



Comparative study of innovative trend analysis technique with Mann-Kendall tests for extreme rainfall

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Received: 18 May 2020 / Accepted: 4 March 2021 / Published online: 17 March 2021
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Abstract

Changes in extreme rainfall have significant effects on the hydrological cycle, and the knowledge about these changes is considerable in planning flood mitigation activities and water resources management. Monthly, seasonal and annual maximum rainfall trends were analysed in this study, using the Mann-Kendall (MK1), modified Mann-Kendall (MK2) trend tests and innovative trend analysis (ITA) technique. Rainfall data were collected from the Indian Meteorological Department (IMD) from 1961 to 2018 for Kondaveeti Vagu, where the proposed legislative capital city of Andhra-Pradesh is located. Variations in trends for seasonal and annual maximum rainfall across Kondaveeti Vagu were analysed with MK1 and MK2 tests and compared with the ITA technique. Using the ITA technique, monotonic and non-monotonic trends are identified in data with or without any condition of the serial correlation, size of the dataset and distributions. Results conclude that rainfall trends showed variability from ITA technique to MK tests. For monsoon season, no trend was detected in MK1 and MK2 whereas the ITA technique detected trends. During the post-monsoon season, trends were seen for all grid points using MK1, MK2 and ITA techniques. The result obtained from the ITA technique agreed with the result obtained from MK1 and MK2 tests. It is also observed that the ITA technique detect trend better than the MK tests.

Keywords Trend analysis · Mann-Kendall test (MK1) · Modified Mann-Kendall test (MK2) · Innovative trend analysis (ITA) · Extreme rainfall

Introduction

In recent years, the occurrence, duration, intensity and extent of extreme events like floods and droughts have become issues of global concern (Li et al. 2016). These extreme events have a significant effect on society, ecological system, water resources and economy, and awareness about all the bodies connected to these systems is essential (Kundzewicz et al. 2014; Toride et al. 2018). Rainfall is the critical variable in the hydrological cycle and is directly related to these extreme

events like droughts and floods. So, effective management of water resources has become a significant concern.

Significant research has been carried out in detecting daily, monthly, seasonal and annual rainfall trends using different parametric/non-parametric trend methods like the Mann-Kendall test (Jain et al. 2013; Kendall 1975; Mann 1945), linear regression (Meshram et al. 2018), Spearman's Rho test (Spearman 1904), Sen's slope (Sen 1968) and cumulative sum approaches (Karpouzou et al. 2010). Non-parametric tests are appropriate for distribution-free (non-normally distributed) datasets compared to parametric tests. The most extensively applied trend detection tests are the Spearman Rho tests and Mann-Kendall (MK), followed by trend rate evaluation tests using the approaches used by Theil (1950) and Sen (1968). Kumar et al. (2010) calculated the long-term rainfall trends for India using the Mann-Kendall test. Trend analysis for temperature and rainfall datasets using MK and Sen's slope tests over India was carried out by Jain and Kumar (2012). Patra et al. (2012) applied the Mann-Kendall and linear regression trend tests for rainfall dataset over the Orissa state of India. Palizdan applied average MK test, MK test coupled with bootstrap and discrete wavelet transform to

Responsible Editor: Broder J. Merkel

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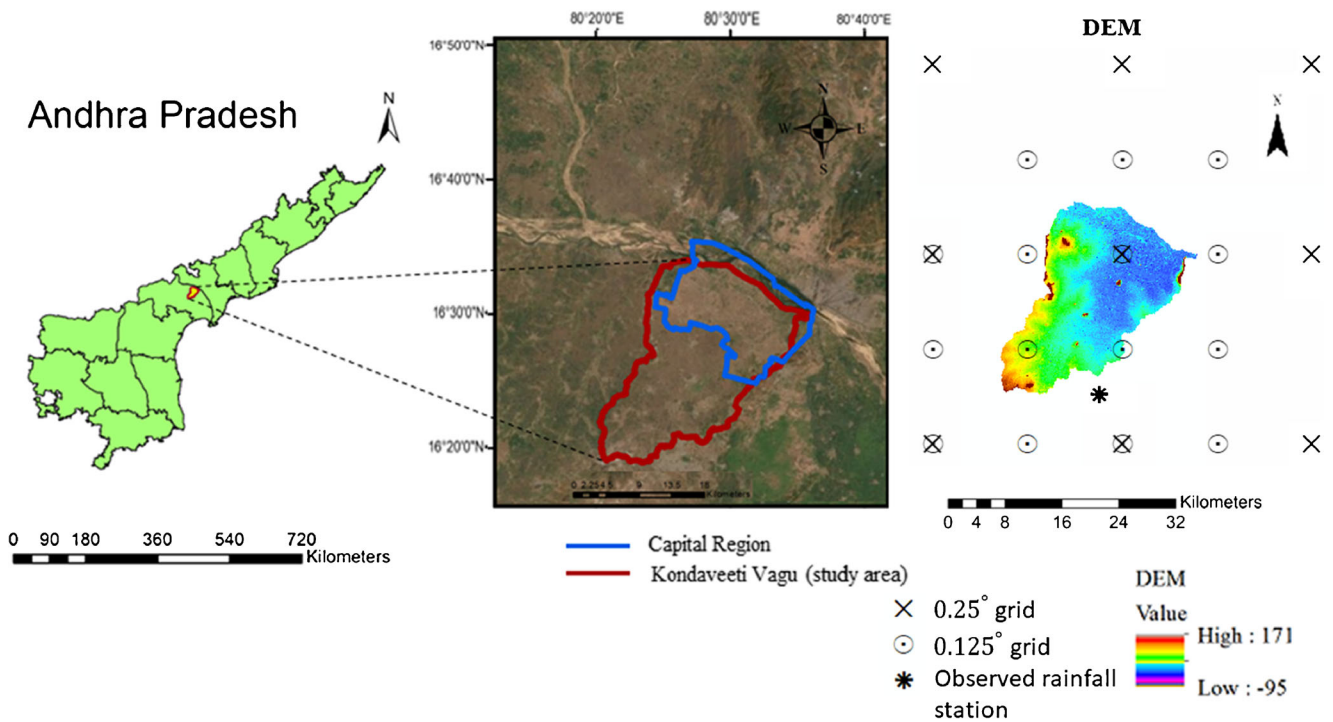


Fig. 1 Study area map with DEM

study rainfall trends over the Langat River Basin, Malaysia (Palizdan et al. 2014; Palizdan et al. 2017). Huang et al. (2014) evaluated the trend in rainfall on a monthly and seasonal basis using Holt’s method. These methods have some assumptions like no seasonal dependence, time series structure to be independent and normality of distribution.

The MK1 test exhibits significant trends for the positively correlated time series, despite having any trend. To remove the consequence of serial correlation is by eliminating lag-1 serial correlation component used before implementing the MK1 test to determine the outcome of the trend. This technique is called trend-free pre-whitening and is named as the

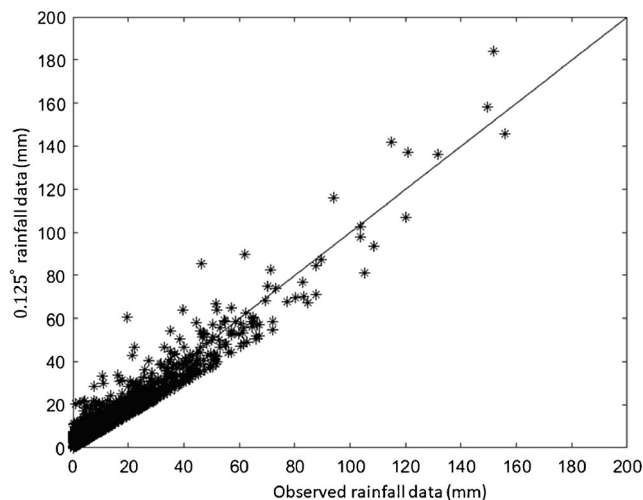


Fig. 2 Comparison of 0.125° rainfall data with observed rainfall data

modified Mann-Kendall test (MK2)(Kumar et al. 2009). Due to the presence of positive serial correlation, the probability of detecting trend increases erroneously for the Mann-Kendall test (von Storch 1995). Additionally, the Mann-Kendall test does not find the contributions of the minimum and maximum of the detected trend. A graphical method is desirable in exploring data for detecting significant hidden short-duration trends with fewer errors (Kundzewicz and Robson 2000).

Şen (2012) proposed a graphical trend evaluation technique named innovative trend analysis (ITA) technique which represents low, medium and high values for the time series. Analysis of trend in meteorological and hydrological variables using the ITA technique and its different modifications have been carried out in recent studies (Kumar and Kumar 2020; Güçlü et al. 2020; Wang et al. 2020; Marak et al. 2020; Farrokhi et al. 2020; Caloiero 2020; Serencam 2019; Malik and Kumar 2020; Balasmeh et al. 2019; Zhou et al. 2018; Wu et al. 2018; Mohorji et al. 2017; Cui et al. 2017; Dabanli et al. 2016). Ay and Kisi (2015) did the trend analysis of monthly total rainfall by MK test and ITA technique. It concluded that the ITA technique could be effectively applied for the estimation of maximum and minimum values of rainfall data for trend analysis. In comparison with other non-parametric tests, the ITA technique has broad applicability, regardless of distribution assumptions, size and serial correlation of a dataset. Because of these advantages, the ITA technique has been extensively applied in detecting trends for meteorological and hydrological variables. Kisi (2015) and Tabari and Willems (2015) used the ITA technique for annual maximum, monthly pan evapotranspiration and streamflow data.

Table 1 Z statistic of MK1 test for monthly maximum rainfall

Grid	Mann-Kendall test (MK1)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
G1	0.89	1.14	0.53	-0.94	0.58	-0.36	-0.06	0.16	-0.12	-0.49	0.24	1.69 [^]
G2	1.66 [^]	1.67 [^]	0.92	0.45	0.66	-0.05	0.61	0.45	0.74	0.65	1.19	1.19
G3	1.79 [^]	1.00	0.58	-0.12	2.57 [#]	0.40	0.06	0.05	-0.21	-1.01	0.85	0.33
G4	1.12	0.44	1.32	0.39	2.59 [#]	0.78	0.34	0.91	-0.07	-0.68	1.11	0.73
G5	1.09	1.10	0.21	-0.55	1.27	0.93	0.08	0.80	-0.65	-0.30	0.92	1.00
G6	0.64	0.93	-0.36	-0.82	2.14 [*]	0.59	-0.78	0.96	-0.23	-0.33	1.30	0.28
G7	1.40	0.83	0.18	-0.31	2.41 [#]	0.71	-0.87	0.91	-0.13	-0.85	1.83 [^]	0.27
G8	0.46	0.23	0.86	0.07	2.56 [#]	1.04	0.03	1.39	-0.07	-0.58	1.90 [^]	0.63
G9	1.80 [^]	1.10	0.30	-0.28	0.82	0.97	-0.15	1.59	0.36	-0.40	1.46	0.99
G10	1.39	0.99	-0.18	-0.37	1.21	0.54	-0.96	1.34	-0.12	-0.94	1.45	0.12
G11	1.25	0.70	0.02	0.01	1.47	0.75	-1.25	1.02	0.05	-0.81	1.84 [^]	0.03
G12	1.06	0.70	0.62	0.22	1.91 [^]	0.79	-0.83	1.15	0.33	-0.53	2.23 [*]	0.33
G13	0.80	0.35	0.33	-0.23	1.43	0.79	-0.41	1.99 [*]	0.21	-0.83	1.54	-0.34
G14	1.51	0.79	0.44	-0.10	1.65 [^]	0.78	-0.68	1.39	0.35	-0.51	1.93 [^]	-0.47
G15	0.46	0.70	0.62	0.12	1.73 [^]	0.90	-0.37	1.70 [^]	0.64	-0.11	2.39 [#]	-0.13

Numbers with symbol [^], ^{*} and [#] show the significance level at 1%, 5% and 10% respectively

ITA technique is applied to hydrological variables like temperature (Ay and Kisi 2015; Şen 2014) and heatwave (Martínez-Austria et al. 2015). (Saphioğlu et al. 2014 employed the MK test, linear regression and ITA technique for monthly and annual river flows and observed a close relationship for the indicators using MK1, MK2 and ITA technique. Sonali and Kumar (2013)

employed 11 approaches for the estimation of temperature changes over India and noticed that the ITA technique matched the trends well compared to those obtained from other methods. In Central India, the ITA technique showed a significant increasing trend in rainfall over MK2 test (Sanikhani et al. 2018). The ITA technique has the advantage of having good capability in

Table 2 Z statistic of MK2 test for monthly maximum rainfall

Grid	Modified Mann-Kendall test (MK2)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
G1	1.03	0.97	0.71	-0.95	0.52	-0.33	-0.06	0.17	-0.13	-0.50	0.25	2.63 [#]
G2	0.86	1.04	0.74	-1.43	2.08 [*]	0.13	-0.52	0.18	-0.16	-0.91	0.89	0.56
G3	1.31	1.00	0.50	-0.17	2.58 [#]	0.54	0.09	0.07	-0.18	-1.02	0.85	0.33
G4	0.82	0.45	1.18	0.35	2.94 [#]	1.27	0.45	1.39	-0.07	-0.84	1.11	0.73
G5	1.25	0.94	0.22	-0.56	1.27	0.86	0.08	0.80	-0.66	-0.31	1.00	1.46
G6	0.64	0.80	0.12	-0.82	2.15 [*]	0.59	-0.78	1.18	-0.28	-0.43	1.51	0.28
G7	1.40	0.83	-0.19	-0.31	2.41 [#]	0.71	-0.91	2.69 [#]	-0.15	-0.85	1.94 [*]	0.26
G8	0.47	0.24	0.21	0.07	3.20 [#]	1.05	0.03	1.40	-0.07	-0.81	1.91 [^]	0.60
G9	1.81 [^]	0.96	0.32	-0.28	0.82	0.97	-0.16	1.60	0.36	-0.40	1.57	1.35
G10	1.40	0.99	-0.30	-0.38	1.22	0.64	-0.96	-0.09	-0.15	-0.94	1.55	0.13
G11	1.25	0.71	0.31	0.01	1.47	0.93	-1.25	2.26 [*]	0.06	-1.08	1.85 [^]	0.04
G12	1.06	0.70	1.01	0.22	1.91 [^]	0.99	-0.83	1.07	0.33	-1.68	2.23 [*]	0.33
G13	0.80	0.35	1.10	-0.23	1.43	0.98	-0.44	0.21	0.21	-0.83	1.54	-0.34
G14	1.51	0.79	0.62	-0.10	1.65 [^]	1.09	-1.03	2.69 [#]	0.35	-0.51	-0.47	1.93 [^]
G15	0.46	0.80	1.69 [^]	0.12	1.73 [^]	1.21	-0.37	2.66 [#]	0.64	-0.14	2.39 [#]	-0.13

Numbers with symbol [^], ^{*} and [#] show the significance level at 1%, 5% and 10% respectively

Table 3 Z statistic of MK1/MK2 tests for seasonal and annual maximum rainfall

Grid	Winter	Pre-monsoon	Monsoon	Post-monsoon	Annual
G1	2.50 [#] /2.51 [#]	0.94/1.13	- 1.72 [^] /-1.61	- 0.15/-0.17	- 0.59/-0.65
G2	2.69 [#] /2.70 [#]	1.34/2.75 [#]	0.11/-0.35	0.79/-0.62	1.24/-0.11
G3	2.49 [#] /2.50 [#]	2.95 [#] /2.95 [#]	0.17/0.23	- 0.48-0.49	0.34/0.28
G4	2.39 [#] /3.28 [#]	3.22 [#] /2.84 [#]	- 0.01/-0.01	- 0.23/-0.32	1.12/0.89
G5	2.63 [#] /3.64 [#]	1.87 [^] /2.34 [#]	0.20/0.20	0/0	0.17/0.20
G6	2.41 [#] /3.24 [#]	2.26 [*] /2.26 [*]	- 0.03/-0.03	0.32/0.32	0.64/0.65
G7	2.16 [*] /2.79 [#]	2.84 [#] /2.46 [#]	- 0.46/-0.43	- 0.05/-0.05	0.61/0.61
G8	2.05 [*] /2.69 [#]	3.12 [#] /3.12 [#]	- 0.13/-0.16	0.33/0.29	1.69 [^] /1.69 [^]
G9	2.55 [#] /3.65 [#]	1.21/1.21	1.006/1.01	- 0.11/-0.12	1.02/1.33
G10	2.00 [*] /2.75 [#]	1.68 [^] /1.68 [^]	0.56/0.56	- 0.19/-0.24	1.02/1.42
G11	1.87 [^] /2.98 [#]	1.7 [^] /1.4	- 0.18/-0.21	0.18/0.24	0.74/0.73
G12	1.89 [^] /3.01 [#]	2.32 [*] /2.31 [*]	0.06/0.06	0.39/0.42	1.43/1.43
G13	2.17 [*] /3.55 [#]	1.83 [^] /1.45	1.09/1.24	- 0.28/-0.37	0.96/0.97
G14	1.99 [*] /3.52 [#]	2.01 [*] /1.59	0.72/0.59	0.01/0.01	1.01/0.95
G15	1.88 [^] /3.34 [#]	2.74 [#] /2.37 [#]	0.71/0.70	0.38/0.34	1.37/1.37

Numbers with symbol ‘^’, ‘*’, and ‘#’, show the significance level at 1%, 5% and 10% respectively

finding trends than non-parametric trend tests (MK tests). Graphical representation in ITA shows hidden sub-trends of time-series that overcome the assumptions of dependency of dataset, distribution normality and length of data.

The area considered for the study is flood-prone, and it is being developed as a legislative capital city of newly formed Andhra Pradesh; hence, flood prediction for the city is essential. The main objectives of this study are to (i) analyse the variation in trends in monthly, seasonal and annual maximum rainfall across Kondaveeti Vagu (KV) by applying MK1, MK2 and ITA techniques; (ii) estimate magnitude of trends using Sen’s slope estimator; (iii) compare monthly, seasonal and annual maximum rainfall trends between MK1 and MK2 tests over ITA technique and identify reasons for its variations. The comparison of the results of trend analysis obtained

from MK1 and MK2 (non-parametric) with the trend analysis using the ITA technique (graphical method) for extreme rainfall is the novelty of this study.

Study area and data

The area considered for the study is the Kondaveeti Vagu (KV) catchment. The legislative capital of Andhra Pradesh, Amaravati, lies in the catchment of KV that joins the Krishna River (Fig. 1). KV has a catchment area of around 420 km². The catchment lies within the global coordinates of 80° 00’ 00” to 81° 00’ 00” E longitudes and 16° 00’ 00” to 17° 00’ 00” N latitudes. The catchment has steep slopes at the upstream location of Kondaveedu hills at Perecherla. The slope falls

Table 4 Mann-Kendall trend statistics for monthly rainfall

Significance level	Monthly significant positive trend		Seasonal and annual significant positive trend	
	Cases (180)	Percentage	Cases (75)	Percentage
1% (values > 2.33)				
MK1	5	2.78%	12	16%
MK2	9	5%	22	29.33%
5% (values >1.96)				
MK1	3	1.67%	8	10.67%
MK2	5	2.78%	2	2.67%
10% (values >1.645)				
MK1	13	7.22%	8	10.67%
MK2	8	4.44%	2	2.67%

Table 5 Mann-Kendall trend statistics for seasonal and annual rainfall

Significance level	Season	Significant positive trend cases
1% (values > 2.33) MK1/MK2	Winter	7/15
	Pre-monsoon	5/7
	Monsoon	0/0
	Post-monsoon	0/0
	Annual	0/0
5% (values >1.96) MK1/MK2	Winter	5/0
	Pre-monsoon	3/2
	Monsoon	0/0
	Post-monsoon	0/0
	Annual	0/0
10% (values >1.645) MK1/MK2	Winter	3/0
	Pre-monsoon	4/1
	Monsoon	1/1
	Post-monsoon	0/0
	Annual	1/1

quickly within the middle catchment area at Tadikonda and becomes flat in the lower catchment area from Neerukonda. KV is a flood-prone area.

The daily $0.25^\circ \times 0.25^\circ$ gridded rainfall (mm) time series is downloaded from the Indian Meteorological Department (IMD) website for the study area, for a period of 58 years (1961–2018) (Pai et al. 2014, <http://www.imdpune.gov.in>). Since the study area is small, the number of grid points in the 0.25° gridded data covering the whole study area and this restricts the spatial variation of the result representation. The data is then interpolated to get $0.125^\circ \times 0.125^\circ$ degree

resolution using the bicubic interpolation method. After interpolation, 15 grid points (G1–G15) are considered for this study which covers the entire KV catchment. Observed rainfall (1991–2013) collected from APCRDA (Andhra Pradesh Capital Region Development Authority) is used for the validation of interpolated rainfall data. XY scatter plot of observed rainfall data and 0.125° rainfall data is shown in Fig. 2. In this study, analyses for monthly, seasonal and annual time series for the one-day maximum rainfall are carried out.

The seasons in India are designated into four types, based on IMD reports as winter season (December–February), pre-

Fig. 3 Spatial distribution of Z statistics of MK1 test for the monthly maximum rainfall

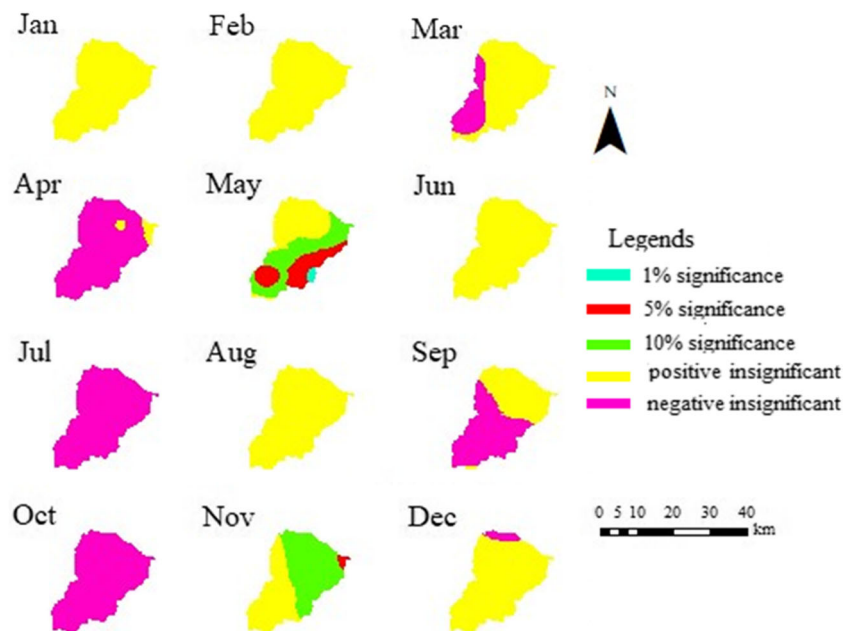
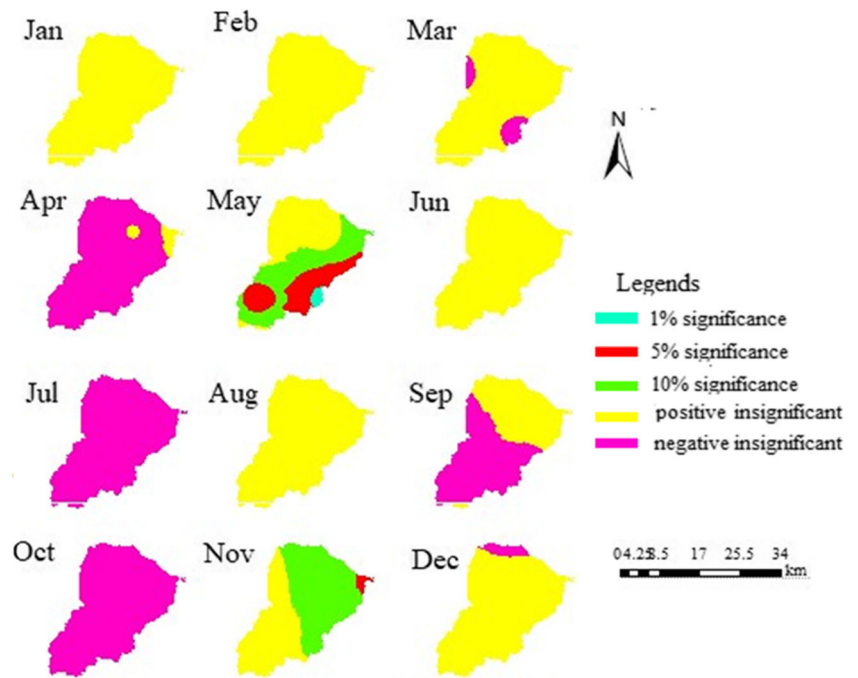


Fig. 4 Spatial distribution of Z statistics of MK2 test for the monthly maximum rainfall



monsoon season (March–May), monsoon season (June–September) and post-monsoon season (October–November) (Jaswal et al. 2015).

Methodology

Three different methods of trend analysis are used in this study. First, the occurrence of monotonic negative or positive trends is identified using the non-parametric MK1 trend test. The MK1 test is considered for monotonic series, and therefore, it is not appropriate for cases with periodic or sequence data. Second, the modified Mann-Kendall(MK2) trend test is used to obtain better results of the trend from the autocorrelated series. Third, using the ITA technique, monotonic and non-monotonic trends are identified in data with or without any condition of the serial correlation, size of the dataset and distributions. Trends in low, medium and high range in the rainfall data are checked using the ITA technique. For finding the proper slope of a linear trend, Sen’s slope technique which uses a linear model for the estimation of residual’s variance and trend’s slope is used. The Kolmogorov–Smirnov(Deepesh and Jha 2012; Kanji 2006) test is used to identify the normality of maximum monthly, seasonal and annual rainfall data. It should be noted that single data error or outliers will not produce a considerable impact on Sen’s slope technique (Gilbert 1987). The spatial distribution of the trends in monthly, seasonal and annual maximum rainfall series was interpolated using the inverse distance weighting (IWD) method in ArcGIS 10.3 environment. The MK1, MK2 and ITA approaches give numerous advantages which make them valuable in analysing hydrological variables.

Mann-Kendall Test (MK1)

MK1 trend analysis is a rank-based non-parametric test (Kendall 1975; Mann 1945). The MK1 test statistic *S* is computed using Eq. (1), and sign function is calculated using Eq. (2).

$$S = \sum_{j=1}^{n-1} \sum_{i=j+1}^n \text{sign}(x_i - x_j) \tag{1}$$

$$\text{sign}(x) = \begin{cases} 1 & \dots & \text{for } (x > 1) \\ 0 & \dots & \text{for } (x = 1) \\ -1 & \dots & \text{for } (x < 1) \end{cases} \tag{2}$$

where *n* is the length of data; *j* is the rank for the *j*th observations (*j* = 1, 2, 3... *n* - 1), *x_j* is the rank for the *i*th observations (*i* = *j* + 1, 2, 3... *n*)

For the time series, *S* is the test statistic considered where the length of observation *n* > 10 is usually asymptotically allocated with variance given in Eq. (3) and mean *E*(*S*) = 0.

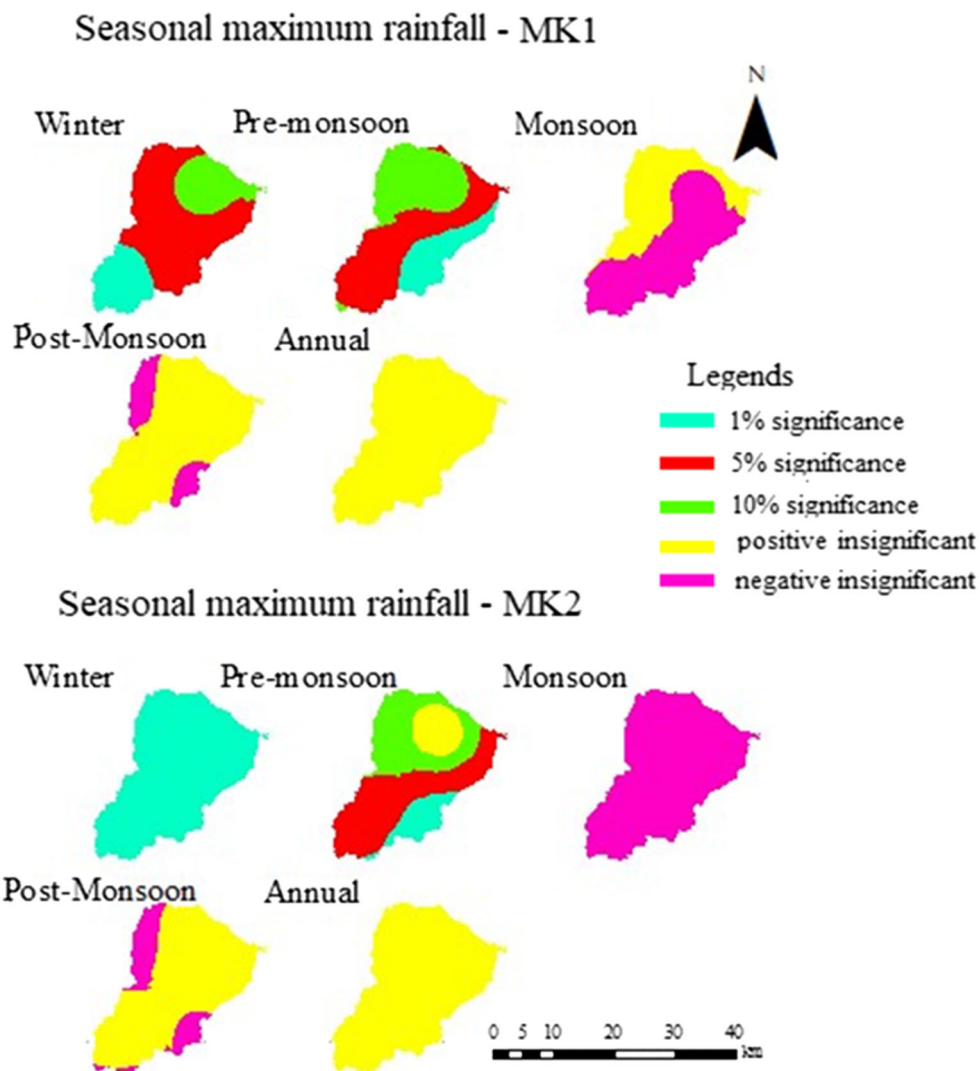
$$V(s) = \frac{n(n-1)(2n+5)}{18} \tag{3}$$

The standardised *Z* value is calculated as

$$Z = \begin{cases} \frac{S-1}{\sqrt{V(s)}} & \text{when } S > 0 \\ 0 & \text{when } S = 0 \\ \frac{S+1}{\sqrt{V(s)}} & \text{when } S < 0 \end{cases} \tag{4}$$

Z follows the standard normal distribution with variance one ($\sigma^2 = 1$) and mean zero ($\mu = 0$).The null hypothesis (*H*₀)

Fig. 5 Spatial distribution of Z statistics of MK1 and MK2 test for seasonal and annual rainfall



indicates that there is no significant trend, and the alternate hypothesis ($H1$) indicates that there is a significant trend. Therefore, in a two-sided test, hypothesis H_0 and $H1$ are verified at significance levels (α), i.e., $\alpha= 10\%$ with $Z = \pm 1.645$, $\alpha = 5\%$ with $Z = \pm 1.96$ and $\alpha = 1\%$ with $Z = \pm 2.33$. If $\pm Z > \pm Z_{\alpha/2}$, then $H1$ is accepted, and H_0 is rejected. Positive Z indicates an increasing trend and negative Z indicates a decreasing trend.

Modified Mann-Kendal

In time series with autocorrelation, to detect a trend, pre-whitening is used, which is likely to decrease the significant trend detection rate in the MK1 test (Cunderlik and Burn 2004; Kumar and Rathnam 2019; Yue et al. 2003; Wang et al. 2020). Hence, the MK2 test (Hamed and Rao 1998) is also applied to the autocorrelated series for better detection of the trend. In this, first, Theil and Sen’s median slope is calculated and subtracted from the data. Then, the ranks of the

observations ρ_k are analysed, and the autocorrelation between these ranks is evaluated. To arrive at the variance correction factor n/n_s^* , only the significant values of ρ_k are evaluated. The variance correction factor for positive n is required since the variance of S is underestimated when auto correlated positively charged data is used (Eq. (5)).

$$\frac{n}{n_s^*} = 1 + \frac{2}{n(n-1)(n-2)} \times \sum_{k=1}^{n-1} (n-k)(n-k-1)(n-k-2)\rho_k \quad (5)$$

where n is the actual length of data, n_s^* is the ‘effective’ number of data to account for autocorrelation, ρ_k is the autocorrelation function of ranks of the data.

Corrected variance, $V^*(S)$ is given by

$$V^*(S) = V(S) \times \frac{n}{n_s^*} \quad (6)$$

where $V(S)$ is given as

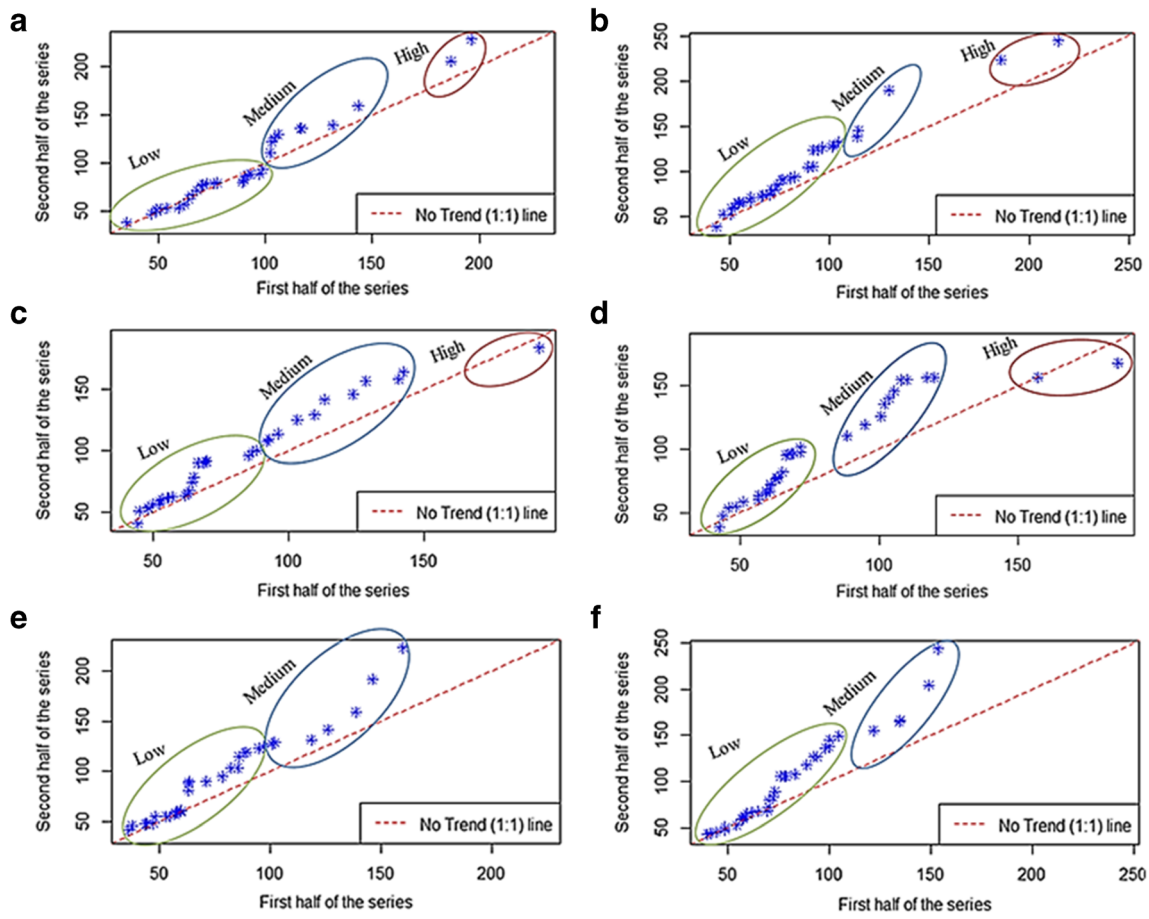


Fig. 6 ITA technique results for annual maximum rainfall for a G2, b G4, c G7, d G8, e G13 and f G14

$$V(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^m t_i(t_i-1)(2t_i+5)}{18} \quad (7)$$

The standardised test statistics $Z(N(0, 1))$ is calculated by

$$Z_{MK} = \begin{cases} \frac{S-1}{\sqrt{V^*(S)}} & \text{when } S > 0 \\ 0 & \text{when } S = 0 \\ \frac{S+1}{\sqrt{V^*(S)}} & \text{when } S < 0 \end{cases} \quad (8)$$

Innovative trend analysis

The ITA technique proposed by Şen (2012) was used to analyse the rainfall trends for maximum monthly, seasonal and annual time series. The advantage that the ITA technique possesses over other trend methods is that it does not involve assumptions like non-normality, serial correlation and sample number. For ITA, the dataset is divided into two equal lengths. Both parts are arranged in increasing order. On the X-axis—first half and the Y-axis—the second half of the dataset are plotted. When the points are plotted on the 45° line (1:1 ideal line), then no trend is observed. An increasing trend exists if

points are in the upper triangular area of the 45° line. If points are in the lower triangular area of the 45° line, then a decreasing trend is observed (Şen 2012). In some situations, non-monotonic trends occur for the variable concerned, where decreasing as well as increasing trends occur within the series temporally. In such cases, for detailed interpretation, points that are plotted on the 45° line graphs are separated into verbal clusters called low, medium and high. The main advantage of the ITA technique is that the MK trend test assumptions are avoided here, and furthermore, square area plots can calculate the trend magnitudes. Therefore, the trends of low, medium and high values of hydro-climatic or hydro-meteorological variables can be accurately recognised through this technique.

Sen’s slope

The magnitude of Sen’s slope (Sen 1968) is calculated as

$$S_i = \text{median} \left(\frac{Y_j - Y_k}{j - k} \right) \text{ for } i = 1, 2, 3, \dots, N(j > k) \quad (10)$$

where Y_j and Y_k are observations at times j and k . The median of the $N = \frac{n(n-1)}{2}$ where n is the number of time periods.

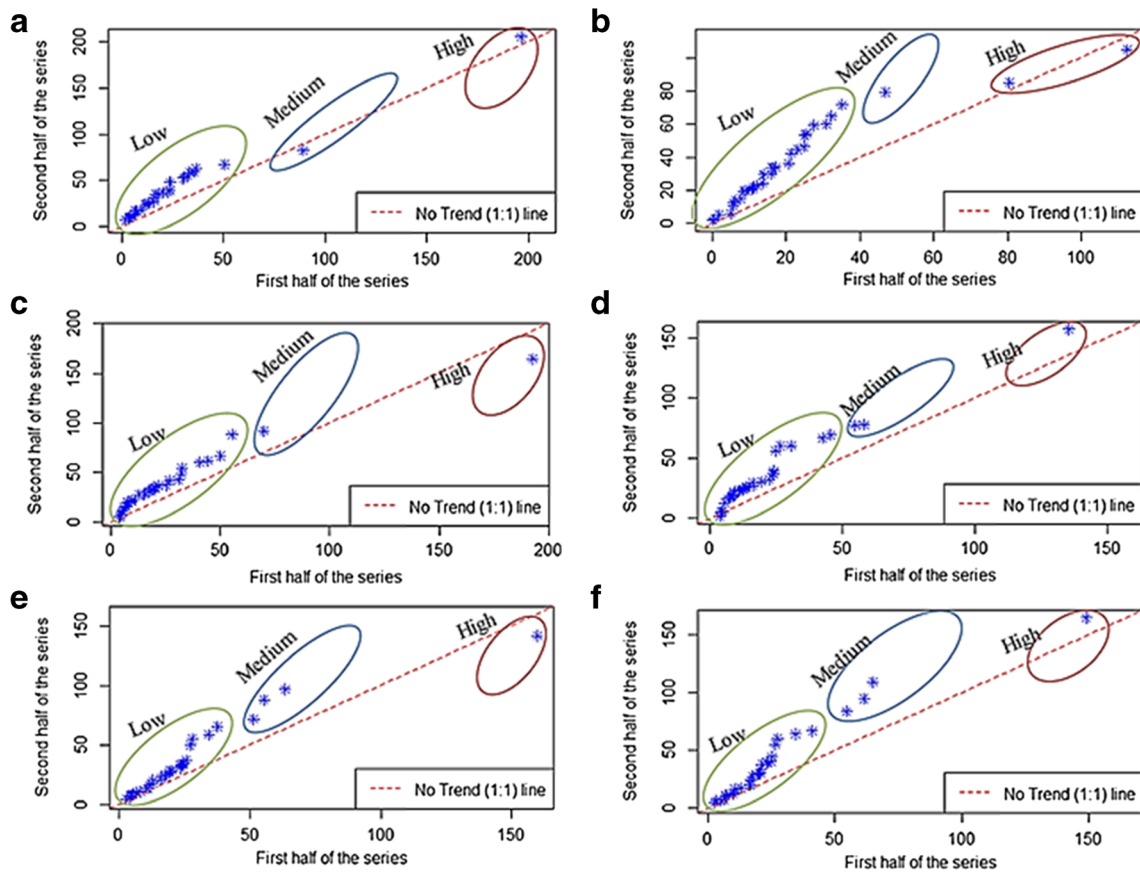


Fig. 7 ITA technique results for the pre-monsoon season maximum rainfall for a G2, b G4, c G7, d G8, e G13 and f G14

Results and discussions

In this study, maximum of monthly, seasonal and annual trends for rainfall are calculated using MK1, MK2 and ITA techniques and the trend magnitudes are calculated using Sen’s slope estimator for 15 grid points in the study area. Using the Kolmogorov–Smirnov test, the normality of maximum monthly and seasonal rainfall data was checked for the entire period (1961–2018). None of the rainfall series used in this study was following a normal distribution. Results of the MK1, MK2 and Sen’s slope approaches are presented for all 15 grid points. ITA technique was employed for annual and seasonal rainfall for the period 1961–2018. Trend detection using the ITA technique was performed without any assumptions to plot the sub-series of the dataset. Due to space constraints, results of the ITA technique are presented only for six grid points (G2, G4, G7, G8, G13 and G14) of annual, winter, pre-monsoon, monsoon, and post-monsoon seasons represented in Figs. 6, 7, 8, 9 and 10. Results from the ITA technique are compared with MK1 and MK2 test concerning only these six grids.

Monthly maximum trends for rainfall

The Z statistics of monthly maximum rainfall data obtained from MK1 and MK2 are presented in Tables 1 and 2. Values

denoted with ‘^’, ‘*’ and ‘#’ represent the level of significance at 1%, 5% and 10% respectively in Tables 1 and 2. Values denoted with ‘^’, ‘*’ and ‘#’ represent the significant trend, both negative and positive. Out of 180 cases, 21 cases (11.6%) displayed positive trends in MK1 while 22 cases (12%) displayed significant positive trends in MK2 considering the three significant levels. In this study, no significant negative trends are exhibited for monthly maximum rainfall. For the MK1 test, positive significance was detected in January, February, May, August and November, whereas for the MK2 test, most of the trends are observed in May, August, November and December. Compared to MK1, the MK2 test exhibited similar significant positive trends. Among the 15 grids, G5 and G10 in the MK1 test and G5, G10 and G13 in the MK2 test do not have any significant trend, while the remaining grids exhibited significant trends for a few months as seen from Tables 1 and 2. From MK1 and MK2 tests, more significant positive trends are seen in May followed by August and November.

Seasonal and annual trends for rainfall

The monthly maximum rainfall was grouped into four seasons. The Z values attained from MK1 and MK2 tests for seasonal and annual rainfall are presented in Table 3. In this

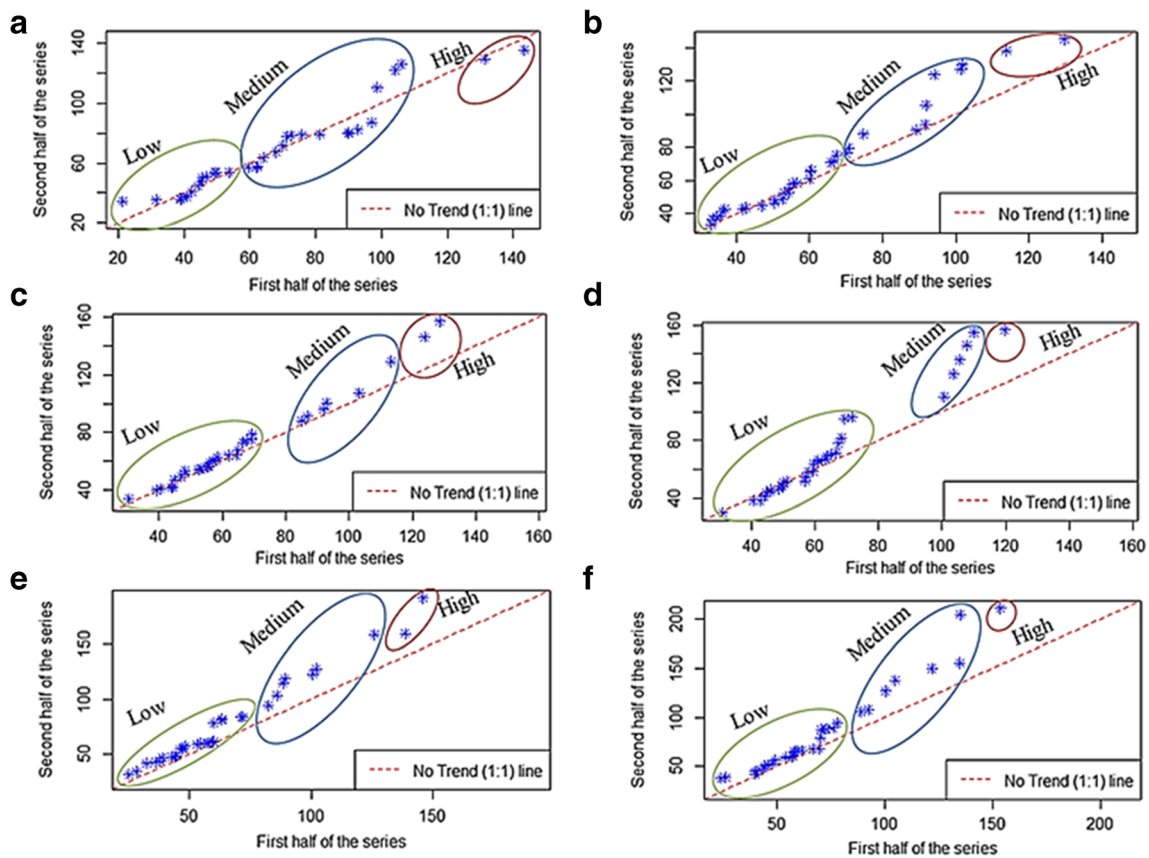


Fig. 8 ITA technique results for the monsoon season maximum rainfall for **a** G2, **b** G4, **c** G7, **d** G8, **e** G13 and **f** G14

study, no significant negative trends are exhibited for seasonal and annual rainfall. It is observed from Table 3 that out of the four seasons, the post-monsoon season showed no trend at all grid points. In contrast, the monsoon season exhibited a significant positive trend only at G1 that too for the MK1 test. Winter season displayed positively significant trend at all grid points for both MK1 and MK2 as seen in Table 3. The significant trend for annual series was observed only at G8 for both tests, while no trend was observed at the remaining 14 grids.

The number of positive significant cases (out of 180) and their percentages for seasonal and annual rainfall at 1%, 5% and 10% significance levels are presented in Table 4. Seasonal trends in 1% significance level have positive significance cases of 12 in MK1 and 22 in MK2 (0.16% for MK1 and 0.29% for MK2). For 5% significance level, eight cases for MK1 and 2 cases for MK2 and with 10% significance level and 8 instances in MK1 and 2 cases in MK2. Seasonally more trends are observed at a 1% significance level compared to 5% and 10% significance levels. Table 5 represents the significant positive trend cases at different significance levels for four seasons. Among the four seasons, winter season exhibited more positive trend cases followed by pre-monsoon season. No significant trend was detected in post-monsoon seasons at any significance level. Inclusively, at a 1% significance level, winter season showed more significant positive trends.

Comparison of spatial changes in trends of MK1 and MK2

Comparison of spatial distribution of Z statistics of MK tests for the monthly, seasonal and annual maximum rainfall is shown in Figs. 3, 4 and 5. From the Figs. 3 and 4, we can observe the similarities between the spatial distributions of trend, except in March. The Z values of MK2 show a more significant trend than MK1 which is not visible in the spatial distribution. Figure 5 shows the comparison of Z values in MK1 and MK2 in seasonal and annual maximum rainfall; from this figure, we can find that winter and pre-monsoon seasons show prominent difference such as MK2 shows a more significant trend.

ITA technique for annual rainfall

The results of the ITA technique for the annual maximum series are presented in Fig. 6. As already mentioned, the results of 6 grid points out of 15 are only presented and explained. ITA plots are divided into three clusters as low, medium and high to examine the trend variations throughout the plot. Explanations for the ITA technique are given concerning these three clusters. Plots G2, G13 and G14 showed no trend and increasing trend in the low phase, while in the medium

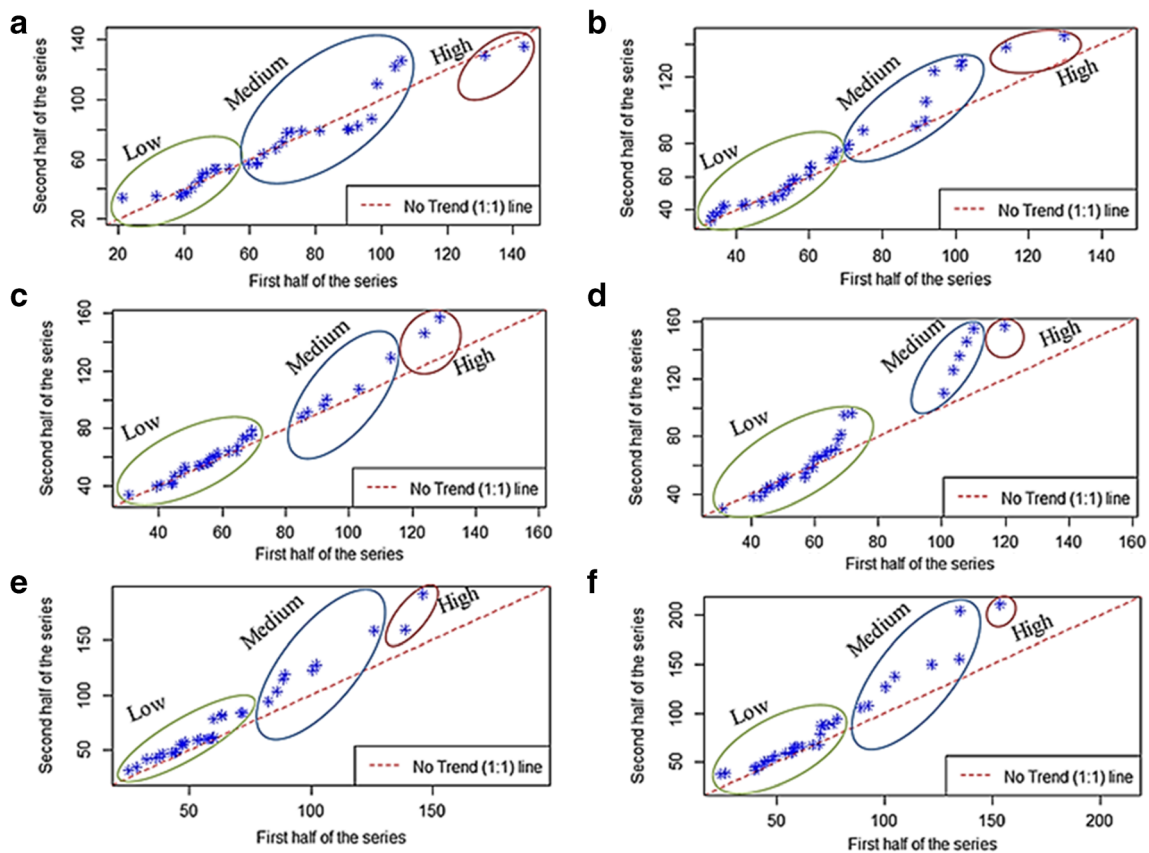


Fig. 9 ITA technique results for the post-monsoon season maximum rainfall for **a** G2, **b** G4, **c** G7, **d** G8, **e** G13 and **f** G14

phase, all grids are showing an increasing trend except for G13, whereas in the high phase a declining trend is exhibited for G7 and G8; grid points G2 and G4 are detected with a growing trend. A complete increasing trend was observed only at G4, while all the remaining grids showed non-monotonic trends as shown in Fig. 6.

ITA technique for seasonal rainfall

The results of the ITA technique for four seasons are presented in Figs. 7, 8, 9 and 10. As for the annual series, seasonal results are also explained for the same 6 grid points out of 15 grid points. Dataset points of pre-monsoon season (Fig. 7) randomly disseminate with an increasing trend in low and medium phases for all the selected 6 grids, whereas in the high phase, increasing trend for three grids (G2, G8 and G4) and a decreasing trend for grids 4 and 7 are observed as shown in Fig. 7.

In the monsoon season (Fig. 8), for all 6 grids, dataset points are spread over low, medium and high phases. In the low phase, no trend was observed in all 6 plots except for G8 and G13 (no trend followed by increasing trend), whereas in medium and high phases, an increasing trend was exhibited for all grids except grid 2. Comparatively, grid 2 exhibited no

trend in low and high phases and a non-monotonic trend was perceived in the medium phase as shown in Fig. 8.

For the post-monsoon season, dataset points of plots G2 and G4 are spread in low, medium and high phase. For all the grids, either no trend or increasing trend was observed in all three phases. G8 exhibited no trend, whereas, for G13 and G14, an increasing trend was observed in the medium phase with no trend in low and high phases. G7 displayed an increasing trend only in the high phase as shown in Fig. 9.

For the winter season, dataset points of G2, G4, G7, G8, G13 and G14 are plotted, and no trend was detected at starting subseries plot, and furthermore, a continuously increasing trend was observed as shown in Fig. 10.

Comparison of seasonal and annual trends

As expected, rainfall trend shows large variability from in ITA technique compared to other trend tests (MK1 and MK2) considered in the study. For annual series, using MK1 and MK2 test, trends are detected only for G8 as shown in Table 3, whereas, in the case of the ITA technique, trends are detected for all grid points as shown in Fig. 6. The ITA technique will not consider any prior conditions like that of MK tests, due to which, the graphical test is more appropriate in detecting monotonic and non-monotonic trends.

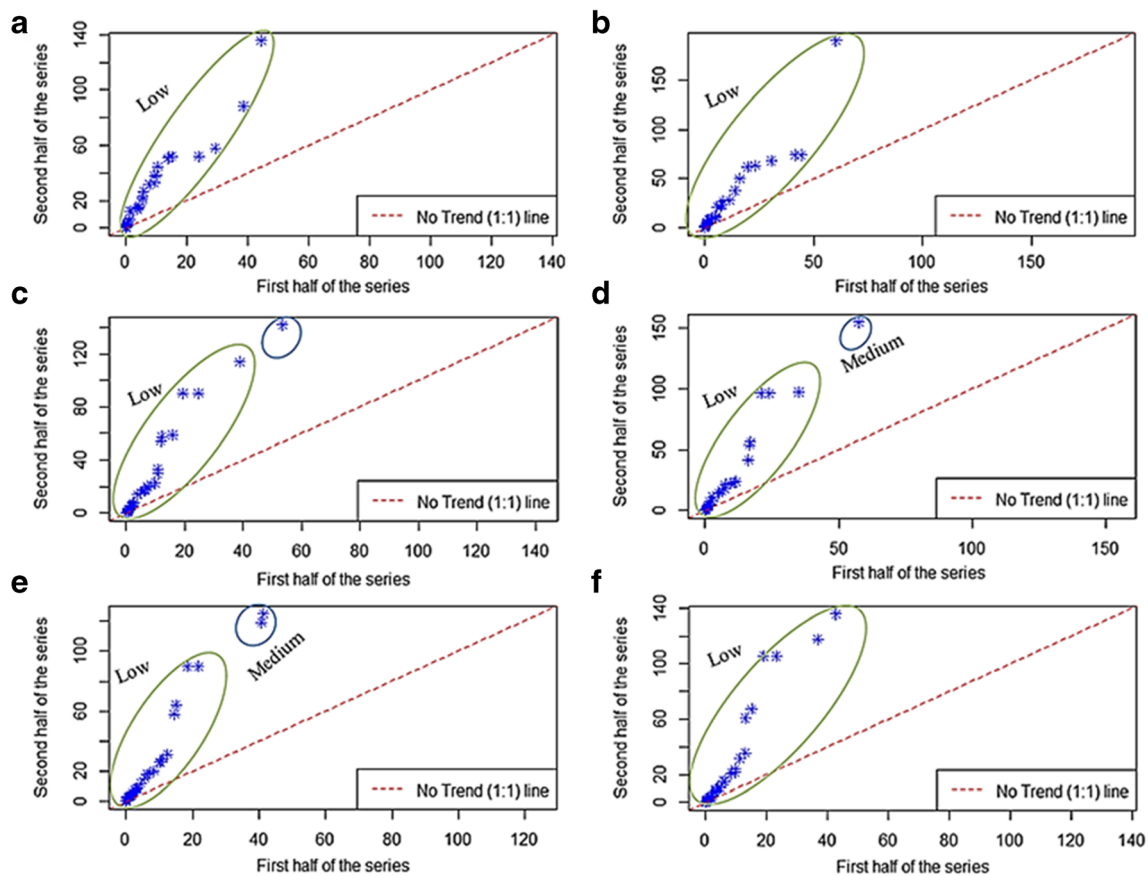


Fig. 10 ITA technique results for the winter season maximum rainfall for **a** G2, **b** G4, **c** G7, **d** G8, **e** G13 and **f** G14

In the pre-monsoon season, trends are detected equally for MK1 and MK2 tests compared to those for the ITA technique. But, for the ITA technique, all trends are limited to only low phase. In the monsoon season, no trend was noticed for MK1 and MK2, whereas, by ITA techniques, increasing trends are observed at G4, G7, G8, G13 and G14. During the post-monsoon season, no trends are detected for all grid points using MK1 and MK2, while for ITA techniques, increasing trends are observed for G4, G13 and G14. In the winter season, trends are detected for all the 15 grid points using MK1 and MK2 tests, whereas a trend was noticed for all 15 grid points in the low phase using the ITA technique. So, the ITA technique showed a tendency for more trends compared to MK1 and MK2 tests without any assumptions.

Sen's slope for maximum monthly rainfall

Monthly maximum rainfall trend magnitudes are calculated using Theil-Sen's slopes and plotted using box plots as shown in Fig. 11. In the box plots, the central thick horizontal line of all the months represents the median. Vertical lines (whiskers) with lower and upper ends signify magnitudes of lowest and highest rainfall values. The upper and lower ends of the boxes represent the 25th and 75th percentiles respectively. For

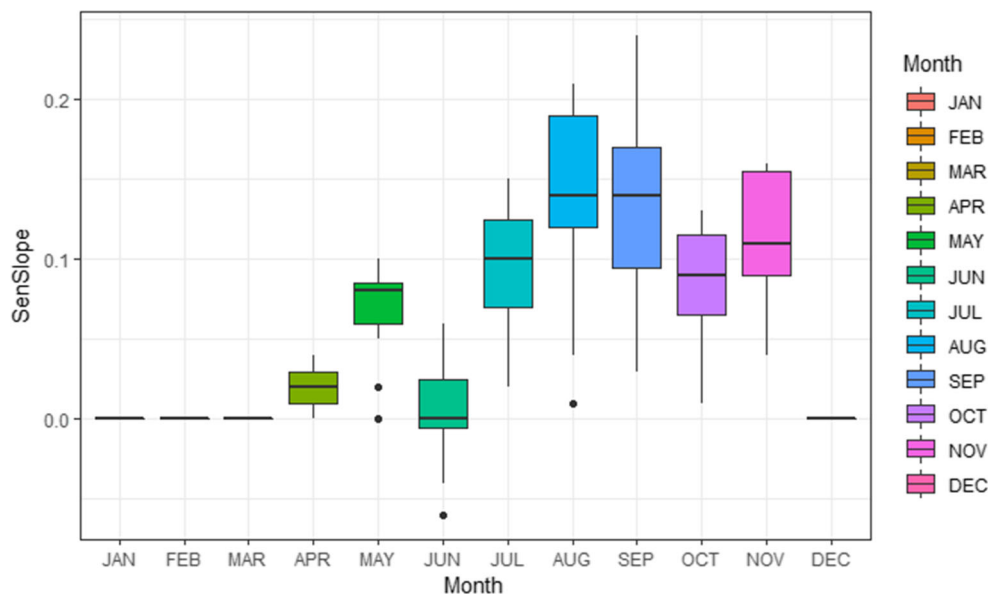
January, February, March, April and December, the median passes through the origin as there are no trend magnitudes for these months. From May to November, the trend magnitudes are positive and negative, falling above and below the origin.

Among all vertical lines, only one month, i.e. October, signifies the lowest negative magnitude, i.e. nearly - 0.08 mm/year followed by July with 0.05 mm/year. Similarly, the highest magnitude occurred in May (nearly 0.17 mm/year) followed by November (nearly 0.14 mm/year).

Sen's slope for seasonal and annual rainfall

Sen's slope approach was used in estimating the magnitudes for seasonal and annual rainfall as shown in Fig. 12. All the four seasonal and annual magnitudes exhibited positive slopes with a peak of 0.23 mm/year in the pre-monsoon season followed annually at 0.18 mm/year. The highest and lowest magnitudes are observed in pre-monsoon (nearly 0.23 mm/year) and post-monsoon seasons respectively. The magnitudes of seasonal and annual rainfall varied between 0 and 0.23 mm/year. The seasonal magnitudes are decreasing from pre-monsoon to post-monsoon and then magnitude increased in winter season as shown in Fig. 12.

Fig. 11 Maximum monthly rainfall trend magnitudes



Conclusions

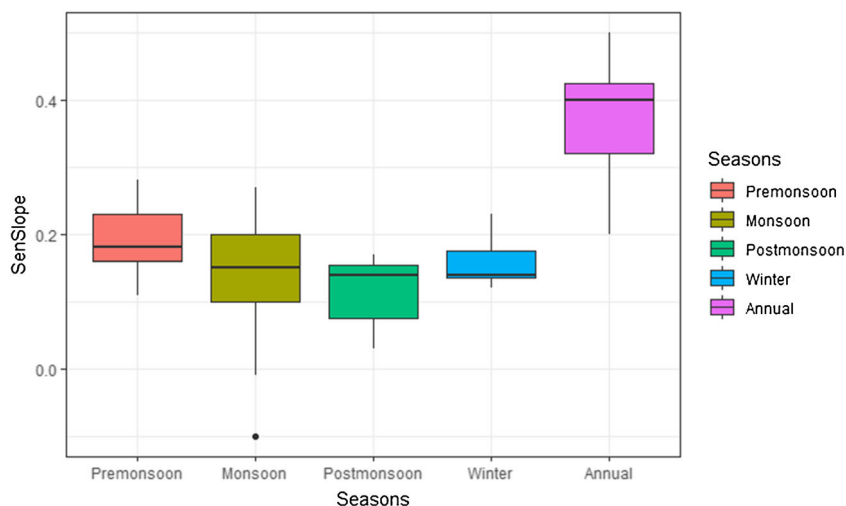
In this study, trends in monthly, seasonal and annual maximum rainfall series are calculated using the MK1, MK2 and ITA technique. The ITA technique has been used for maximum seasonal and annual rainfall series and compared with MK1 and MK2 tests at 15 grid points considered for the study region.

From the analysis of extreme monthly rainfall using Sen’s slope, it is observed that Sen’s slope has the lowest magnitude in October, i.e. nearly - 0.08 mm/year, whereas the highest magnitude occurred in May (nearly 0.17 mm/year). The MK2 test exhibited equal significant positive trends compared to MK1 for extreme monthly rainfall. For MK1 and MK2 tests, winter seasons exhibited signif-

icant positive trends for 15 grids followed by the pre-monsoon season. No trends are detected for 14 grid points (except for G8) for extreme annual rainfall for MK1 and MK2 test, whereas, by ITA technique, growing increasing trends are detected at G4.

The result obtained from the ITA technique agreed with the result obtained from MK1 and MK2 tests. It is also observed that the ITA technique detects trends better than MK tests. The graphical representation is a novelty as it shows hidden sub-trends of the dataset series. The ITA technique overcomes the assumptions of dependency of the dataset, distribution normality and dataset length. The detailed study of trends for rainfall and its comparison by three trend analysis methods will form the basis for coping up proper management of extremes (drought or flood) in the study area.

Fig. 12 Seasonal and annual maximum rainfall trend magnitudes



Declarations

Conflict of interest The authors declare that they have no competing interests.

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