Chapter 4
Long Term Rainfall Trend Analysis (1871–2011) for Whole India

Sananda Kundu, Deepak Khare, Arun Mondal, and Prabhash Kumar Mishra

Abstract Climate change has aroused serious consciousness among human beings as it has a strong impact on different parameters like rainfall, temperature, evapotranspiration etc. Change in climatic parameters also affects the agriculture and water demand of an area. The changed pattern of rainfall leads to extreme conditions like flood, drought and cyclones which have increased in frequency in the last few decades making the rainfall trend analysis extremely important for India where a large part of the economy depends upon rain-fed agriculture. The trend of rainfall for 141 years of India was analyzed in the present study from 1871 to 2011. Detection of trend was done by analyzing 306 stations of India divided into seven regions of Homogeneous Indian Monsoon, Core-Monsoon India, North West India, West Central India, Central Northeast India, North East India and Peninsular India. Temporal as well as spatial rainfall variability was shown on monthly, seasonal and annual basis. The Mann–Kendall (MK) Test and Sen's slope was applied in the study. Mann–Whitney–Pettitt (MWP) test was used to give the break point in the series. Annually, 5 regions have decreasing trend

S. Kundu (✉) • D. Khare • A. Mondal
Department of Water Resources Development and Management,
Indian Institute of Technology Roorkee, Roorkee, India
e-mail: sanandakundu@gmail.com; kharefwt@gmail.com; arun.iirs@gmail.com

P.K. Mishra
Department of Water Resources Development and Management,
Indian Institute of Technology Roorkee, Roorkee, India

Scientist, Water Resources Systems Division, National Institute of Hydrology,
Roorkee, India
e-mail: erprabhash@gmail.com

M. Singh et al. (eds.), *Climate Change and Biodiversity: Proceedings of IGU Rohtak Conference, Vol. 1*, Advances in Geographical and Environmental Sciences,
DOI 10.1007/978-4-431-54838-6_4, © Springer Japan 2014

except for core-monsoon and north-east India. Monsoon season depicted decrease in the rainfall magnitude in most of the regions. This result is extremely significant as monsoon rainfall serves the major water demand for agriculture. Change Percentage for 141 years had shown rainfall variability throughout India with the highest increase in North-West India (5.14 %) and decrease in Core-monsoon India (−4.45 %) annually.

Keywords Change percentage • India • MK test • MWP test • Rainfall trend

4.1 Introduction

With the growing frequency of different extreme events like flood, drought, cyclones etc., there has been increasing concern regarding the adverse effects of climate change. Changing rainfall pattern that is occurring because of climatic variations have raised the concern about extreme events (IPCC 2007). Evidences of climate change are extremely prominent in various sectors and it has been found that rainfall variation may have a significant impact on the agricultural and water of Asia-Pacific (Cruz et al. 2007). Increasing rainfall trend was observed in New York of USA (Burns et al. 2007), Australia (Suppiah and Hennessy 1998) etc. while a decrease was found in Italy (Buffoni et al. 1999) and Kenya (Kipkorir 2002). There were greater variation in the spatial and temporal distribution of rainfall like in Spain (Rodrigo et al. 2000) and North America (Englehart and Douglas 2006). Rainfall distribution and variability is also related to the temperature pattern which was found to be quite varied in Italy (Brunetti et al. 2000), Western and Central Europe (Moberg and Jones 2005), South Africa (Kruger 2006), Iran (Masih et al. 2010) etc. All these changes in rainfall trend have initiated more research in this field to analyze the distribution.

Both parametric and non-parametric tests were used for the trend analysis, but non-parametric tests were considered as better as they can be used on independent data sets (Hamed and Rao 1998). Mann–Kendall tests are non-parametric tests used most frequently for the trend analysis (Yue et al. 2003; Singh et al. 2008; González et al. 2008).

In India monsoon rainfall forms an important part of the climatic characteristics. It supplies the majority of rainfall required for the agricultural sector. The south-west monsoon supplies rainfall in north India while the winter or north-east rainfall serves the south India. Variation in rainfall have resulted in increasing threat over the economy of the country as there is rising problem in the agricultural sectors and planners must allocate the water resources properly to avoid problem of water scarcity in the future. In the present study, rainfall trend analysis of the entire country was done with the data of 141 years from 1871 to 2011 with 7 major regions of India. Mann–Kendall test and Mann–Whitney–Pettitt test was applied to the rainfall data on monthly, annual and seasonal basis.

4.2 Study Area

Indian rainfall ranges from 160 to 1,800 mm/year all over the country varying both spatially and temporally. As India is a large country with different climatic condition, 7 regions were formed for whole India on the basis of meteorological characteristics. These regions are, Homogeneous Indian Monsoon, Core-Monsoon India, North West India, West Central India, Central Northeast India, North East India and Peninsular India (except the hilly regions in the north) as given in Fig. 4.1. The study area covers about 2,880,000 km^2 areas for whole India. The data were assessed by annual, seasonal and monthly basis where summer months extend from March to May, monsoon from June to September, post-monsoon from October to November and winter from December to February. A total of 306 stations located all over India were analyzed for the study.

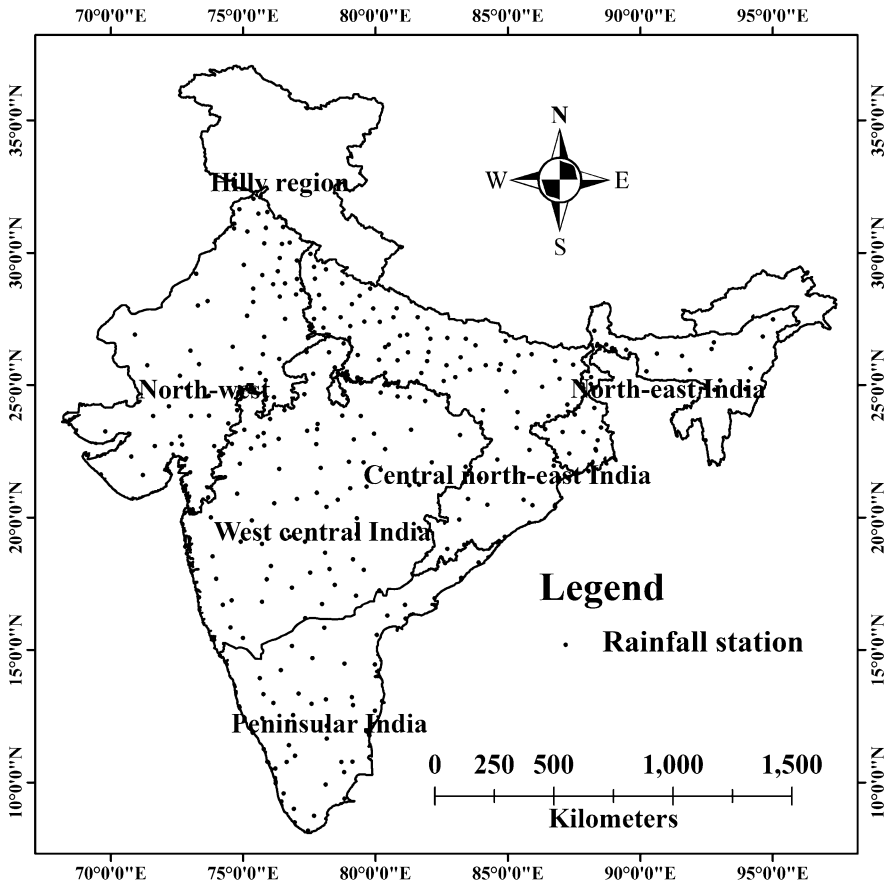

Fig. 4.1 Study area

4.3 Methodology

Monthly, seasonal and annual rainfall trend series was studied for 141 years to analyze the trend. Homogeneity test was applied on the series with Standard Normal Homogeneity Test (SNHT) at the 5 % significance level (Alexandersson 1986) and the observed series was found to be homogenous (Khaliq and Ouarda 2007). Serial correlation and pre-whitening method was applied on the series to remove the effect of correlation on MK Test (Storch 1993). MK test was then applied on the pre-whitened rainfall series (Mann 1945; Kendall 1975) with the Theil–Sen's estimator (Theil 1950; Sen 1968) to get the trend and magnitude of rainfall. Then Mann–Whitney–Pettitt (MWP) test was done to find the change point of the series (Pettitt 1979). At the end percentage of change was calculated (Yue and Hashino 2003).

4.3.1 Serial Correlation

The coefficient of serial correlation ρk for lag-k in a discrete time series is given as (Yue et al. 2003)

$$\rho_k = \frac{\sum_{t=1}^{n-k} (x_t - \overline{x}_t)(x_{t+k} - \overline{x}_{t+k})}{\left[\sum_{t=1}^{n-k} (x_t - \overline{x}_t)^2 \times \sum_{t=1}^{n-k} (x_{t+k} - \overline{x}_{t+k})^2\right]^{1/2}} \tag{4.1}$$

Here $\overline{x}_t$ and x_t stand for sample mean and sample variance of the first $(n - k)$ terms respectively, $\overline{x}_{t+k}$ and *Var* (x_t+k) are regarded as sample mean and sample variance of the last $(n - k)$ terms respectively. No correlation hypothesis are examined by the lag-1 serial correlation coefficient as $H_0 : \rho_1 = 0$ against $H_1 : |\rho_1| > 0$

$$t = |\rho_1| \sqrt{\frac{n-2}{1-\rho_1^2}} \tag{4.2}$$

The t test is the Student's t-distribution with $(n - 2)$ degrees of freedom (Cunderlik and Burn 2004). For $|t| \geq t_{\alpha/2}$, the null hypothesis about zero correlation is discarded at the significance level α.

4.3.2 Mann–Kendall Test and Theil–Sen's Estimator

The MK statistic is given as

$$Z_c = \begin{cases} \dfrac{S-1}{\sqrt{Var(S)}} \; if, \; S > 0 \\ 0 \;\; if, \; S = 0 \\ \dfrac{S+1}{\sqrt{Var(S)}} \; if, \; S < 0 \end{cases} \tag{4.3}$$

where,

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}\left(x_j - x_i\right) \tag{4.4}$$

Here x_j and x_i give the data values which are in sequence with n data, sgn (θ) is equivalent to 1, 0 and -1 if θ is more than, equal to or less than 0 respectively. If Z_c is more than $Z_{\alpha/2}$ then the trend is regarded as significant and α is the level of significance (Xu et al. 2003).

$$\beta = median\left(X_i - X_j / i - j\right) \; \forall j < i, \tag{4.5}$$

where $1<j<i<n$ and β estimator represent the median of the entire data set (Xu et al. 2003).

4.3.3 Mann–Whitney–Pettitt Method (MWP)

The n length time series {X1, X2. . ., Xn} is taken. t represents the time of the most expected change point. Two samples {X1, X2,. . ., Xt} and {Xt+1, Xt+2,. . ., Xn} can be attained by dividing the time series at t time. The Ut index is calculated in the following way:

$$U_t = \sum_{i=1}^{t} \sum_{j=t+1}^{n} \operatorname{sgn}\left(X_i - X_j\right) \tag{4.6}$$

where,

$$\operatorname{sgn}\left(x_j - x_i\right) = \left\{ \begin{array}{c} 1 \ldots\ldots if\left(x_j - x_i\right) > 0 \\ 0 \ldots\ldots if\left(x_j - x_i\right) = 0 \\ -1 \ldots\ldots if\left(x_j - x_i\right) < 0 \end{array} \right\} \tag{4.7}$$

Constantly increasing value of |Ut| with no change point will be obtained by plotting Ut against t in a time series. But if there is a change point, then $|Ut|$ will increase up to the change point level and then will decrease. The significant change point t represents the point where value of $|Ut|$ is highest:

$$K_T = \max_{1 \le t \le T} |U_\tau| \tag{4.8}$$

The approximated significant probability $p(t)$ for a change point (Pettitt 1979) is:

$$p = 1 - \exp\left[\frac{-6K_T^2}{n^3 + n^2}\right] \tag{4.9}$$

When probability $p(t)$ overcomes (1–α), then the change point is significant statistically at time t with the significance level of α.

4.4 Results and Discussion

Homogeneity test was conducted for the series where T_0 at the 95 % level was found to be less than 9.468 (Table 4.3) (Khaliq and Ouarda 2007). Table 4.1 represents the serial correlation values for seven regions and gives the coefficients of monthly, seasonal and annual rainfall. The Lag-1 serial correlation was calculated to observe the presence of any positive or negative correlation and pre-whitening was applied to eliminate the effect. Maximum correlation was found in Peninsular India and North-West India (0.228).

The rate of change for 141 years for each month and the level of significance is given in Fig. 4.2. Positive and negative trends in the series were calculated from the MK test and some significant values were observed in different regions. The rainfall trend was significant in the month of April showing highest positive or increasing trend and decreasing trend was observed in July (<−15 %) so there was declining rainfall trend during the monsoon period. Significant negative rainfall trend was found in the month of July in the West Central India where the rate of change was −10 to −15 % over 141 years. In North-east India significant negative rainfall trend was noticed in the month of August (−10 to −15 %). The month of June also had a negative rate of change in the West Central India.

Apart from the monsoon months of June, July and August, decreasing trend was also noticed in December. Thus rainfall reduction in July–August or monsoon months indicates a problem for the agricultural economy. The north-west and peninsular India have mostly positive change rate in 141 years, unlike other regions particularly during July–August. The peninsular India experience the effect of both south-west and retreating monsoons which might have caused more rainfall here. However, during the time of retreating monsoon in Peninsular India, the rate of change was comparatively low (0–5 %). The North-west India also receives more rainfall.

Table 4.1 Serial correlation

Station name	Whole India	Homogeneous Indian monsoon	Core-monsoon India	North West India	West Central India	Central Northeast India	North East India	Peninsular India
Jan	0.142	0.082	0.114	0.127	0.062	−0.011	0.022	0.228
Feb	−0.012	−0.025	0.028	−0.059	0.051	−0.064	0.006	−0.027
Mar	−0.091	−0.08	−0.053	−0.029	−0.106	−0.102	−0.147	−0.049
Apr	−0.103	−0.097	−0.083	0.158	−0.122	−0.077	−0.05	0.022
May	−0.003	0.042	0.078	0.01	0.015	0.062	0.059	−0.066
June	0.004	0.073	0.091	0.173	0.042	−0.066	0.127	−0.127
July	−0.035	−0.114	−0.09	−0.092	−0.071	−0.12	−0.071	0.023
Aug	−0.093	−0.067	−0.054	−0.059	−0.034	−0.026	−0.037	−0.123
Sept	−0.039	0.035	0.065	−0.038	0.081	−0.127	0.013	−0.06
Oct	0.13	0.213	0.194	0.228	0.181	0.011	−0.055	0.045
Nov	−0.008	−0.034	−0.046	0.166	−0.055	−0.053	−0.121	0.088
Dec	0.055	0.025	0.065	−0.161	0.102	−0.045	−0.115	−0.033
Annual	−0.005	−0.004	0.028	−0.039	0.051	−0.062	0.063	0.042
Pre-monsoon	−0.076	−0.006	0.041	0.029	0.017	−0.079	−0.038	0.021
Monsoon	−0.092	−0.091	−0.055	−0.059	−0.051	−0.015	−0.001	−0.155
Post-monsoon	0.118	0.203	0.152	0.212	0.173	0.021	−0.075	0.005
Winter	0.02	0.044	0.078	−0.049	0.119	−0.04	−0.034	0.031

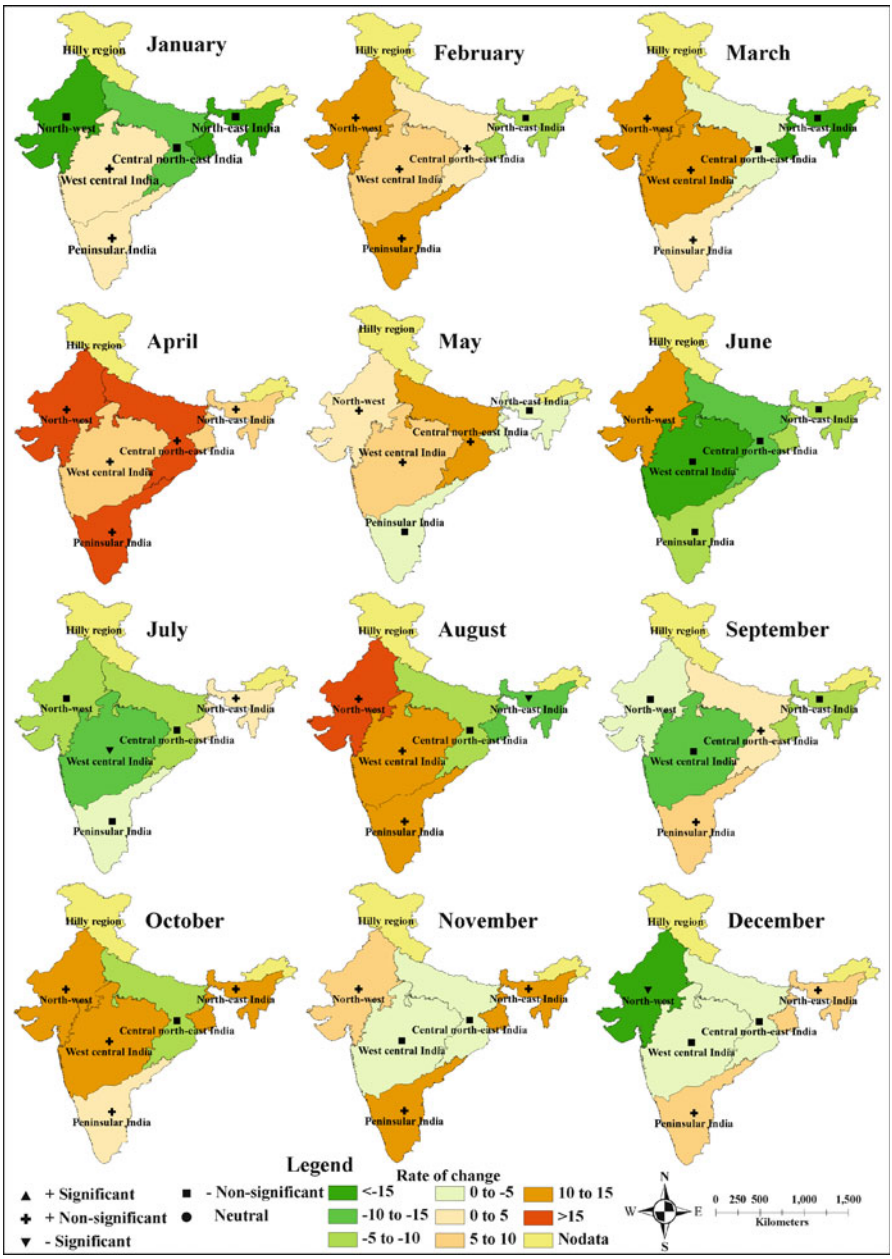

Fig. 4.2 Monthly rainfall trend and rate of change

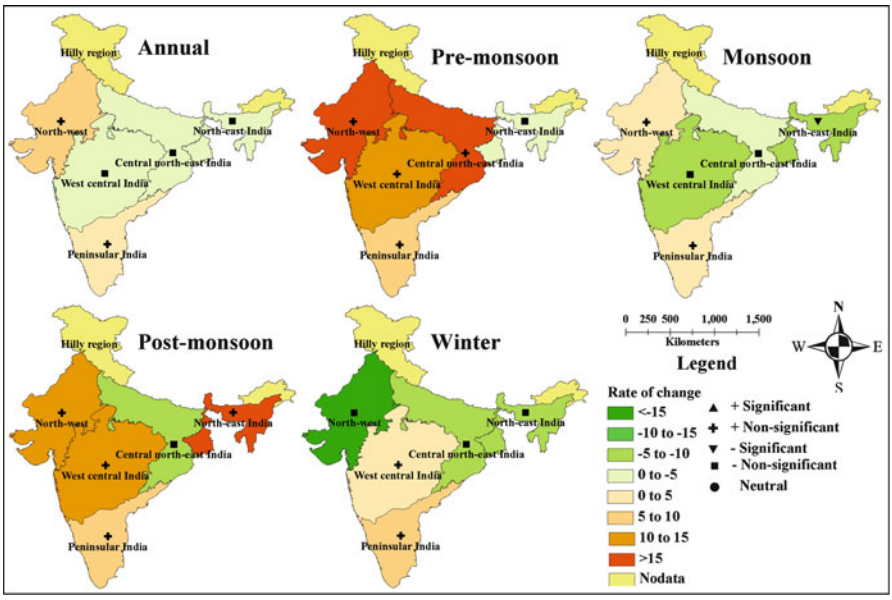

Fig. 4.3 Monthly rainfall trend and rate of change

The seasonal and annual rate of change along with the negative and positive trend values is illustrated in the Fig. 4.3. The monsoon and winter seasons have declining rainfall ranging from −5 % to less than −15 % in 141 years. Annually, highest rate of change in rainfall was observed in North-west India (5–10 %) followed by Peninsular India (0–5 %). West Central, Central North-east and North-east India faced decreasing trend and rate of change (0 to −5 %). Pre-monsoon and post-monsoon periods have increasing rainfall which is evident from the maps, while the maximum reduction was observed in the monsoon and winter seasons particularly in the North-east India.

The rainfall trend magnitude of 141 years is given in Table 4.2. As a whole India reflects a significant positive trend in the month of April (0.036 mm/year) and significant decreasing trend was observed in July (−0.137 mm/year). Rainfall of Homogeneous Indian Monsoon is showing a reduction in rainfall in July (−0.236 mm/year), Core-Monsoon India reflects significant negative rainfall trends in July (−0.287 mm/year), West Central India shows significant reduction in July (−0.314 mm/year) and North East India shows the significant negative rainfall magnitude in August (−0.334 mm/year) and in Monsoon season (−0.724 mm/year). Among all the significant rainfall magnitude results, only the month of April shows the positive trend which is a pre-monsoon month.

The MWP test was done to calculate the change point in these 141 years where the change point for whole India was considered as 1961 (Table 4.3).

The annual total rainfall of 7 regions and whole India is shown in Fig. 4.4 from 1871 to 2011. Linear regression method was used to see the rainfall trend which

Table 4.2 Sen's slope

Station name	Whole India	Homogeneous Indian monsoon	Core-monsoon India	North West India	West Central India	Central Northeast India	North East India	Peninsular India
Jan	−0.011	−0.003	−0.002	−0.010	0.003	−0.012	−0.023	0.003
Feb	0.005	0.006	0.000	0.006	0.005	0.001	−0.013	0.008
Mar	0.003	0.006	0.006	0.004	0.007	−0.001	−0.106	0.003
Apr	**0.036**	0.013	0.004	0.004	0.006	0.039	0.051	0.064
May	0.008	0.011	0.000	0.002	0.011	0.040	−0.057	−0.023
June	−0.102	−0.085	−0.118	0.055	−0.205	−0.120	−0.189	−0.075
July	**−0.137**	**−0.236**	**−0.287**	−0.096	**−0.314**	−0.169	0.047	−0.028
Aug	0.076	0.225	0.258	0.176	0.196	−0.117	**−0.334**	0.123
Sept	−0.078	−0.115	−0.145	−0.017	−0.181	0.030	−0.103	0.063
Oct	0.040	0.048	0.041	0.012	0.060	−0.029	0.139	0.056
Nov	0.025	0.001	0.003	0.002	−0.001	−0.002	0.022	0.111
Dec	−0.004	−0.004	−0.003	−0.009	−0.002	−0.002	0.004	0.017
Annual	−0.043	−0.099	−0.311	0.199	−0.317	−0.165	−0.458	0.379
Pre-monsoon	0.040	0.038	0.006	0.032	0.031	0.088	−0.072	0.058
Monsoon	−0.236	−0.276	−0.409	0.074	−0.435	−0.270	**−0.724**	0.093
Post-monsoon	0.077	0.059	0.051	0.016	0.077	−0.034	0.191	0.168
Winter	0.001	−0.013	−0.023	−0.020	0.000	−0.018	−0.032	0.042

Bold value indicates 95 % significance level

Table 4.3 MWP and SNHT test

	Pettitt's test			SNHT test		
Station	K	t	P value	T_0#	t	P value
Whole lndia	653	1961	0.89	3.03	1964	0.24
Homogeneous Indian monsoon	688	1964	0.91	3.087	1894	0.25
Core-monsoon India	872	1894	0.98	4.896	1894	0.60
North West India	829	1941	0.97	1.824	1941	0.04
West Central India	1155	1964	1.00	5.006	1964	0.62
Central Northeast India	746	1961	0.94	5.96	2008	0.73
North East India	1195	1956	1.00	13.523	2007	0.99
Peninsular India	723	1914	0.93	6.842	2004	0.82

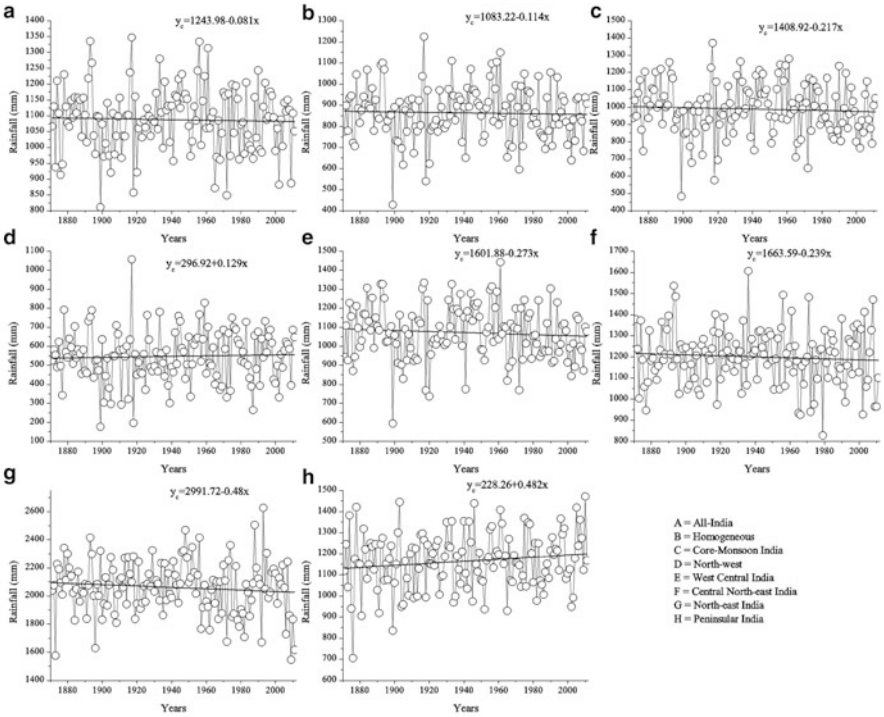

Fig. 4.4 Annual rainfall trend by Linear Regression method from 1871 to 2011

illustrates the greater frequency of decreasing rainfall pattern after 1961 particularly in the North-east, Central North-east and West Central India. However, the increasing rainfall pattern was found in Peninsular India.

The entire rainfall pattern of India indicates significant variability in different regions with some prominent changes in the trend. The overall rainfall trend shows

significant decrease in the monsoon months which poses considerable threat to the agricultural economy and will aggravate the demand of water in near future. The change point of 1960–1961 is also significant as the rate of decrease was much more after this period. Decrease in the monsoon of North-east India which was known for its highest rainfall, along with the majority of other regions is also a foremost concern. On the other hand, Peninsular India and North-west India have shown an increasing rainfall trend.

4.5 Conclusion

The study involves the rainfall trend analysis of whole India for 141 years from 1871 to 2011 with MK test and linear regression. Reduction in rainfall trend was observed in the regions of West Central India, Central Northeast India, North-east India and in the zones of Homogeneous Indian Monsoon and Core-Monsoon India. Only two regions depict positive rainfall trends in the Northwest and Peninsular India. Seasonally the trend indicated decrease in the monsoon season which is quite significant for the planning purposes. The range of magnitude of rainfall varies significantly from 0.036 mm/year to −0.334 mm/year. Rate of change was computed for annual and different seasons where the range varies from −5 % in North-east, Central North-east India to about 10 % in North West India annually. A significant reduction was also noticed in monsoon particularly in North East India. The change point in the series was observed in 1961 by MWP Test which indicates the period of dominant decrease after this year. Both spatial and temporal decline were observed in all the regions except for the Peninsular India and North-west India which might be due to the land-atmosphere wind circulation and the contribution of both southwest and retreating monsoons. Reduction in rainfall trend especially in the monsoon season may have a significant effect on agricultural production particularly in the rain fed cultivation system.

Acknowledgments The authors are thankful to the Indian Institute of Tropical Meteorology (IITM) for the rainfall data, Council of Scientific & Industrial Research (CSIR) and University Grant Commission (UGC) for the financial support in the research.

Appendix

Table A1 Mann–Kendall test

Station name	Whole India	Homogeneous Indian monsoon	Core-monsoon India	North West India	West Central India	Central Northeast India	North East India	Peninsular India
Jan	−0.80	−0.19	−0.17	−1.03	0.31	−0.65	−1.30	0.28
Feb	0.35	0.57	0.00	0.79	0.38	0.03	−0.39	0.87
Mar	0.18	0.59	0.97	0.73	0.65	−0.05	−1.48	0.14
Apr	**2.10**	1.29	0.56	0.93	0.47	1.95	0.53	1.67
May	0.25	0.65	0.02	0.09	0.48	0.86	−0.60	−0.33
Jun	−1.22	−0.96	−0.86	0.70	−1.52	−0.83	−1.27	−1.25
Jul	**−2.17**	**−2.00**	**−2.06**	−0.75	**−2.52**	−1.41	0.33	−0.34
Aug	0.85	1.62	1.70	1.20	1.43	−1.09	**−2.72**	1.38
Sep	−0.98	−0.97	−0.94	−0.17	−1.44	0.29	−0.83	0.75
Oct	0.73	0.91	0.67	0.87	0.85	−0.30	1.04	0.43
Nov	0.72	0.12	0.24	1.00	−0.03	−0.10	0.62	0.87
Dec	−0.29	−0.66	−0.63	−1.72	−0.27	−0.37	0.45	0.31
Annual	−0.18	−0.42	−0.95	0.62	−1.15	−0.57	−1.12	1.28
Pre-monsoon	0.98	1.15	0.22	1.38	0.76	1.42	−0.37	0.67
Monsoon	−1.41	−1.07	−1.36	0.25	−1.60	−1.15	**−2.33**	0.50
Post-monsoon	1.10	0.91	0.71	0.79	0.85	−0.32	1.21	0.89
Winter	0.03	−0.52	−0.75	−0.86	0.02	−0.39	−0.58	0.51

Bold value indicates 95 % significance level

Table A2 Rate of change over 141 years

Station name	Whole India	Homogeneous Indian monsoon	Core-monsoon India	North West India	West Central India	Central Northeast India	North East India	Peninsular India
Jan	−14.40	−4.44	−3.16	−20.25	4.89	−11.23	−22.35	3.81
Feb	5.69	9.57	0.05	11.67	7.75	0.42	−6.35	11.60
Mar	2.55	10.55	13.62	10.30	10.77	−1.13	−24.04	2.62
Apr	**19.31**	20.00	8.76	15.89	6.48	33.59	5.44	23.29
May	2.18	9.36	0.32	2.18	7.05	13.32	−3.45	−3.83
Jun	−8.75	−9.34	−10.94	11.88	−17.00	−10.34	−7.09	−6.36
Jul	**−7.13**	**−12.93**	**−13.25**	−7.26	**−14.58**	−7.50	1.67	−2.08
Aug	4.41	14.29	14.03	15.88	10.38	−5.33	**−13.29**	11.03
Sep	−6.47	−11.23	−12.37	−2.95	−13.80	2.00	−5.15	6.02
Oct	7.22	16.60	14.11	13.65	14.21	−5.84	14.04	4.35
Nov	11.14	1.53	2.87	6.31	−0.55	−1.68	11.13	12.77
Dec	−5.34	−9.85	−6.74	−32.35	−3.32	−3.79	6.92	5.82
Annual	−0.56	−1.61	−4.45	5.14	−4.17	−1.94	−3.14	4.60
Pre-monsoon	5.95	15.82	3.21	21.89	10.00	16.79	−2.38	5.90
Monsoon	−3.92	−5.17	−6.54	2.12	−6.64	−3.82	**−7.24**	2.00
Post-monsoon	10.02	15.49	13.06	14.17	13.99	−5.59	16.01	7.76
Winter	0.31	−7.71	−13.90	−15.06	0.16	−6.37	−8.81	9.62

Bold value indicates 95 % significance level

References

Alexandersson H (1986) A homogeneity test applied to precipitation data. J Climatol 6:661–675
Brunetti M, Buffoni L, Maugeri M, Nanni T (2000) Precipitation intensity trends in northern Italy. Int J Climatol 20:1017–1031
Buffoni L, Maugeri M, Nanni T (1999) Precipitation in Italy from 1833 to 1996. Theor Appl Climatol 63:33–40
Burns DA, Klaus J, McHale MR (2007) Recent climate trends and implications for water resources in the Catskill Mountain region, New York, USA. J Hydrol 336:155–170
Cruz RV, Harasawa H, Lal M, Wu S, Anokhin Y, Punsalmaa B, Honda Y, Jafari M, Li C, Huu Ninh N (2007) Asia climate change 2007: impacts, adaptation and vulnerability. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) Fourth Assessment Report of the Intergovernmental Panel on climate change. Cambridge University Press, Cambridge, pp 469–506
Cunderlik JM, Burn DH (2004) Linkages between regional trends in monthly maximum flows and selected climatic variables. ASCE J Hydrol Eng 9(4):246–256
Englehart PJ, Douglas AV (2006) Defining intraseasonal rainfall variability within the North American monsoon. J Clim 19(17):4243–4253
González JM, Cháidez JJN, Ontiveros VG (2008) Analysis of rainfall trends (1920–2004) in Mexico. Investigaciones Geográficas, Boletín del Instituto de Geografía UNAM 65:38–55
Hamed KH, Rao AR (1998) A modified Mann–Kendall trend test for auto correlated data. J Hydrol 204:182–196
IPCC (Intergovernmental Panel for Climate Change) (2007) Climate Change 2007 – the Scientific Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel for Climate Change
Kendall MG (1975) Rank correlation methods. Charles Griffin, London
Khaliq MN, Ouarda TBMJ (2007) Short Communication on the critical values of the standard normal homogeneity test (SNHT). Int J Climatol 27:681–687
Kipkorir EC (2002) Analysis of rainfall climate on the Njemps Flats, Baringo District, Kenya. J Arid Environ 50:445–458
Kruger AC (2006) Observed trends in daily precipitation indices in South Africa: 1910–2004. Int J Climatol 26:2275–2285
Mann HB (1945) Nonparametric tests against trend. Econometrica 13:245–259
Masih I, Uhlenbrook S, Maskey S, Smakhtin V (2010) Streamflow trends and climate linkages in the Zagros Mountains, Iran. Clim Change 104:317–338
Moberg A, Jones PD (2005) Trends in indices for extremes in daily temperature and precipitation in central and Western Europe, 1901–99. Int J Climatol 25:1149–1171
Pettitt AN (1979) A non-parametric approach to the change-point detection. Appl Statist 28(2):126–135
Rodrigo S, Esteban-Parra MJ, Pozo-Vázquez D, Castro-Díez Y (2000) Rainfall variability in southern Spain on decadal to centennial time scales. Int J Climatol 20(7):721–732
Sen PK (1968) Estimates of the regression coefficient based on Kendall's tau. J Am Stat Assoc 63(324):1379–1389
Singh P, Kumar V, Thomas T, Arora M (2008) Changes in rainfall and relative humidity in different river basins in the northwest and central India. Hydrol Processes 22:2982–2992
Storch HV (1993) Misuses of statistical analysis in climate research. Analysis of climate variability: applications of statistical techniques. In: Proceedings of an autumn school organized by the commission of the European Community on Elba from October 30 to November 6, 1993, 2nd ed, Springer, Berlin, 11–26
Suppiah R, Hennessy KJ (1998) Trends in total rainfall, heavy rain events and number of dry days in Australia, 1910–1990. Int J Climatol 10:1141–1164
Theil H (1950) A rank invariant method of linear and polynomial regression analysis, Part 3. Netherlands Akademie van Wettenschappen. Proceedings 53:1397–1412

Xu ZX, Takeuchi K, Ishidaira H (2003) Monotonic trend and step changes in Japanese precipitation. J Hydrol 279:144–150

Yue S, Pilon P, Phinney B (2003) Canadian streamflow trend detection: impact of serial and cross-correlation. Hydrol Sci J 48(1):51–63

Yue S, Hashino M (2003) Long term trends of annual and monthly precipitation in Japan. J Am Water Resour Assoc 39(3):587–596