



# Innovative trend analysis of spatio-temporal variations of rainfall in India during 1901–2019

RN Singh<sup>1</sup> · Sonam Sah<sup>2</sup> · Bappa Das<sup>3</sup> · Sunil Potekar<sup>1</sup> · Amresh Chaudhary<sup>1</sup> · H. Pathak<sup>1</sup>

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## Abstract

Spatio-temporal trends of rainfall during the last 119 years (1901 to 2019) in different meteorological sub-divisions of India were analyzed using gridded rainfall data. Innovative trend analysis (ITA) was performed for detecting the trends in seasonal and annual rainfall. The results of long-term trends and their magnitudes obtained from the ITA method were compared with traditional Mann-Kendall (M-K), modified Mann-Kendall (mM-K), and linear regression analysis (LRA) methods. Significant trends in seasonal and annual rainfall were detected in almost all the sub-divisions of India. The monsoon and annual rainfall showed increasing trends in most sub-divisions of the peninsular and northwest India, whereas decreasing trends were observed in the central northeast part of the country. Winter rainfall showed decreasing trends in most of the sub-divisions of the country. Results of M-K/mM-K and LRA concurred with the trends detected by ITA. However, the ITA is more sensitive in detecting hidden trends missed out by the traditional M-K/mM-K and LRA tests. This study will provide scientific reference for assessment and proactive mitigation of climate change impacts on water resources to manage the risk of climate variability.

## 1 Introduction

According to the Intergovernmental Panel on Climate Change (IPCC 2018), the increase in the global surface temperature may alter the hydrological cycle at global and local scales. Rainfall is one of the primary components of the hydrological cycle and understanding the patterns of its variability plays a vital role in understanding the aspects of climatological, hydrological, meteorological, and agricultural studies worldwide (Almazroui et al. 2012; Xia et al. 2015; Chatterjee et al. 2016; Sanchez et al. 2017; Yang et al. 2017; Ahmad et al. 2018; Amin et al. 2018; Malik and Kumar 2020). The economy and food security of countries like India are dependent on the timely availability of rainfall. So, accurate information of

long-term rainfall trends is necessary for the sustainable use of water resources (Zolina et al. 2010; Fatichi et al. 2013; Sun et al. 2018).

The Mann-Kendall (M-K), modified Mann-Kendall (mM-K), Sen's slope estimator (SS), and simple linear regression analysis (LRA) are the most widely used trend detection tests in recent studies (Tabari et al. 2011; Bari et al. 2016; Wang et al. 2016; Bisht et al. 2018; Singh et al. 2020). These methods are extensively used in trend analysis, but their application in time series analysis requires certain assumptions about the data, such as independence from autocorrelation and normality of the distribution (Yue et al. 2002). Şen (2012) proposed a new innovative trend analysis (ITA), which allows graphical evaluation of trends without any assumptions on the time series data. The ITA was widely applied for the detecting trends in hydro-meteorological variables in different regions of the world (Kisi 2015; Wu and Qian 2017; Caloiero et al. 2018; Caloiero 2020; Singh et al. 2020). Moreover, for effective trend detection, use of multiple tests has been suggested for time series data (Machiwal and Jha 2017), but only a few studies from India have used this approach. Jain et al. (2013) studied the long-term trends of monthly, seasonal, and annual rainfall data of northeast India for the period 1871–2008 using MK and SS test and reported no clear increasing or decreasing rainfall trends in the region as a whole. Lacombe and McCartney (2014) analyzed India's daily gridded rainfall

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RN Singh and Sonam Sah contributed equally to this work.

✉ RN Singh  
ramnsingh.icar@gmail.com

<sup>1</sup> ICAR-National Institute of Abiotic Stress Management, Baramati, Maharashtra, India

<sup>2</sup> G.B. Pant University of Agriculture & Technology, Pantnagar, Uttarakhand, India

<sup>3</sup> ICAR-Central Coastal Agricultural Research Institute, Old Goa, Goa, India

(1951–2007) data using M-K test and reported decreasing trends across central India and increasing rainfall trends over the south peninsula and the northeast, with a very heterogeneous pattern across the rest of the country. Subash and Sikka (2014) analyzed the rainfall data of 30 meteorological sub-divisions of India for the period 1904–2003 using M-K and SS tests and they reported significantly increasing trends in annual rainfall of India. Mondal et al. (2015), using the Indian Institute of Tropical Meteorology (IITM) dataset for rainfall, reported decreasing trends for the entire India from 1871 to 2011 using M-K test and SS estimator. Malik and Kumar (2020) utilized M-K, mM-K, SS, and LRA tests to examine the spatio-temporal trends of the rainfall of Uttarakhand, India using station data of more than 15 districts of the state. They reported significantly increasing and decreasing rainfall trends in monthly, seasonal, and annual time scales in different districts. Many researchers conducted studies on rainfall trends for different states and regions of India using M-K, SS, and LRA tests, e.g. Maharashtra (Singh et al. 2020), Chhattisgarh (Meshram et al. 2017), Assam (Goyal 2014), Odisha (Patra et al. 2012), Rajasthan (Pingale et al. 2014; Mundetia and Sharma 2014), Kerala (Krishnakumar et al. 2009; Nair et al. 2014), Jharkhand (Chandniha et al. 2017; Sharma and Singh 2017), West Bengal (Ghosh 2018), Himachal Pradesh (Jaswal et al. 2015), Madhya Pradesh (Duhan and Pandey 2013), Bundelkhand region (Jana et al. 2017), Terai region (Sah et al. 2020), and western Himalayas (Singh and Mal 2014). Caloiero et al. (2018) studied the temporal rainfall variability in the South Island of New Zealand using ITA and M-K tests with a dataset of more than 150 rain gauges using seasonal and annual rainfall data of more than 50 years and observed significant trends in seasonal and annual rainfall in the region. Machiwal et al. (2019) investigated 35 years of India's arid coastal region rainfall data, using M-K/mM-K and ITA tests, and they reported increasing trends in monsoon and annual rainfall in India's arid coastal region. Güçlü (2020) used MK and ITA tests for analyzing 50 years of rainfall data collected from meteorological stations in Turkey and reported significantly increasing trends in the region. In most of the studies, which used M-K, SS, and ITA, a comparison between these tests has been made, showing advantages of the ITA over the traditional trend detection tests.

This paper aims to analyze the trends and their magnitudes in seasonal and annual rainfall data of 119 years (1901–2019) for mainland meteorological sub-divisions of India using M-K, mM-K, SS, LRA, and ITA methods. The uniqueness of the study is the comparison between the recent Sen's innovative trend analysis with the M-K/mM-K and LRA on the sub-divisional level. The study highlights the potential of comprehensive statistical analysis for a better understanding of rainfall distribution patterns over space and time.

## 2 Materials and methods

### 2.1 Study area and data

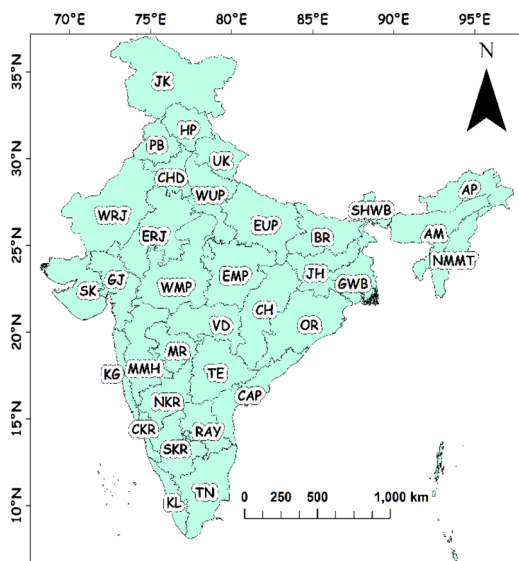
India is the seventh largest country in the world, positioned north of the equator between  $8^{\circ} 4' \text{ N}$ – $37^{\circ} 6' \text{ N}$  latitude and  $68^{\circ} 7' \text{ E}$ – $97^{\circ} 25' \text{ E}$  longitude, with a geographical area of 329 million ha. India has been divided into 36 meteorological sub-divisions (34 on the mainland and 2 on islands). In this paper, the rainfall patterns of 34 mainland meteorological sub-divisions in India are analyzed (Fig. 1). In this study, we have used daily rainfall data of 1901–2019 (119 years) generated by the India Meteorological Department (IMD) at a grid size of  $0.25^{\circ}$  latitude  $\times$   $0.25^{\circ}$  longitude. IMD's gridded dataset was developed using quality-controlled rainfall data collected from a network of well-distributed more than 3000 rain gauge stations all over India. The detailed information of the data generation is explained by Pai et al. (2014). As per IMD classification, there are four meteorological seasons over India: winter season: January–February, pre-monsoon season: March–May, monsoon season: June–September, and post-monsoon season: October–December. The daily rainfall data of each sub-division is further processed to obtain monthly data. It was further cumulated over the seasons to obtain the total seasonal and annual rainfall. The seasonal and annual rainfall data of each sub-division were analyzed for basic statistical parameters, including mean, standard deviation (SD), coefficient of skewness (CS), and coefficient of kurtosis (CK).

### 2.2 Methodology

The Mann-Kendall (M-K), modified Mann-Kendall (mM-K), Sen's slope (SS) estimator, linear regression analysis (LRA), and Sen's innovative trend analysis (ITA) methods were employed to evaluate the trends and their magnitudes in the seasonal and annual rainfall.

#### 2.2.1 Mann-Kendall/modified Mann-Kendall and Sen's slope estimator

The non-parametric Mann-Kendall (M-K) test (Mann 1945; Kendall 1975) was used to detect significant trends in various long-term time series data (Tabari et al. 2011; Shifteh Some'e et al. 2012; Suryavanshi et al. 2014; Pingale et al. 2014; Gajbhiye et al. 2016; Kumar et al. 2017). Detecting trends in time series data is often affected by the presence of serial autocorrelation (Novotny and Stefan 2007). Significant autocorrelations were calculated using the method proposed by Shahin et al. (1993) and Haan (2002). Lag-1 autocorrelation coefficient in the data series was calculated and tested at 5% confidence limits. For serially correlated data, having a significant lag-1 autocorrelation coefficient, modified Mann-Kendall (mM-K) test using the Hamed and Ramachandra



Main land met sub-divisions of India (34)			
Arunachal Pradesh	AP	Madhya Maharashtra	MMH
Assam & Meghalaya	AM	Marathwada	MR
Bihar	BR	Naga, Mani. Mizo. & Tripura	NMMT
Chhattisgarh	CH	North Interior Karnataka	NKR
Coastal Andhra Pradesh	CAP	Orissa	OR
Coastal Karnataka	CKR	Punjab	PB
East Madhya Pradesh	EMP	Rayalaseema	RAY
East Rajasthan	ERJ	Saurashtra, Kutch & Diu	SK
East Uttar Pradesh	EUP	South Interior Karnataka	SKR
Gangatic West Bengal	GWP	Sub-Him. W. Bengal & Sikkim	SHWB
Gujarat	GJ	Tamilnadu & Pondicherry	TN
Hary. Chand. & Delhi	CHD	Telangana	TE
Himachal Pradesh	HP	Uttaranchal	UK
Jammu & Kashmir	JK	Vidarbha	VD
Jharkhand	JH	West Madhya Pradesh	WMP
Kerala	KL	West Rajasthan	WRJ
Konkan & Goa	KG	West Uttar Pradesh	WUP

Fig. 1 Location of 34 mainland meteorological sub-divisions of India

Rao (1998) variance correction approach was employed (Kumar et al. 2017). The positive and negative values of standardized M-K and mM-K test statistic ( $Z_{MK}$  and  $Z_{MMK}$ ) indicate increasing and decreasing trends, respectively. The non-parametric Sen’s slope (SS) estimator is used to estimate the magnitude (true slope) of the trend (Theil 1950; Sen 1968). Positive and negative values of SS indicate increasing and decreasing trends, respectively.

2.2.2 Linear regression analysis

Linear regression analysis is a parametric approach to analyze the variation in trends. The regression line is used to explain the trend of long-term seasonal and annual pattern of rainfall. The regression formula proposed by Meshram et al. (2017) was used in this study. The positive and negative values of the slope of LRA (SL) represent increasing and decreasing trends, respectively.

2.2.3 Innovative trend analysis

The innovative trend analysis (ITA) proposed by Şen (2012) was also applied to detect the trends in rainfall time series. Unlike the most commonly used classical trend analysis methods like the M-K/mM-K and SS tests, the ITA method is free from the assumptions of serial autocorrelation, normality, and length of the records. The time series is divided into two equal parts in ITA from the first date to the end date. Both sub-series are arranged in ascending order. The first half of the series is placed on X-axis, and the second half is placed at the Y-axis of the Cartesian coordinate system. If the data points are collected on 1:1 line, it indicates there is no trend in the data. If the data points fall above the 1:1 line, it is indicative of a positive trend, while if the data points accumulate below the

1:1 line, it indicates a negative trend. The slope of the ITA (SITA) test was proposed by Şen (2017). A positive SITA value indicates an increasing trend, while a negative SITA shows a decreasing trend in time series. The ITA was performed using “trendchange” package (Patakamuri and Das 2019) in R software version 4.0.2 (R Core Team 2020). In this paper, the null hypothesis of no trend against the alternate hypothesis of there is a trend in the rainfall time series was tested at two different significance levels ( $\alpha$ ), i.e.,  $\alpha = 5\%$  and  $\alpha = 1\%$ .

3 Results and discussion

3.1 Statistical summary of rainfall

Descriptive statistical parameters of the seasonal and annual rainfall of 34 meteorological sub-divisions of India during 1901–2019, including mean, standard deviation (SD), coefficients of variation (CV), skewness (CS), and kurtosis (CK), are summarized in Table 1. The highest mean rainfall of winter, pre-monsoon, monsoon, post-monsoon, and annual was observed in HP (171.2 mm), AP (669.9 mm), KG (2869.2 mm), KL (493.6 mm), and CKR (3138.3 mm) sub-divisions, respectively, while the lowest was recorded in KG (2.0 mm), SK (7.3 mm), JK (249.0 mm), WRJ (9.3 mm), and WRJ (299.8 mm), respectively. Rainfall variability was classified by Hare (2003) as low ( $CV < 20\%$ ), medium ( $20\% < CV < 30\%$ ), and high ( $CV > 30\%$ ). The rainfall variability was high ( $CV > 30\%$ ) during the winter season in all the sub-divisions. Except AM in pre-monsoon and KL in post-monsoon seasons, all other sub-divisions had high rainfall variability in pre- and post-monsoon seasons. In monsoon and annual rainfall, variability was high only in 3 sub-divisions (JK, WRJ, and SK), and the variability was low ( $CV < 20\%$ ) to

**Table 1** Statistical summary of annual and seasonal rainfall in meteorological sub-divisions of India

Stations	Winter			Pre-monsoon			Monsoon			Post-monsoon			Annual												
	Mean	SD	CK	Mean	SD	CK	Mean	SD	CK	Mean	SD	CK	Mean	SD	CK										
	CV	CS	CK	CV	CS	CK	CV	CS	CK	CV	CS	CK	CV	CS	CK										
AM	49.5	25.9	52.4	1.2	6.6	0.4	3.3	1560.1	208.3	13.4	1.0	6.5	173.1	67.7	39.1	0.3	2.7	2365.2	293.2	12.4	0.3	5.8			
AP	106.4	48.8	45.9	0.5	3.3	30.7	0.3	2.8	1825.7	435.3	23.8	0.7	3.3	197.2	92.4	46.9	0.7	4.2	2799.1	595.2	21.3	0.3	3.2		
BR	26.7	20.6	76.9	0.8	2.8	36.9	40.4	0.2	3.0	1041.4	175.2	16.8	0.1	3.2	77.6	62.4	80.5	1.2	4.0	1237.2	192.3	15.5	-0.1	3.0	
CAP	20.6	22.5	109.3	1.7	6.2	60.8	67.4	3.1	19.4	573.5	113.6	19.8	0.2	2.3	324.2	114.8	35.4	0.1	2.4	1008.4	169.4	16.8	0.6	3.3	
CH	31.1	29.1	93.5	1.8	7.1	58.7	34.0	57.9	1.3	4.8	1195.7	165.4	13.8	0.3	3.6	83.5	51.4	61.6	0.7	2.8	1368.9	200.2	14.6	0.2	3.1
CHD	37.1	25.0	67.4	0.8	3.3	37.5	28.0	74.8	1.7	7.1	473.3	138.8	29.3	0.3	2.7	25.0	29.3	117.2	2.4	10.0	572.9	145.0	25.3	0.4	2.9
CKR	4.2	7.4	177.5	3.0	12.8	154.7	96.9	62.6	1.7	6.8	2723.5	493.4	18.1	0.6	4.3	256.0	96.3	37.6	0.4	2.7	3138.3	512.6	16.3	1.0	5.5
EMP	38.1	30.9	81.0	1.2	4.4	30.9	25.7	83.3	1.7	5.9	1069.3	190.9	17.9	-0.1	2.5	59.8	48.1	80.5	1.1	3.9	1198.0	217.1	18.1	0.0	2.6
ERJ	12.2	11.4	93.4	1.3	4.2	18.1	16.8	92.8	2.1	9.1	619.6	156.5	25.2	0.1	3.3	24.2	28.1	116.3	2.0	8.3	674.1	165.4	24.5	0.4	4.6
EUP	32.0	22.9	71.6	1.0	4.4	35.4	22.1	62.4	1.0	3.8	884.9	181.6	20.5	0.4	3.6	53.5	50.8	95.0	1.9	8.1	1005.8	192.5	19.1	0.3	3.1
GJ	3.1	5.3	169.6	3.9	25.0	8.7	15.1	173.1	3.6	19.2	882.9	263.0	29.8	0.1	2.5	30.7	36.5	119.0	2.1	8.8	925.4	268.2	29.0	0.2	2.5
GWB	35.4	30.3	85.5	1.4	6.6	188.3	70.7	37.5	0.6	3.6	1097.7	189.1	17.2	0.4	3.0	139.9	82.2	58.7	0.9	3.2	1461.3	231.9	15.9	0.3	3.2
HP	171.2	74.5	43.5	1.2	5.1	219.8	91.8	41.8	1.2	5.3	763.1	184.5	24.2	0.2	2.8	85.6	64.9	75.9	1.8	7.4	1239.7	224.5	18.1	0.5	2.9
JH	39.7	32.4	81.4	1.4	5.4	95.8	39.8	41.5	0.4	2.8	1082.3	157.7	14.6	0.1	2.6	101.4	68.0	67.1	1.0	3.7	1319.3	185.0	14.0	0.1	2.8
JK	143.2	73.2	51.1	1.4	6.9	219.0	101.4	46.3	1.4	4.7	249.0	116.2	46.7	1.8	6.8	79.5	57.7	72.6	1.6	5.9	690.8	254.0	36.8	1.1	3.5
KG	2.0	4.3	210.6	3.3	14.9	43.5	47.1	108.2	2.2	8.3	2869.2	486.6	17.0	-0.1	3.7	150.9	94.5	62.7	1.4	5.7	3065.6	515.1	16.8	0.1	3.5
KL	33.2	26.1	78.4	1.0	3.6	330.9	120.7	36.5	1.2	4.3	1762.4	374.6	21.3	0.2	5.0	493.6	101.2	25.8	0.0	2.6	2620.1	421.4	16.1	0.1	3.8
MMH	4.8	7.7	159.2	2.9	12.4	35.0	23.5	67.2	1.0	3.2	687.8	179.1	26.0	3.3	25.8	101.2	57.5	56.8	0.7	2.8	828.9	194.9	23.5	2.6	18.7
MR	10.7	13.3	124.7	1.8	6.3	32.6	25.8	79.3	1.6	5.7	691.7	169.7	24.5	0.5	3.0	90.5	58.1	64.2	0.7	3.0	825.5	190.4	23.1	0.4	2.8
NKR	6.0	8.3	137.0	1.7	5.4	76.4	34.4	45.0	0.9	3.6	480.4	115.6	24.1	1.3	7.9	130.3	68.2	52.3	0.9	4.6	693.1	145.4	21.0	1.2	6.2
NMMT	45.4	30.5	67.1	1.6	8.2	465.5	127.5	27.4	0.2	3.2	1212.0	147.8	12.2	0.5	3.8	171.4	71.9	41.9	0.5	2.8	1894.4	249.2	13.2	0.4	4.2
OR	33.1	28.5	86.2	1.4	5.0	123.7	53.2	43.1	1.6	7.5	1132.1	148.7	13.1	0.2	3.2	162.0	91.3	56.4	0.5	2.7	1450.9	183.9	12.7	0.1	3.0
PB	57.2	32.3	56.5	0.5	2.5	55.4	35.2	63.5	1.5	6.3	509.0	149.2	29.3	0.7	4.0	33.3	43.2	129.9	5.1	39.7	654.9	159.3	24.3	0.9	4.0
RAY	13.3	17.5	132.0	2.0	6.6	75.3	36.8	48.8	1.3	5.3	384.7	102.5	26.7	0.9	3.8	244.8	93.6	38.3	0.4	3.1	718.1	144.4	20.1	0.5	3.0
SHWB	34.8	24.3	69.9	1.3	5.4	431.2	103.9	24.1	0.4	3.4	2166.7	288.3	13.3	0.1	3.2	157.8	92.9	58.9	1.3	5.3	2790.6	331.7	11.9	0.0	3.5
SK	2.5	4.3	170.7	2.5	10.3	7.3	16.3	222.2	4.2	22.4	495.3	203.2	41.0	0.4	2.9	22.9	34.1	149.0	2.6	10.7	528.1	208.9	39.6	0.5	3.0
SKR	7.7	9.4	122.2	1.9	6.5	139.9	43.9	31.3	0.4	2.5	562.7	105.9	18.8	-0.1	2.6	203.7	76.7	37.6	0.3	2.7	913.9	142.3	15.6	0.1	3.0
TE	15.0	17.3	114.8	1.8	6.6	61.0	33.4	54.7	1.5	6.1	762.0	156.7	20.6	0.4	2.8	116.4	65.8	56.5	0.7	2.9	954.4	178.4	18.7	0.3	2.5
TN	39.1	40.0	102.3	1.5	4.6	128.3	49.0	38.2	0.9	3.9	331.5	89.3	26.9	1.7	11.8	460.7	140.9	30.6	0.1	2.8	959.6	185.6	19.3	-0.2	5.2
UK	118.5	60.0	50.7	1.0	4.9	152.2	68.8	45.2	0.6	2.5	1123.4	224.2	20.0	0.3	3.0	71.0	64.6	91.0	2.3	9.8	1465.1	251.6	17.2	0.2	2.7
VD	22.8	23.4	102.9	1.5	4.7	34.0	27.5	80.9	1.6	6.2	992.2	182.0	18.3	0.1	2.7	76.0	50.9	67.0	0.8	3.8	1125.0	204.4	18.2	0.1	2.7
WMP	16.0	15.2	94.8	1.2	3.7	15.9	14.3	90.3	1.8	6.5	883.2	173.7	19.7	0.5	3.0	47.4	42.3	89.4	1.2	3.9	962.5	187.0	19.4	0.5	4.0
WRJ	8.5	8.8	103.3	1.4	4.4	17.8	16.3	91.7	1.8	6.5	264.1	104.7	39.6	0.7	3.9	9.3	13.3	142.4	2.7	11.4	299.8	111.5	37.2	0.9	4.9
WUP	37.0	26.2	70.7	0.9	3.4	31.6	22.4	71.1	1.3	4.6	754.9	172.1	22.8	-0.2	2.7	41.2	47.6	115.6	2.1	7.0	864.7	183.2	21.2	-0.1	2.6

SD, standard deviation; CS, coefficient of skewness; CK, coefficient of kurtosis

**Table 2** Values of the slope of linear regression (SL) and Sen’s slope (SS) for seasonal and annual rainfall in meteorological sub-divisions of India

Sub-division	Winter		Pre-monsoon		Monsoon		Post-monsoon		Annual	
	SL	SS	SL	SS	SL	SS	SL	SS	SL	SS
AM	-0.13	<b>-0.15</b>	0.11	0.01	0.72	<b>0.65</b>	0.07	0.05	0.76	<b>1.23</b>
AP	0.07	<b>0.07</b>	0.43	<b>0.64</b>	-3.78**	<b>-3.36</b>	-0.27	<b>-0.26</b>	-3.55*	<b>-2.73</b>
BR	-0.14**	-0.11*	0.12	0.16	-0.96*	-1.05*	-0.02	0.02	-1	-1.14*
CAP	-0.06	-0.03	0.14	0.07	0.78**	0.79*	-0.02	-0.08	0.84	0.86
CH	-0.29**	-0.20**	-0.26**	-0.20**	-1.12*	-1.21**	-0.18	-0.14	-1.86**	-1.81**
CHD	-0.07	-0.07	0.13	<b>0.10**</b>	-0.13	-0.13	-0.08	<b>-0.04</b>	-0.15	-0.18
CKR	-0.01	0.00	0.12	0.14	4.61**	<b>4.68**</b>	0.03	-0.1	4.75**	<b>5.17**</b>
EMP	-0.16	<b>-0.13**</b>	-0.17*	-0.12*	-1.22*	-1.39*	-0.2	-0.16	-1.75**	-1.90**
ERJ	-0.04	-0.04	0	0.02	0.27	0.24	-0.02	-0.01	0.21	0.26
EUP	-0.10	-0.1	-0.01	0.01	-1.37	-1.22**	-0.2	-0.08	-1.68**	<b>-1.68**</b>
GJ	-0.04**	-0.01**	-0.09*	-0.03**	0.39	0.28	0.02	0.03	0.28	0.15
GWB	-0.13	-0.07	-0.16	-0.12	0.81	0.94	0.36	0.29	0.87	1.07
HP	0.13	0.17	0.1	<b>0.08</b>	-1.22*	-1.13*	0.02	<b>0.02</b>	-0.96	<b>-0.83</b>
JH	-0.35**	-0.26**	-0.03	0.02	-0.92*	-0.97*	0.02	0.06	-1.28**	-1.15*
JK	0.58**	<b>0.58**</b>	1.23**	<b>1.00**</b>	1.56**	<b>1.12**</b>	0.52**	<b>0.41**</b>	3.91**	<b>3.31**</b>
KG	-0.03*	-0.00*	-0.06	0.01	4.04**	4.03**	0.12	0.2	4.07**	3.79**
KL	-0.19**	-0.18**	-0.29	-0.18	-3.00**	-2.68**	-0.73*	<b>-0.84*</b>	-4.20**	<b>-3.70**</b>
MMH	-0.05**	-0.01*	-0.09	-0.07	0.5	<b>0</b>	0.04	0.01	0.4	<b>-0.02</b>
MR	-0.09*	-0.03**	-0.06	-0.05	-0.21	-0.3	0.16	0.13	-0.19	-0.26
NKR	-0.04	0.00	0.06	0.03	0.4	0.25	0.03	0.07	0.46	0.44
NMMT	-0.19*	-0.18**	-0.11	-0.21	0.55	0.41	0.08	0.04	0.34	0.04
OR	-0.20**	-0.12*	0.06	0.05	-0.02	-0.13	-0.06	-0.17	-0.23	-0.19
PB	-0.04	-0.03	0.1	<b>0.09</b>	0.51	0.61	-0.06	<b>-0.04</b>	0.51	0.68
RAY	-0.14**	-0.05*	0.12	0.14	0.41	0.41	0.15	0.08	0.53	0.62
SHWB	0.03	<b>0.01</b>	0.77**	0.78**	-1.58*	-1.81*	0.01	0.04	-0.78	-0.95
SK	-0.04**	-0.01**	-0.06	-0.02**	1.26*	1.01	0.11	0.03	1.27*	1.05
SKR	-0.05	-0.02	0.01	-0.05	0.73**	0.81**	-0.15	-0.21	0.54	0.79*
TE	-0.06	-0.02	0.02	0.01	0.5	0.6	0.11	0.11	0.58	0.55
TN	-0.31**	-0.24**	-0.03	-0.09	0.18	<b>0.07</b>	-0.12	-0.09	-0.29	<b>-0.09</b>
UK	-0.19	-0.23	0.32	<b>0.32</b>	-1.31*	-1.28*	-0.25	<b>-0.19</b>	-1.43*	-1.2
VD	-0.14*	-0.09*	-0.14	<b>-0.11*</b>	-0.27	-0.39	-0.04	-0.02	-0.6	-0.75
WMP	-0.05	<b>-0.05**</b>	-0.05	-0.03	0.48	0.28	-0.04	-0.04	0.34	0.29
WRJ	-0.02	-0.01	0.08	0.06	0.31	0.4	0.03	<b>0</b>	0.4	0.57
WUP	-0.09	-0.09	0.02	0.04	-0.74	-0.82	-0.16	<b>-0.05</b>	-0.98*	-1.19*

\*Trend at 5% significance level (p < 0.05); \*\*Trend at 1% significance level (p < 0.01). Bold values indicate mM-K test values (series with significant autocorrelation)

medium (20% < CV < 30%) in the rest of the sub-divisions. CS values for winter, pre-monsoon, and post-monsoon seasons for all the sub-divisions indicate positively skewed rainfall data. In contrast, CS values indicate that in monsoon 4 sub-divisions and 3 sub-divisions in annual rainfall had small negative CS. Apart from this, all other sub-divisions had a positively skewed distribution in monsoon and annual rainfall (Table 1).

### 3.2 Rainfall trends and their magnitudes

The seasonal and annual rainfall trends as detected by traditional methods (LRA and M-K/mM-K test) are summarized in Table 2. The results of ITA are presented in Tables 3, 4, 5, 6, and 7, and results were graphically presented in Fig. 2. The comparison of the traditional methods with ITA in detecting trends and their



**Table 3** Results of innovative trend analysis of winter rainfall in meteorological sub-divisions of India

Sub-division	SITA	SSD	Correlation $\rho_{Y_1 Y_2}$	Lower CL Significance level ( $p < 0.05$ )	Upper CL Significance level ( $p < 0.05$ )	Lower CL Significance level ( $p < 0.01$ )	Upper CL Significance level ( $p < 0.01$ )
AM	-0.13**	0.02	0.91	-0.03	0.03	-0.04	0.04
AP	0.18**	0.02	0.97	-0.04	0.04	-0.05	0.05
BR	-0.21**	0.01	0.99	-0.01	0.01	-0.01	0.01
CAP	-0.03**	0.01	0.98	-0.01	0.01	-0.02	0.02
CH	-0.33**	0.01	0.99	-0.01	0.01	-0.02	0.02
CHD	-0.13**	0.01	0.97	-0.02	0.02	-0.02	0.02
CKR	-0.02**	0.00	0.96	-0.01	0.01	-0.01	0.01
EMP	-0.21**	0.01	0.98	-0.02	0.02	-0.02	0.02
ERJ	-0.06**	0.00	0.99	-0.01	0.01	-0.01	0.01
EUP	-0.17**	0.01	0.96	-0.02	0.02	-0.03	0.03
GJ	-0.05**	0.00	0.96	0.00	0.00	-0.01	0.01
GWB	-0.14**	0.02	0.95	-0.03	0.03	-0.04	0.04
HP	-0.01	0.03	0.97	-0.05	0.05	-0.07	0.07
JH	-0.40**	0.01	0.99	-0.01	0.01	-0.01	0.01
JK	0.38**	0.06	0.88	-0.11	0.11	-0.14	0.14
KG	-0.03**	0.00	0.92	-0.01	0.01	-0.01	0.01
KL	-0.22**	0.01	0.98	-0.02	0.02	-0.02	0.02
MMH	-0.06**	0.00	0.94	-0.01	0.01	-0.01	0.01
MR	-0.10**	0.00	0.99	0.00	0.00	-0.01	0.01
NKR	-0.03**	0.00	0.96	-0.01	0.01	-0.01	0.01
NMMT	-0.21**	0.02	0.87	-0.05	0.05	-0.06	0.06
OR	-0.17**	0.01	0.94	-0.03	0.03	-0.04	0.04
PB	-0.14**	0.01	0.99	-0.02	0.02	-0.02	0.02
RAY	-0.13**	0.01	0.95	-0.02	0.02	-0.02	0.02
SHWB	-0.01	0.01	0.98	-0.01	0.01	-0.02	0.02
SK	-0.04**	0.00	0.94	0.00	0.00	-0.01	0.01
SKR	-0.06**	0.00	0.98	-0.01	0.01	-0.01	0.01
TE	-0.06**	0.00	0.99	-0.01	0.01	-0.01	0.01
TN	-0.36**	0.02	0.95	-0.04	0.04	-0.05	0.05
UK	-0.17**	0.04	0.92	-0.07	0.07	-0.10	0.10
VD	-0.16**	0.01	0.96	-0.02	0.02	-0.03	0.03
WMP	-0.07**	0.01	0.98	-0.01	0.01	-0.01	0.01
WRJ	-0.03**	0.00	0.99	0.00	0.00	0.00	0.00
WUP	-0.16**	0.01	0.98	-0.01	0.01	-0.02	0.02

\*Trend at 5% significance level ( $p < 0.05$ ); \*\*Trend at 1% significance level ( $p < 0.01$ ). SSD, slope of SD

magnitude for seasonal and annual rainfall has been depicted in Figs. 3 and 4, respectively.

### 3.2.1 Winter

The results of winter rainfall showed trends dominated by negative values, and except LRA and SS of JK, only negative trends were significant ( $p < 0.05$  or  $p < 0.01$ ). Overall, 14 and 17 sub-divisions had significant rainfall trends using LRA and M-K/mM-K tests, respectively. The trends detected using ITA are given in Table 3

and depicted in Fig. 2. The results of ITA showed that the significant number of slopes ( $p < 0.01$ ) was dominated by negative values, except AP and JK, which exhibited significant increasing trends ( $p < 0.01$ ). This indicates that significant trends in winter rainfall of 17 sub-divisions that cannot be identified by LRA and M-K/mM-K tests can be detected using ITA. JH showed sharpest decreasing trends in winter rainfall of more than 2.5 mm per decade ( $p < 0.01$ ) during 1901 to 2019, and only JK exhibited significantly increasing trend of more than 3.8 mm per decade in winter rainfall ( $p < 0.01$ ) using LRA, M-K/mM-K, and ITA tests.

**Table 4** Results of innovative trend analysis of pre-monsoon rainfall in meteorological sub-divisions of India

Sub-division	SITA	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
AM	-0.53**	0.04	0.98	-0.08	0.08	-0.11	0.11
AP	-0.35**	0.07	0.97	-0.14	0.14	-0.19	0.19
BR	0.15**	0.02	0.96	-0.03	0.03	-0.04	0.04
CAP	0.10*	0.04	0.89	-0.08	0.08	-0.11	0.11
CH	-0.31**	0.01	0.99	-0.01	0.01	-0.02	0.02
CHD	0.19**	0.01	0.97	-0.02	0.02	-0.03	0.03
CKR	0.03	0.03	0.98	-0.06	0.06	-0.08	0.08
EMP	-0.21**	0.01	0.99	-0.01	0.01	-0.02	0.02
ERJ	0.02*	0.01	0.96	-0.01	0.01	-0.02	0.02
EUP	0.02**	0.01	0.99	-0.01	0.01	-0.01	0.01
GJ	-0.08**	0.01	0.95	-0.01	0.01	-0.02	0.02
GWB	-0.07**	0.02	0.98	-0.04	0.04	-0.06	0.06
HP	0.25**	0.03	0.98	-0.05	0.05	-0.07	0.07
JH	-0.02	0.01	0.98	-0.02	0.02	-0.03	0.03
JK	1.47**	0.03	0.98	-0.06	0.06	-0.08	0.08
KG	-0.09**	0.02	0.98	-0.03	0.03	-0.04	0.04
KL	-0.65**	0.03	0.98	-0.06	0.06	-0.09	0.09
MMH	-0.08**	0.01	0.98	-0.01	0.01	-0.02	0.02
MR	-0.05**	0.01	0.98	-0.02	0.02	-0.02	0.02
NKR	0.05**	0.01	0.99	-0.02	0.02	-0.02	0.02
NMMT	-0.51**	0.04	0.98	-0.07	0.07	-0.09	0.09
OR	0.07*	0.03	0.92	-0.06	0.06	-0.08	0.08
PB	0.18**	0.02	0.93	-0.04	0.04	-0.05	0.05
RAY	-0.02	0.012	0.978	-0.023	0.023	-0.031	0.031
SHWB	0.39**	0.02	0.99	-0.04	0.04	-0.05	0.05
SK	-0.07**	0.01	0.97	-0.01	0.01	-0.02	0.02
SKR	-0.12**	0.01	0.99	-0.02	0.02	-0.03	0.03
TE	-0.04**	0.01	0.96	-0.03	0.03	-0.04	0.04
TN	-0.24**	0.01	0.98	-0.03	0.03	-0.03	0.03
UK	0.55**	0.02	0.99	-0.03	0.03	-0.04	0.04
VD	-0.17**	0.00	1.00	-0.01	0.01	-0.01	0.01
WMP	-0.06**	0.01	0.95	-0.01	0.01	-0.02	0.02
WRJ	0.11**	0.01	0.97	-0.01	0.01	-0.02	0.02
WUP	0.05**	0.01	0.96	-0.02	0.02	-0.03	0.03

\*Trend at 5% significance level ( $p < 0.05$ ); \*\*Trend at 1% significance level ( $p < 0.01$ ). SSD, slope of SD

**3.2.2 Pre-monsoon**

The pre-monsoon rainfall showed positive trends values in more sub-divisions, but most of them (18 sub-divisions) were non-significant. Only 8 sub-divisions showed significant trends, among these JK, CHD, and SHWB exhibited significant increasing trends, while CH, VD, GJ, SK, and EMP have significant decreasing trends ( $p < 0.05$  or  $p < 0.01$ ). The results of rainfall trend analysis of pre-monsoon rainfall using ITA are given in Table 4. ITA results showed that except RAY, CKR, and JH, the slope of ITA successfully captured rainfall trends in all other 31 meteorological sub-divisions of India. Significant positive and

negative trends were observed in 14 and 17 sub-divisions, respectively ( $p < 0.01$ ). Significant trends in 23 sub-divisions were detected only by ITA. JK exhibited the highest increasing trend in pre-monsoon rainfall at a rate of more than 10 mm per decade using LRA, M-K/mM-K, and ITA tests ( $p < 0.01$ ).

**3.2.3 Monsoon**

The trends in monsoon rainfall detected by LRA and M-K/mM-K tests showed significant trends in 16 sub-divisions. Among these, 6 sub-divisions (JK, SKR, KG, CAP, SK, and CKR) showed significantly increasing trends at  $p < 0.05$  or  $p < 0.01$ ,

**Table 5** Results of innovative trend analysis of monsoon rainfall in meteorological sub-divisions of India

Sub-division	SITA	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
AM	1.27**	0.06	0.98	-0.12	0.12	-0.16	0.16
AP	-4.40**	0.11	0.99	-0.21	0.21	-0.28	0.28
BR	-1.09**	0.06	0.97	-0.12	0.12	-0.16	0.16
CAP	0.63**	0.02	0.99	-0.04	0.04	-0.05	0.05
CH	-1.80**	0.07	0.97	-0.13	0.13	-0.17	0.17
CHD	0.22**	0.04	0.98	-0.08	0.08	-0.11	0.11
CKR	4.67**	0.17	0.97	-0.34	0.34	-0.44	0.44
EMP	-1.63**	0.05	0.99	-0.09	0.09	-0.12	0.12
ERJ	-0.18**	0.05	0.98	-0.10	0.10	-0.13	0.13
EUP	-1.47**	0.08	0.96	-0.15	0.15	-0.20	0.20
GJ	-0.45**	0.09	0.98	-0.18	0.18	-0.23	0.23
GWB	1.24**	0.06	0.98	-0.12	0.12	-0.16	0.16
HP	-1.95**	0.05	0.98	-0.11	0.11	-0.14	0.14
JH	-1.13**	0.03	0.99	-0.06	0.06	-0.08	0.08
JK	1.40**	0.05	0.97	-0.09	0.09	-0.12	0.12
KG	1.30**	0.10	0.99	-0.19	0.19	-0.25	0.25
KL	-3.68**	0.11	0.98	-0.22	0.22	-0.29	0.29
MMH	0.04	0.18	0.78	-0.36	0.36	-0.47	0.47
MR	-0.39**	0.07	0.97	-0.13	0.13	-0.17	0.17
NKR	0.40**	0.07	0.91	-0.14	0.14	-0.19	0.19
NMMT	0.12*	0.05	0.97	-0.11	0.11	-0.14	0.14
OR	-0.52**	0.04	0.99	-0.07	0.07	-0.10	0.10
PB	0.43**	0.06	0.97	-0.11	0.11	-0.14	0.14
RAY	0.52**	0.03	0.99	-0.05	0.05	-0.07	0.07
SHWB	-1.60**	0.09	0.98	-0.18	0.18	-0.24	0.24
SK	0.75**	0.05	0.99	-0.10	0.10	-0.13	0.13
SKR	0.71**	0.03	0.99	-0.05	0.05	-0.07	0.07
TE	0.20**	0.04	0.99	-0.08	0.08	-0.10	0.10
TN	0.29**	0.06	0.90	-0.12	0.12	-0.16	0.16
UK	-1.71**	0.07	0.98	-0.14	0.14	-0.18	0.18
VD	-0.98**	0.06	0.98	-0.11	0.11	-0.15	0.15
WMP	-0.08	0.07	0.97	-0.13	0.13	-0.17	0.17
WRJ	0.29**	0.04	0.97	-0.08	0.08	-0.11	0.11
WUP	-0.57**	0.04	0.99	-0.09	0.09	-0.11	0.11

\*Trend at 5% significance level ( $p < 0.05$ ); \*\*Trend at 1% significance level ( $p < 0.01$ ). SSD, slope of SD

while 10 sub-divisions (AP, CH, KL, EMP, UK, HP, EUP, JH, BR, and SHWB) showed significantly decreasing trends ( $p < 0.05$  or  $p < 0.01$ ). The rainfall trends of the monsoon season, detected by ITA, are given in Table 5. The ITA results showed that, except for 2 sub-divisions, all other sub-divisions have significant trends ( $p < 0.05$  or  $p < 0.01$ ). Among these, exactly half exhibited significantly increasing trends. In monsoon rainfall, significant trends in 16 sub-divisions that were not identified by LRA and MK/mM-K tests were detected by the ITA. AP exhibited the highest decrease of more than 37 mm and 44 mm per decade in monsoon rainfall using LRA and ITA tests,

respectively ( $p < 0.01$ ). In monsoon, CKR has the highest significant increase in trend with the magnitude of more than 46 mm per decade, using all the tests.

### 3.2.4 Post-monsoon

In post-monsoon, only JK and KL had significant rainfall trends as detected by LRA and M-K/mM-K tests. In JK, significantly increasing trends ( $p < 0.01$ ) of more than 4 mm per decade in post-monsoon rainfall were detected using LRA and M-K/mM-K tests, whereas KL showed significantly decreasing trends ( $p < 0.05$ ) of



**Table 6** Results of innovative trend analysis of post-monsoon rainfall in meteorological sub-divisions of India

Sub-division	SITA	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
AM	0.04*	0.02	0.99	-0.04	0.04	-0.05	0.05
AP	-0.48**	0.04	0.97	-0.07	0.07	-0.09	0.09
BR	0.02	0.02	0.97	-0.04	0.04	-0.06	0.06
CAP	-0.10**	0.02	0.99	-0.04	0.04	-0.06	0.06
CH	-0.27**	0.01	0.99	-0.02	0.02	-0.03	0.03
CHD	-0.13**	0.01	0.99	-0.01	0.01	-0.02	0.02
CKR	-0.22**	0.03	0.98	-0.06	0.06	-0.08	0.08
EMP	-0.22**	0.02	0.96	-0.04	0.04	-0.05	0.05
ERJ	-0.04**	0.01	0.97	-0.02	0.02	-0.03	0.03
EUP	-0.17**	0.01	0.99	-0.02	0.02	-0.03	0.03
GJ	-0.08**	0.02	0.96	-0.03	0.03	-0.04	0.04
GWB	0.16**	0.02	0.99	-0.04	0.04	-0.05	0.05
HP	-0.20**	0.02	0.97	-0.05	0.05	-0.06	0.06
JH	-0.11**	0.01	0.99	-0.02	0.02	-0.03	0.03
JK	0.52**	0.01	0.99	-0.03	0.03	-0.04	0.04
KG	-0.26**	0.02	0.99	-0.04	0.04	-0.06	0.06
KL	-0.97**	0.05	0.97	-0.09	0.09	-0.12	0.12
MMH	-0.15**	0.01	0.99	-0.02	0.02	-0.03	0.03
MR	0.14**	0.01	0.99	-0.03	0.03	-0.03	0.03
NKR	0.00	0.01	0.99	-0.02	0.02	-0.03	0.03
NMMT	0.07**	0.02	0.99	-0.03	0.03	-0.04	0.04
OR	-0.38**	0.04	0.97	-0.07	0.07	-0.09	0.09
PB	-0.20**	0.03	0.87	-0.07	0.07	-0.09	0.09
RAY	0.27**	0.02	0.99	-0.05	0.05	-0.06	0.06
SHWB	0.06*	0.03	0.98	-0.05	0.05	-0.07	0.07
SK	0.07**	0.02	0.92	-0.04	0.04	-0.06	0.06
SKR	-0.28**	0.02	0.98	-0.04	0.04	-0.06	0.06
TE	0.15**	0.02	0.99	-0.03	0.03	-0.04	0.04
TN	0.04	0.03	0.99	-0.06	0.06	-0.08	0.08
UK	-0.37**	0.02	0.98	-0.04	0.04	-0.05	0.05
VD	-0.05**	0.01	0.99	-0.02	0.02	-0.03	0.03
WMP	-0.06**	0.01	0.97	-0.03	0.03	-0.04	0.04
WRJ	0.01**	0.00	0.98	-0.01	0.01	-0.01	0.01
WUP	-0.17**	0.02	0.97	-0.04	0.04	-0.05	0.05

\*Trend at 5% significance level ( $p < 0.05$ ); \*\*Trend at 1% significance level ( $p < 0.01$ ). SSD, slope of SD

rainfall at a rate of more than -7 mm per decade. The trends detected in post-monsoon rainfall of the meteorological sub-divisions by ITA are shown in Table 6. The results showed that ITA captured significant trends in 31 sub-divisions, mostly dominated by negative values ( $p < 0.01$ ). Out of these 31 sub-divisions, 29 trends were captured only by ITA, and only 10 sub-divisions (NMMT, JK, MR, WRJ, TE, RAY, SK, AM, GWB, and SHWB) have significantly increasing trends ( $p < 0.05$  or  $p < 0.01$ ). The highest and lowest significantly increasing trends ( $p < 0.01$ ) of rainfall were observed in JK and WRJ with 5.2 and 0.1 mm per decade, respectively. The highest and lowest significant decreasing

trends ( $p < 0.01$ ) were exhibited by KL and ERJ with -9.7 and -0.4 mm per decade, respectively, using the ITA test.

### 3.2.5 Annual

The annual rainfall has increasing trends for 18 sub-divisions using LRA or M-K/mM-K test, and 4 of them (JK, KG, SK, and CKR) were significant. Significant decreasing trends ( $p < 0.05$  or  $p < 0.01$ ) were detected in 9 sub-divisions (AP, CH, KL, EMP, UK, EUP, WUP, JH, and BR) using LRA or M-K/mM-K test. The results of ITA for annual rainfall were given in Table 7.

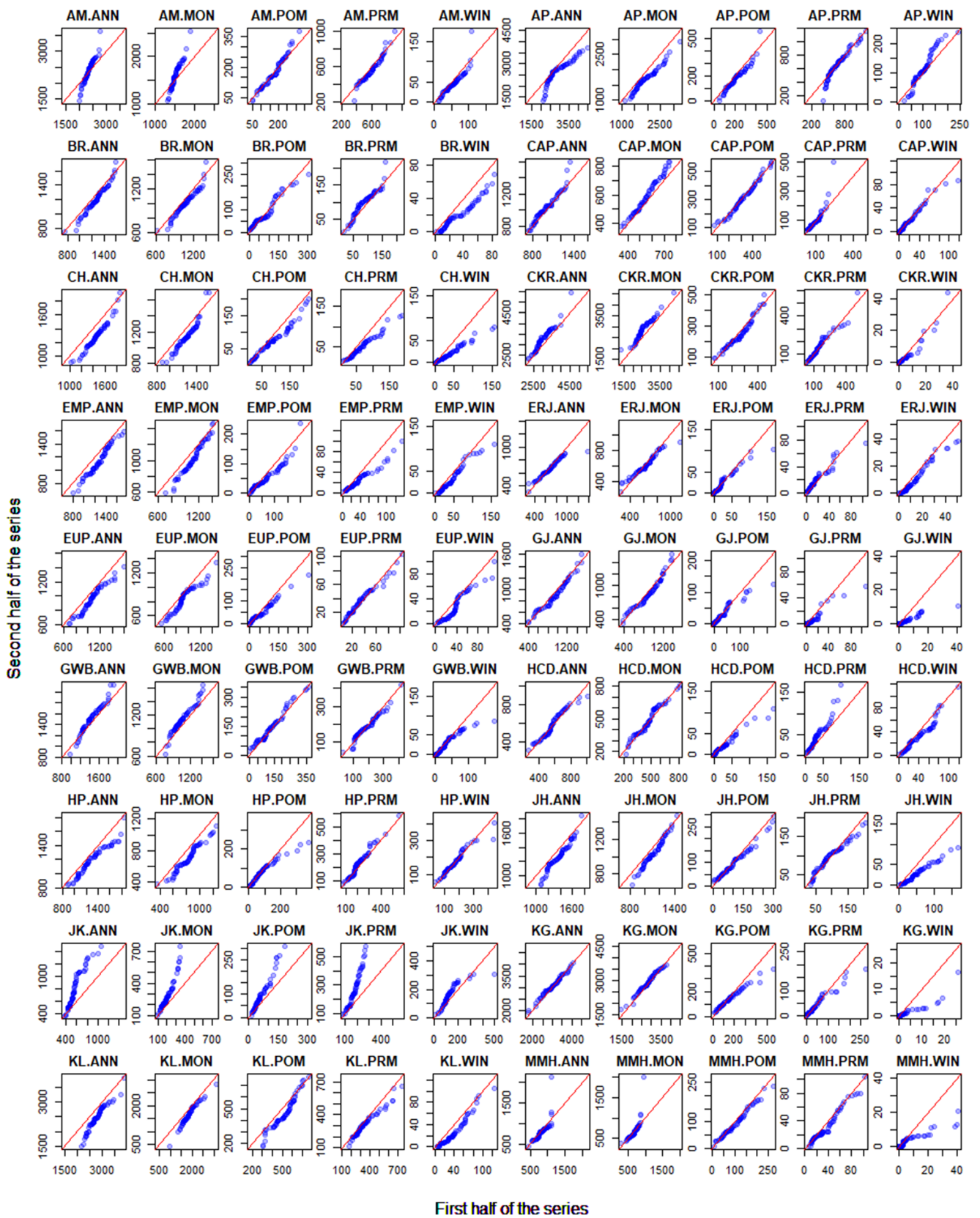
**Table 7** Results of innovative trend analysis of annual rainfall in meteorological sub-divisions of India

Sub-division	SITA	SSD	Correlation $\rho_{y_1 y_2}$	Lower CL Significance level ( $p < 0.05$ )	Upper CL Significance level ( $p < 0.05$ )	Lower CL Significance level ( $p < 0.01$ )	Upper CL Significance level ( $p < 0.01$ )
AM	0.64**	0.10	0.98	-0.19	0.19	-0.25	0.25
AP	-5.05**	0.34	0.93	-0.66	0.66	-0.87	0.87
BR	-1.13**	0.05	0.98	-0.11	0.11	-0.14	0.14
CAP	0.60**	0.06	0.97	-0.12	0.12	-0.15	0.15
CH	-2.71**	0.06	0.98	-0.11	0.11	-0.14	0.14
CHD	0.15**	0.05	0.98	-0.10	0.10	-0.13	0.13
CKR	4.46**	0.17	0.98	-0.34	0.34	-0.45	0.45
EMP	-2.26**	0.05	0.99	-0.10	0.10	-0.14	0.14
ERJ	-0.26**	0.07	0.96	-0.14	0.14	-0.18	0.18
EUP	-1.80**	0.06	0.98	-0.12	0.12	-0.16	0.16
GJ	-0.66**	0.08	0.98	-0.15	0.15	-0.20	0.20
GWB	1.19**	0.06	0.98	-0.13	0.13	-0.17	0.17
HP	-1.91**	0.07	0.98	-0.15	0.15	-0.19	0.19
JH	-1.66**	0.06	0.98	-0.11	0.11	-0.15	0.15
JK	3.78**	0.12	0.95	-0.23	0.23	-0.31	0.31
KG	0.91**	0.09	0.99	-0.18	0.18	-0.23	0.23
KL	-5.51**	0.15	0.97	-0.29	0.29	-0.38	0.38
MMH	-0.24	0.20	0.77	-0.40	0.40	-0.52	0.52
MR	-0.40**	0.08	0.97	-0.15	0.15	-0.20	0.20
NKR	0.42**	0.06	0.97	-0.11	0.11	-0.14	0.14
NMMT	-0.53**	0.09	0.97	-0.18	0.18	-0.23	0.23
OR	-1.00**	0.05	0.98	-0.10	0.10	-0.14	0.14
PB	0.27**	0.05	0.98	-0.10	0.10	-0.14	0.14
RAY	0.65**	0.03	0.99	-0.06	0.06	-0.09	0.09
SHWB	-1.16**	0.10	0.98	-0.19	0.19	-0.25	0.25
SK	0.71**	0.05	0.99	-0.09	0.09	-0.12	0.12
SKR	0.25**	0.05	0.97	-0.10	0.10	-0.13	0.13
TE	0.25**	0.04	0.99	-0.09	0.09	-0.11	0.11
TN	-0.27**	0.09	0.95	-0.17	0.17	-0.23	0.23
UK	-1.70**	0.06	0.99	-0.12	0.12	-0.15	0.15
VD	-1.36**	0.06	0.98	-0.12	0.12	-0.16	0.16
WMP	-0.27**	0.07	0.97	-0.14	0.14	-0.19	0.19
WRJ	0.38**	0.06	0.94	-0.12	0.12	-0.16	0.16
WUP	-0.86**	0.07	0.97	-0.13	0.13	-0.17	0.17

\*Trend at 5% significance level ( $p < 0.05$ ); \*\*Trend at 1% significance level ( $p < 0.01$ ). SSD, slope of SD

The results of ITA detected significant trends in 33 sub-divisions. Except for SITA of MMH, all are significant ( $p < 0.01$ ) and dominated by negative slope values (19 sub-divisions). AP and KL exhibited significant decreasing trends ( $p < 0.01$ ) at a rate of more than 50 mm per decade. Fourteen sub-divisions showed significant increasing trends ( $p < 0.01$ ). CKR exhibited the highest significant increasing trends ( $p < 0.01$ ) at a rate of 51.7 mm per decade using SS estimator. In contrast, the highest significant decreasing trends ( $p < 0.01$ ) at a rate of 55.1 mm per decade were detected at KL using the ITA test.

Our analysis revealed significant trends for seasonal and annual rainfall in sub-divisions of India during the period 1901–2019. The decreasing trends were dominated in winters. Rainfall in the sub-divisions of north and central part of India, viz. EUP, WUP, JH, BR, WMP, and EMP, which receive winter rainfall due to the western disturbances, is also decreasing significantly. During pre-monsoon, rainfall is decreasing over most parts of central and peninsular India. There are increasing monsoon rainfalls in sub-divisions of peninsular and western parts of the country. During the post-monsoon, rainfall is increasing significantly



**Fig. 2** Innovative trend analysis for seasonal and annual rainfall in meteorological sub-divisions of India (suffix used at the top of each figure after the abbreviations of meteorological sub-divisions—WIN, winter; PRM, pre-monsoon; MON, monsoon; POM, post-monsoon; ANN, annual)

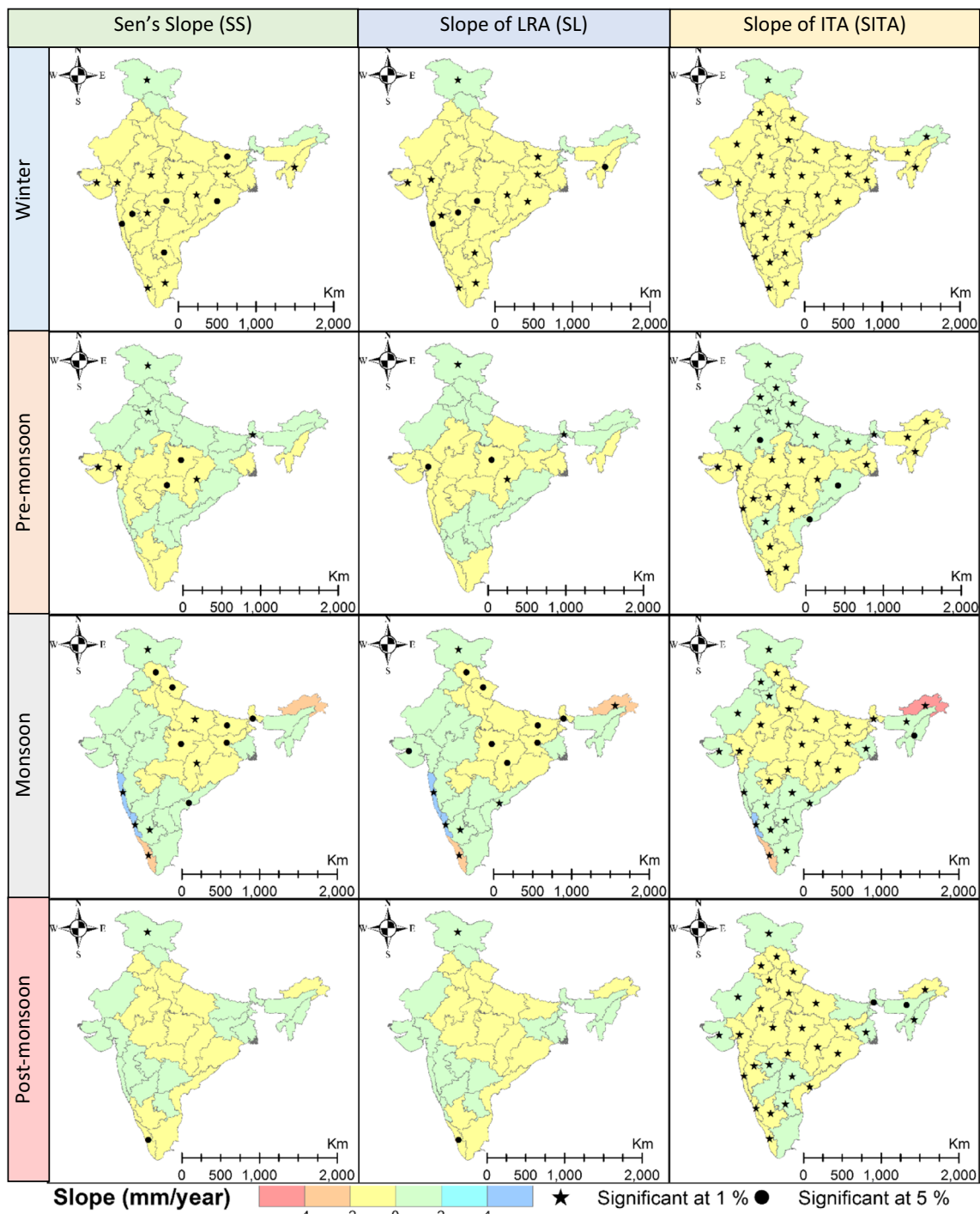


Fig. 2 (continued)

over the Deccan Plateau, Himalayan, and northeastern region. In annual rainfall, the central and most of the sub-divisions in the northern part showed a significant decrease in the rainfall. In contrast, the sub-divisions of western parts have increasing rainfall trends. We compared the results of our analysis with similar

studies conducted by different researchers on a nearly identical spatial scale. Guhathakurta and Rajeevan (2008) analyzed the rainfall trends over the meteorological sub-division of India using linear trend analysis, they reported that in monsoon season, JH, CH, and KL showed decreasing and GWB, WUP, JK, KG,

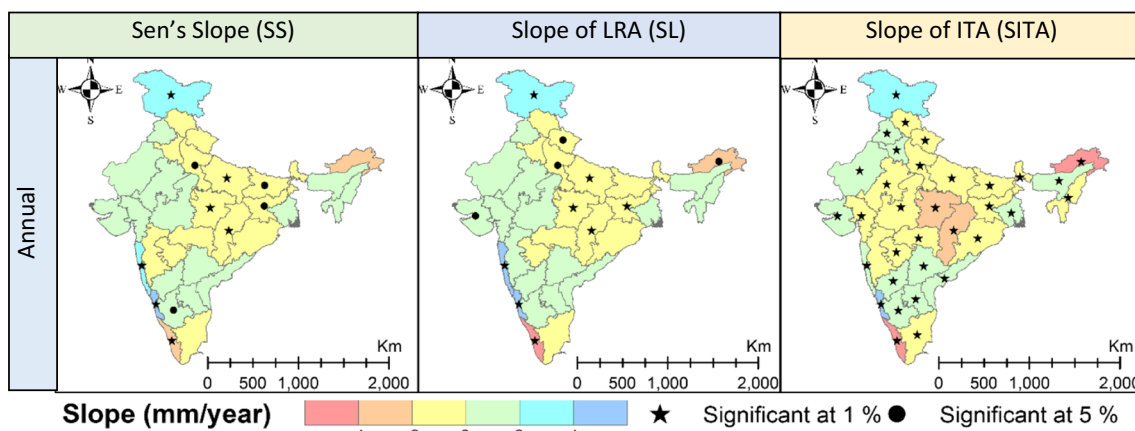




**Fig. 3** Comparison and spatial variations of Sen's slope (SS), slope of LRA (SL), and slope of ITA (SITA) for seasonal rainfall in meteorological sub-divisions of India

MMH, RAY, CAP, and NKR showed increasing trends. They also reported decreasing trends in almost all the sub-divisions during the winter season. During the pre-monsoon season, rainfall was decreasing significantly in GR, WMP, EMP, VD, CH, and JH. They reported increasing trends in almost all sub-divisions except KG, MMH, NKR, RAY, CAP, GWB, AM, and JK in the post-monsoon season, while a significant increase

was reported in annual rainfall. Kumar et al. (2010) analyzed the monthly rainfall of 135 years (1871–2005) for 30 sub-divisions of India using MK and SS tests; they reported a large variability in rainfall trends in meteorological sub-divisions of India. In their study, nearly half of the sub-divisions had an increasing annual rainfall trend, while the remaining had shown decreasing trends. The pre-monsoon, monsoon, post-monsoon, and winter rainfall



**Fig. 4** Comparison and spatial variations of Sen's slope (SS), slope of LRA (SL), and slope of ITA (SITA) for annual rainfall in meteorological sub-divisions of India

increased over 23, 10, 27, and 20 sub-divisions, respectively. Subash et al. (2011) reported decreasing rainfall trends in five meteorological zones of central NE India using MK and LRA tests on gridded dataset, which is in line with the findings of our study. Subash and Sikka (2014) also reported an increasing annual rainfall trends in all the homogeneous rainfall regions of India, except the North East. Das et al. (2014) also analyzed the monsoon season's rainfall trends in the meteorological sub-divisions of India using gridded data of 1971–2005 by applying MK and SS tests. They reported increasing rainfall trends over the east coast, Deccan Plateau region, and northern hilly parts of the Himalaya. Meteorological sub-divisions over the west coast, north and central plains, the western arid region, and the humid northeastern region showed significantly decreasing rainfall trends during the summer monsoon period. Adarsh and Janga Reddy (2015) reported an increasing annual rainfall trends in three sub-divisions of southern India (TN, NKR, and TE) and a decreasing trend in KL using MK test. Sah et al. (2020) reported significantly decreasing trends in the 15 districts of the Terai region of UP (part of EUP and WUP) using M-K/mM-K, SS, SR, and LRA tests, using the gridded dataset for the period of 1951–2015. Our results also corroborate with the observations reported in other similar studies of meteorological sub-divisions of India (Malik and Kumar 2020; Singh et al. 2020; Meshram et al. 2017).

### 3.2.6 Comparison of trend analysis methods

We have analyzed 170 rainfall time series data using LRA, M-K/mM-K, and ITA tests. The comparison between the results of trend detection by these methods is presented in Table 8 and depicted in Figs. 3 and 4. It was observed that significant trends were detected in 49 (28.8%) and 52 (30.5%) time series using LRA and M-K/mM-K tests, respectively. At the same time, ITA detected significant trends in 159 (93.5%) rainfall time series, which indicated that a large number of significant trends (especially decreasing), that were missed by M-K/mM-K or LRA, can be

identified using the ITA method. Also, all the significant trends ( $p < 0.05$  or  $p < 0.01$ ) that were detected by LRA or M-K/mM-K test (57 time series) are also identified by the ITA. Apart from this, ITA detected trends in 102 time series (60%), which cannot be detected either by LRA or M-K/mM-K tests. Our results on trend analysis in rainfall time series using the above three methods indicated that the new ITA method is superior to the traditional M-K/mM-K and LRA tests. Kisi (2015) compared the ITA with the M-K test for assessing the water quality parameters of the Kizilirmak River of Turkey and recommended ITA over M-K in detecting trends of hydrological time series. Wu and Qian (2017) investigated the trends in annual and seasonal rainfall of Shaanxi Province, China, using ITA, M-K, and LRA. They reported a significant decreasing trend in annual rainfall and endorsed the ITA method over MK and LRA. Cui et al. (2017) studied the rainfall and temperature characteristics in the Yangtze River Basin of China during 1960–2015 using M-K, ITA, and LRA and proposed ITA to be more effective for the study of the climatic conditions. Similarly, many researchers reported advantages of ITA and its ability to capture trends more effectively in meteorological time series as compared to the traditional trend detection methods in corroboration with our study (Kisi and Ay 2014; Caloiero et al. 2018; Gedefaw et al. 2018; Kişi et al. 2018; Ali and Abubaker 2019; Malik et al. 2019; Güçlü 2020; Marak et al. 2020; Wang et al. 2020).

## 4 Conclusions

Variation in long-term rainfall trends of 34 meteorological sub-divisions of India during the period 1901–2019 was investigated using LRA, M-K/mM-K, and ITA tests. The meteorological sub-divisions of India showed both significant increasing and decreasing trends in seasonal and annual rainfall. The monsoon and annual rainfall are increasing in most sub-divisions of the peninsular and northwest parts of India, whereas decreasing rainfall is observed over central northeast India. Winter rainfall is



**Table 8** Comparison of results of trend analysis from LRA, M-K/mM-K, and ITA

Sub-division	Winter			Pre-monsoon			Monsoon			Post-monsoon			Annual		
	LRA	M-K/mM-K	ITA	LRA	M-K/mM-K	ITA	LRA	M-K/mM-K	ITA	LRA	M-K/mM-K	ITA	LRA	M-K/mM-K	ITA
AM	No	No	Yes (--)	No	No	Yes (-)	No	No	Yes (+)	No	No	Yes (++)	No	No	Yes (++)
AP	No	No	Yes (++)	No	No	Yes (-)	Yes (-)	No	Yes (-)	Yes (-)	No	Yes (-)	Yes (-)	No	Yes (-)
BR	Yes (-)	Yes (-)	Yes (-)	Yes (-)	Yes (-)	Yes (-)	Yes (-)	Yes (-)	Yes (-)	No	No	Yes (-)	Yes (-)	Yes (-)	Yes (-)
CAP	No	No	Yes (-)	Yes (++)	Yes (++)	Yes (++)	Yes (++)	Yes (++)	Yes (++)	Yes (++)	Yes (++)	Yes (++)	Yes (++)	Yes (++)	Yes (++)
CH	Yes (-)	Yes (-)	Yes (-)	No	Yes (-)	Yes (-)	No	No	Yes (-)	Yes (-)	No	Yes (-)	No	No	Yes (-)
CHD	No	No	Yes (-)	No	No	Yes (-)	No	No	Yes (-)	No	No	Yes (-)	No	No	Yes (-)
CKR	No	No	Yes (-)	No	No	Yes (-)	No	No	Yes (-)	No	No	Yes (-)	No	No	No
EMP	No	Yes (-)	Yes (-)	No	No	Yes (-)	No	No	Yes (++)	No	No	Yes (++)	No	No	Yes (++)
ERJ	No	No	Yes (-)	No	No	Yes (-)	No	No	Yes (++)	No	No	Yes (++)	No	No	Yes (++)
EUP	No	No	Yes (-)	No	No	Yes (-)	No	No	Yes (++)	No	No	Yes (++)	No	No	Yes (++)
GJ	Yes (-)	Yes (-)	Yes (-)	No	No	Yes (-)	Yes (++)	Yes (++)	Yes (++)	No	No	Yes (++)	No	Yes (+)	Yes (++)
GWB	No	No	Yes (-)	No	No	Yes (-)	Yes (-)	Yes (-)	Yes (-)	Yes (-)	Yes (-)	Yes (-)	Yes (-)	Yes (-)	Yes (-)
HP	No	No	No	No	No	No	No	No	Yes (++)	No	No	Yes (++)	No	No	Yes (++)
JH	Yes (-)	Yes (-)	Yes (-)	No	No	Yes (-)	Yes (++)	Yes (++)	Yes (++)	No	No	Yes (++)	Yes (++)	Yes (++)	Yes (++)
JK	Yes (++)	Yes (++)	Yes (++)	No	No	Yes (++)	Yes (++)	Yes (++)	Yes (++)	No	No	Yes (++)	Yes (++)	Yes (++)	Yes (++)
JL	Yes (-)	Yes (-)	Yes (-)	Yes (+)	Yes (+)	Yes (+)	Yes (++)	Yes (++)	Yes (++)	No	No	Yes (++)	No	No	Yes (++)
KG	Yes (-)	Yes (-)	Yes (-)	Yes (-)	Yes (-)	Yes (-)	No	No	Yes (-)	No	No	Yes (-)	No	No	Yes (-)
KL	Yes (-)	Yes (-)	Yes (-)	Yes (-)	Yes (-)	Yes (-)	Yes (+)	Yes (+)	Yes (++)	No	No	Yes (++)	Yes (+)	Yes (++)	Yes (++)
MMH	Yes (-)	Yes (-)	Yes (-)	No	No	Yes (-)	Yes (++)	Yes (++)	Yes (++)	No	No	Yes (++)	Yes (++)	Yes (++)	Yes (++)
MR	Yes (-)	Yes (-)	Yes (-)	No	No	Yes (-)	No	No	Yes (++)	No	No	Yes (++)	No	No	Yes (++)
NKR	Yes (-)	Yes (-)	Yes (-)	No	No	Yes (-)	No	No	Yes (++)	No	No	Yes (++)	No	No	Yes (++)
NMMT	No	No	Yes (-)	No	No	Yes (-)	No	No	Yes (++)	No	No	Yes (++)	No	No	Yes (++)
OR	Yes (-)	Yes (-)	Yes (-)	Yes (-)	Yes (-)	Yes (-)	Yes (-)	Yes (-)	Yes (-)	No	No	Yes (-)	No	No	Yes (-)
PB	No	No	Yes (-)	No	No	Yes (-)	Yes (-)	Yes (-)	Yes (-)	Yes (-)	No	Yes (-)	Yes (-)	Yes (-)	Yes (-)
RAY	Yes (-)	Yes (-)	Yes (-)	No	Yes (++)	Yes (++)	No	No	Yes (++)	No	No	Yes (++)	No	No	Yes (++)
SHWB	No	No	No	No	No	No	Yes (++)	Yes (++)	Yes (++)	No	No	Yes (++)	No	No	Yes (++)
SK	Yes (-)	Yes (-)	Yes (-)	Yes (-)	Yes (-)	Yes (-)	Yes (-)	Yes (-)	Yes (-)	Yes (-)	Yes (-)	Yes (-)	No	No	Yes (-)
SKR	No	No	Yes (-)	No	No	Yes (-)	No	No	Yes (++)	No	No	Yes (++)	Yes (-)	Yes (-)	Yes (-)
TE	No	No	Yes (-)	No	No	Yes (-)	No	No	Yes (++)	No	No	Yes (++)	Yes (-)	Yes (-)	Yes (-)
TN	Yes (-)	Yes (-)	Yes (-)	No	No	Yes (-)	No	No	Yes (++)	No	No	Yes (++)	No	No	Yes (++)
UK	No	No	Yes (-)	No	No	Yes (-)	No	No	Yes (++)	No	No	Yes (++)	No	No	Yes (++)
VD	Yes (-)	Yes (-)	Yes (-)	No	No	Yes (-)	No	No	Yes (++)	No	No	Yes (++)	No	No	Yes (++)
WMP	No	Yes (-)	Yes (-)	No	No	Yes (-)	Yes (-)	Yes (-)	Yes (-)	No	No	Yes (-)	Yes (-)	Yes (-)	Yes (-)
WRJ	No	No	Yes (-)	No	No	Yes (-)	Yes (-)	Yes (-)	Yes (-)	No	No	Yes (-)	No	No	Yes (-)
WUP	No	No	Yes (-)	Yes (++)	Yes (++)	Yes (++)	Yes (-)	Yes (-)	Yes (-)	No	No	Yes (-)	No	No	Yes (-)

+ and - indicate significant increasing and decreasing trends at 5% significance level (p < 0.05); ++ and -- indicate significant increasing and decreasing trends at 1% significance level (p < 0.01). No indicates non-significant results

decreasing in most of the sub-divisions of the country. The ITA method detected trends in almost all sub-divisions across India in both seasonal and annual rainfall. The ITA detected trends in 93.5% of the time series, while the traditional LRA and M-K/mM-K tests detected trends in only 33.5% of time series analysed. All significant trends which are detected by the LRA and M-K/mM-K methods were also effectively identified using ITA. Trends in 60% of the rainfall time series data that were not detected by LRA and M-K/mM-K tests were identified using the ITA, which indicated that the ITA is more powerful and sensitive than LRA and M-K/mM-K tests. ITA method is simple, easy to understand, and more sensitive in detecting trends that cannot be captured using traditional LRA and M-K/mM-K methods. The study comprehensively investigated the variations in rainfall trends across India during 1901–2019, which will help in understanding regional climatology and hydrology and their impacts on sectors based on water resources.

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**Author contribution** Conceptualization: RN Singh; methodology: RN Singh and Sonam Sah; formal analysis and investigation: RN Singh, Bappa Das, and Amresh Chaudhary; writing—original draft preparation: Sonam Sah, Sunil Potekar, and RN Singh; writing—review and editing: Amresh Chaudhary, Sonam Sah, Bappa Das, and H. Pathak.

**Data availability** The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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