

Study of Climate Change in Uttarakhand Himalayas: Changing Patterns of Historical Rainfall

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Abstract The subject area of climate change is vast, but the changing pattern of rainfall is a topic within this field that deserves urgent and systematic attention since it affects the availability of freshwater, food production and the occurrence of water related disasters triggered by extreme events. The detection of trends in rainfall is essential for the assessment of the impacts of climate variability and change on the water resources of a region. In June 2013, several days of extremely heavy rain caused devastating floods in the region, resulting in more than 5000 people missing and presumed dead. The present study aims to determine trends in the annual, seasonal, and monthly rainfall over Uttarakhand State. Long-term (1901–2013) gridded daily rainfall data at 0.25° grid have been used. Daily rainfall data at ten grid center locations (five each in Garhwal and Kumaon divisions) in the vicinity of Haridwar, Tehri, Uttarkashi, Rudraprayag, Joshimath, Almora, Bageshwar, Munsiyari, Pithoragarh, and Rudrapur have been processed and analyzed for a period of 113 years (1901–2013). Historical trends in daily rainfall have been examined using parametric (regression analysis) and non-parametric (Mann–Kendall (MK) statistics). On the basis of regression and MK test, rising and falling trend in rainfall and anomalies at various stations have been analyzed. The result shows that many of these variables demonstrate statistically significant changes occurred in last eleven decades. Statistically significant increasing trends of annual as well as monsoon rainfall have been observed at Haridwar, Rudraprayag, Joshimath, Almora, and Munsiyari whereas statistically significant decreasing trends of monthly rainfall (August, September, and October) have been observed at Uttarkashi and Tehri stations.

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Introduction

The climate of earth was never stable for any extended period. Potential climate change and its impacts on hydrologic systems pose a threat to water resources throughout the world. There are a number of natural causes of climate variability, namely variations in the amount of energy emitted by the Sun, changes in the distance between the Earth and the Sun, the presence of volcanic pollution in the upper atmosphere and presence of green house gases, etc. (Scafetta and West 2005). Natural and human influences, called “forcings” in the climate-science literature alter the flow of radiant energy in the atmosphere, cooling and warming Earth by perturbing its energy balance. Positive forcings warm the planet while negative ones cool it. One of these forcings is induced by the greenhouse gases, which alter the planet’s energy balance by absorbing infrared radiation that would otherwise escape to space. The major greenhouse gases include CO₂, methane, nitrous oxide, tropospheric ozone, chlorofluorocarbons (CFCs), and water vapor. With the exception of water vapor, the concentrations of all the greenhouse gases are more or less directly dependent on human activities. (Water vapor levels depend on Earth’s temperature and the availability of liquid water, and thus are indirectly affected by humans). Other forcings include reflective aerosols (mostly sulfate particles from burning of fossil fuel), black carbon particles (soot), land-cover changes, variations in solar output, and cloud-cover changes resulting from global temperature variations and aerosols (IPCC 2013).

The important climatic variables that influence the ecosystem are precipitation, radiation, temperature and stream flow. It is a challenge to the scientific community to understand the complicated processes involved in climate change and alert the society to tackle the problem. The changing pattern of precipitation deserves urgent and systematic attention as it will affect the availability of food supply (Dore 2005) and the occurrence of water related disasters triggered by extreme events. Precipitation is the major driving force of the land phase of the hydrologic system, and changes in its pattern could have direct impacts on water resources. A higher or lower rainfall or changes in its distribution would influence the spatial and temporal distribution of runoff, soil moisture, groundwater reserves, and would alter the frequency of droughts and floods.

The southwest monsoon, which brings about 80% of the total precipitation over the country, is critical for the availability of fresh water for drinking and irrigation. Changes in climate over Indian region, particularly the southwest monsoon, would have a significant impact on agriculture production, water resources management, and overall economy of the country. According to IPCC (2013), future climate change is likely to affect agriculture, increase the risk of hunger and water scarcity, and would lead to more rapid melting of glaciers. Freshwater availability in many river basins in Asia is likely to decrease due to climate change. This reduction along with population growth and rising living standards could adversely affect more than a billion people in Asia by the 2050s. Accelerated glacier melt is likely to cause an increase in the number and severity of glacier melt related floods, slope

destabilization and a decrease in river flows as glaciers recede (IPCC 2013). Lal (2001) has discussed implications of climate change on Indian water resources. Gosain et al. (2006) have quantified the impact of climate change on the water resources of Indian River systems.

Global averaged precipitation is projected to increase, but both increases and decreases are expected at the regional and continental scales (IPCC 2007). Similar trends were reported in rainfall by various authors in India (Thapliyal and Kulshrestha 1991; Kumar et al. 1992; Sinha Ray and De 2003; Singh et al. 2008). Though the monsoon rainfall in India is found to be trendless over a long period of time, particularly on the all India scale, pockets of significant long-term rainfall changes have been identified (Srivastava et al. 1998). Climate change projections using various global climate models (GCMs) and regional climate models (RCMs) showed increasing temperature and changing patterns in rainfall during the twenty-first Century over India (Kumar et al. 2006; Rajendran and Kitoh 2008).

In last few decades, several individual and collaborative researches were undertaken to study climate change. The linear relationship is one of the most common methods used for detecting rainfall trends (Hameed et al. 1997). Both parametric and non-parametric tests are widely used for trend study. The advantage with a non-parametric test is that it only requires data to be independent and can tolerate outliers in the data (Hameed and Rao 1998). One of the popular non-parametric tests widely used for detecting trends in the time series is the Mann–Kendall test (Mann 1945; Kendall 1955). The two important parameters of this test are the significance level that indicates the trend strength and the slope magnitude that indicates the direction as well as the magnitude of the trend (Burn and Elnur 2002). The advantage of the test is that it is distribution-free, robust against outliers and has a higher power than many other commonly used tests (Hess et al. 2001). Many climate studies applying Mann–Kendall test have been carried out in the last decade. Modarresa and Silva (2007) studied the rainfall trend in Iran; Birsan et al. (2005) used the test to study the stream flow trend in Switzerland; Shan Yu et al. (2002) studied the impact of climate change on water resources in Taiwan; Hesse et al. (2005) studied the temperature trends over India; Zhang et al. (2005) analyzed the trend of precipitation, temperature, and runoff in the Yangtze basin China. Mcbean and Rovers (1998) examined historical trends in precipitation, temperature, and stream flows in the Great Lakes using regression analysis and Mann–Kendall statistics.

Keeping in view the above back ground, the present study has been carried to evaluate the trend of rainfall in the State of Uttarakhand, India. The Uttarakhand State is located in the Himalayan region has been selected for the study. Several major and minor hydro-electric power stations are being built in over the tributaries of Ganga River in the mountainous part of the State several more are under consideration. Hence, it is very important to understand the impact of climate change on the hydrology of this Hilly State for proper planning and management of the

water resources. The major objective of the study was to observe the trend of rainfall in the State in the last 113 years. Trend analysis has been carried out using linear regression method and Mann–Kendall test.

Study Area and Data Used

Uttarakhand is a state in the northern part of India. It is often referred to as the “Land of the Gods” due to the many holy Hindu temples and pilgrimage centers found throughout the state. Uttarakhand is known for its natural beauty of the Himalayas, the Bhabhar, and the Terai. It borders the Tibet Autonomous Region on the north; the Mahakali Zone of the Far-Western Region, Nepal on the east; and the Indian states of Uttar Pradesh to the south and Himachal Pradesh to the northwest. The state is divided into two divisions, Garhwal and Kumaon, with a total of 13 districts. Two of the most important rivers in Hinduism originate in the region, the Ganga at Gangotri and the Yamuna at Yamunotri.

Uttarakhand has a total area of 53,484 km², of which 93% is mountainous and 65% is covered by forest. Most of the northern part of the state is covered by high Himalayan peaks and glaciers. Uttarakhand lies on the southern slope of the Himalaya range, and the climate and vegetation vary greatly with elevation, from glaciers at the highest elevations to subtropical forests at the lower elevations. The highest elevations are covered by ice and bare rock. Below them, between 3,000 and 5,000 m (9,800 and 16,400 ft.) are the western Himalayan alpine shrub and meadows. The temperate western Himalayan sub-alpine conifer forests grow just below the tree line. At 3,000–2,600 m (9,800–8,500 ft.) elevation they transition to the temperate western Himalayan broadleaf forests, which lie in a belt from 2,600 to 1,500 m (8,500 to 4,900 ft.) elevation. Below 1,500 m (4,900 ft.) elevation lie the Himalayan subtropical pine forests. The Upper Gangetic Plains moist deciduous forests and the drier Terai-Duar savanna and grasslands cover the lowlands along the Uttar Pradesh border in a belt locally known as Bhabhar. These lowland forests have mostly been cleared for agriculture, but a few pockets remain. In June 2013, several days of extremely heavy rain caused devastating floods in the region, resulting in more than 5000 people missing and presumed dead. The flooding was referred to in the Indian media as a “Himalayan Tsunami.”

Daily rainfall data at ten grid center locations (five each in Garhwal and Kumaon divisions) in the vicinity of Haridwar, Tehri, Uttarkashi, Rudraprayag, Joshimath, Almora, Bageshwar, Munsiyari, Pithoragarh, and Rudrapur procured from India Meteorological Department (IMD) have been used in this study. These stations are shown in Fig. 1 which represents the study area, i.e., the Uttarakhand State. Analysis has been performed for a period from 1901 to 2013, i.e., 113 years.

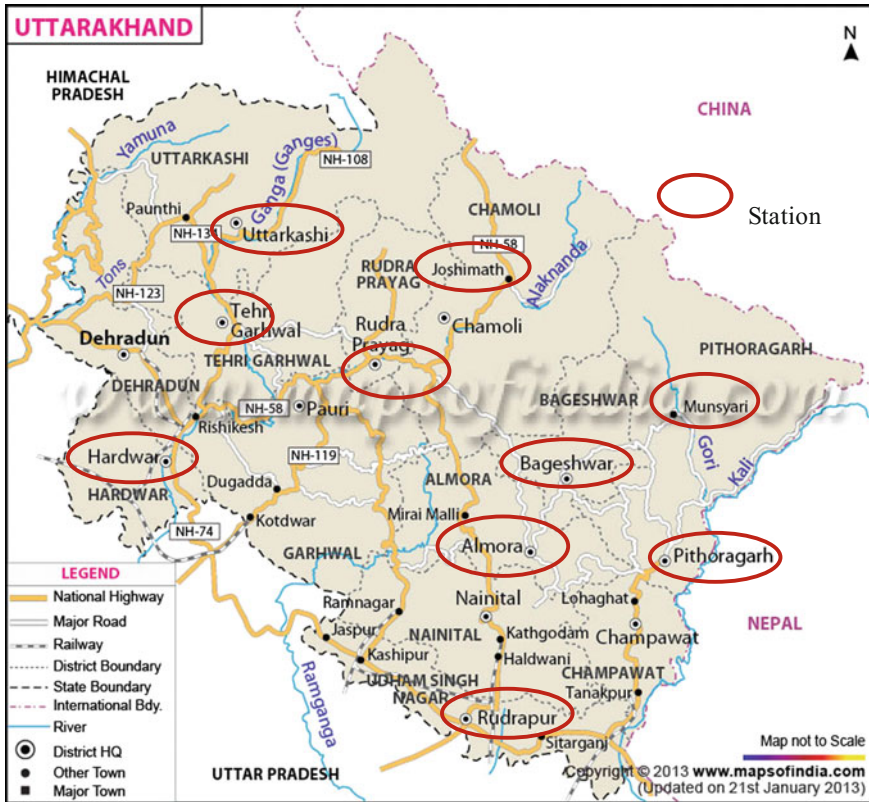


Fig. 1 Study area

Methodology

Trend Analysis

In the present study, two methods viz. regression and MK test have been used. These are described in the following sections.

Regression Model

One of the most useful parametric models to detect the trend is the “Simple Linear Regression” model. The method of linear regression requires the assumptions of normality of residuals, constant variance, and true linearity of relationship (Helsel

and Hirsch 1992a, b). The model for Y (e.g., precipitation) can be described by an equation of the form:

$$Y = at + b \quad (1)$$

where,

t time (year)

a slope coefficient; and

b least-squares estimate of the intercept

The slope coefficient indicates the annual average rate of change in the hydrologic characteristic. If the slope is significantly different from zero statistically, it is entirely reasonable to interpret that there is a real change occurring over time. The sign of the slope defines the direction of the trend of the variable: increasing if the sign is positive, and decreasing if the sign is negative.

Mann Kendall Model

Simple linear regression analysis may provide a primary indication of the presence of a trend in the time-series data. Other methods, such as the non-parametric Mann–Kendall (MK) test, which is commonly used for hydrologic data analysis, can be used to detect trends that are monotonic but not necessarily linear. The MK test does not require the assumption of normality, and only indicates the direction but not the magnitude of significant trends (USGS 2005).

The trend in the data if any was quantified using Mann–Kendall’s S-statistic (Mann 1945; Kendall 1955). The MK method assumes that the time series under research is stable, independent, and random with equal probability distribution (Zhang et al. 2005). The MK test is applied to uncorrelated data because it was reported that the presence of serial correlation might lead to an erroneous rejection of the null hypothesis (Helsel and Hirsch 1992a, b; Kulkarni and von Storch 1995; Yue et al. 2002; Yue and Wang 2002; Yue and Pilon 2003).

The computational procedure for the MK test is described in Adamowski and Bougadis (2003). Let the time series consist of n data points and T_i and T_j be two sub—sets of data where $i = 1, 2, 3, \dots, n - 1$ and $j = i + 1, i + 2, i + 3, \dots, n$. Each data point T is used as a reference point and is compared with all the T_j data points such that:

$$\text{Sign}(T) = \begin{cases} 1 & \text{for } T_j > T_i \\ 0 & \text{for } T_j = T_i \\ -1 & \text{for } T_j < T_i \end{cases} \quad (2)$$

The MK test used in the present study is based on the test statistic, S , defined as follows:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sign}(T_j - T_i) \tag{3}$$

The variance for the S -statistic is defined by:

$$\sigma^2 = \frac{n(n-1)(2n+5) - \sum_{i=1}^n t_i(i)(i-1)(2i+5)}{18} \tag{4}$$

where t_i denotes the number of ties to extent i . The summation term in Eq. (4) is only used if data series contains the “tied” values. The test statistic, Z_s , can be calculated as

$$Z_s = \begin{cases} (S - 1)/\sigma & \text{for } S > 0 \\ 0 & \text{for } S = 0 \\ (S + 1)/\sigma & \text{for } S < 0 \end{cases} \tag{5}$$

In which, Z_s follows a standard normal distribution. Equation (5) is useful for record lengths greater than 10 and if the number of tied data is low. The test statistic, Z_s is used as a measure of the significance of the trend. In fact, this test statistic is used to test the null hypothesis, H_0 : There is no monotonic trend in the data. If $|Z_s|$ is greater than $Z_{\alpha/2}$ where α represents the chosen significance level (usually 5%, with $Z_{0.025} = 1.96$), then the null hypothesis is rejected, meaning that the trend is significant. For this study, the simple regression analysis technique was used to test the slopes of the trend lines for statistical significance at 5% level. The Mann–Kendall trend test procedure is applied to further verify the outcomes of regression analysis for the hydrological variables considered.

MK test holds well in the case of non-auto-correlated time-series data. For auto-correlated data, modified Mann–Kendall test proposed by Rao and Hamed (1997) was used, which is robust in presence of autocorrelation. It is based on the modified variance of S given by Eq. (5).

$$V^*(S) = \text{var}(S) \frac{n}{n_s^*} = \frac{n(n-1)(2n+5)}{18} \frac{n}{n_s^*} \tag{6}$$

The recommended approximate value of n/n_s^* n/n_2 is given by the Eq. (7)

$$\frac{n}{n_s^*} = 1 + \frac{2}{n(n-1)(n-2)} \sum_{i=1}^{n-1} (n-i)(n-i-1)(n-i-2)\rho_s(i) \tag{7}$$

where n is the actual number of observations and $\rho_s(i)$ is the autocorrelation function of the ranks of the observations. The accuracy of the approximation given

by the Eq. (6) was found to improve as n increases. The autocorrelation between ranks of observations $\rho_s(i)$ is first evaluated. The value of ranks of observations $\rho_s(i)$, however, must be calculated after subtracting a suitable non-parametric trend estimator (Sen 1968). Due to the nature of calculation in Eq. (5), which involves a large number of terms, it was found that insignificant values of $\rho_s(i)$ will have an adverse effect on the accuracy of the estimated variance of S . Therefore, only significant values of $\rho_s(i)$ are used in Eq. (6). This is achieved by requiring a suitable preset significance level for the autocorrelation to be included in the calculations, which can be taken equal to that of the rest.

In the present study, non-parametric Mann–Kendall trend test and modified Mann–Kendall test as proposed by Rao and Hamed (1997) were applied to study the historical trend in annual and monthly rainfall described in the following sections.

Data Preparation

The daily hydro-meteorological data available for above cited period at different grids/stations have been used to prepare annual, seasonal, and monthly series of rainfall as described below:

- (1) *Annual*: Using the daily data, series of average annual data have been prepared for trend analysis for all the variables at various grids/stations
- (2) *Seasonal*: Four types of average seasonal data series have been prepared. Data were divided into four seasons, namely pre-monsoon (March–May), monsoon (June–August), post-monsoon (September–November), and winter (December–February) based on the prevailing climate of India.
- (3) *Monthly*: Using the daily data, series of average monthly data have been prepared for trend analysis for all the variables at various grids/stations.

Trend Analysis and Results

Using the gridded data of daily rainfall from IMD for the ten grid center locations (referred to as stations hereafter) under the present study, monthly, seasonal and annual rainfall series were generated for all the ten stations. Then, the time series were checked for randomness, autocorrelation, and long-term persistence before conducting the Mann–Kendall test. Time series having no autocorrelation were analyzed with Mann–Kendall’s Test for the detection of trend and if significant autocorrelation was found in the data, the time series was tested with modified Mann–Kendall test as suggested by Rao and Hamed (1997). In this study, monthly, seasonal and annual rainfall for ten grid points were analyzed as given in Table 1 and Table 2 for Garhwal and Kumaon region, respectively. The selected stations

Table 1 Trend in different season for rainfall data (Garhwal Region)

Period	MKZ statistics				
	Joshimath	Rudraprayag	Uttarkashi	Tehri	Haridwar
January	-0.38	-0.93	-1.22	-0.75	-1.09
February	+0.76	+1.17	+1.34	+1.46	+0.96
March	+1.04	+0.53	+1.21	+1.27	-0.39
April	-0.28	+1.08	+1.49	+1.87	+0.72
May	+1.87	+1.85	+2.43	+2.05	+0.85
June	+1.37	+1.44	+0.78	+0.47	+3.48
July	+2.85	+2.84	-1.66	-1.73	+2.75
August	+1.49	+0.87	-2.57	-2.50	+1.17
September	-1.14	-0.99	-5.12	-5.15	-1.28
October	-1.39	-1.62	-2.43	-2.26	-0.94
November	-0.37	-1.20	-1.18	-0.83	-1.87
December	-0.01	+0.58	+0.06	+0.21	+1.35
Pre-mon	-1.01	-0.50	-0.26	-0.19	-0.33
Monsoon	+2.92	+2.47	-0.32	-0.59	+2.81
Post-mon	+0.72	+0.17	-0.10	-0.05	+0.50
Winter	-0.36	+0.62	-0.87	-0.07	-2.25
Annual	+2.27	+3.05	-0.07	-0.37	+2.78

Table 2 Trend in different season for rainfall data (Kumaon region)

Period	MKZ statistics				
	Almora	Bageshwar	Pithoragarh	Rudrapur	Munsiyari
January	-1.25	+0.30	-0.41	+0.24	+0.28
February	+0.21	+0.61	+0.97	+0.38	+1.11
March	-0.62	+0.24	-0.09	-0.88	+0.58
April	-0.05	+0.13	+0.26	+0.43	+0.33
May	+0.17	+0.70	+0.88	+2.71	+0.86
June	+1.11	+0.09	-0.18	+2.60	+0.20
July	+0.46	+0.54	-0.74	+0.29	+1.75
August	+0.22	-0.22	-1.20	-0.77	+0.64
September	-1.83	-1.66	-1.95	-1.89	-1.08
October	-1.23	-1.59	-1.75	-0.91	-1.77
November	-1.40	-0.57	-1.45	-0.86	-0.43
December	-0.03	-0.23	-0.41	+0.85	-0.29
Pre-mon	-0.62	-0.75	+0.52	+0.17	-0.22
Monsoon	+2.00	+1.35	+0.38	+1.53	+2.27
Post-mon	-0.41	+0.08	-0.02	+1.09	+0.90
Winter	-1.65	-0.06	-0.22	-1.67	+1.12
Annual	+2.05	+1.73	+0.58	+1.73	+2.63

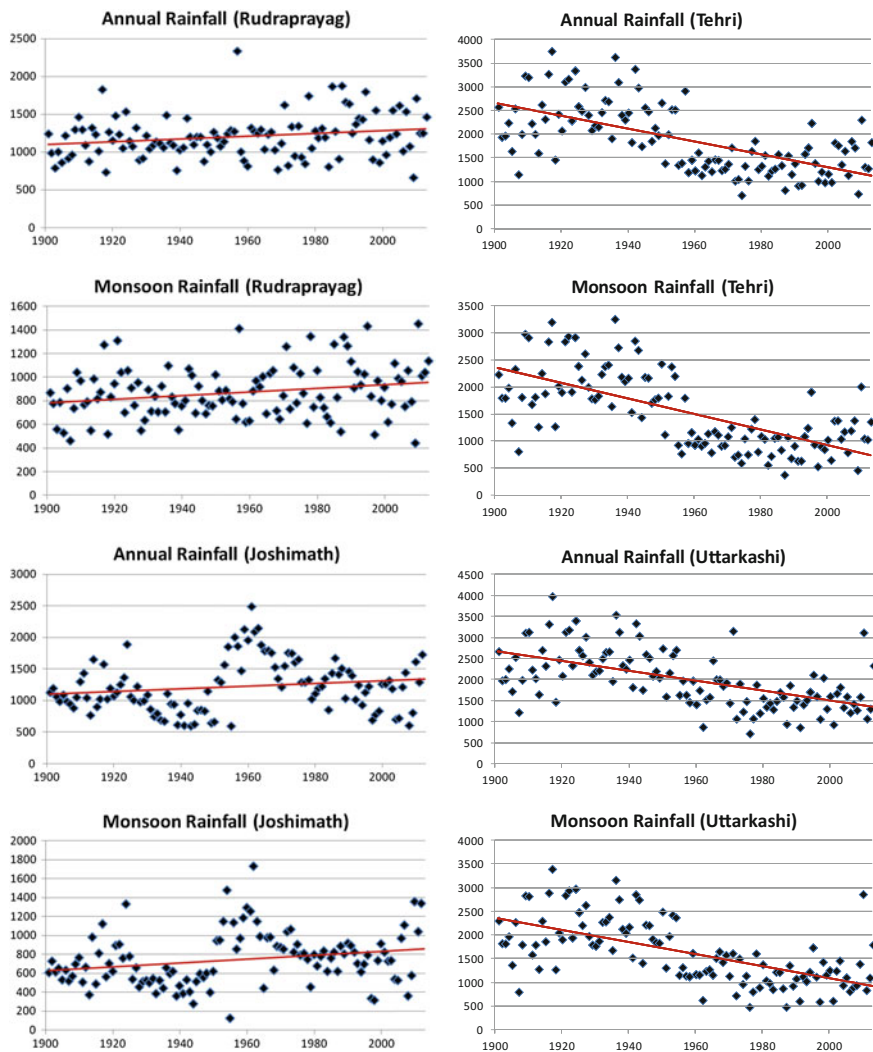


Fig. 2 Trends in annual and monsoon rainfall for all the stations

have 113 years of record length each. Linear regression analysis has been carried out for all the stations. Graphical presentations are shown in Fig. 2 for trends in annual and monsoon rainfall for all the stations. Annual and seasonal spatial trends in the Uttarakhand state are shown in Fig. 3.

Annual analysis of rainfall trends (Tables 1 and 2) shows a significantly increasing trend (at 5% significance level) at five rainfall stations, three in the Garhwal region and two in the Kumaon region. Monsoon rainfall also follows similar trends. However, the monthly rainfall analysis shows significantly

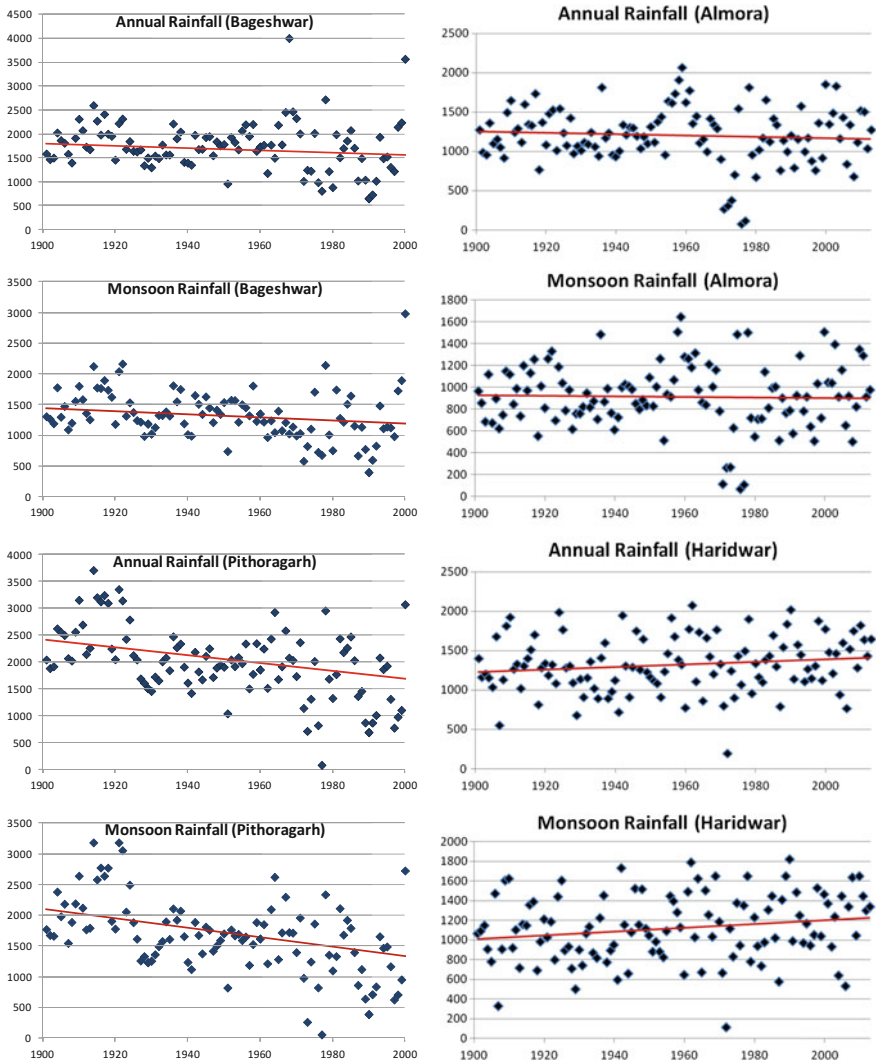


Fig. 2 (continued)

increasing trend of rainfall in the month of April over Bageshwar and Pithoragarh stations in the Kumaon region of the State. Statistically significant increasing rainfall trend has also been observed over Chamoli station of the Garhwal region during the month of August. Besides the above trends, the regression analysis shows increasing as well as decreasing trend of rainfall in all the stations during the different time period, but such trend is not statistically significant.

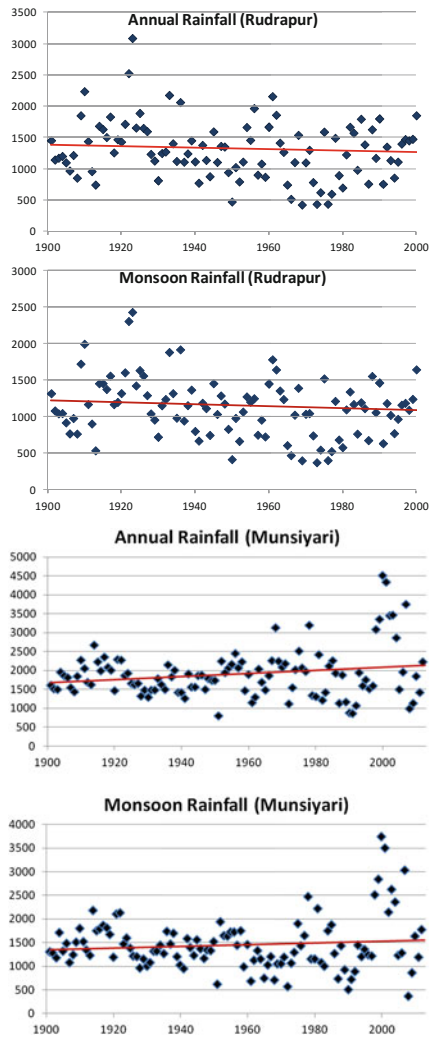


Fig. 2 (continued)

Conclusions

The Himalayas are highly sensitive to climate change. Any change in rainfall highly influences stream flow downstream. The Himalayan Rivers have witnessed a steep rise in glacial retreat in recent past. These events are a strong indication of climate change in the Uttarakhand State. However, the influence of anthropogenic factors cannot be rejected. The present study is based on the analysis daily rainfall data using simple linear regression and non-parametric Mann–Kendall trend test.

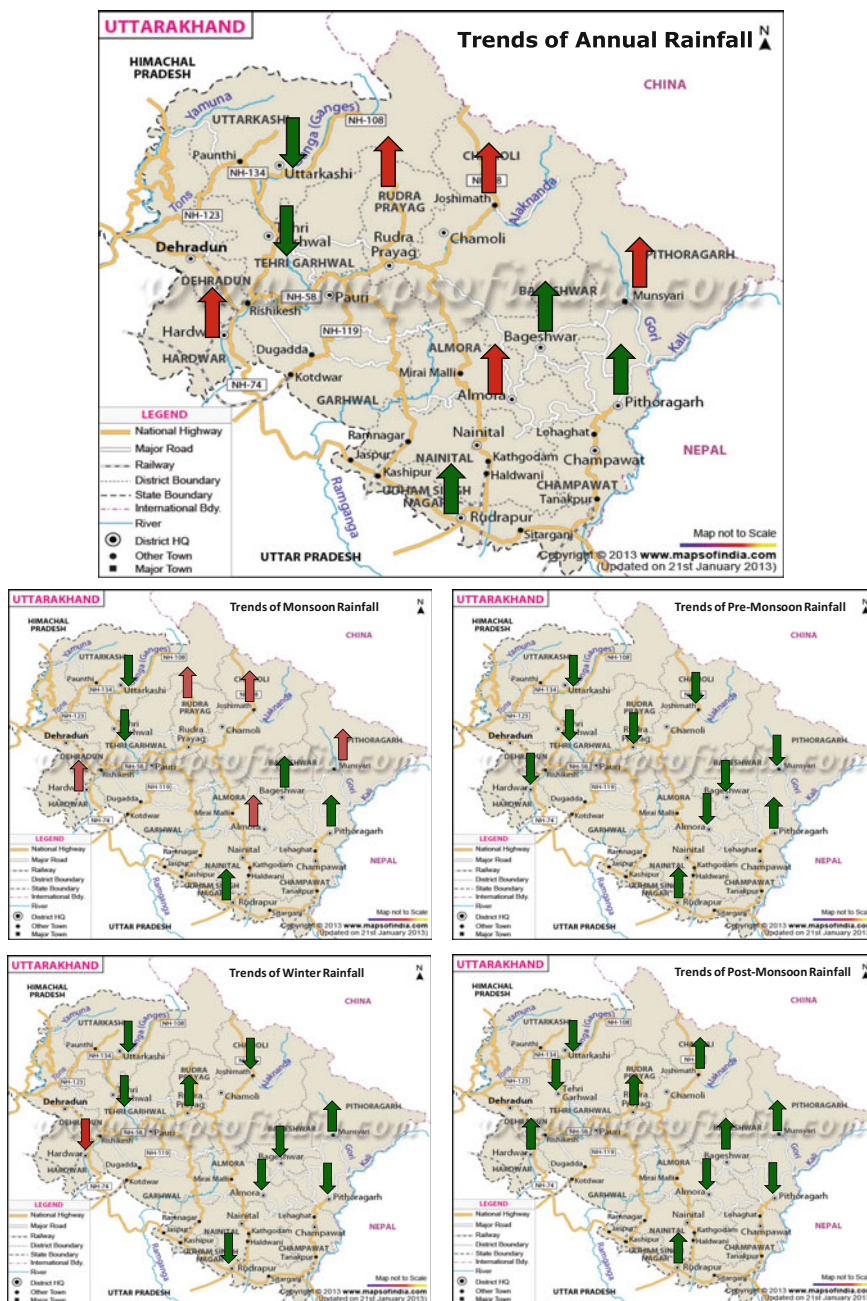


Fig. 3 Trend of annual rainfall over 113 Years (1901–2013)

It demonstrates statistically significant changes in rainfall over some stations during the last 113 years.

The analysis shows significantly increasing trend in annual and monsoon rainfall at some of the stations, however, increasing trend in monthly rainfall has been observed for some of the months at few stations. The results observed in this study are an encouragement to explore the impact of climate change on the local climate of the region. Also, there is need to understand the rainfall regime of the Uttarakhand State in detail with more rainfall station data and the likely impacts of climate change to plan and manage the water resources for future.

References

- Adamowski K, Bougadis J (2003) Detection of trends in annual extreme rainfall. *Hydrological Processes* 17(18):3547–3560
- Birsan MV, Molnar P, Burlando P, Pfaundler M (2005) Streamflow trends in Switzerland. *J Hydrol* 314(1):312–329
- Burn DH, Elnur MAH (2002) Detection of hydrological trends and variability. *J Hydrol* 255: 107–122
- Burn DH, Cunderlik JM, Pietroniro A (2004) Hydrological trends and variability in the Liard river basin. *Hydrological Science Journal* 49:53–67
- Dore MHI (2005) Climate change and changes in global precipitation patterns: what do we know? *Environ Int* 31:1167–1181
- Gosain AK, Rao S, Basuray D (2006) Climate change impact assessment on hydrology of Indian river basins. *Curr Sci* 90:346–353
- Hamed KH, Rao AR (1998) A modified Mann-Kendall trend test for autocorrelated data. *J Hydrol* 204:182–196
- Hameed T, Marino MA, De Vries JJ, Tracy JC (1997) Method for trend detection in climatological variables. *J Hydrol Eng* 4:154–160
- Helsel DR, Hirsch RM (1992a) *Statistical methods in water resources*. Elsevier, Amsterdam, p 522
- Helsel DR, Hirsch RM (1992b) *Statistical methods in water resources*. Elsevier, New York
- Hess A, Iyer H, Malm W (2001) Linear trend analysis: a comparison of methods. *Atmos Environ* 35:5211–5222
- Hesse BW, Nelson DE, Kreps GL, Croyle RT, Arora NK, Rimer BK, Viswanath K (2005) Trust and sources of health information: the impact of the Internet and its implications for health care providers: findings from the first Health Information National Trends Survey. *Arch Intern Med* 165(22):2618–2624
- Kendall MG (1955) *Rank correlation methods*. Griffin, London
- Kulkarni A, von Storch H (1995) Monte Carlo experiments on the effect of serial correlation on the Mann-Kendall test of trend. *Meteorol Z* 4(2):82–85
- Lal M (2001) Climatic change—implications for India's water resources. *J Indian Water Res Soc* 21:101–119
- Mann HB (1945) Nonparametric tests against trend. *Econometrica* 13:245–259
- McBean EA, Rovers FA (1998) *Statistical procedures for analysis of environmental monitoring data and assessment*
- Modarressa R, Silva VPR (2007) Rainfall trends in arid and semi-arid regions of Iran. *J Arid Environ* 70:344–355
- Rajendran K, Kitoh A (2008) Indian summer monsoon in future climate projection by a super high-resolution global model. *Curr Sci* 95:1560–1569

- Rao AR, Hamed KH (1997) Regional frequency analysis of Wabash River flood data by L-moments. *J Hydrol Eng* 2(4):169–179
- Rupa Kumar K, Pant GB, Parthasarathy B, Sontakke NA (1992) Spatial and sub seasonal patterns of the long term trends of Indian summer monsoon rainfall. *Int J Climatol* 12:257–268
- Rupa Kumar K, Sahai AK, Kumar KK, Patwardhan SK, Mishra PK, Revadekar JV, Kamala K, Pant GB (2006) High-resolution climate change scenarios for India for the 21st century. *Curr Sci* 90:334–345
- Scafetta N, West BJ (2005) Estimated solar contribution to the global surface warming using the ACRIM TSI satellite composite. *Geophys Res Lett* 32:L18713. doi:[10.1029/2005GL023849](https://doi.org/10.1029/2005GL023849)
- Sen PK (1968) Estimates of the regression coefficient based on Kendall's tau. *J Am Stat Assoc* 63:1379–1389
- Shan Yu P, Yang TC, Wu CK (2002) Impact of climate change on water resources in southern Taiwan. *J Hydrol* 260:161–175
- 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 Process* 22:2982–2992
- Sinha Ray KC, De US (2003) Climate change in India as evidenced from instrumental records. *WMO Bulletin* 52:53–58
- Srivastava HN, Sinha Ray KC, Dikshit SK, Mukhopadhaya RK (1998). Trends in rainfall and radiation over India. *Vayu Mandal* 41–45
- Thapliyal V, Kulshreshtha SM (1991) Climate changes and trends over India. *Mausam* 42:333–338
- Yue S Wang CY (2002) Applicability of prewhitening to eliminate the influence of serial correlation on the Mann-Kendall test, *Water Resour Res* 38(6). doi:[10.1029/2001WR000861](https://doi.org/10.1029/2001WR000861)
- Yue S, Pilon P (2003) Interaction between deterministic trend and autoregressive process. *Water Resour Res* 39(4). doi:[10.1029/2001WR001210](https://doi.org/10.1029/2001WR001210)
- Yue S, Pilon P, Cavadias G (2002) Power of the Mann-Kendall and Spearman's rho tests for detecting monotonic trends in hydrological series. *J Hydrol* 259:254–271
- Zhang Q, Jiang T, Gemmer M, Becker S (2005) Precipitation, temperature and runoff analysis from 1950 to 2002 in the Yangtze basin, China. *Hydrol Sci* 50(1):65–79