in Lahaul and Spiti from May to June 2024 provided exceptional experiential clarity to these climatological observations. Farmers were largely consistent across districts, reporting increases in ambient temperatures that led to premature snowmelt and reduced water availability during the early growing stages of crops. In their perception, irrigation water demand would increase mainly at transplanting and flowering due to these changes, necessitating formal channelization of water, an adaptation new in an area where a gravity-fed kuhl system had previously been sufficient. Farmers also reported more erratic rainfall, characterized by very short, intense spells

followed by lengthy dry periods, posing constraints for crop scheduling and water budgeting. These perceptual insights are supported by instrumental data and underscore the critical need to align scientific inference with local knowledge to plan for effective adaptation (Plate 1).

A decline in PET could imply less demand for irrigation; however, it conversely implies the limitation of transpiration-induced cooling, posing greater thermal stress, especially inside polyhouses, where microclimatic buffering is the least. The intricacy of this pathogen dynamic has been recorded at the international level, varying with crop species, canopy architecture and agronomic management (Raza & Bebbber 2022).

Similar insights have emerged from tropical regions, where cropland expansion has significantly influenced the temporal dynamics of evapotranspiration (Laipelt et al. 2024). Their findings underscored PET's susceptibility to land-use variations, reaffirming the importance of viewing PET trends in the context of broader landscape and land-cover changes. Resemblances with international experiences further

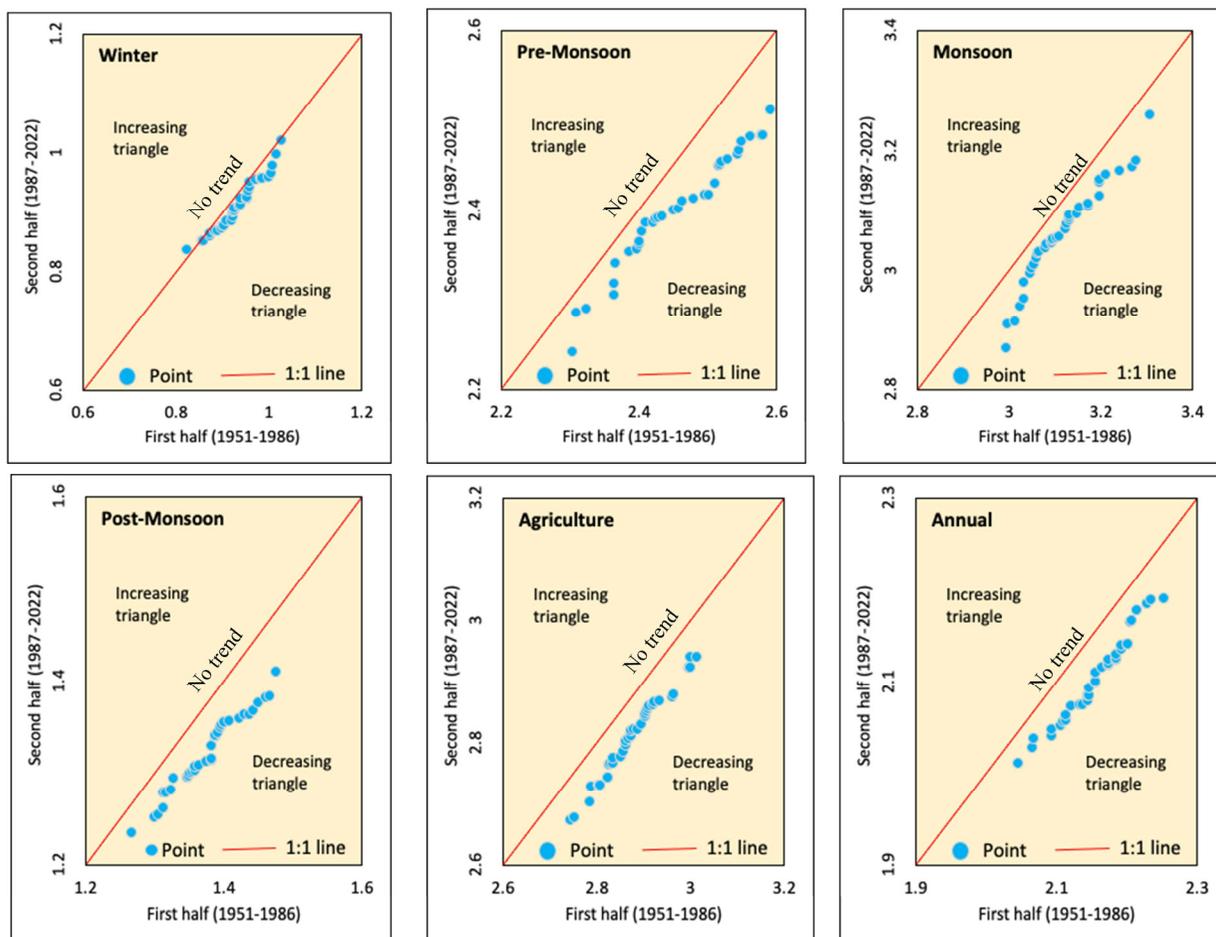


Fig. 6: Innovative trend analysis (ITA) for potential evapotranspiration during 1951 to 2022.

contribute to this debate. For example, Multsch et al. (2020) demonstrated the impacts of extensive irrigation expansion in Brazil on PET and water resource availability, Al-Hasani et al. (2022) highlighted the strong coupling of PET dynamics with phenological responses in temperate zones, further underscoring complex PET-crop-climate feedbacks.

### Adaptive Strategy for Agriculture

Hence, the agrarian strategy for Lahaul-Spiti must pivot around two interlinked principles: water prudence and crop resilience. Consequently, the following adaptation measures are recommended:

- **Demand-responsive irrigation:** Adopting soil moisture sensor-based drip and sprinkler systems instead of flood irrigation can match water delivery with reduced PET levels, thus avoiding over-application and conserving limited stored snowmelt reserves.
- **Climate-smart crop choices:** Diversification can include short-duration, disease-resistant cultivars, such as Kufri Himalini (potato), along with pseudo-cereals, such as buckwheat, which have low Kc values to improve water-use efficiency (Negi & Joshi 2004).
- **Integrated Disease Management (IDM):** Instituting weekly spore surveillance coupled with weather-based agro-advisories distributed through KVKs would go a long way in preempting outbreaks under changing PET and humidity regimes (Thakur & Klate 2023).
- **Hydrological buffers:** Constructing high-altitude lined meltwater ponds and solar-powered nighttime irrigation may provide a service ameliorate the mismatch between early snowmelt and mid-season crop water demand.
- **Polyhouse retrofitting:** Ridge ventilators and reflective

mulches in protected cultivation should be installed to moderate temperature and vapor pressure deficits, discouraging pathogen infection under the lowered PET scenario.

### LIMITATIONS

Despite its robust methodology and duration, the present study has some caveats that warrant mentioning. The use of CRU TS v4.07 data at a spatial resolution of  $0.5^\circ \times 0.5^\circ$  is a good candidate for large-scale climatological studies, but it might fall short in reflecting the topo-climatic heterogeneity of the Lahaul and Spiti mountainous terrain. Furthermore, the analysis only deals with PET, without examining the parallel variations in AET or soil moisture, which are needed to verify the agro-hydrological validity of PET trends. These would be excellent candidates for inclusion as major components of future work involving much finer-scale observations from ground research relevant to adaptive agricultural planning.

### CONCLUSIONS

The present analysis of long-term trends in Potential Evapotranspiration (PET) in Lahaul and Spiti deepens the understanding of climate–agriculture interactions in high-altitude arid regions. In addition to finding declining PET trends, the study discusses how such climatic alterations intersect with changes experienced at a larger level in agricultural transformations, such as decreasing cropping intensity, irrigation practices, and microclimatic conditions. Hence, the complex nexus between the reduced atmospheric demand and changed agricultural practices is compelling enough to demand a more data-based resource planning approach. More importantly, the findings imply that PET



Plate 1: (A) A woman farmer irrigates their field using the traditional system, (B) The author conducted the primary survey in Losar village in Lahaul and Spiti district.

may be used as an indicator in conjunction with the entire hydro-meteorological and agroecological context consisting of soil moisture availability, actual evapotranspiration, and crop water requirements.

With crop planning aimed at ensuring agricultural resilience in Lahaul and Spiti, agriculture should focus on short-duration and moderately water-sensitive crops, such as barley, buckwheat, and green peas, which correspond with the restricted growing season of the area. Water conservation measures could include micro-irrigation systems, runoff harvesting from glaciers, and measures to enhance canal (Kuhl/piped) efficiency to counter seasonal variability and glacial dependency. Other climate-resilient agrarian measures may endorse technologies for protected cultivation, agro-climatic zoning, and disease forecasting systems that provide adaptive responses to changing PET patterns, humidity regimes, and thermal extremes for this ecologically fragile, high-energy terrain.

As agriculture in Lahaul and Spiti gradually intensifies due to better infrastructure and market access, the sustainability of this expansion will depend on the adaptive response to climate change. Policymakers and agricultural planners must consider the opportunities arising from decreased evaporative stress and the risks associated with the onset of humidity-induced plant diseases and thermal imbalances. Future studies on PET trends, crop modelling, water budgeting, and remote sensing-based assessments will enable us to focus on local adaptation measures. Building institutional capacity for climate-resilient planning would also be a step toward livelihood and food security in this ecologically fragile Himalayan district.

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