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Original Research

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

Ashwani and Pankaj Kumar†

[1]Department of Geography, Delhi School of Economics, University of Delhi, Delhi, India

†Corresponding author: Pankaj Kumar; pankajdsedu@gmail.com

ORCID IDs of Authors

Ashwani (0000-0002-3336-0139); Pankaj Kumar (0000-0002-4453-1677)

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ABSTRACT

Long-term variations in Potential Evapotranspiration (PET) hold importance in evaluating climate changes impacting agriculture in sensitive high-altitude regions. The study intends to observe the PET temporal trends between 1951 and 2022 and study the agricultural implications for the cold desert district of Lahaul and Spiti in the Indian State of Himachal Pradesh. Monthly PET data were taken from the CRU TS v4.07 dataset and calculated using the FAO Penman-Monteith method. The non-parametric statistical tests used for detecting seasonal and annual trends are the Mann-Kendall test, the Modified Mann-Kendall test, and the Innovative Trend Analysis method. The increases and decreases across all seasons were statistically significant, with the strongest negative trend seen during the agricultural season (April–October), with MK Z-values ranging from –6.47 to –2.92 and m-MK values ranging from –12.16 to –2.14. Annual PET declined at a rate of –0.0030 mm/year at Grid Point 1 (Z = –7.04). With these results, the declining atmospheric demand for moisture may reduce crop irrigation requirements. However, changes in relative humidity, cropping intensity and protected cultivation system might also increase susceptibility to disease. The study stresses the need to plan adaptive water and crop management strategies that conform to the changing PET scenario.

INTRODUCTION

Potential Evapotranspiration (PET) amounts to the atmospheric demand for moisture: the quantity of water that would evaporate and transpire from a surface if water were not limited (Allen et al., 1998). Being a diagnostic entity in the hydrological cycle, PET induces losses by 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 henceforth adapted to the water demands of the crops, the drought frequencies, and the yield capacities. Variations in PET analytes can significantly disrupt the agroecological balance, especially in agroecosystems that are mostly rainfed or depend on glacial meltwater. This makes the long-term trend analysis in 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 the PET, such as air temperature, wind speed, solar radiation, and humidity (Donohue et al., 2010; Trenberth et al., 2007). PET trends, mainly related to global warming and atmospheric stability, have been reported in studies spanning Europe, Asia, and North America. With these changes, hydrological modelling and agricultural forecasting have been made more complex, especially in arid and mountainous regions, where minor changes in evapotranspiration could have outsized impacts on water availability (Sheffield et al., 2012). In agricultural systems, PET is a measure of the evaporative demand and an indicator of crop stress, irrigation scheduling, and the length of growing seasons (Fisher et al., 2011). Higher PET causes water shortages, lesser soil moisture, and reduced productivity, which may occur if precipitation is not rising in equivalence, especially for water-intensive crops. Recent investigations have revealed the influence of seasonal precipitation regimes on PET concentrations, surface water, and vegetation dynamics in Baghdad's urban ecosystem (Al Rukabie et al., 2024).

PET patterns in India have exhibited substantial spatial variability, with huge increments observed in the north-western Himalayan belt, semi-arid areas, and the 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' vulnerability to climate fluctuations. On the one hand, national studies have shown increasing temperature trends and changing precipitation regimes. However, few region-specific studies on the PET variation exist, especially in high-altitude cold desert zones. Hence, this implies a significant gap in understanding how atmospheric water demand changes with time in vulnerable mountain ecosystems and what this means for food and water security.

Across the wider Indian Himalayan region, Potential Evapotranspiration (PET) trends exhibit considerable variability across various altitudinal gradients, seasonal radiation fluxes, and changing snowfall amounts. While eastern Himalayan states like Sikkim and Arunachal Pradesh have witnessed upward trends in PET because of warming and shortening of the snow period, western Himalayas possess more complex patterns that are frequently shaped by topographic heterogeneity and changing monsoon behaviours (Dimri et al., 2022; Kalubarme & Sharma, 2006). Previous studies by Kumar et al. (2010) and Mall et al. (2011), concluded an increase in PET for north-western Himalaya; however, such studies have often overlooked sub-district-level spaces 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 demand. This indeed forms the 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 north-western Himalayas of Himachal Pradesh, the Lahaul and Spiti constitute a cold desert agroecological zone due to their peculiar topographic and climatic features. An extremely low precipitation regime (less than 200 mm per year), high solar radiation, and seasonal glacial meltwater constitute climate-sensitive agriculture in this district (Negi & Joshi, 2004). This region has a short growing period, usually from May to September, and irrigation through sources dependent on snow meltwater. It tends to be highly susceptible to any rise in PET values. The higher PET value would increase crop water stress, thus hindering sowing and harvesting operations and the incidence of agricultural droughts. Under warming phases with aberrant precipitation regimes and diminishing glacier reserves, such impacts are expected to magnify (Shrestha et al., 2012; Immerzeel et al., 2010). Notwithstanding these risks, empirical studies relating to the long-term trends of PET in the Lahaul and Spiti are few and far between. 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 quantified PET trends systematically using suitable statistical methods that consider autocorrelation, data distribution, and nonlinear trends. Considering this district's strategic importance in food security and ecological equilibrium, this gap needs to be filled on a priority basis.

This study fills the gap through a detailed temporal analysis of PET trends in Lahaul and Spiti over 72 years (1951-2022). The PET values were computed using the FAO Penman-Monteith method, the most accurate and standardized approach toward assessing evapotranspiration under various climatic conditions (Allen et al., 1998). For the detection and interpretation of trends, 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 rectifies serial correlation (Hamed & Rao, 1998), and the Innovative Trend Analysis (ITA), which is more sensitive in detecting nonlinear and segmented trends (Şen, 2012). Individually, these techniques can assert trends in an extended climatic dataset. Besides trend detection, the study also investigates the interplay between PET and agriculture in Lahaul and Spiti in crop water requirements, seasonal moisture balance, and potential changes in cropping patterns. By fusing the study of meteorological data with those of agricultural interest, the research aims to provide some actionable outputs for local policymakers, agricultural planners, and climate adaptation agencies. The study's findings will then go into forming irrigation strategies, cropping calendars, and resource allocation frameworks for the mountain region from climate stress towards resilience.

Hence, the study strives to assess the long-term spatiotemporal trends pertaining to PET across the Lahaul and Spiti district for 72 years (1951–2022). The investigation is based on three principal research objectives: first, to determine Seasonal and annual trends in PET employing non-parametric statistical methods that are robust; second, to assess spatial heterogeneity of the 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, integrating climatological trend analysis with its agricultural context, this investigation aims to generate empirical insight considering adaptive water management and climate-resilient agricultural planning for fragile mountain ecosystems.

2. MATERIALS AND METHODS

2.1. Study Area

The Lahaul and Spiti district is the largest in Himachal Pradesh, with Keylong as its headquarters. With a geographical area of approximately 13,833 square kilometres, it is located in the north-eastern part of the state between latitude 31°44′57″N to 32°59′57″N and longitude 76°46′29″E to 78°41′34″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, viz., Udaipur, Lahaul, and Spiti and are administered from Udaipur, Keylong, and Kaza, respectively (Kumar et al., 2023).

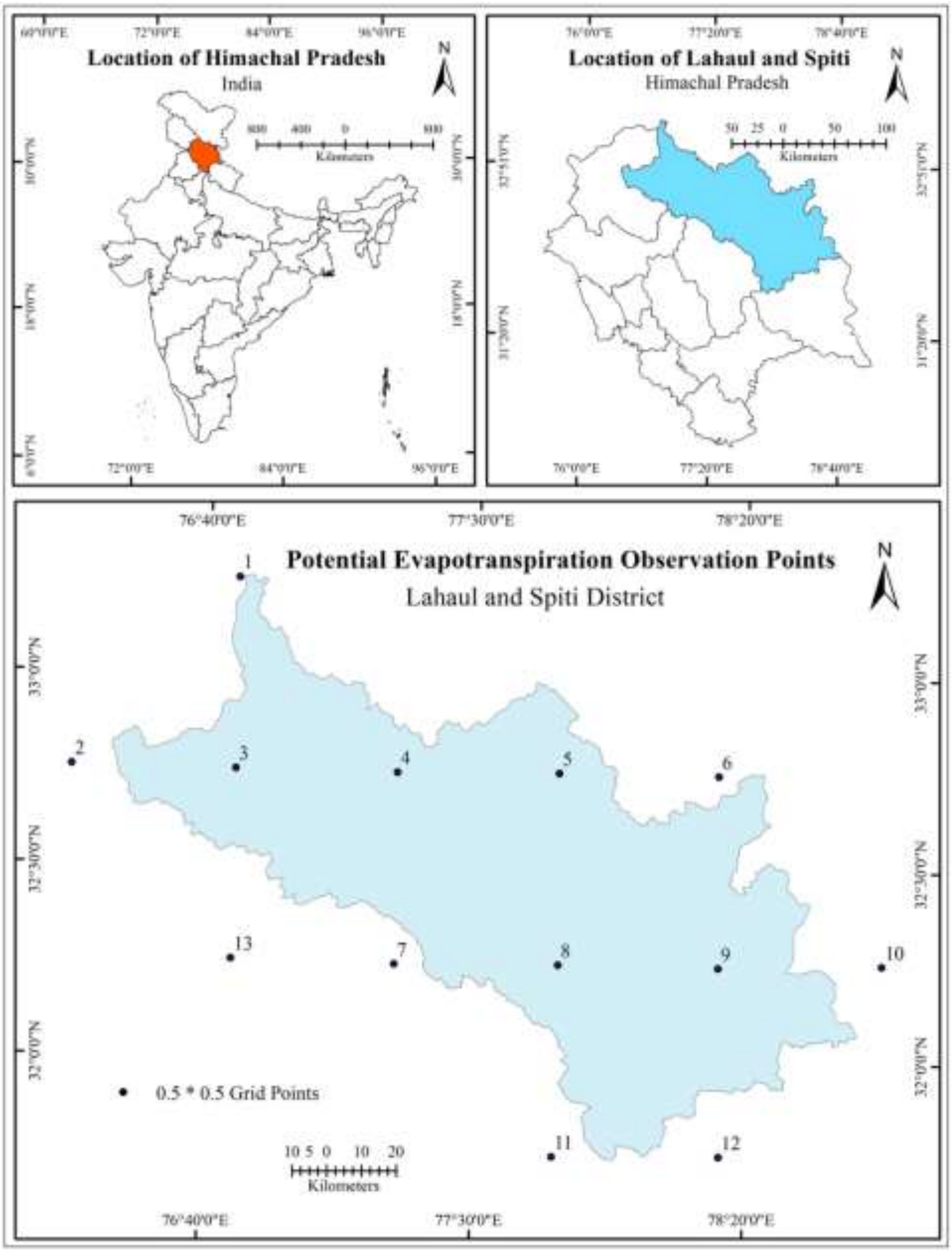

Fig. 1: Location and observation points of Potential Evapotranspiration

Recognized as a tribal region, Lahaul and Spiti fall under the ambit of 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 the agricultural sector 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 is irrigated growing of temperate crops, like peas on an area of 1,069 ha with a production of 117,590 quintal; potatoes on 680 ha, producing 108,800 quintal; and cauliflower on 839 ha, producing 208,880 quintal. High yields are obtained in vegetables, whereas cereals such as wheat and barley are cultivated only in smaller areas, worth 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 cultivating temperate fruits, dry fruits, and speciality 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.

2.2. 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 presents gridded monthly climatic variables at a relatively high spatial resolution of 0.5° × 0.5° latitude–longitude from 1901 onward (Harris et al., 2020). This dataset is considered the best among others, as it is consistent in itself, of global coverage, and thoroughly validated; hence, it shall be taken for the analyses of long-term climate trends. For the present study, PET values were extracted for 1951–2022 using latitude–longitude coordinates depicting the spatial extent of the Lahaul and Spiti district.

The CRU PET data are calculated using the FAO Penman-Monteith equation (Allen et al., 1998) from temperature, vapour pressure, cloud cover, and sunshine duration to maximize the physical basis for evapotranspiration in high-altitude arid terrains. The CRU dataset is chosen for its good temporal coverage and reliability, thus 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 thereafter processed by using climate data tools in Python for statistical analysis.

2.3. Methodology

The Mann-Kendall test is widely used to detect trends in time series of hydrologic and meteorological data, to name a few. As it is, in common usage, a test for statistical significance of trends in time series data, it 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 quite 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, that is detected. Doing so allows better determination of the direction and rate of change within seasonal or time-dependent datasets.

2.3.1. 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. The method is thus mainly applied to detect monotonic increases and decreases in given data without assuming any distribution for the variable. Secondly, 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 exit when, in reality, there is none. To circumvent such a 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 gets refocused, analyzing the trends more quickly and accurately.

The test statistics S is determined using this procedure:

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

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

$$sgn\,(x_j - x_k) = \begin{Bmatrix} +1\; if\; (x_j > x_k) \\ 0\; if\; (x_j = x_k) \\ -1\; if\; (x_j < x_k) \end{Bmatrix} \quad (2)$$

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

In Equation (3), p indicates the number of tied groups, and t 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)

$$z_{Mk} = \begin{Bmatrix} \frac{S-1}{V(S)}\; for\; S > 0 \\ 0\; for \quad 0 \\ \frac{S+1}{V(S)}\; for\; S < 0 \end{Bmatrix} \quad (4)$$

2.3.2. 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 in a time series. It was outlined by Hamed and Rao in 1998. The adjusted spatial and temporal variance formula of Var (S) is given as follows:

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

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

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

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

2.3.3. Sen's Slope Estimator

The method of Sen was first advocated to study the length and direction of linear trends in long-term observational data series (Das et al., 2020). Known as Sen's slope estimator, this method is best at detecting consistent linear changes through time because it operates well even in the presence of outliers and extreme values that would typically interfere with conventional methods (Kumar et al., 2023). These features make the method ideal when analyzing environmental and climatic datasets, which generally are highly variable and contain anomalies. It has been widely used for assessing trends in climatic variables such as temperature and precipitation. In the method, slopes Qi are computed for all possible pairs of points in time within the time series of observation data. These slope values provide information on the speed and direction of change with time. Each Qi is calculated from a simple, valuable formula for verifying trends of an environmental variable over time.

$$Q_i = \frac{Y_j - Y_i}{j-1} \quad (9)$$

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:

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

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

2.3.4. Innovative Trend Analysis

Innovative Trend Analysis (ITA) has gained practicality and popularity in hydro-meteorological research to analyze trends within time series data over the last few years. Refined over time, ITA has become the answer to many drawbacks in the standard statistical methods (Sen, 2012). Trends in time series were accepted under conditions including data normality, independence of observations, and the length of the data set. On the other hand, one distinct advantage of ITA is that it works well even with 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 values. It involves simple steps: The dataset is divided into two halves of equal size. The first observation is thrown away if an odd number of observations is present. Each half is then sorted in ascending order. Next comes the plotting of the scatter diagram, with the first half treated as the x-coordinate and the second half as the y-coordinate. Next, a 1:1 reference line will be drawn along this 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 signal downward trends. A clear visual interpretation makes ITA a very effective and user-friendly tool for recognizing complex trend patterns in hydrological and climatological datasets.

3. RESULTS AND DISCUSSIONS

The results of the analysis were generated for both annual and seasonal scales. The classifications were given by the Indian Meteorological Department, namely: Winter; January-February; Pre-Monsoon; March-April-May; Monsoon; June-July-August-September; and Post-Monsoon: October-November-December (IMD, 2022). Also, a single growing season is observed for high-altitude cold desert regions, Lahaul and Spiti. Its duration extends from April to October (Spehia et al., 2024). The MK trend and m-MK trend analysis show a 95% ($p < 0.05$) and 99% ($p < 0.01$) confidence level.

3.1. Mann Kendall Trend Analysis

Mann-Kendall test indicates a significant decreasing trend during all the seasons. During Winter, PET shows a definite decreasing trend, with Z-values between -3.42 and -0.62. The declining trend depicts that lesser 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 follows a distinct decreasing trend, with the respective Z-values varying from -4.59 to -2.33 (Fig. 2b). Similar trends emerge during the monsoon season, with Z-values between -4.66 and -1.73. The decrease in PET during monsoon fall is perhaps due to increased cloud cover and rainfall, with decreased evaporation despite rising temperatures (Fig. 2c). Through the post-monsoon period, a significant reduction in PET is indicated with Z values between -6.69 and -3.50, suggesting that atmospheric water demand has 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 the interval of -7.04 to -3.38, indicating that there have been marked declines in evapotranspiration rates over the decades (Fig. 2e). During the agricultural period, one of the strongest decreasing trends appears with Z-values ranging from -6.47 to -2.92, indicating that rates for evapotranspiration during the growing season have significantly decreased, which could affect water management for crops and irrigation (Fig. 3a).

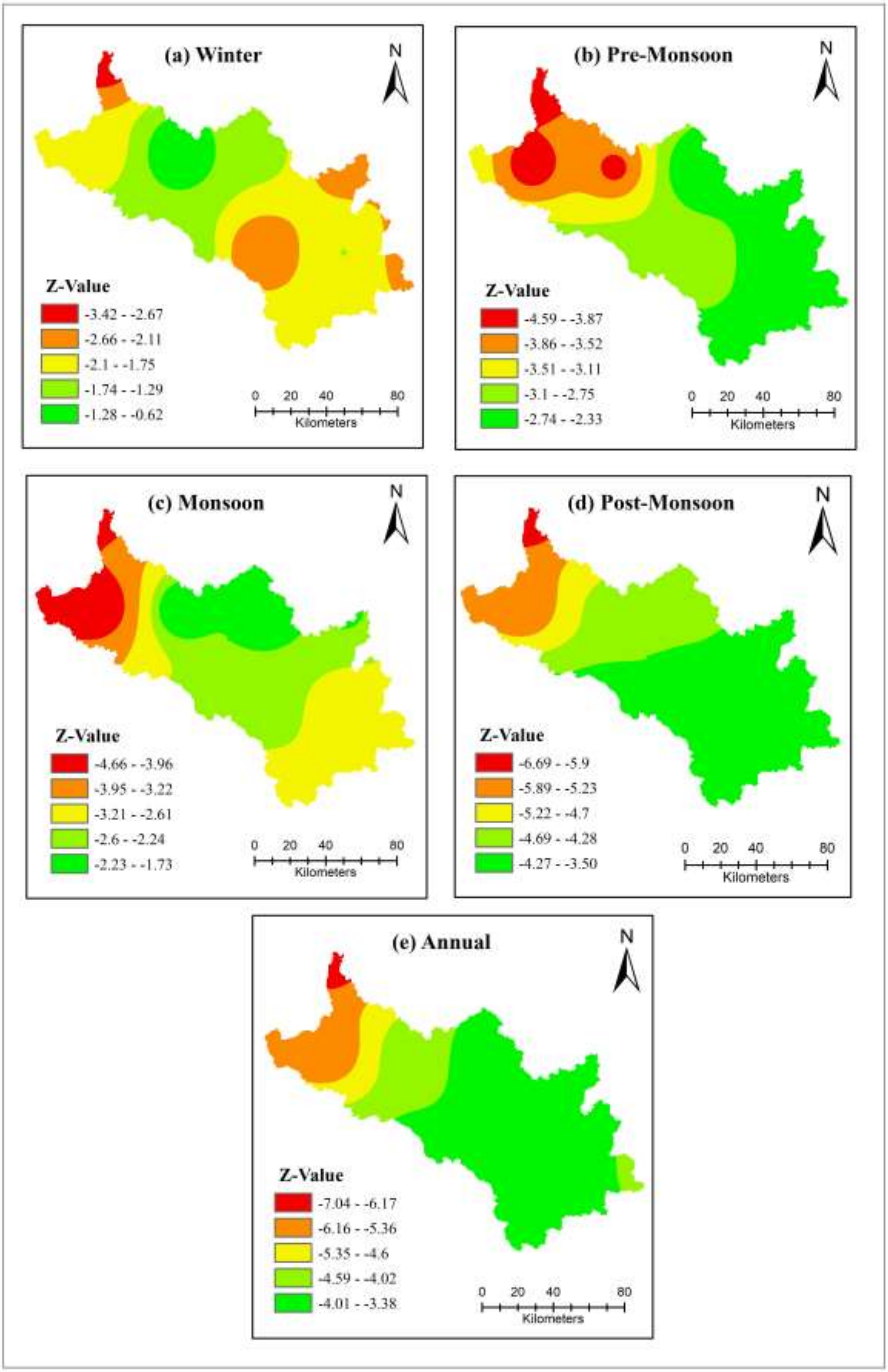

Fig. 2: Seasonal and Annual Spatial Distribution of PET Z_{mk} values from 1951 to 2022.

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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 MK test evidenced 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 at 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 throughout 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 has a decreasing trend during the monsoon season, notably at Grid Point 3, near Udaipur in 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 trends. The most significant fall can be seen at Grid Point 1, near Chimrat panchayat in Lahaul block (Z = -6.69, magnitude = -0.0026 mm/year) and is trailed closely by Grid Point 3, near Udaipur in Lahaul block (Z = -5.80) and Grid Point 2, near Tindi panchayat in Lahaul block (Z = -5.35). Such strong trends indicate that there has been a considerable reduction in PET over time. The Agricultural season also shows a significant decrease in PET; sizable decreases are seen in all grid points at 99% significance. The most significant decreasing trend is noted in Grid Point 1 (Z = -6.47, magnitude = -0.0025 mm/year) with 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 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).

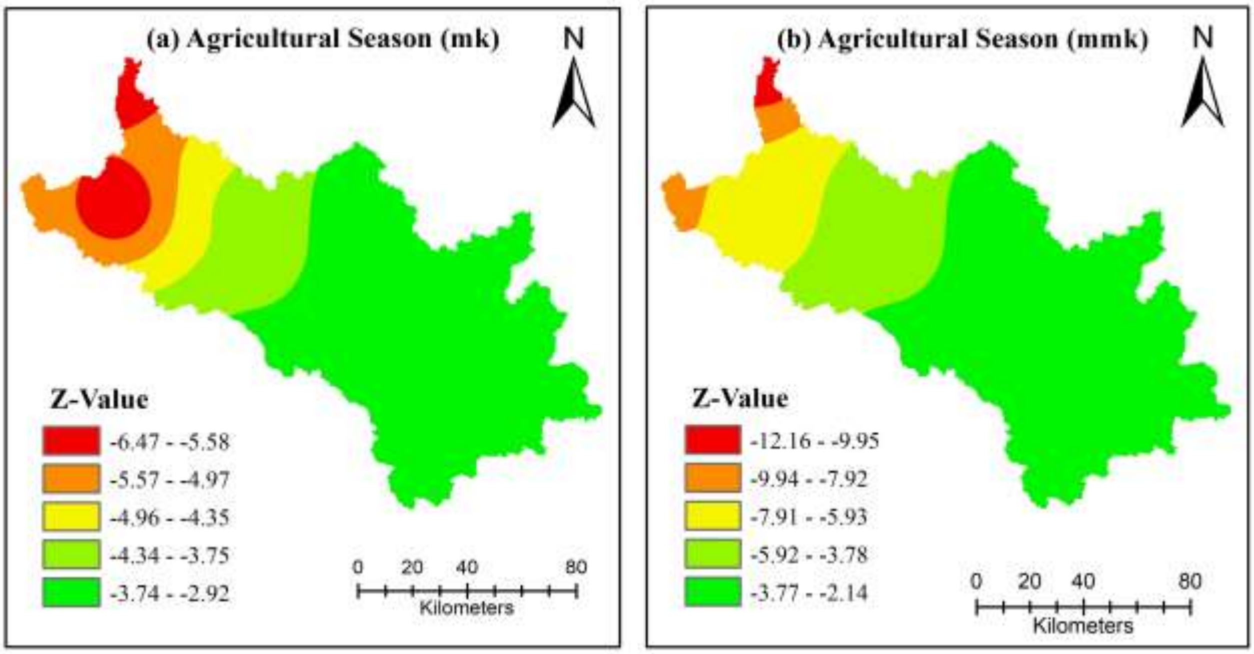

Fig. 3: Spatial distribution of Agricultural season (a) Mann Kendall (b) Modified-Mann Kendall

3.2. Modified Mann Kendall Trend Analysis

The m-MK test enunciated a remarkable decreasing trend for all seasons, indicating the decreasing atmospheric moisture demand through time. A substantial decline in PET has been noted during the winter months; the Z-value ranges from -7.17 to -0.94, thus suggesting that the rates of winter evaporation and transpiration have been decreasing (Fig. 4a). The other significant declination of PET is observed during pre-monsoon periods, reflected in Z-values from -11.13 to -2.00 (Fig. 4b). Monsoon PET follows the same trend with Z values ranging from -12.48 to -1.59, thus suggesting the decline of PET owing to increased humidity and higher rainfall through the wet season, which would lower direct evaporation from the land surface (Fig. 4c). During post-monsoon, 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 mean retention of moisture in soils for long 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).

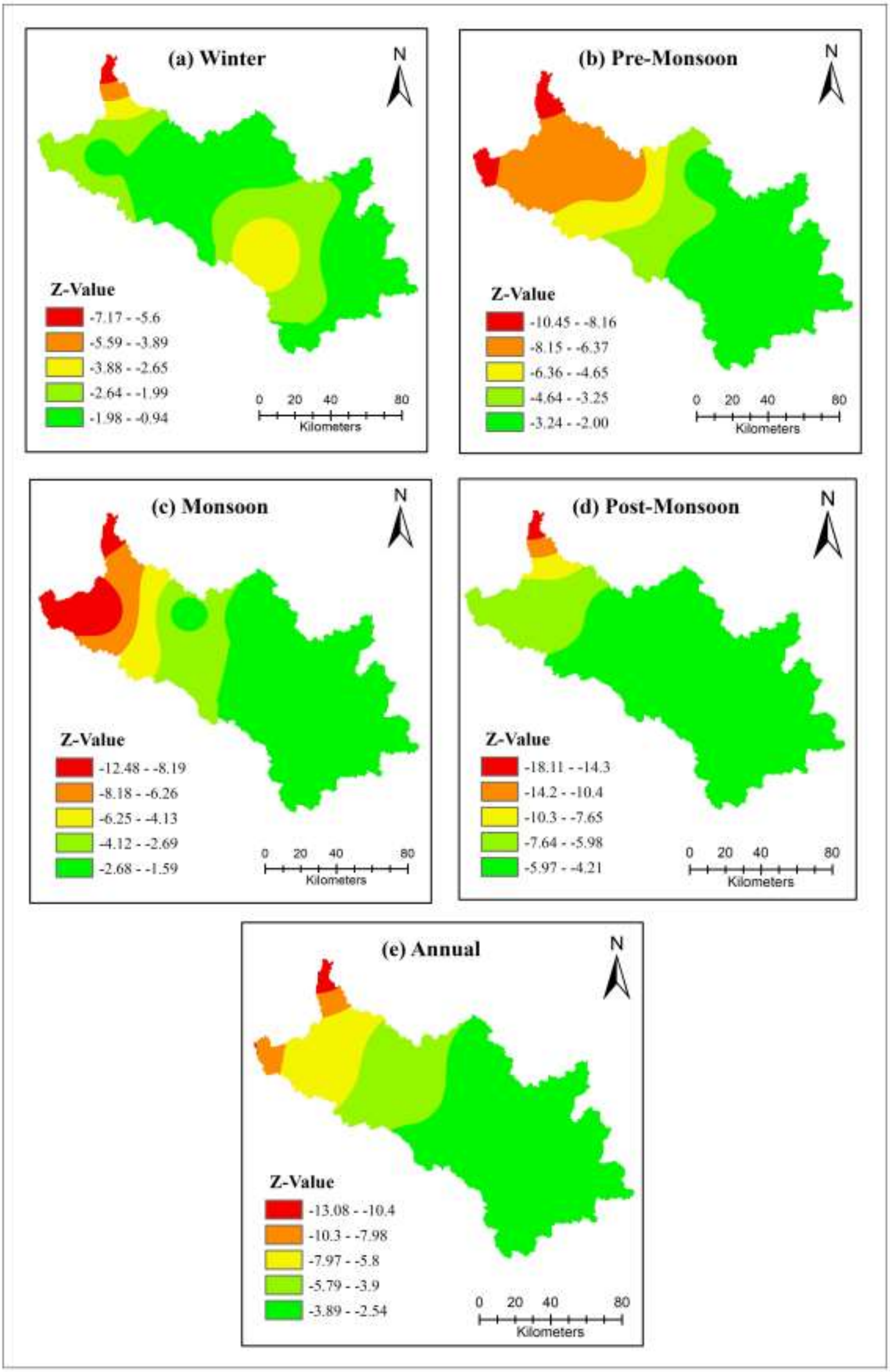

Fig. 4: Seasonal and Annual Spatial distribution of PET Z_{mmk} values from 1951 to 2022

In Winter, most grid points showed a significant decreasing trend in PET, while 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 evaporative demand. Declines were also indicated for Grid Points 3, 4, and 5; however, such trends were not statistically significant. Evapotranspiration rates experienced a pronounced and broad decline: Pre-Monsoon season PET followed a similar, albeit less intense pattern. In this, nine grid points are significant at 99% level and remaining at 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 also at Grid Point 1, 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, the PET trends decreased over all grid points, and five grid points were statistically significant at 99%. The highest decrease in PET was observed for Grid Point 2, near Tindi panchayat in Lahaul block (Z = -12.48, magnitude = -0.0028 mm/year). The Post-Monsoon season has 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 that there may be a progressive decline in crop water demand, necessitating adaptation of irrigation strategies to improve water usage while maintaining soil moisture levels. The trend analysis for PET on an annual basis confirms 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). The sustained trend of decline in annual PET may signal a shift in the net evaporative dynamics relating to large-scale climate variability, decreasing solar radiation, and altered atmospheric moisture columns (Table 1).

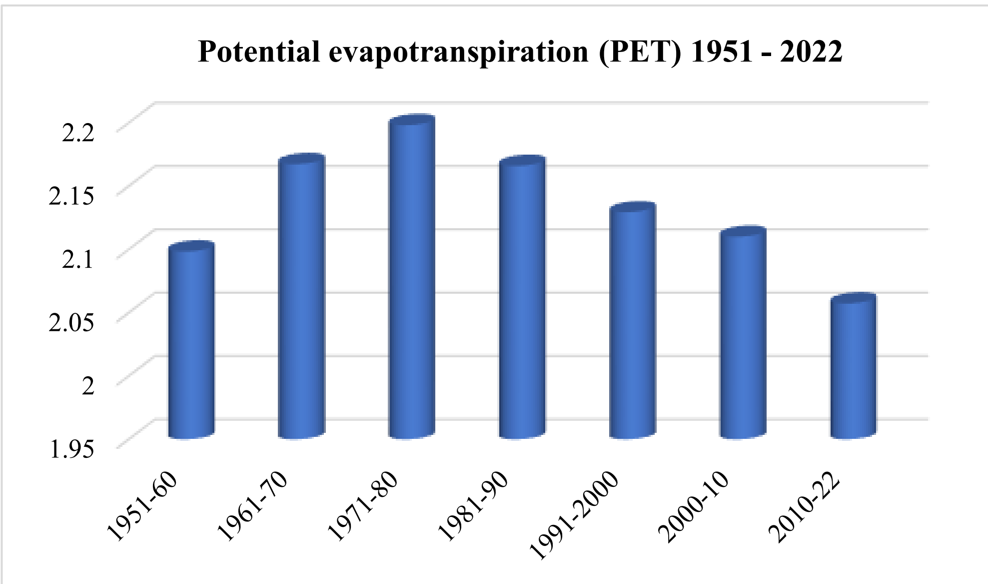

Fig. 5: Decadal variation in annual Potential Evapotranspiration across Lahaul and Spiti from 1951 to 2022

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

3.3. Innovative Trend Analysis

Innovative Trend Analysis (ITA) on PET from 1951 to 2022 posits 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 unchanged or no trend condition. Values beneath 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) cluster in a supposedly decreasing triangle, clearly marking declining PET trends. The decline in winter PET could have been due to solar radiation being less or cooling temperatures, with respective influences declining the evaporation rate.

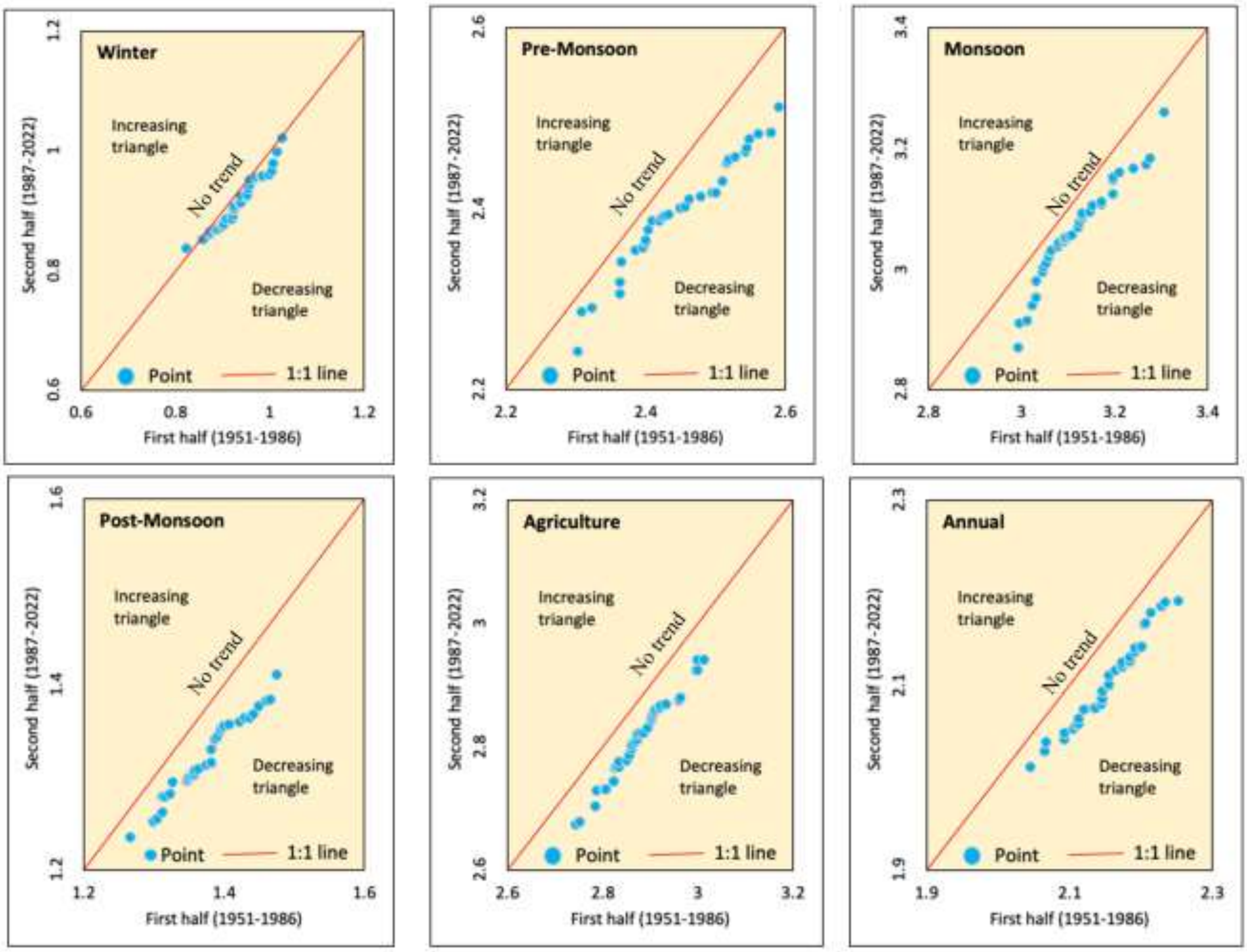

Fig. 6: Innovative trend Analysis (ITA) for Potential Evapotranspiration during 1951 to 2022

In historical decline, the same situation is observed concerning pre-monsoon and monsoon PET, indicating a lesser atmospheric demand for moisture within these vital pre-monsoon and monsoon periods due to temperature reduction and increased humidity. Another downward trend in post-monsoon, which further confirms the gradual weakening of evaporative demand, is observed. For agricultural season PET, a similar downward trend indicates less demand for irrigation water due to reduced atmospheric moisture loss from 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).

3.4. 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 seasonal decreasing trend. The trend was found through the application of 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 ecosystem.

Agriculture in Lahaul and Spiti is vertically oriented toward high-value crops like potato, green peas, barley, and buckwheat (Negi & Joshi, 2004). There is a short growing season for such agriculture, and irrigation remains dependent on glacial and snowmelt. A rapid agro-economic transformation has occurred in the region since such infrastructural development has included the Atal Tunnel, which has improved connectivity and market access (Sherup, 2023; Kumar et al., 2023). This has also led to increased agent areas and mechanisation, shifting toward polyhouse cultivation on a broader scale of intensification. Assuming that the lowering of PET is evidenced by Z_{mk} values between -6.47 and -2.92 and Z_{mmk} values between -12.16 and -2.14, it indicates that the moisture demand of the atmosphere dwindled.

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.

An agricultural household survey of 295 farmers conducted in Lahaul and Spiti from May to June 2024 brought exceptional experiential clarity to these climatological observations. The farmers were mainly unanimous in their responses from one district to another, noting increases in ambient temperatures, resulting in premature snowmelt and shortened water availability during the early growing stages. In their perception, irrigation water demand would be increasing mainly at the time of transplanting and flowering demand due to these changes, necessitating formal channelisation of water, an adaptation new in an area where previously a gravity-fed kuhl system was sufficient. Farmers also spoke of an increase in erratic rainfall, chocked with very short, intense spells followed by lengthy dry periods, with its share of constraints for crop scheduling and water budgeting. These perceptual insights gain credence from instrumental data and alert us to the critical need for aligning scientific inference with local knowledge to plan for adaptation effectively (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 least (Santosh et al., 2023). The intricacy of this pathogen dynamic has been recorded at the international level, varying with crop species, canopy architecture, and agronomic management (Raza & Bebber, 2022).

Some insights of a similar nature have originated from tropical domains, where the expansion of croplands significantly influenced the dynamics of evapotranspiration over time (Laipelt et al., 2024). Their findings illuminated PET's susceptibility to variations in land use, reaffirming the importance of viewing PET trends in the context of larger landscape and land cover changes. Resemblances that exist with international experiences further add to this debate. For example, Multsch et al. (2020) demonstrated the impacts of vast irrigation expansion in Brazil on PET and water resource availability; thus, Al-Hasani et al. (2022) highlighted the strong coupling of PET dynamics with phenological responses in temperate zones, further stressing the convoluted PET-crop-climate feedbacks.

3.4.1. Adaptive Strategy for Agriculture

The agrarian strategy for Lahaul-Spiti must henceforth 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 the reduced PET levels, thus avoiding over-application and conserving the limited stored snowmelt reserves.

- **Climate-smart crop choices**: Diversification can include short-duration, disease-resistant cultivars like Kufri Himalini (potato) along with pseudo-cereals such as buckwheat that 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 out-breaks under the changing PET and humidity regimes (Thakur & Klate, 2023).

- **Hydrological buffers**: Constructing high-altitude lined meltwater ponds and solar-powered night-time irrigation may provide a service ameliorating 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 vapour pressure deficits, discouraging pathogen infection under the lowered PET scenario.

4. LIMITATIONS

Despite having robust methodology and duration, the present study is weighed by some caveats that warrant mentioning. The use of CRU TS v4.07 data at a spatial resolution of 0.5° × 0.5° is a very 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 the PET trends. These would be excellent candidates to be included as a major component of future works involving much finer scale observations from ground research relevant to adaptive agricultural planning.

5. CONCLUSIONS

The present analysis of long-term trends of Potential Evapotranspiration (PET) in Lahaul and Spiti deepens an understanding of climate–agriculture interactions in high-altitude arid regions. Besides finding declining PET trends, the study discusses how such climatologic alterations intersect with changes experienced at a larger level in agricultural transformations, like 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 may be taken as a indicator and used in conjunction with the entire hydro-meteorological and agroecological context consisting of soil moisture availability, actual evapotranspiration, and crop water requirements.

With crop planning being 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; these crops 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 the 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 for 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 expansion will depend on the adaptive response to climate change. Policymakers and agricultural planners must consider opportunities arising from decreased evaporative stress and the risks increasing 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 up 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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