RESEARCH

Spatio-temporal variations of reference evapotranspiration using Innovative and Mann–Kendall trend analysis under limited weather data in semi-arid region of Indian Punjab

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Abstract

The trend detection in hydro-climatological series is a prime priority in the context of changing climate. Evapotranspiration is a crucial component of the hydrological cycle and surface energy balance that plays a key role in irrigation water management. The present study examined the spatio-temporal variations of annual and seasonal reference evapotranspiration using Mann–Kendall and Innovative trend analysis, in South West and central part of Punjab over the period of 1980–2021. The results revealed that reference evapotranspiration (RET) for the annual, pre-monsoon, and post-monsoon series at Sangrur (Central Zone) and for winter at Bathinda (South-West) were serially correlated using the autocorrelation test of lag-1 at a 5% significance level. The highest aridity index (0.34 ± 0.10) and the lowest moisture index (-0.66 ± 0.10) were detected at Moga station, followed by Sangrur station in Central Punjab. The overall results revealed that annual and seasonal trend of reference evapotranspiration was significantly decreasing over the period 1980–2021. The spatial distribution of Sen's slope percentage change was highest at Mansa station, followed by Sangrur station. Mann–Kendall trend analysis of annual and post-monsoon series revealed that out of a total of six stations, Barnala, Muktsar Sahib, and Sangrur showed a significant decreasing trend. The Sen's slope and ITA trend slope of monsoon series are statistically decreasing at 1% and 5% significance level all over the districts. In the pre-monsoon season, an increasing trend of RET was detected throughout all the stations, with the highest percentage change of 4.3% detected at Mansa station. The ITA trend slope of ET_0 exhibited decreasing magnitude in the annual, monsoon, post monsoon except at pre-monsoon season all round the districts. While the contrasting trend is found in MK slope exhibited increasing and decreasing trend in the pre-monsoon season. The innovative trend slope revealed the presence of a hidden trend for RET that was missed by the traditional MK/MMK test. The study may guide planners and policymakers in the effective implementation of crop water management strategies to improve the status of water resources in Punjab.

1 Introduction

Evapotranspiration is a crucial component of the hydrological cycle and surface energy balance by which water in its liquid state evaporates from plant and soil surfaces to the atmosphere (Sellers et al. 1996). The rise in rainfall and temperature is expected to drastic increase in evapotranspiration and soil water storage up to 45% (Azmat et al. 2018). Evapotranspiration is the key component of surface energy balance which is useful for estimation of crop water demand, irrigation allocation in canal command area and uniform distribution of water in arid and semiarid region where agricultural productivity greatly relies on irrigation water supply (Zahid et al 2023; Madane and Waghaye 2023). Evapotranspiration determines crop water demand, water budget, seasonal water needs, water distribution, and groundwater recharge for the management of hydraulic structures for sustainable water use (Ghafouri-Azar et al. 2018). The evapotranspiration trend of long-term, decadal, seasonal, and annual would be utmost importance for the planning and management of water resources in a sustainable manner.

The scenario of reference evapotranspiration has direct influence on growth of agricultural crops (Madane et al. 2023b). The Punjab state has a major growing potential of rice–wheat, maize-cotton cropping system cultivated under traditional irrigation system based on canal and groundwater resources (Madane et al. 2023a). The extensive Indira Gandhi canal network carries water from the Sutlej and Beas river

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which irrigate vast dry land in Punjab (CGWB 2023). The scenario of ET_0 has diverse trend especially in the arid and semiarid region and which enable to projections of complex spatio-temporal trends of ET_0 (Kingra 2018). Temperature changes can have a significant impact on various elements of the water cycle: precipitation, evapotranspiration, soil moisture, etc. Evapotranspiration (ET_0) is a major component of the water cycle and influences plant water demand and future plans (Madane et al 2023a). Hence, a complete understanding of ET_o spatio-temporal variability and an accurate assessment of the impact of climate change. The long-term ET_o trend analysis is essential for the efficient use of water resources and vegetation management (Drogue et al. 2004; Chen et al.2007; Han and Hu 2012 and Han et al. 2014).

Besides, numerous studies have been focused to quantify the ET_0 trend analysis indicated by various researchers such as Kingra et al. (2017), reported that long-term ET_0 using the Papadaki method found increasing crop water requirements from 2011–2040 (1027 mm) to 2071–2100 (1150 mm). Darshana et al. (2013); Duhan and Pandey (2013) found that reference evapotranspiration (ET_0) has been significantly decreasing at 1, 5, and 10% significant levels. However the magnitude of the decreasing annual ET_0 varied from 1.75 to 8.98 mm per year. Jhajharia and Singh (2011) reported that the ET_0 annual trend significantly decreased at a rate of 7.7% in north-east India during 1979–2000. Singh et al. (2022) reported that the classical trend of ET_0 was decreasing in all the seasons (spring, autumn, summer, and winter) at a 5% significance level in the Ludhiana district of central Punjab. Jhajharia et al. (2015) reported a decrease in reference evapotranspiration over the Thar Desert due to the calm atmosphere witnessed over the arid region and caused mainly by aerodynamic components of a decrease in wind speed. The literature showed that a decline trend of ET_0 was observed in the last couple of decades in various parts of India. The inconsistent scenario of ET_0 trend indicated by various researchers at regional level which will be intended to direct the influence of water resources. It is utmost important to projections of clear notation of the historical trend of ET_0 and its response to climate change in order to achieve futuristic planning of water resource strategies and water security.

Most researchers conducted studies on the spatiotemporal trend of reference evapotranspiration around the world and cited here. The MK/MMK methods are frequently used in trend detection studies, but there are certain limitations, such as serially independent series and the normality of the distribution (Yue et al. 2002). To overcome these limitations, Şen (2012) proposed a new innovative trend analysis (ITA) for the trend detection of rainfall, stream flow, pan evaporation, and water quality parameters in different regions of the world (Tabari et al. 2017; Ahmas et al. 2018; Caloiero et al. 2018; Caloiero 2020; Singh et al. 2020, 2021). The use of spatiotemporal trend analysis in hydrologic and meteorological domains, as well as

its magnitude at regional and national scales, benefits socio-economic development (Singh et al. 2020, 2021). Pastagia and Metha (2022) analyzed the long-term (1902–2021) temporal trends of seasonal and annual floods and droughts in Rajsamand district of Rajasthan, India. They reported that the ITA approach categorizes trends into low, medium, and high, with positive or negative trends used for future forecasting of floods and droughts. Singh et al. (2020) studied spatio-temporal trends and variability of seasonal and annual for the 36 districts of Maharashtra, India, using traditional tests and innovative ITA tests. They reported that the ITA approach was simple and sensitive in trend detection for a total of 56.6% of the time series, which the MK/MMK, SRC, and SLR tests did not capture. Wang et al. (2020) studied comparative trend analysis by using ITA and the classical method for 14 stations of the Yangtze River, China, during the period of 1961–2016. The results revealed that the ITA trend was significant and increasing at the 99 percent confidence interval. The results confirmed by ITA call for more attention to flood and drought risk management as compared to classical trend methods (Kumar et al. 2021). However, most of previous studies used classical trend analysis of reference evapotranspiration, which did not reflect hidden characteristics at the seasonal scale. The attempt innovative trend analysis of ET_O is lacking in the study area. Therefore, the attempt has been made with the objective of identifying long-term trends and spatio-temporal variability in seasonal and annual reference evapotranspiration using the Mann–Kendall test and innovative trend (ITA) analysis method.

2 Material and methods

2.1 Study area

The study area includes Central Punjab (three stations) and South West Punjab (three stations), as depicted in the study area map (Fig. 1). The observed gridded data of corresponding latitude and longitude of monthly maximum temperature, minimum temperature, rainfall, and solar radiation are acquired from the Indian Meteorological Department (IMD) website (https://www.imdpune.gov.in/) for the period of 1980–2021. The locations of the study area are represented in Table 1. The Central Zone of Punjab is semi-arid to dry sub-humid with a mean annual rainfall of 561 mm, and the South Western Zone is semi-arid to arid with a mean annual rainfall of 363 mm (ENVIS 2021).

2.2 Methodology

The sequential methodology adopted is represented in the flow chart (Fig. 2). The seasonal rainfall series of monsoon season (June to September), post-monsoon season (October to November), winter season (December to February), and pre-monsoon season (March to May) were prepared
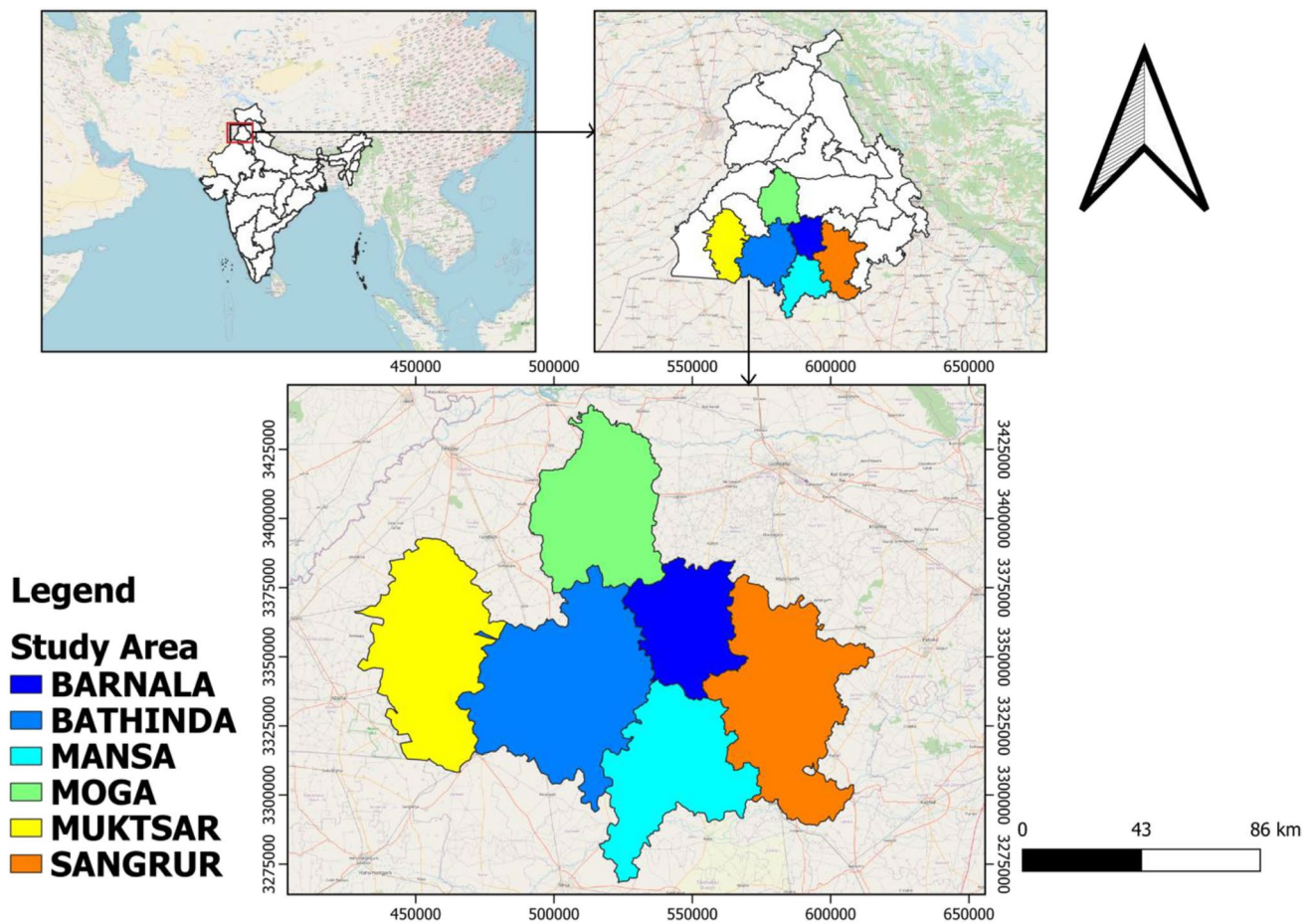
Fig. 1 Study area map

Table 1 Locations of selected stations in the Punjab state

Station name	Latitude (°N)	Longitude (°E)
Central Punjab		
Barnala	30.3	75.61
Moga	30.7	75.19
Sangrur	30.2	75.88
South West Punjab		
Bathinda	30.3	75.0
Mansa	29.9	75.42
Muktsar	30.5	74.55

for reference evapotranspiration (MK/MMK and ITA) trend analysis (Kingra 2018; IMD 2021).

2.2.1 Computation of reference evapotranspiration (ET$_0$)

The Hargreaves method for estimation of reference evapotranspiration is based on minimum and maximum temperatures and gives a reasonable estimation due to its linkage with solar radiation (Ra). This method is highly suitable for the limited availability of weather data for estimation of reference evapotranspiration. However, Gocic and Trajkovic (2014) reported that ET$_0$ estimated using the FAO-56 Penman Monteith method and adjusted Hargreaves indicates almost similar trends on the annual and seasonal time scales. The reference evapotranspiration was computed by using the Hargreaves equation with the help of R 4.2.1 software (Hargreaves and Samani 1985).

$$ET_0 = 0.0023 \times R_a \times \delta T^{0.5} \times (T + 17.8) \tag{1}$$

where, R_a is the mean extra-terrestrial radiation (mm/day), δT is the mean monthly temperature difference of maximum and minimum temperature and T is the mean air temperature in °C.

2.2.2 Estimation of aridity index

The aridity index for arid region was 0.03 to 0.20 and for semiarid region was 0.20–0.50 according to (UNEP 1997).

Fig. 2 Flow chart showing the trend analysis architecture of reference evapotranspiration
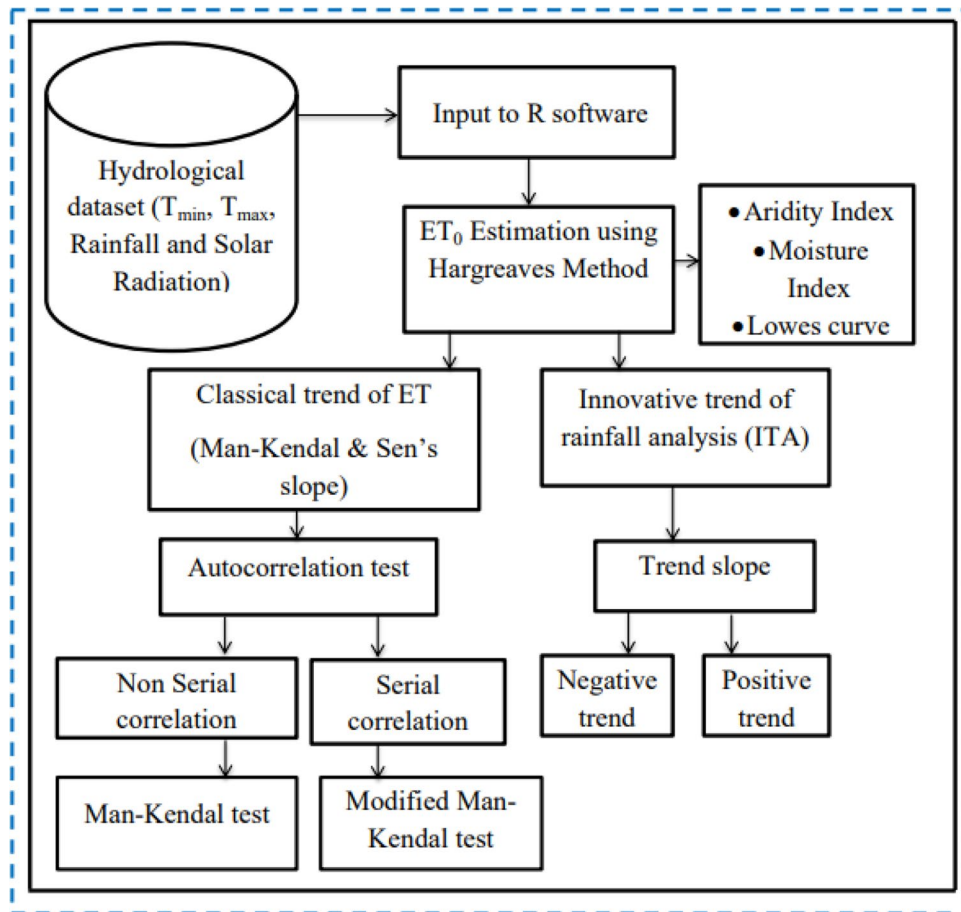
The aridity index (AI) was estimated using the following relationship (UNESCO 1979; UNEP 1997).

$$AI = \frac{P}{ET_0} \qquad (2)$$

where, AI is the aridity index, ET_0 is the annual mean of reference evapotranspiration (ET), annual mean of precipitation (P).

2.2.3 Estimation of moisture index

The availability of vegetation moisture content was estimated using the moisture index (MI) by Krishnan and Singh (1972) as follows: (3)

$$MI = \frac{(P - ET_0)}{ET_0} \qquad (3)$$

The moisture index for arid (dry) region was (-60 to -40) and for semi-arid (-80 to -60) classified by (Krishnan and Singh 1972).

2.2.4 Statistical tests

The Lowes curve (nonparametric regression curve) of mean annual RET of selected station was estimated using XLSTAT software. The trend analysis of MK and Innovative (ITA) was carried out using R software version 4.0.2 (R Core Team 2020).

Autocorrelation test The autocorrelation test was used to determine the serially independed trend of the rainfall time series. The autocorrelation function (Box and Jenkins 1976) is defined as follows for the precipitation series $P_1, P_2 ..., P_n$ at times $t_1, t_2, ..., t_n$.

$$r_k = \frac{\sum_{i=1}^{n-k} \left(P_i - \overline{P} \right) \left(P_{i+k} - \overline{P} \right)}{\sum_{i=1}^{n} \left(P_i - \overline{P} \right)^2} \qquad (4)$$

The precipitation time series was tested for lag-1, autocorrelation, at $\alpha = 0.05$.

Where, $\overline{P} = \sum_{i=1}^{n} P_t$ is the average of 'n' samples.

Mann–Kendall test The MK test is non-parametric test (Shifteh Some'e et al. 2012; Subash et al. 2011; Tabari et al. 2011) was used to detect reference evapotranspiration (RET) trends of annual and seasonal data using Eq. (5);

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \text{sgn}(X_j - X_k) \tag{5}$$

where, X_1, X_2, X_3, …,X_n shown data points and X_j represents at j^{th} time. Statistically positive test represents the increasing trend and vice versa.

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

The E [S] = 0 and variance is given by,

$$\text{variance} V[S] = \frac{n(n - 1)(2n + 5) - \sum_{i=1}^{m} t_i(t_i - 1)(2t_i + 5)}{18} \tag{6}$$

where, n is total number of observations and m is tied groups in data set and t_j is the number of sample points in j^{th} tied group.

The standardized z-statistic is given by Eq. (7);

$$Z = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}} if S > 0 \\ 0 \, if S = 0 \\ \frac{S+1}{\sqrt{\text{Var}(S)}} if S < 0 \end{cases} \tag{7}$$

In this trend positive Z values indicate upward trend, while negative Z values indicate downward trend. The MK test was used at 5% and 1% significance level. The serially auto-correlated reference evapotranspiration series data is often affecting trend detection (Novotny and Stefan 2007). The modified Mann–Kendall test is used for serially correlated dataset using variance correction approach (Hamed and Ramachandra Rao 1998).

Sen's slope test Sen's slope test is used to determine the magnitude of the trend (Sen 1968) and is given by median of all slopes and value of median d_k is calculated by using Eq. (8);

$$\beta = \frac{X_j - X_i}{j - i} \tag{8}$$

For all, $1 \le i \le j \le n$.

The percentage change in magnitude is calculated using following equation.

$$\text{Percentage change (\%)} = \frac{\beta \times \text{length of year}}{\text{mean}} \times 100 \tag{9}$$

where, β = Sen's slope value.

The spatial distribution of percentage change was carried out by IWDinterpolation techniques using open source Q GIS software.

2.2.5 Innovative trend analysis (ITA)

The MK/MMK and Sen's slope test were used for classical trend analysis of rainfall time series; similarly, innovative trend analysis (ITA) was used for rainfall time series, which was proposed by Şen (2012). The ITA series has been divided into two parts, which are the first half and the second half, and this is free from serial autocorrelation, normal homogeneity, and length of records. The X axis represents the first half series and the Y axis represents the second half series in the Cartesian coordinate system. The data points accumulated on the 1:1 line indicate no trend in the time series, while data points distributed above the line indicate a positive trend and below the 1:1 line represent a negative trend. According

Table 2 Preliminary result analysis

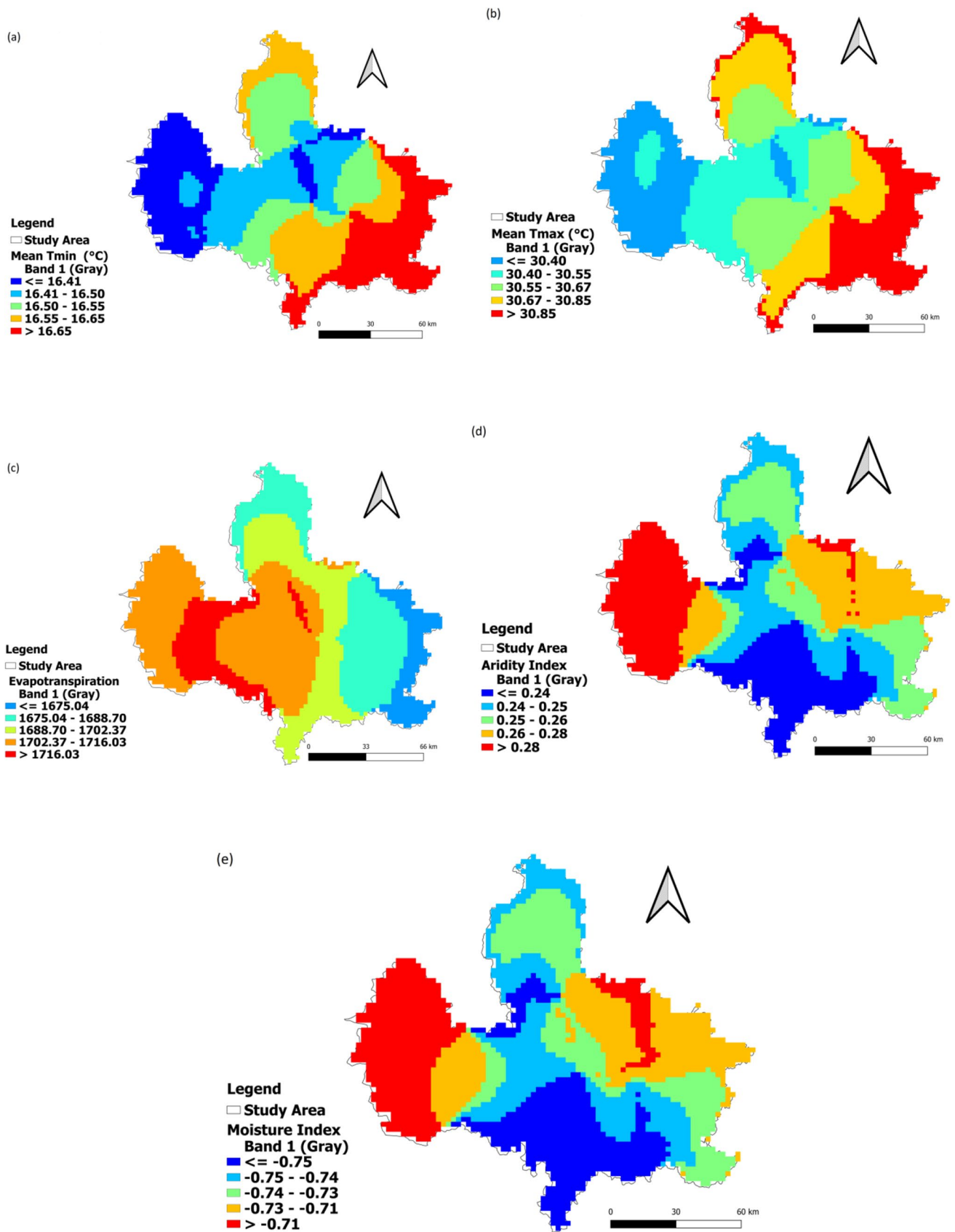| Stations	T_{min} (°C)	T_{max} (°C)	ET_0 (mm)	Aridity Index (%)	Moisture Index (%)
Central Zone					
Moga	16.3 ± 1.9	30.3 ± 0.6	1675.7 ± 40.2	0.34 ± 0.10	-0.66 ± 0.10
Sangrur	16.2 ± 0.4	30.2 ± 0.8	1661.1 ± 52.2	0.30 ± 0.10	-0.69 ± 0.10
Barnala	16.6 ± 0.4	30.9 ± 0.6	1709.2 ± 39.4	0.25 ± 0.09	-0.74 ± 0.09
South West Zone					
Bathinda	**16.8 ± 0.5**	**31.1 ± 0.7**	**1730.2 ± 53.4**	0.26 ± 0.07	-0.73 ± 0.07
Mansa	16.5 ± 1.7	30.4 ± 1.6	1694.5 ± 81.4	0.22 ± 0.08	-0.77 ± 0.08
Muktsar Sahib	16.7 ± 1.9	30.9 ± 0.6	1712.3 ± 39.2	0.22 ± 0.09	-0.77 ± 0.09

Fig. 3 Spatio-temporal variations of mean **a**) Minimums temperature, **b**) Maximum Temperature, **c**) Reference evapotranspiartaion, **d**) Aridity Index, **e**) Moisture Index
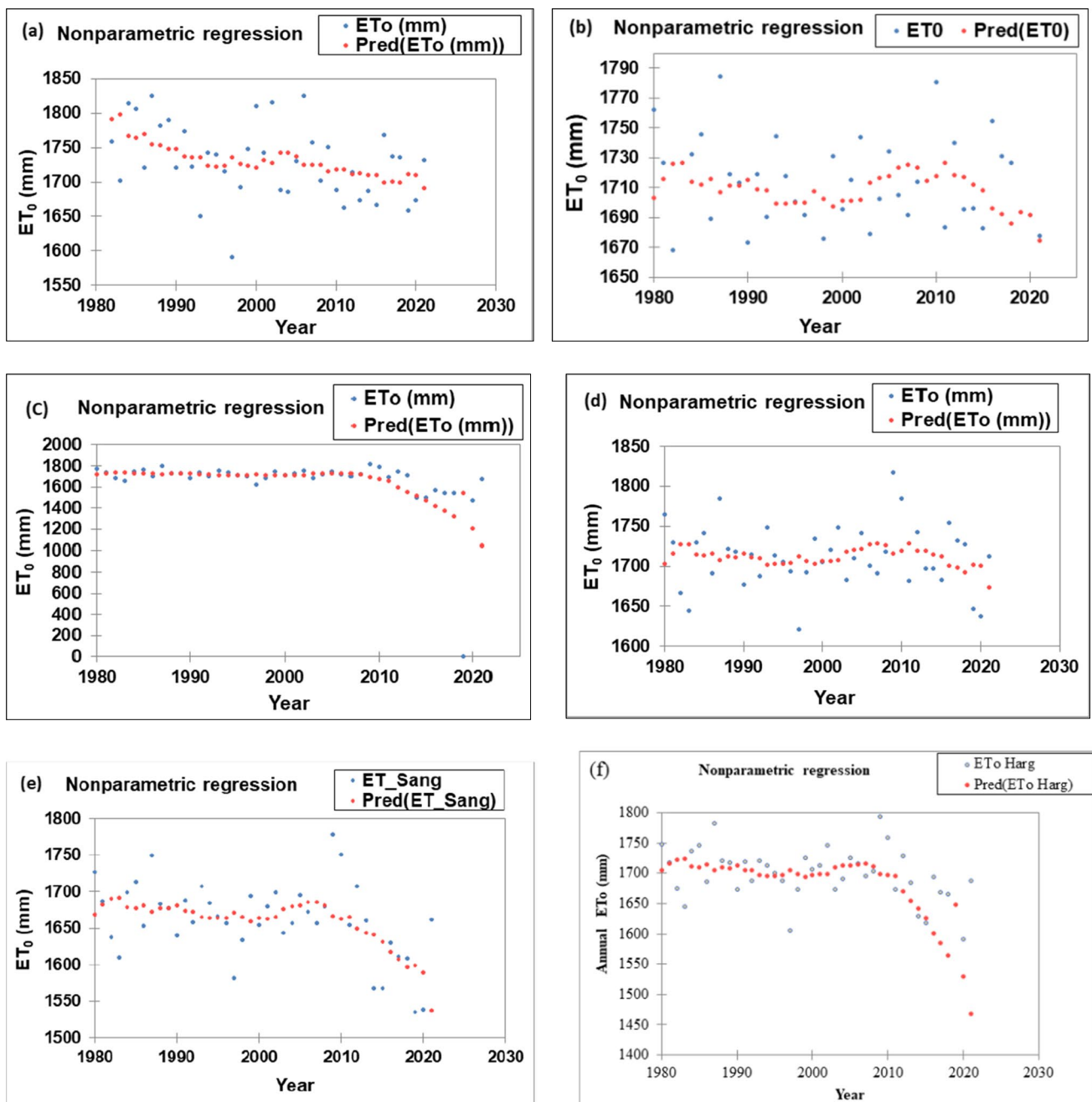
Fig. 4 LOWESS curve analysis of annual reference evapotranspiration of (**a**) Bathinda, (**b**) Barnala, (**c**) Manasa, (**d**) Muktsar Sahib (**e**) Sangrur (**f**) Moga

to Şen (2017), the ITA slope (SITA) was tested; a positive value indicates an increasing trend, while a negative value indicates a decreasing trend in the rainfall time series. The trend change package and R software version 4.0.2 (R Core Team 2020) were used for ITA.

2.2.6 Spatial mapping of RET

The spatial distribution of MK/MMK slope and ITA slope was prepared using IWD interpolation by using open source Q GIS Software (ver.3.34.1).

3 Results and discussion

3.1 Results of preliminary analysis

The mean monthly maximum temperature (Tmax), minimum temperature (Tmin), reference evapotranspiration (ET_0), aridity index (AI), and moisture index (MI) are depicted in Table 2 and IWD Interpolation depicted in Fig. 3. The mean reference evapotranspiration (RET) estimated using the Hargreaves method (Hargreaves 1994) for the Central Zone varied from 1661.1 ± 52.2, at Sangrur to 1709.2 ± 39 at Barnala. In the south-west zone, the mean monthly RET varied from 1694.5 ± 81.4 at Bathinda to 1694.5 ± 81.4 at Mansa. The highest mean monthly minimum, maximum temperature and reference evapotranspiration were detected 16.8 ± 0.5 °C, 31.1 ± 0.7 °C and 1730.2 ± 53.4 mm, respectively, at Bathinda Station in South West Punjab. The highest aridity index of 0.34 ± 0.10 and the lowest moisture index (-0.66 ± 0.10) were detected at Moga station, followed by Sangrur station in Central Punjab. The aridity index detects a semi-arid region that varied from 0.22 ± 0.09 at Manasa (South West Punjab) to 0.34 ± 0.10 at Moga (Central Punjab) (UNEP 1997). The decreasing soil moisture index detected in the semi-dry region ranged from -0.66 ± 0.10 at Moga (Central Punjab) to -0.77 ± 0.9 at Muktsar Sahib (South-West Punjab) (Aatralarasi et al. 2021; Krishnan and Singh 1972).

3.2 Non parametric analysis (LOWESS curve) for annual RET

The annual RET for the period of 41 years (1980–2021) was used to analyze the non-parametric regression (LOWESS curve). The local fluctuations in the RET series were reduced by fitting them with the LOWESS curve depicted in Fig. 4 (Cleveland 1979; Cleveland 1984; Helseland and Hirsch 2002; Taxak et al. 2014). The LOWESS curves of annual RET showed a decreasing RET trend from 1980 to 2021 (Fig. 4 a-f). The LOWESS curves of the annual series at Bathinda showed decreasing trend of RET from the period of 1980 to 2021, with very small fluctuations in the series depicted in Fig. 4 (a). The LOWESS curve of annual RET at Mansa depicts a constant trend from up to 2008 and then gradually decreases up to 2021, as depicted in Fig. 4 (c). The LOWESS curve of the annual trend of RET at Muktsar Sahib showed a slightly increasing and decreasing trend, as depicted in Fig. 4 (d). The annual RET of the LOWESS curve of Sangrur and Moga initially showed a slightly increasing and decreasing trend and a highly decreasing trend beyond 2005 onwards, as depicted in Fig. 4 (e and f).

3.3 Results of autocorrelation coefficient

The mean annual and seasonal reference evapotranspiration of all the districts was tested for serial correlation using the autocorrelation test of lag-1 at a 5% significance level (Anderson 1954). The reference evapotranspiration for annual, pre-monsoon, and post-monsoon series at Sangrur (Central Zone) was tested for serial correlation, having an autocorrelation coefficient of 0.47, 0.31, and 0.33, respectively, as depicted in Table 3. The autocorrelation coefficient (r1) of annual series with the upper limit (0.47) at Sangrur and lower limit (0.18) at Moga of the Central Zone was determined using the autocorrelation test. The reference evapotranspiration of annual and seasonal series at Mansa (South West Zone) was serially correlated, and results of the classical trend were obtained using the modified Mann–Kendall test. The evapotranspiration series of the winter season was serially correlated at Bathinda (South West Zone), and classical trend results were obtained using the modified Mann–Kendall test depicted in Table 4. The lowest autocorrelation coefficient was obtained at Muktasr, and the highest was recorded at Bathinad (South West Zone).

3.4 Trend analysis of MK/MMK and Sen's slope test

The results of the MK/MMK (Z) test, Sen's slope test (β), and percentage change of mean monthly reference evapotranspiration statistically tested at 5% significance level are depicted in Table 4. The results revealed a statistically

Table 3 Autocorrelation coefficient (r_1) results

Station	Annual (r_1)	Monsoon (r_1)	Pre monsoon (r_1)	Post monsoon (r_1)	Winter (r_1)
Central Zone					
Moga	0.18	-0.08	0.25	-0.009	0.02
Sangrur	**0.47**	0.21	**0.31**	**0.33**	0.25
Barnala	0.29	- 0.13	-0.13	0.09	0.21
South West Zone					
Bathinda	0.24	0.01	0.27	0.19	**0.33**
Mansa	**0.19**	**0.5**	**0.44**	**0.44**	**0.37**
Muktsar Sahib	0.16	-0.14	0.05	0.29	0.09

Table 4 Mann–Kendall/ Modified Mann–Kendall (Z), Sen's slope (β) and Percentage change (%) of monthly reference evapotranspiration

Station Name	Barnala			Bathinda			Mansa			Moga			Muktsar			Sangrur		
Parameters	Z	β	% Change	Z	β	% Change	Z	β	% Change	Z	β	% Change	Z	β	% Change	Z	β	% Change
January	-2.65	-0.12	-7.4	-3.75*	-0.32*	-20.10*	-3.79*	-0.23*	-14.10*	-2.38	-0.12	-7.6	-2.38	0.12	7.5	-3.22*	-0.17*	-10.6*
February	0.41	0.02	1	-0.48	-0.05	-2.5	-1.57*	-0.13*	-6.30*	0.62	0.05	2.5	0.62*	0.05*	2.50*	-0.12	-0.01	-0.5
March	1.32	0.16	4.9	-0.28	-0.08	-2.4	-0.08	0.10*	3.10*	1.57	0.16	5.1	1.57	0.2	6.2	0.98	0.12	3.7
April	1.00*	0.14*	3.00*	0.16*	0.02*	0.40*	-1.09*	-0.15*	-3.30*	1.12*	0.05*	1.10*	1.12*	0.18*	3.90*	0.08*	0.01*	0.2*
May	-0.08	0.1	1.8	-0.28*	-0.06*	-1.10*	-1.99	-0.44	-8.1	-0.21*	-0.01*	-0.20*	-0.08*	0.01*	0.20*	-1.33*	-0.24*	-4.5*
June	-0.96	-0.18	-3.5	-1.06	-0.21	-4	-3.14	-0.7	-13.9	-1.07	-0.3	-5.9	-1.07	-0.21	-4	-2.46	-0.47	-9.5
July	0.64*	0.08*	1.90*	-0.31	-0.05	-1.2	-1.51	-0.22	-5.3	0.47*	0.04*	1.00*	0.47*	0.08*	1.90*	-1.37	-0.16	-4
August	-0.33	-0.03	-0.8	-1.14	-0.18	-4.7	-2.74	-0.3	-8.1	-0.77	-0.1	-2.7	-0.77	-0.07	-1.9	-2.09	-0.19	-5.3
September	-0.91	-0.1	-2.9	-1.16	-0.15	-4.2	-3.28	-0.37	-10.8	-0.94	-0.09	-2.6	-0.94	-0.1	-2.9	-2.85*	-0.28*	-8.4*
October	-0.26*	-0.01*	-0.30*	-1.35	-0.11	-3.5	-2.49*	-0.22*	-6.90*	0.04*	-0.02*	-0.60*	0.04*	0.01*	0.30*	-1.78	-0.14	-4.5
November	-1.27	-0.05	-2.2	-3.54	-0.24	-10.6	-2.49*	-0.15*	-6.70*	-1.15*	-0.04*	-1.80*	-1.15	-0.06	-2.7	-2.1	-0.12	-5.5
December	-1.72	-0.09	-5.4	-2.6	-0.17	-10	-2.65	-0.15	-8.8	-1.07*	-0.04*	-2.40*	-1.04	-0.05	-3	-2.2	0.1	6

*Indicates significant trend at 5% significance level

significant upward slope of 0.14 mm/year in April and a downward slope of -0.18 mm/year with a decreasing percentage change of -7.40 detected at Barnala (Central Punjab). Overall, the study's findings are supported by other studies by (Singh et al. 2021), reported that decline trend of ET_0 at 5% significance level at Ludhiana district (Central Punjab). However, a significant decrease in reference evapotranspiration was recorded at all the stations in the month of April. The results of mean monthly reference evapotranspiration obtained through the Mann Kendall/Modified Mann–Kendall test showed a decreasing trend throughout the Bathinda station over the period of 1980–2021. The Sen's slope test analyzed the magnitude of the trend for an upward slope of 0.02 mm/year in the month of April and a downward slope of -0.32 mm/year at Bathinda Station, with a maximum decreasing percentage change of 20.10% and an increasing percentage change of 0.4%. The results of the mean monthly RET obtained by the Mann–Kendall test were significantly decreasing and varied from -3.79 to -0.08. While the magnitude of the mean monthly ET_0 varied from -0.70 mm/year to 0.10 mm/year at Mansa Station. The significant increasing and decreasing trend at a 5% significance level was obtained at Moga station in the months of April, May, July, October, November, and December, respectively (Singh et al. 2021). The downward slope of magnitude from -0.30 mm/year to 0.16 mm/year was obtained at Moga district, and the decreasing percentage change was recorded as -7.60. In Muktsar Station, a significant increasing trend of monthly ET_0 was obtained in the months of February, April, May, July, and October, respectively. The magnitude of the ET_0 trend in the upward slope was 0.20 mm/year, and the downward slope was -0.21 mm/year at Muktsar Station. The study corroborated by Aatralarasi et al. (2021) and Kingra (2018) findings supported in South West Punjab. However findings of Darshana et al. (2013) found that reference evapotranspiration (ET_0) has been significantly decreasing at 1, 5, and 10% significant level at central India.
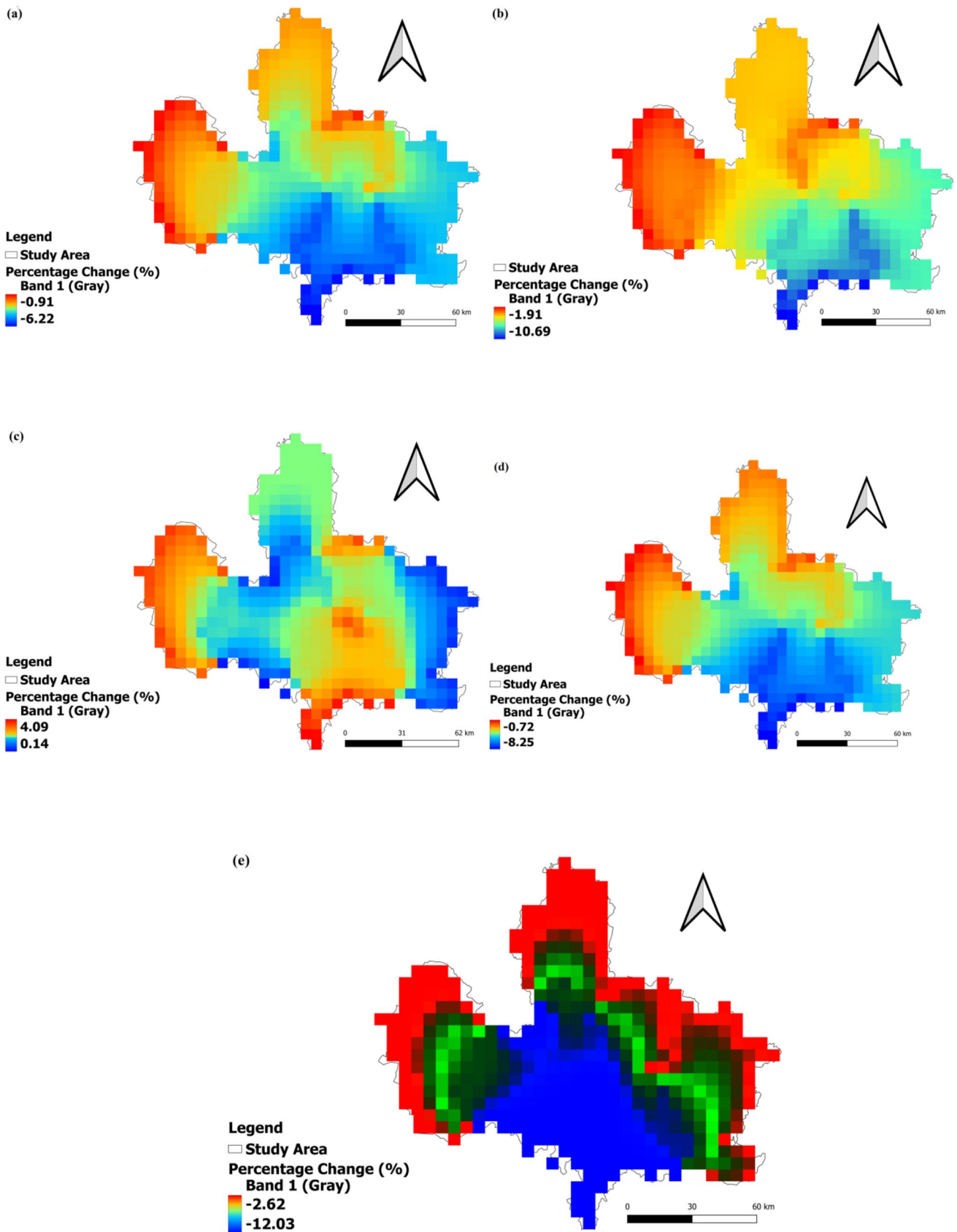
3.5 Spatial distribution of Sen's slope percentage of RET

The spatio-temporal percentage change of annual and seasonal reference evapotranspiration using IWD interpolation is depicted in the Fig. 5 (a-e). The annual and seasonal monsoon, post monsoon, and winter seasons showed decreasing percentage changes except for the pre-monsoon season. The spatial distribution of Sen's slope percentage change was highest at Mansa station, followed by Sangrur station, as represented in Table 5 and Fig. 5 (a-e). In the pre-monsoon season, an increasing RET was detected throughout all the stations, with the highest percentage change of 4.3% detected at Mansa station Fig. 5 (d).

Fig. 5 Spatial distribution percentage change (%) of reference evapotranspiration of (**a**) Annual, (**b**) Monsoon, (**c**) Pre monsoon, (**d**) Post monsoon and (**e**) Winter

Table 5 Mann–Kendall/ Modified Mann–Kendall (Z), Sen's slope (β) and Percentage change (%) of annual and seasonal RET

Stations	Annual			Monsoon			Pre-Monsoon			Post-Monsoon			Winter		
	Z	β	% Change	Z	β	% Change	Z	β	% Change	Z	β	% Change	Z	β	% Change
Central Zone															
Moga	-1.6	-0.85	-2.2	-2.36	-0.65	-4.1	-0.64	0.26	2	-1.36	-0.11	-2.1	-1.26	-0.14	-2.7
Sangrur	-2.42*	-1.62*	-4.1	-3.67	-1.12	-7	0.13*	0.064*	0.5	-2.04*	-0.25*	-4.8	-1.79	-0.24	-4.5
Barnala	-0.71*	-0.42*	-1.0	-0.74	-0.21	-1.8	2.21*	0.48*	3.6	-1.02*	-0.07*	-1.3	-1.82	-0.23	-4.3
South West															
Bathinda	-2.54	-1.84	-4.5	-1.52	-0.76	-4.5	-0.05*	0.01*	0.1	-2.88	-0.33	-6	-3.02*	-0.64*	-12.1
Mansa	-2.10	-2.73	-6.4	-3.13	-1.74	-11.1	-0.57	-0.38	4.3	-2.38	-0.33	-8.5	-2.92	-0.46	-11.4
Muktsar Sahib	-0.57*	-0.37*	-0.9	-1.19	-0.31	-1.9	1.29	0.57	3.6	-0.67*	-0.04*	-0.7	-1.11*	-0.14*	-2.6

*Indicates significant trend at 5% significance level

3.6 Trend analysis of annual and seasonal series of RET

The trend analyses of annual and seasonal RET of six districts belonging to parts of Central Punjab and South West Punjab statistically tested at 5% significance level is depicted in Table 5. The Sen's slope magnitude of classical trend of annual and seasonal series is spatially interpolated using IWD method and depicted in the Fig. 6 (a-e). The result revealed that trend of reference evapotranspiration was significantly decreasing at 5% in annual and seasonal amounts over the period 1980–2021 (Singh et al. 2022; Kingra 2018; Aatralarasi et al. 2021). The annual trend of RET detects statistically at 5% significant decreases at Sangrur and Barnala (Central Punjab). The magnitude of the RET trend ranges from -2.73 to 0.42 mm/year. The seasonal trend of ET_0 for the monsoon season was non-significantly decreasing at 5% level and varied from -1.76 (Mansa) to -0.21 (Barnala) mm/year. The seasonal trend of reference evapotranspiration was significantly decreasing at 5% level for three stations (Barnala, Bathinda, and Sangrur), while the maximum percentage change was obtained at 3.6% at Barnala Station. The seasonal trend of reference evapotranspiration in the post-monsoon season was significantly decreasing at 5% level in three stations: Barnala, Muktsar Sahib, and Sangrur, while the maximum percentage change was obtained at Muktsar Sahib. However, the winter season trend was significantly decreasing in two stations (Bathinda and Muktsar Sahib), with the maximum percentage change being 2.6% at Muktsar Sahib (South West Punjab). Trend analysis in the annual and post-monsoon series revealed that out of a total of six stations, only Barnala, Muktsar Sahib, and Sangrur showed a significant at 5% decreasing trend. The monsoon season trends showed that the magnitude of ET_0 was decreasing in all six stations, with a downward slope of -1.76 mm/year obtained in the Mansa station and an upward slope of -0.21 mm/year in the Barnala station. The reference evapotranspiration trend in the pre-monsoon season was obtained as a significant decreasing trend in three stations: Barnala, Bathinda, and Sangrur, and the maximum percentage change were recorded at 4.3% in Mansa Station, followed by Barnala Station. Overall the findings supported by others studies of Singh et al. 2022; Aatralarasi et al. 2021.

3.7 Spatial distribution slope of ITA trend slope and Sen'sslope of RET

The spatial distribution of MK slope for annual and seasonal RET is depicted in Fig. 6. ITA trend slope of spatially interpolation using IWD method depicts in Fig. 7. In the Central zone, the Sen's slope estimatorof annual trend showed significantly
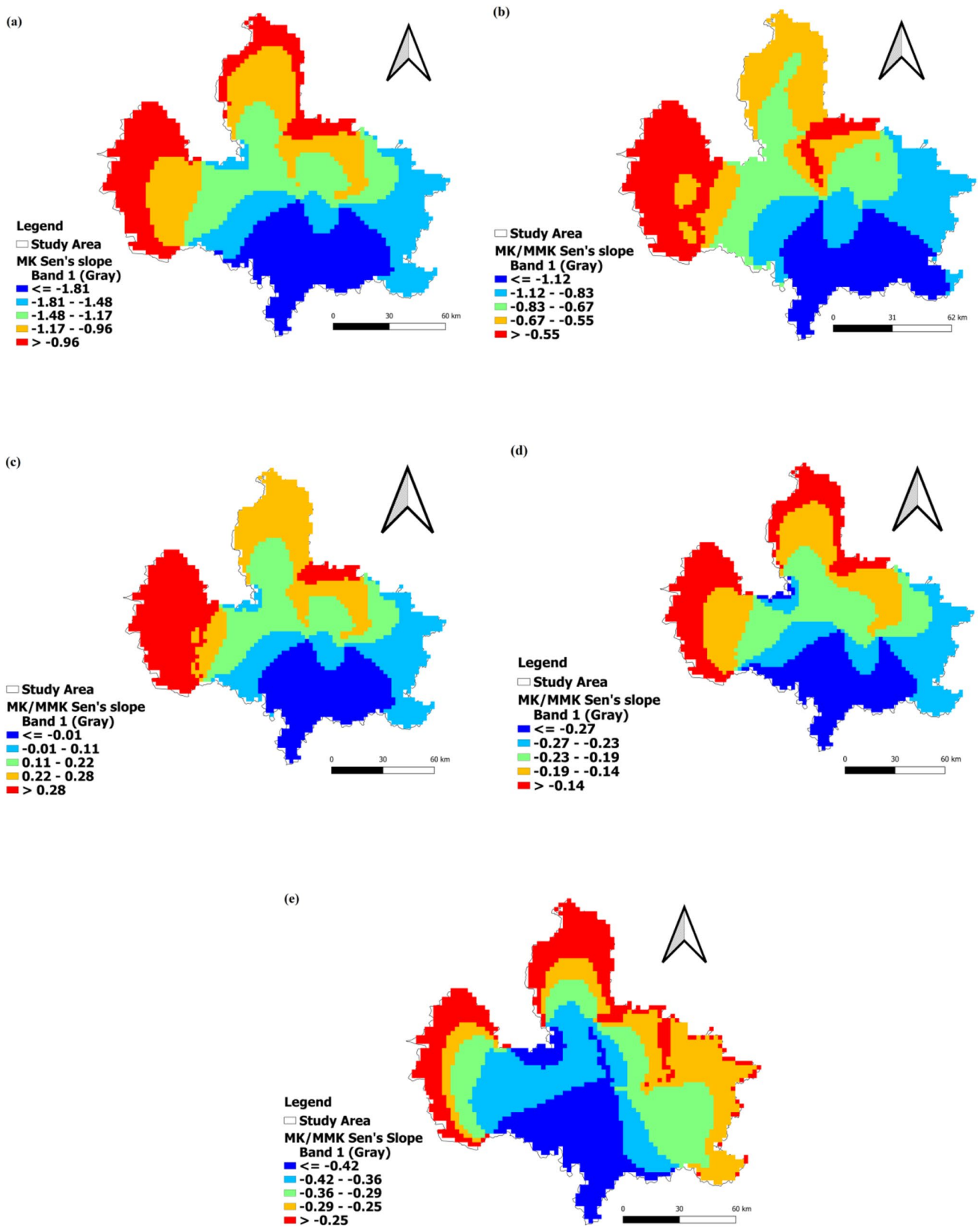
Fig. 6 Spatial distribution MK/MMK sen's slope of (**a**) Annual, (**b**) Monsoon, (**c**) Pre monsoon, (**d**) Post monsoon and (**e**) Winter
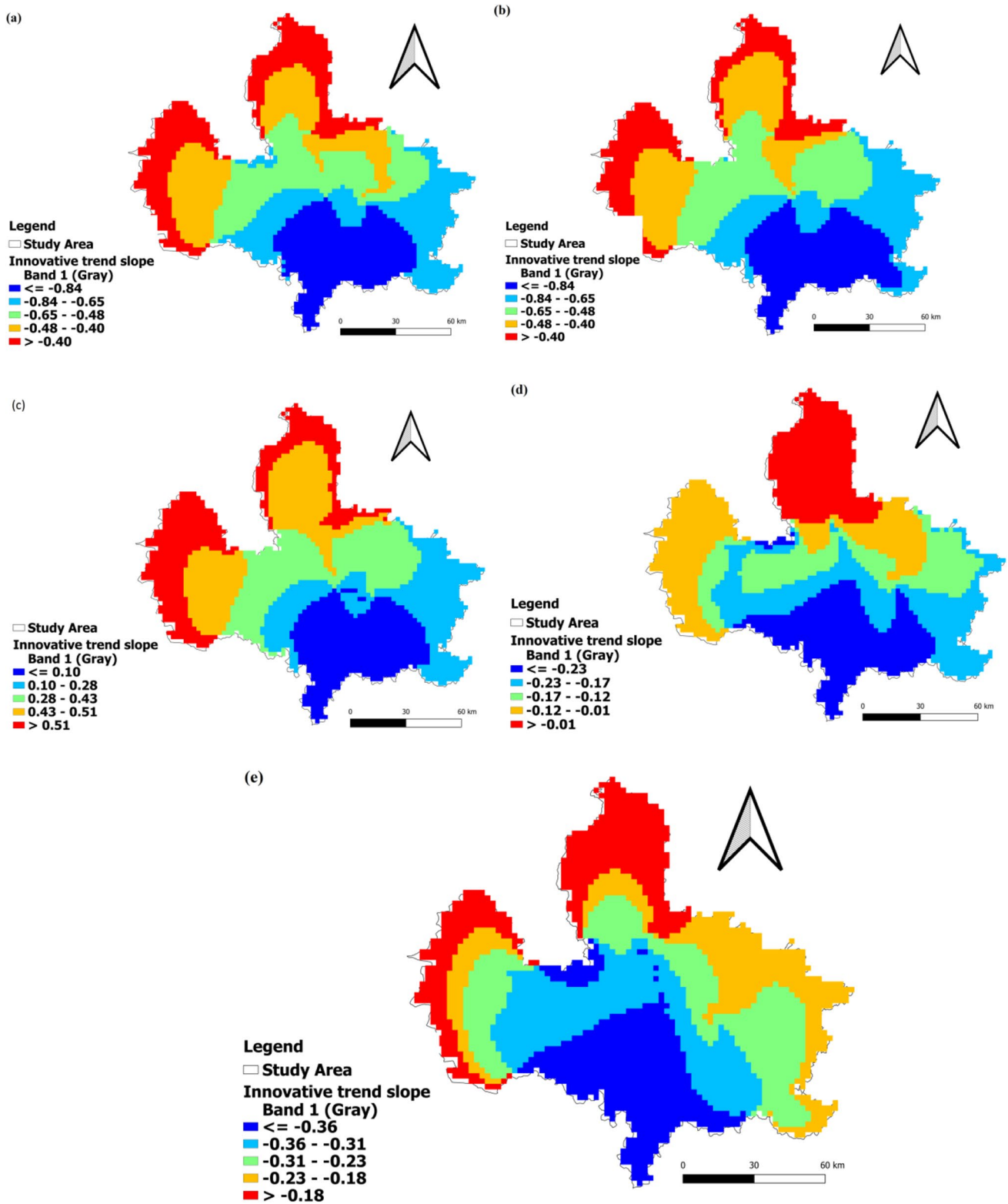
Fig. 7 Spatial temporal distribution of reference evapotranspiration of ITA Slope (**a**) Annual, (**b**) Monsoon, (**c**) Pre monsoon, (**d**) Post monsoon, (**e**) Winter

Table 6 Innovative trend analysis (ITA) of annual and seasonal reference evapotranspiration (RET)

Punjab Districts	TS	TA	SSD	Correlation $\rho\, y_1\, y_2$	Lower CL Significance level ($p < 0.05$)	Upper CL	Lower CL Significance level ($p < 0.01$)	Upper CL
Central Zone								
Sangrur								
Annual	-1.0**	-0.12	0.08	0.97	-0.17	0.17	-0.22	0.22
Monsoon	-0.82*	-0.25	0.04	0.97	-0.08	0.08	-0.10	0.10
Pre monsoon	0.21**	0.08	0.07	0.93	-0.14	0.14	-0.18	0.18
Post monsoon	-0.18**	-0.17	0.025	0.94	-0.04	0.04	-0.06	0.06
Winter	-0.20**	-0.19	0.03	0.91	-0.06	0.06	-0.08	0.08
Barnala								
Annual	0.25**	0.03	0.06	0.97	-0.12	0.12	-0.15	0.15
Monsoon	-0.15**	-0.04	0.04	0.96	-0.08	0.08	-0.10	0.10
Pre monsoon	0.60**	0.22	0.07	0.92	-0.14	0.14	-0.18	0.18
Post monsoon	-0.016	-0.015	0.021	0.94	-0.04	0.04	-0.05	0.05
Winter	-0.18**	-0.16	0.02	0.94	-0.05	0.05	-0.06	0.06
Moga								
Annual	0.13*	0.01	0.06	0.97	-0.13	0.13	-0.17	0.17
Monsoon	-0.34**	-0.10	0.02	0.98	-0.05	0.05	-0.07	0.07
Pre monsoon	0.57**	0.22	0.10	0.96	-0.13	0.13	-0.17	0.17
Post monsoon	-0.004	-0.004	0.02	0.88	-0.05	0.05	-0.07	0.07
Winter	-0.002	-0.002	0.01	0.97	-0.02	0.02	-0.03	0.03
South West								
Bathinda								
Annual	-1.23**	-0.14	0.21	0.87	-0.41	0.41	-0.54	0.54
Monsoon	-0.66**	-0.18	0.13	0.89	-0.26	0.26	-0.34	0.34
Pre monsoon	0.33**	0.11	0.06	0.95	-0.13	0.13	-0.17	0.17
Post monsoon	-0.36**	-0.31	0.03	0.92	-0.07	0.07	-0.09	0.09
Winter	-0.55**	-0.48	0.03	0.96	-0.06	0.06	-0.07	0.07
Mansa								
Annual	-2.67**	-0.32	0.20	0.94	-0.39	0.39	-0.52	0.52
Monsoon	-1.36**	-0.41	0.09	0.92	-0.19	0.19	-0.25	0.25
Pre monsoon	-0.48**	-0.18	0.09	0.94	-0.18	0.18	-0.24	0.24
Post monsoon	-0.34**	-0.32	0.05	0.83	-0.10	0.10	-0.13	0.13
Winter	-0.45**	-0.41	0.03	0.92	-0.07	0.07	-0.10	0.10
Muktsar								
Annual	0.31**	0.03	0.05	0.98	-0.11	0.11	-0.14	0.14
Monsoon	-0.24**	-0.07	0.03	0.97	-0.07	0.07	-0.09	0.09
Pre monsoon	0.67**	0.25	0.07	0.92	-0.14	0.14	-0.19	0.19
Post monsoon	-0.012	-0.01	0.02	0.93	-0.04	0.04	-0.06	0.06
Winter	-0.10**	-0.09	0.01	0.96	-0.03	0.03	-0.04	0.04

[*]Indicates either 1% or 5% significance level, ** indicates significance at 1% and 5% level

decreasing at Sangrur and Barnala stations and non-significantly decreasing at Moga at statistically 5% significance level (Fig. 6 a). The ITA trend slope estimated in the Central Zone was statistically significant, and increasing at a 5% significance level at Mogaand Barnalaat 1% and 5% significance levels, as depicted in Fig. 7 (a). In the South-West Zone, both stations, Bathinda and Mansa, indicate a non-significant decreasing

MK/MMK test and Sen's trend, while Muktsar Sahib showed a significant decreasing trend at the 5% significance level (Fig. 6 (a)). The ITA slope of the annual RET trend detects a significant decrease at Bathinda and Mansa while significantly decreasing at Bathinda and Mansa while significantly increasing at Muktsar Sahib district at 1% and 5% significance levels, respectively, as depicted in Fig. 7 (a).

Fig. 8 Innovative trend analysis (ITA) of annual series of **a**) Barnala, **b**) Moga, **c**) Sangrur, **d**) Bathinda, **e**) Manasa and **f**) Muktsar Sahib
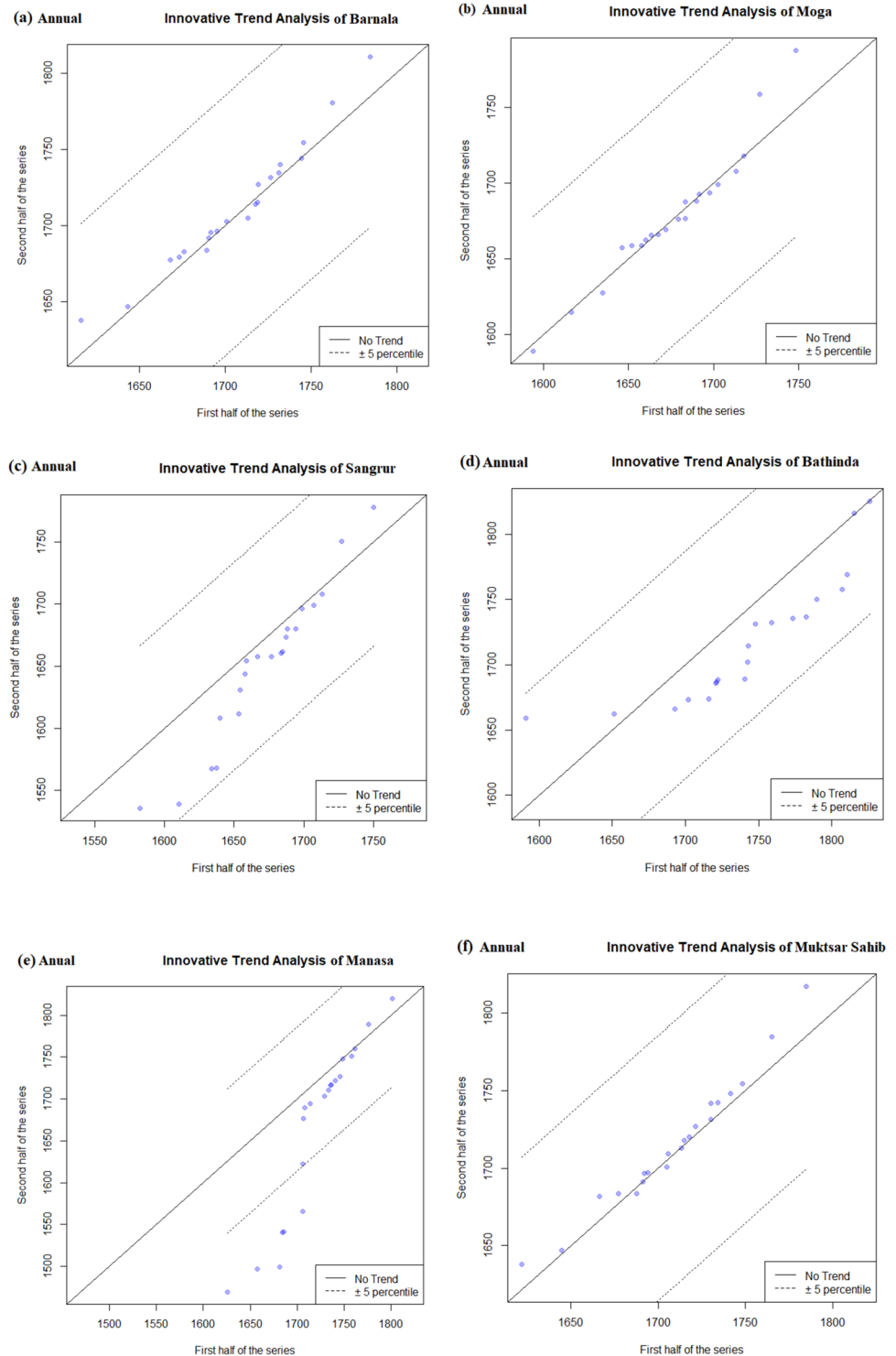
The Sen's slope and ITA trend slope of monsoon serise are statistically decreasing at 1% and 5% significance level throughout districts depicted in Fig. 6 (b) and Fig. 7(b). The MK/MMK and Sen's slope pre-monsoon trends indicate a significant increasing trend at Sangrur and Barnala (Central Punjab) (Fig. 6 (c). While the ITA trend detects a significant increasing trend in Sangrur and Barnala(Central Punjab) and Bathinda and Muktsar Sahib (South-West) at 1% and 5% significance levels except at Manasa, as depicted in Fig. 7 (c). At Sangrur and Barnala during the post-monsoon season of MK/MMK, Sen's slope detects a significant decreasing trend at a 5% significance

Fig. 9 Innovative trend analysis (ITA) of Monsoon series of **a**) Barnala, **b**) Moga, **c**) Sangrur, **d**) Bathinda, **e**) Manasa and **f**) Muktsar Sahib
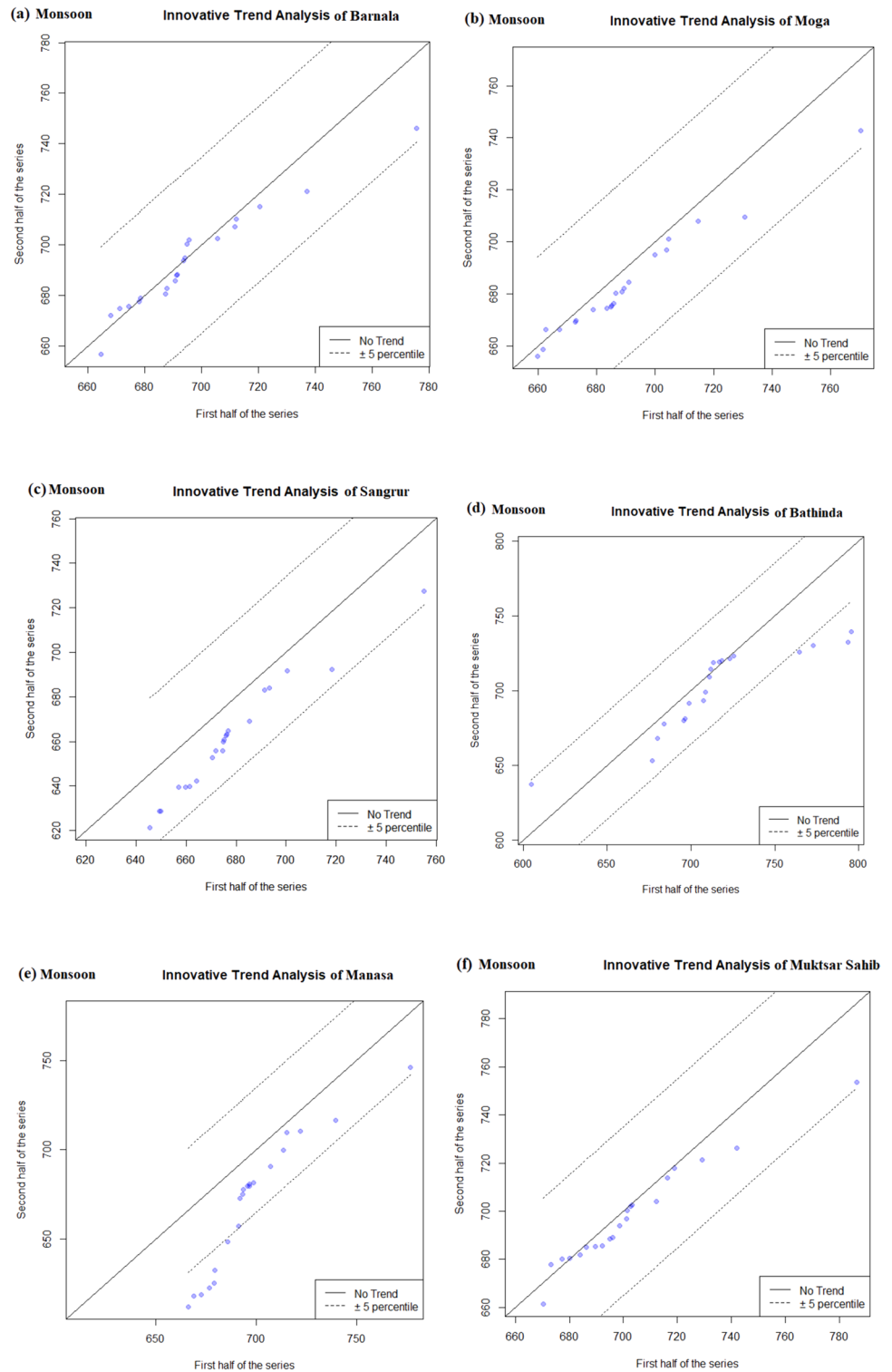
level, except at Moga station in Central Punjab, depicted in Fig. 6 (d). While the ITA slope detects a significant decrease at Sangrur, at Barnala and Moga stations it shows an increasing trend with a 1% and 5% significance level depicted in Fig. 7 (d). The classical trend of RET indicates a statistically non-significant trend in parts of central Punjab, while in the south-west Punjab, the classical trend detects a statistically significant trend at Bathinda and Muktsar Sahib stations at a 5% significance level, as depicted in Fig. 6 (e). The winter season ITA trend detects a statistically significant trend at the 1% and 5% significance levels at Sangrur and Barnalastations, except

Fig. 10 Innovative trend analysis (ITA) of Post-monsoon series of **a**) Barnala, **b**) Moga, **c**) Sangrur, **d**) Bathinda, **e**) Manasa and **f**) Muktsar Sahib
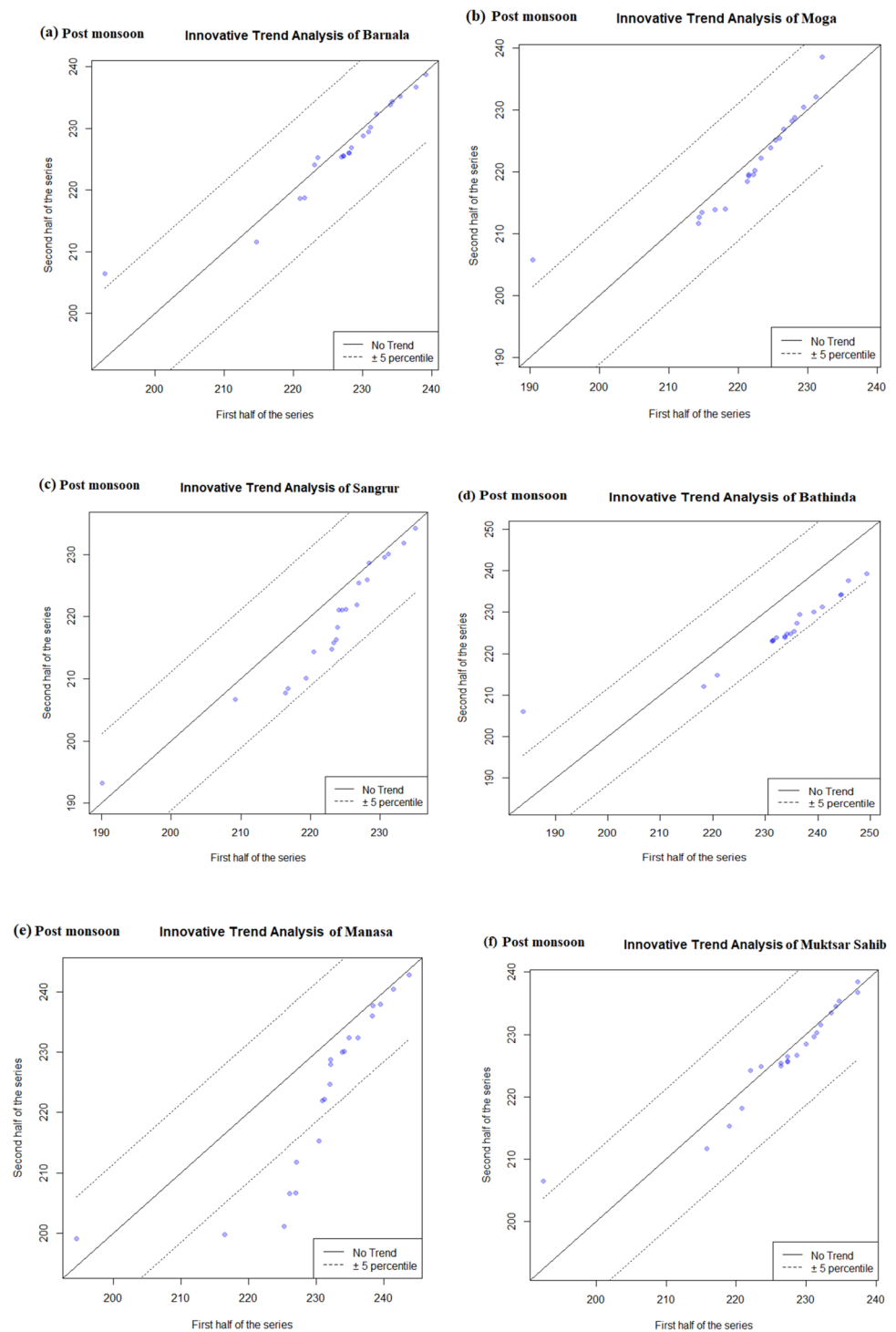
at Maga station, which detects a statistically non-significant trend in parts of Central Punjab. While the ITA trend for the winter season trend showed statistically negative throughout all stations at a 1% and 5% significance level, as depicted in Fig. 7(e). The overall results showed that ITA is more sensitive and detected a hidden trend that was not detected by the MK/MMK test.

3.8 ITA trend analysis of annual and seasonal series of RET

The innovative (ITA) trend analysis of reference evapotranspiration in central Punjab and South-Western Punjab statistically tested at 1% and 5% significance level is depicted in Table 6. The ITA method detects a trend of significantly

Fig. 11 Innovative trend analysis (ITA) of winter series of **a**) Barnala, **b**) Moga, **c**) Sangrur, **d**) Bathinda, **e**) Manasa and **f**) Muktsar Sahib
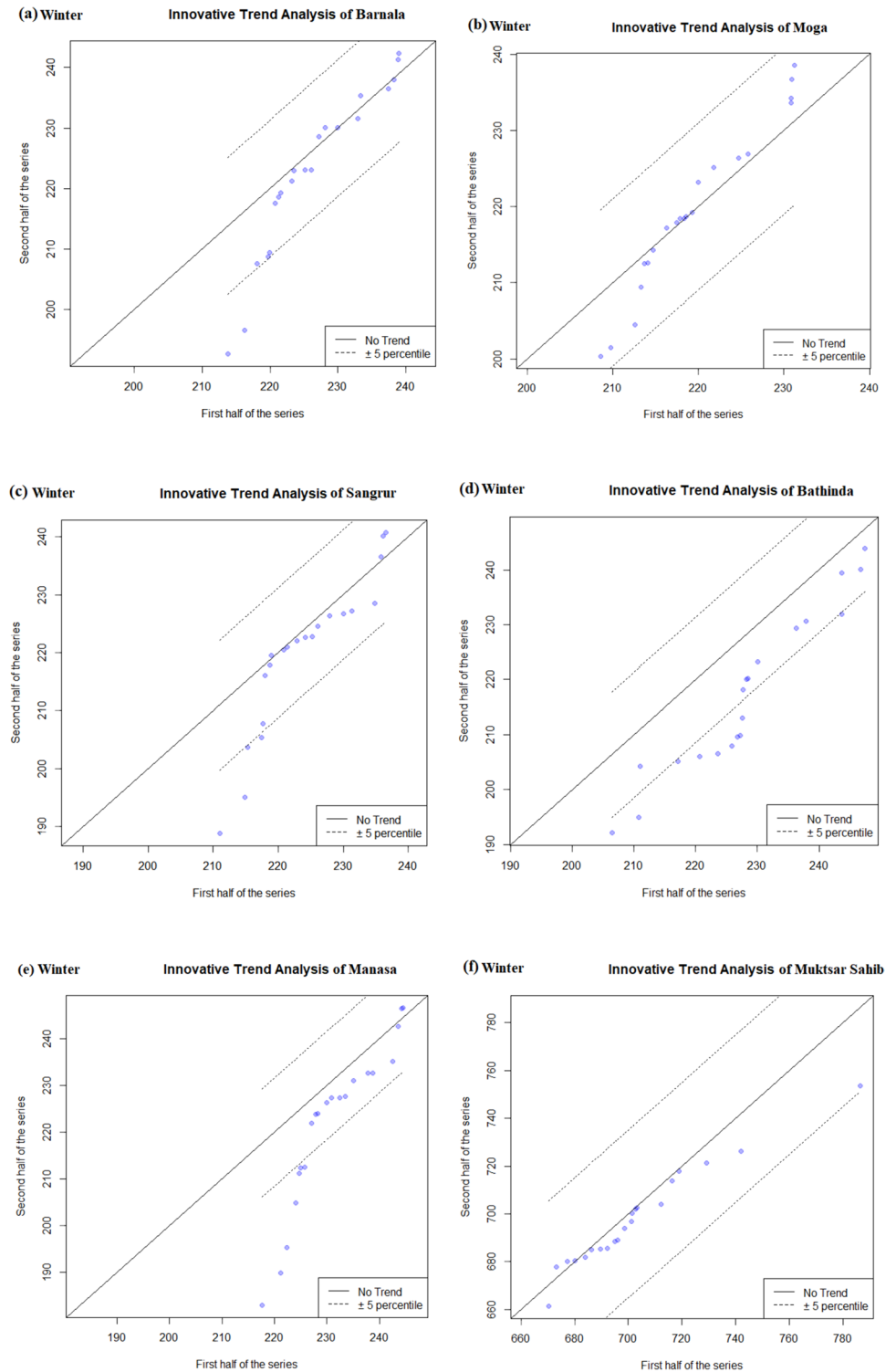
decreasing in most of the districts at the 1% and 5% significance levels depicts in Figs. 8, 9, 10, 11, and 12. In the Central Zone, the ITA annual trend of reference evaporation was increasing at Barnala and Moga stations at 1% and 5% significance levels, except at Sangrur (Fig. 8 (a-f)). The highest magnitude of an increasing trend was detected in

Barnala district (0.25 mm/year) of Central Punjab at the 1% and 5% significance levels (Fig. 8 a). In the Central Zone, the ITA trend of winter reference evaporation was significantly decreasing at the 1% and 5% significance levels at Sangrur and Barnala stations, except at Moga. The annual ITA trend of RET for Bathinda and Mansa stations

Fig. 12 Innovative trend analysis (ITA) of Pre-monsoon series of **a**) Barnala, b) Moga, **c**) Sangrur, **d**) Bathinda, **e**) Manasa and **f**) Muktsar Sahib
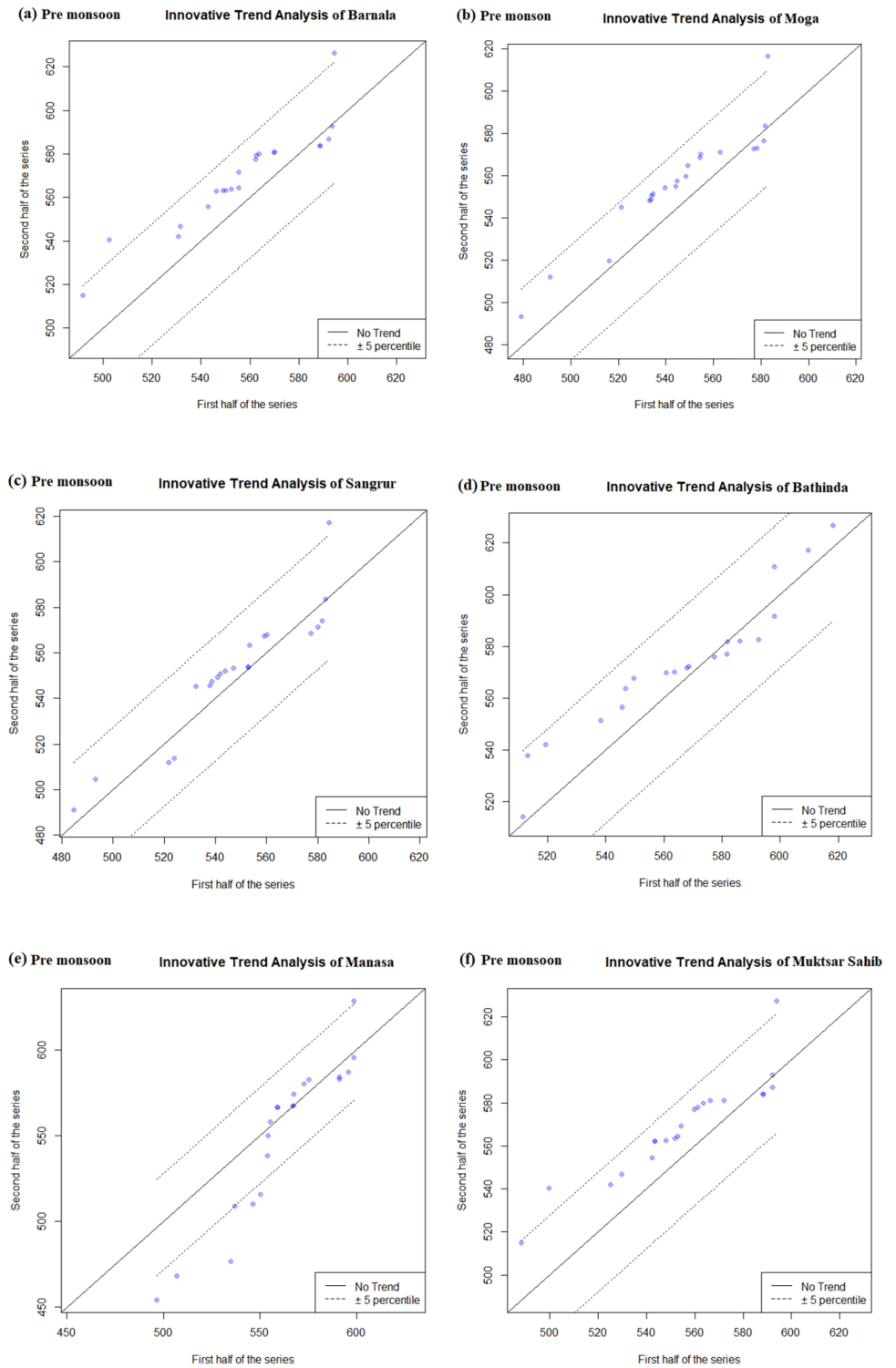
was decreasing at the 1% and 5% significance levels, while a significantly increasing trend was shown at Muktsar Sahib Station in south-west Punjab, depicted in Fig. 8 (f). The highest decreasing magnitude of reference evaporation was obtained at Mansa (-2.67 mm/year) and Bathinda (-1.23 mm/year) stations in South-West Punjab. The ITA

trend slope of monsoon ET_O showed decreasing trends in stations in Central Punjab, while the highest magnitude (-0.82 mm/year) of a decreasing trend at a 1% significance level was detected in the Sangrur station in Central Punjab (Fig. 9 (c)). The ITA trend of monsoon reference evaporation showed decreasing trends at the 1% and 5% significance

levels in all the stations of south-west Punjab, and the highest decrease in magnitude was shown (-1.36 mm/year) at Mansa (Fig. 9(e)). The ITA trend of reference evaporation in the post-monsoon season was significantly lower at Sangrur and non-significantly decreasing at Barnala and Moga stations in Central Punjab (Fig. 10 (a-f)). The highest decrease in magnitude of -0.18 mm/year was detected at the 1% and 5% significance levels in the Sangrur station of Central Punjab (Fig. 10 (c)).The ITA trend showed the highest magnitude of winter reference evaporation (-0.20 mm/year) at Sangrur and (-0.18 mm/year) at Barnala station in Central Punjab (Fig. 11(a)).The ITA trend of winter reference evaporation has been shown to be significantly decreasing in all the stations of south-west Punjab, with the highest decreasing magnitude of -0.55 mm/year at Bathinda station at the 1% and 5% significance levels (Fig. 11(d)). The ITA trend of pre-monsoon reference evaporation showed an increasing and decreasing trend, with the highest magnitude of 0.67 mm/year at Muktsar Sahib Station (Fig. 12(f)), followed by Bathinda (0.33 mm/year) at the 1% and 5% significance levels, respectively. In the Central Zone stations, the ITA trend slope of pre-monsoon reference evaporation showed an increasing trend at the 1% and 5% significance levels, and the highest magnitude of 0.60 mm/year was obtained in the Barnala district of Central Punjab (Fig. 12(a)).The highest decreasing pre-monsoon reference evaporation was detected at Mansa station at 1% and 5% significance levels with decreasing magnitude (-0.48 mm/year) in the south-west part of Punjab (Fig. 12(e)). The various researchers also analysed innovative trend analysis (ITA) for meteorological variables such as rainfall, stream flow, pan evaporation, and water quality parameters in different regions of the world and obtained consistent results in terms spatiotemporal variations (Tabari et al. 2017; Ahmas et al. 2018; Caloiero et al. 2018; Caloiero 2020; Singh et al. 2020, 2021). Thus, in-depth knowledge about the trend variability of reference evapotranspiration is needed in order to change the climate for efficient management of irrigation water.

4 Conclusion

In this study, the variation of annual and seasonal reference evapotranspiration was investigated using the ITA and MK slopes across the semi-arid region of Punjab during 1980–2021. The highest aridity index (0.34 ± 0.10) and the lowest moisture index (-0.66 ± 0.10) were detected at Moga station, followed by Sangrur station in Central Punjab. The significant decrease in monthly reference evapotranspiration was recorded at all the stations in the month of April except Barnala (Central Punjab). The spatial distribution of mean reference evapotranspiration increasing

spatial variations from South-West to Central Punjab and reached the peak at Bathinada. The magnitude of Sen's slope of annual RET trend showed increasing and decreasing trend. However, the ITA slope of the annual RET trend detects a significantly decreasing trend at Bathinda and Mansa and a significantly increasing trend at Muktsar Sahib district at 1% and 5% significance levels, respectively. The Sen's slope and ITA trend slope of monsoon series are statistically decreasing at 1% and 5% significance levels throughout districts. In the pre-monsoon season, an increasing trend of RET was detected throughout all the stations, with the highest percentage change of 4.3% detected at Mansa station. The spatial variations of ITA trend slope of ET_0 exhibited decreasing magnitude in the annual, monsoon, post monsoon except at pre-monsoon season, while the MK slope exhibited an increasing and decreasing trend in the pre-monsoon season. The overall ITA shows a hidden trend that would be more helpful for policymakers and the planning of crop water management.

Declarations

Ethics approval All authors read and approved the final manuscript.

Consent to participate All authors have agreed to participate.

Consent for publication All authors have agreed to publication.

Competing interests The authors have no relevant financial or non-financial interests to disclose.

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