Trends in rainfall amount and number of rainy days in river basins of India (1951–2004)

Vijay Kumar and Sharad K. Jain

ABSTRACT

This study aims to determine trends in annual and seasonal rainfall and rainy days over different river basins across India. The data used consists of daily gridded rainfall at 1° × 1° resolution for the period 1951–2004. Sen's non-parametric estimator of slope was used to estimate the magnitude of trend whose statistical significance was assessed by the Mann–Kendall test. Among 22 basins studied, 15 showed a decreasing trend in annual rainfall; only one basin showed a significant decreasing trend at 95% confidence level. Of the 6 basins showing an increasing trend, 1 basin showed a significant positive trend. The monsoon rainfall increased over 6 basins, decreased over 16 basins and a decreasing trend for 2 basins was found statistical significant. With the exception of Ganga, Brahmaputra and EFR4, all river basins experienced the same direction of trend in monsoon and annual rainfall. Four river basins experienced increasing (non-significant) trend in annual rainy days; three basins did not show any change in annual rainy days whereas 15 basins have shown a decreasing trend in annual rainy days. The decreasing trend in three basins was statistically significant. Most of the basins have shown the same direction of trend in rainfall and rainy days at the annual and seasonal scale.

Key words | climate change, India, Mann–Kendall, rainfall trend, river basin, seasonal analysis

Vijay Kumar
National Institute of Hydrology,
Roorkee,
India

Sharad K. Jain (corresponding author)
Indian Institute of Technology,
Roorkee 247667,
India
E-mail: *s_k_jain@yahoo.com*

INTRODUCTION

The agriculture-based economy and food security of India is dependent on the timely availability of adequate amounts of water. The rainfall received over an area is an important factor in assessing the amount of water available to meet various demands such as agricultural, industrial, domestic water supply and hydroelectric power generation. Global climate changes may influence long-term rainfall patterns impacting the availability of water, along with the danger of increasing occurrences 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 the Indian region, particularly the southwest monsoon, would have a significant impact on agricultural production, water resources management and the overall economy of the country. The heavy concentration of rainfall in monsoon months (June to September) results in a scarcity of water in many parts of the country during the non-monsoon periods.

In the past, a number of studies have attempted to investigate trends in climatic variables for the country. These studies have looked at the issues on the country scale, regional scales and at the individual stations. The literature review in the following section covers the various reported studies. Very few studies have tried to examine the trends in the climatic variables at the scale of river basins. Work reported in this paper has used a much larger and recent database.

Due to the uneven distribution of rainfall and the mismatch between water availability and demand, large storage reservoirs are required to redistribute the natural flow in accordance with the requirements of specific regions. The general practice of designing a reservoir is based on the assumption that climate is stationary (Mehrotra 1999). Changes in rainfall due to global warming will influence the

doi: 10.2166/nh.2011.067

hydrological cycle and the pattern of stream flows and demands (particularly agricultural), requiring a review of reservoir design and management practices. An understanding of the hydrological response of a river basin under changing climatic conditions would help in understanding problems associated with floods, droughts and the availability of water for various uses. This input can also be used in review of design and management practices for water regulation structures. Changes in runoff and its distribution will depend on likely future climate scenarios (IPCC 2007). The trend analysis of rainfall data on different spatial scales is required for the construction of climate scenarios. Using these scenarios, an assessment of water availability can be made in different basins in the context of future requirements.

STUDIES CONCERNING PAST RAINFALL TRENDS IN INDIA

Some past studies related to changes in rainfall over India have concluded that there is no clear trend of increase or decrease in average annual rainfall over the country (Mooley & Parthasarathy 1984; Sarker & Thapliyal 1988; Thapliyal & Kulshrestha 1991; Lal 2001; Sinha Ray & De 2003). Although the monsoon rainfall in India exhibited no significant trend 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; Kumar *et al*. 2005; Dash *et al*. 2007). Rupa Kumar *et al*. (1992) have shown that the areas of northeast peninsula, northeast India and northwest peninsula experienced a decreasing trend (between –6% and –8% of the normal per 100 years) in the monsoon rainfall whereas west coast, central peninsula and northwest India have experienced an increasing trend (10–12% of the normal per 100 years) in monsoon rainfall. Here the term 'peninsula' refers to the landmass of triangular shape south of Narmada basin (Figure 1).

Studies by Sinha Ray & Srivastava (1999), Khan *et al*. (2000), Shrestha *et al*. (2000), Mirza (2002), Lal (2003), Min *et al*. (2003), Goswami *et al*. (2006) and Dash *et al*. (2007) show that the frequency of more intense rainfall events in many parts of Asia has generally increased while the number of rainy days and total annual precipitation has decreased. An increase in intense rainfall events leads to more severe floods and landslides. The number of cyclones originating from the Bay of Bengal and Arabian Sea has been found to decrease since 1970, but their intensity has increased (Lal 2001). Moreover, the damage caused by intense cyclones has risen significantly in India. In three consecutive years since 2002, there were large floods in northeast states of India, but rainfall deficiency was observed in the year 2006/07; over 26–27 July 2005 a record 944 mm of rain fell in Mumbai. Severe floods were observed in many parts of Gujarat and Rajasthan (basins of Luni & others, Sabarmati and Mahi) during the monsoon season of 2006 and 2007 (India Meteorological Department 2006, 2007). Droughts are caused by the other extreme of rainfall. A number of droughts during 1999 to 2007 in northwest India accompanied by large withdrawals of groundwater for various uses led to a decline in water tables in the region. In the recent past, India has faced droughts in 1971, 1979, 1987 and 2002. In 2009 the monsoon rainfall in the country was 76% of the long period average.

In India, attempts have been made to determine the trend in the rainfall on the country and regional scales. Most of the rainfall studies are confined to the analysis of annual and seasonal series of rainfall for some individual stations or groups of stations (Mooley & Parthasarathy 1984; Thapliyal & Kulshrestha 1991; Srivastava *et al*. 1998; Sinha Ray & De 2003; Kumar *et al*. 2005; Dash *et al*. 2007). Few studies (Mirza *et al*. 1998; Singh *et al*. 2005, 2008a), have investigated the trend and magnitude of variations in rainfall on the basin scale. Mirza *et al*. (1998) have studied the changes over only three river basins, namely Ganges, Brahmaputra and Meghna. They showed that precipitation in the Ganges basin is by and large stable. One of three subdivisions of the Brahmaputra basin showed a decreasing trend while another showed an increasing trend. Ranade *et al*. (2008) found no trend in starting or ending date, duration and total rainfall amount of the hydrological wet season over different river basins of India. Using data from 316 rain gauges, Singh *et al*. (2005) found that annual rainfall over major basins in Central India (Sabarmati, Mahi, Narmada, Tapi, Godavari and Mahanadi) showed a decreasing trend since the 1960s while in other basins (Indus, Ganga, Brahmaputra, Krishna and Cauvery) an increasing trend is found. Singh *et al*. (2008a) have studied the changes in rainfall over the last century in nine

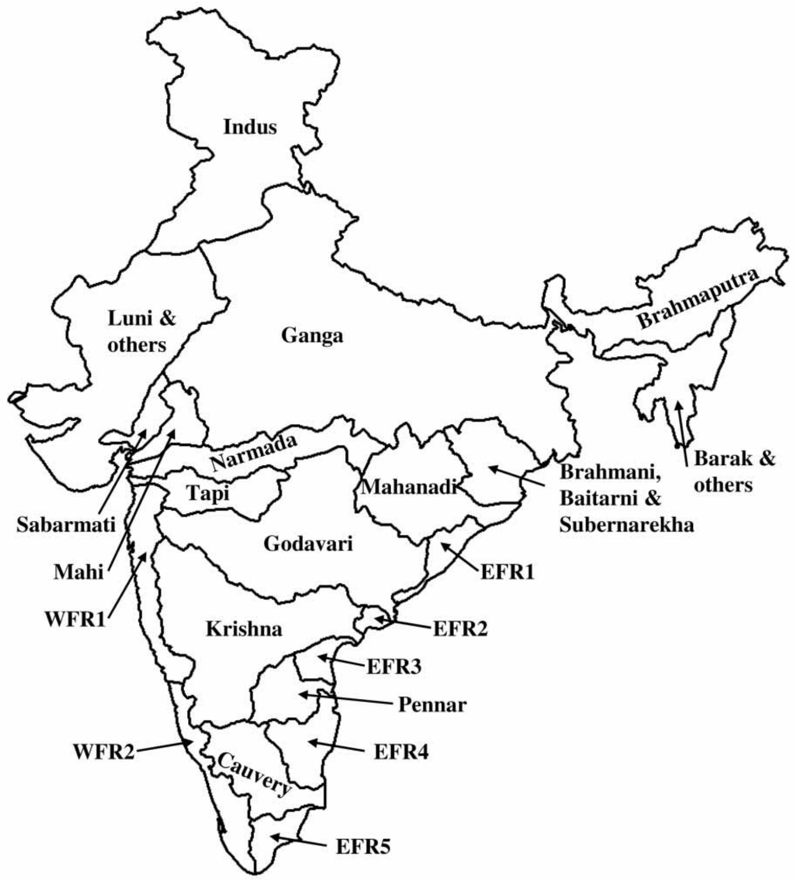

Figure 1 | River basin map of India.

river basins of northwest and central India by analyzing the data from 43 stations. The rate of change of rainfall at each of these 43 stations was estimated by linear trend line slope. These point values were interpolated to obtain the spatial distribution of rainfall change over the study area. They found increasing trends in annual rainfall over eight river basins in the range 2–19% of the mean per 100 years. One of the limitations of the study was the use of data for a limited number of rainfall stations for analysis. Also, the statistical significance of trend was tested for only a single individual station.

Climate projections for India using global models

Climate change projections using various Global Climate Models (GCMs) and Regional Climate Models (RCMs) show an increasing temperature and changing patterns in rainfall during the 21st century over India (Rupa Kumar *et al*. 2006; Rajendran & Kitoh 2008). PRECIS (**P**roviding **RE**gional **C**limates for **I**mpacts **S**tudies, a regional climate modelling system, developed by the Met Office, UK, http://precis.metoffice.com/) simulations under scenarios of increasing greenhouse gas concentrations and sulphate aerosols indicate a general increase in both rainfall and temperature for the country as a whole towards the end of the 21st century (Rupa Kumar *et al*. 2006). The maximum increase in rainfall was projected over west coast and northeast India. On the other hand, Rajendran & Kitoh (2008) used a super-high-resolution global model to predict a widespread but spatially varying increase in rainfall over the interior regions and a significant reduction in orographic rainfall over the west coast of Kerala and Karnataka and eastern hilly regions around Assam. The two studies referred to above projected opposite trends in rainfall in some parts of India (for example, the west coast), suggesting that large uncertainties in future projections of rainfall exist. A climate change impact assessment on water resources using output of GCMs is characterized by uncertainty due to incomplete knowledge about the underlying geophysical processes of global change and due to uncertain future scenarios (Mujumdar & Ghosh 2008). Several earlier studies (Rupa Kumar & Ashrit 2001; De 2001) have cautioned against the direct use of model scenarios to study the impacts on a regional scale.

Likely impacts of climate change on hydrologic regime

While summarizing the findings concerning projections of climate change impacts on freshwater resources and their management, Kundzewicz *et al.* (2008) conclude that the negative impacts of projected climate change on freshwater resources will outweigh its benefits. According to the IPCC (2007), future climate change is likely to affect agriculture hence increasing the risk of hunger and water scarcity, and will lead to more rapid melting of glaciers globally. Freshwater availability in many river basins in Asia is likely to decrease due to climate change. This decrease along with population growth and rising living standards could adversely affect more than a billion people in Asia by the 2050s. Gosain *et al.* (2006) have quantified the impact of climate change on the water resources of Indian river systems. Their study has revealed that climatic changes may result in increased severity of droughts in some parts of the country and enhanced intensity of floods in other parts, with an overall reduction in the quantity of the available runoff under the greenhouse gas scenario considered. Accelerated glacier melt is likely to increase the number and severity of glacier melt-related floods, slope destabilization and a decrease in river flows as glaciers recede (IPCC 2007).

The effect of change in precipitation suggested a linear increase/decrease in snowmelt runoff and total stream flow in mountainous areas, while glacier melt runoff was found inversely related to changes in precipitation (Singh & Kumar 1997; Singh *et al.* 2006). The flow in rain-fed rivers of Central, Western and Southern India depends on the condition of monsoon rainfall. These rivers are charged by groundwater and their flows are reinforced by the seasonal rainfall. Many rivers such as the desert rivers of Luni and Mahi flowing through Rajasthan are totally fed by the monsoon rains and cease to flow during the rest of the year. A poor monsoon rainfall leads to drought conditions; the situation is further aggravated if the monsoon fails for consecutive years. The analysis of the sensitivity of annual runoff of nine sub-basins of the Ganga River basin to climate change by Mirza (1997) indicated that runoff of a drier sub-basin will be more sensitive to climate change compared to a wetter sub-basin. All the studied sub-basins demonstrated an increase in mean annual runoff with an increase in precipitation.

Gosain & Rao (2003) found that total runoff from Mahanadi, Brahmani, Ganga, Godavari and Cauvery basins did not increase with projected increase in precipitation in these river basins. However, the Sabarmati and Luni basins showed a considerable decrease in precipitation and consequent decrease in total runoff, totalling two-thirds of the prevailing runoff. MOEF (2004) has reported water availability of different river basins in India estimated using the Soil and Water Assessment Tool (SWAT) and the outputs of the HadRM2 regional climate model. River basins of Mahi, Pennar, Sabarmati and Tapi are likely to experience constant water scarcity and shortage. River basins of the Cauvery, Ganga, Narmada and Krishna are likely to experience seasonal or regular water-stressed conditions. River basins of the Godavari, Brahmani and Mahanadi are projected to experience water shortages in only a few locations. Bouwer *et al.* (2006) analyzed the relationship between climate, water consumption and changing runoff for the Krishna river basin in India. They found that changes in precipitation due to climate variability alone resulted in very little variation in river runoff, whereas increasing water consumption has caused a persistent decrease in annual river runoff. In spite of the uncertainties about the precise magnitude of future climate change and its possible impacts, measures must be taken to anticipate, prevent or minimize the causes of climate change and mitigate its adverse affects (Mall *et al.* 2006).

There has been no recent study of rainfall trends for the whole country using a long data series of dense networks of stations. No study has been conducted where the trends in rainfall and rainy days have been analyzed for all the river basins of India. Keeping this in view, in the present study changes in rainfall and rainy days have been studied on seasonal and annual scales over 22 river basins distributed across India. The dataset consists of gridded data at $1° \times 1°$ resolution, which was prepared by the India Meteorological Department

(IMD). Such a detailed analysis of rainfall trends over different river basins across India is important for the assessment of climate-induced risks and the pursuit of countermeasures.

STUDY AREA AND DATA USED

Twelve Indian rivers are classified as major rivers (basin catchment areas exceeding 20,000 km^2) whose total catchment area is 2.528 million km^2. Of the major rivers, the Ganga- Brahmaputra-Meghna system is the largest with a catchment area of about 1.1 million km^2. This is more than 43% of the catchment area of all the major rivers in the country and about 34% of the drainage area of the country. The other major rivers with a catchment area of more than 0.1 million km^2 are the Indus, Godavari, Krishna and Mahanadi. Three of these basins, namely Indus, Ganga and Brahmaputra, are snow-fed in summer; the remaining basins are purely monsoon rainfall-dependent. Basins of the Godavari, Krishna and Mahanadi rivers draining to the sea in the east cover 22% of the total drainage area of the country. Seven other medium-sized basins of the Sabarmati, Mahi, Narmada and Tapi rivers flowing west and the Subarnarekha, Brahmani–Baitarani and Cauvery rivers flowing east together cover 15% of the total drainage area of India. The catchment area of medium rivers is about 25×10^4 km^2; with a 1.9×10^4 km^2 catchment area, Subarnarekha is the largest river among the medium rivers in the country. Major river basins of India are shown in Figure 1 and details such as river length, catchment area and average annual water availability are provided in Table 1.

Table 1 | Details of river basins of India (Jain *et al.* 2007)

Serial number (SN)	Subdivision	Length (km)	Catchment area (km^2)	Average annual availability of water (km^3 a^{-1})
1	Ganga	2525 +	861,452 +	525.02
2	Indus	1114 +	321,289 +	73.31
3	Brahmaputra	916 +	194,413 +	537.32
4	Barak & other rivers flowing into Barak (Barak+)	-	41,273	48.36
5	Luni and others west flowing rivers of Kutch and Saurashtra (Luni+)			15.10
6	Sabarmati	371	21,674	3.81
7	Mahi	583	34,842	11.02
8	Narmada	1312	98,796	45.64
9	Tapi	724	65,145	14.88
10	West flowing river from Tapi to Tadri (WFR1)			87.41
11	West flowing river south of Tadri (WFR2)			113.53
12	Brahmani, Baitarni & Subernarekha (BBS)		71,118	41.85
13	Mahanadi	851	141,589	66.88
14	Godavari	1465	312,812	110.54
15	Krishna	1401	258,948	78.12
16	Cauvery	800	81,155	21.36
17	Pennar	597	55,213	6.32
18	East flowing river between Mahanadi and Godavari (EFR1)			22.52
19	East flowing river between Godavari and Krishna (EFR2)			
20	East flowing river between Krishna and Pennar (EFR3)			
21	East flowing river between Pennar and Cauvery (EFR4)			16.46
22	East flowing river south of Cauvery (EFR5)			

Daily gridded rainfall data at 1° × 1° resolution provided by the IMD was used in the analysis. This dataset was prepared based on 1803 stations, having at least 90% data availability for the period 1951–2004 (Rajeevan *et al.* 2005). This period of analysis was chosen on account of data availability. Incidentally, this period also nearly coincides with India's independence (1947) to the latest available good quality data. As per the IMD norms, the raw data was subjected to quality control checks.

The basin map of India was digitized in ILWIS GIS (ITC 2001) and a point map of data points (i.e. grid points) was created. Both these maps are merged in the GIS and the data points falling in different river basins determined. The rainfall for a particular day in a year for a particular basin was prepared as the arithmetic average of rainfall of that day in that year for all the grid points falling in that particular basin. The daily data was used to form the monthly dataset for a particular river basin. A day with 24 hour rainfall of 2.5 mm or more is considered as a rainy day as per the criteria of IMD. To investigate the changes in rainfall for different seasons, a year was divided into four seasons: winter (December–February), pre-monsoon (March–May), monsoon (June–September) and post-monsoon (October–November). Rainfall analysis was carried out for all the seasons as well as for the whole year separately. Note that for this study, the post-monsoon season contains only two months while the monsoon season has four months (Kumar *et al.* 2005; Singh *et al.* 2008a, b). Monthly rainfall series were used to form seasonal and annual series.

Temporal and spatial distribution of rainfall and rainy days

The rainfall characteristics of different river basins are reported in Table 2. Table 2 also indicates higher variability

Table 2 | Statistical properties of basin-wise annual and seasonal rainfall series (CV: coefficient of variation)

SN	Basin	Annual Mean (mm)	CV	Pre-monsoon Mean (mm)	CV	Monsoon Mean (mm)	CV	Post-monsoon Mean (mm)	CV	Winter Mean (mm)	CV
1	Ganga	1051.2	0.13	56.4	0.39	898.3	0.12	57.9	0.66	38.5	0.45
2	Indus	1097.1	0.18	248.3	0.39	538.5	0.33	63.8	0.92	246.5	0.33
3	Brahmaputra	2589.2	0.14	537.9	0.24	1798.4	0.16	175.4	0.39	77.5	0.43
4	Barak +	2171.8	0.15	514.2	0.31	1413.7	0.14	195.4	0.42	48.6	0.75
5	Luni +	397.0	0.35	13.8	1.03	360.8	0.37	16.0	1.33	6.3	0.82
6	Sabarmati	654.5	0.33	9.4	1.51	614.7	0.34	25.8	1.55	4.6	1.79
7	Mahi	1002.6	0.32	7.8	1.73	948.2	0.34	40.9	1.35	5.7	1.94
8	Narmada	1108.7	0.18	22.7	0.73	1006.2	0.19	47.9	0.73	31.9	0.80
9	Tapi	764.6	0.19	17.4	1.06	667.6	0.20	65.7	0.71	13.9	1.20
10	WFR1	2872.0	0.15	65.0	0.90	2641.7	0.15	158.1	0.50	7.2	2.30
11	WFR2	3107.0	0.16	355.6	0.40	2240.4	0.20	454.9	0.30	56.0	0.76
12	BBS	1417.3	0.17	120.3	0.43	1146.7	0.17	111.1	0.69	39.3	0.80
13	Mahanadi	1344.4	0.18	70.2	0.53	1144.2	0.17	99.2	0.66	30.8	0.73
14	Godavari	1106.8	0.16	47.2	0.59	941.4	0.17	96.4	0.53	21.8	0.92
15	Krishna	838.1	0.14	70.0	0.39	619.1	0.17	137.0	0.42	12.0	1.13
16	Cauvery	1031.7	0.17	157.9	0.39	485.4	0.26	304.4	0.36	83.9	0.65
17	Pennar	719.8	0.19	84.0	0.50	384.0	0.27	218.4	0.39	33.4	0.87
18	EFR1	1183.0	0.19	120.6	0.73	786.5	0.16	245.6	0.56	30.3	0.82
19	EFR2	1074.4	0.25	66.4	1.40	699.1	0.32	277.0	0.57	31.9	1.49
20	EFR3	784.3	0.28	86.6	1.00	358.2	0.40	295.1	0.50	44.4	1.27
21	EFR4	1002.4	0.16	98.5	0.56	423.4	0.22	370.0	0.34	110.5	0.80
22	EFR5	973.9	0.15	169.8	0.34	297.5	0.27	376.3	0.30	130.3	0.52

(larger coefficient of variation) of rainfall and rainy days during winter, pre-monsoon and post-monsoon seasons. WFR2 basin receives the maximum mean annual rainfall followed by WFR1 and Brahmaputra, whereas Luni+ and Sabarmati basin receive the minimum mean annual rainfall. Looking at the seasonal rainfall depths, the maximum rainfall in the pre-monsoon season was received over Brahmaputra and Barak+ basins followed by WFR2; in the monsoon season over WFR1 followed by WFR2 and Brahmaputra; in the post-monsoon season over WFR2 followed by EFR5 and EFR4; and in winter season maximum rainfall is received on Indus basin followed by EFR5 and EFR4. It can be seen that there are large temporal variations in rainfall; the coefficient of variation is the largest for arid regions and the smallest for the rivers having a high water yield. It shows that large water management infrastructure is needed for the arid region since it cannot depend on rainfall alone to meet water needs. Further, rivers in the Ganga basin and central peninsular region receive most of the rainfall during the monsoon season only, and these require large infrastructure to regulate their flow. The Indus and rivers in South India receive rainfall in the monsoon as well as winter season. Due to this, temporal variability in their flows is less pronounced. This summary gives a good snapshot of rainfall variability for the country which has important implications for water management as well as to appreciate the impacts of climate change. These are described in the results.

METHODOLOGY

The magnitude of the trend in the seasonal and annual series was determined using Sen's estimator (Sen 1968). The statistical significance of the trend in the time series was analyzed using the Mann–Kendall (MK) test (Mann 1945; Kendall 1975).

Magnitude of trend

The magnitude of trend in a time series was determined using a non-parametric method known as Sen's estimator (Sen 1968). This method assumes a linear trend in the time series and has been widely used for determining the magnitude of trend in hydro-meteorological time series (Lettenmaier *et al.* 1994; Yue & Hashino 2003; Partal & Kahya 2006). In this method, the slopes (T_i) of all data pairs are first calculated by

$$T_i = \frac{x_j - x_k}{j - k} \qquad \text{for i} = 1, 2, \ldots, N \tag{1}$$

where x_j and x_k are data values at time j and k ($j > k$) respectively. The median of these N values of T_i is Sen's estimator of slope which is calculated as

$$\beta = \begin{cases} T_{\frac{N+1}{2}} & \text{if } N \text{ is odd,} \\ \frac{1}{2}\left(T_{\frac{N}{2}} + T_{\frac{N+2}{2}}\right) & \text{if } N \text{ is even.} \end{cases} \tag{2}$$

A positive value of β indicates an upwards (increasing) trend and a negative value indicates a downwards (decreasing) trend in the time series.

Significance of trend

To ascertain the presence of a statistically significant trend in hydrologic climatic variables such as temperature, precipitation and streamflow with reference to climate change, the non-parametric Mann–Kendall (MK) test has been employed by a number of researchers (Yu *et al.* 1993, 2003; Douglas *et al.* 2000; Burn *et al.* 2004; Singh *et al.* 2008a, b). The MK method searches for a trend in a time series without specifying whether the trend is linear or non-linear. The MK test was also applied in the present study. The MK test checks the null hypothesis of no trend versus the alternative hypothesis of the existence of an increasing or decreasing trend. Following Bayazit & Onoz (2007), no pre-whitening of the data series was carried out as the sample size is large ($n \geq 50$) and slope of the trend was high (>0.01).

The statistic S is defined as (Salas 1993):

$$S = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \text{sgn}(x_j - x_i) \tag{3}$$

where N is the number of data points. Assuming $(x_j - x_i) = \theta$, the value of sgn(θ) is computed as follows:

$$\text{sgn}(\theta) = \begin{cases} 1 & \text{if } \theta > 0, \\ 0 & \text{if } \theta = 0, \\ -1 & \text{if } \theta < 0. \end{cases} \quad (4)$$

This statistic represents the number of positive differences minus the number of negative differences for all the differences considered. For large samples ($N > 10$), the test is conducted using a normal distribution (Helsel & Hirsch 1992) with the mean and the variance as follows:

$$E[S] = 0 \quad (5)$$

$$Var(S) = \frac{N(N-1)(2N+5) - \sum_{k=1}^{n} t_k(t_k-1)(2t_k+5)}{18} \quad (6)$$

where n is the number of tied (zero difference between compared values) groups and t_k is the number of data points in the kth tied group. The standard normal deviate (Z-statistics) is then computed as (Hirsch *et al.* 1993):

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

If the computed value of $|Z| > z_{\alpha/2}$, the null hypothesis H_0 is rejected at the α level of significance in a two-sided test. In this analysis, the null hypothesis was tested at 95% confidence level.

RESULTS

All the river basins of India (except EFR5) receive most of the annual rainfall in monsoon season. Basins lying near the east coast of peninsula also receive a large percentage of annual rainfall in the post-monsoon period. The WFR2 river basin experienced the maximum number of annual rainy days and Luni+ experienced the minimum number of annual rainy days.

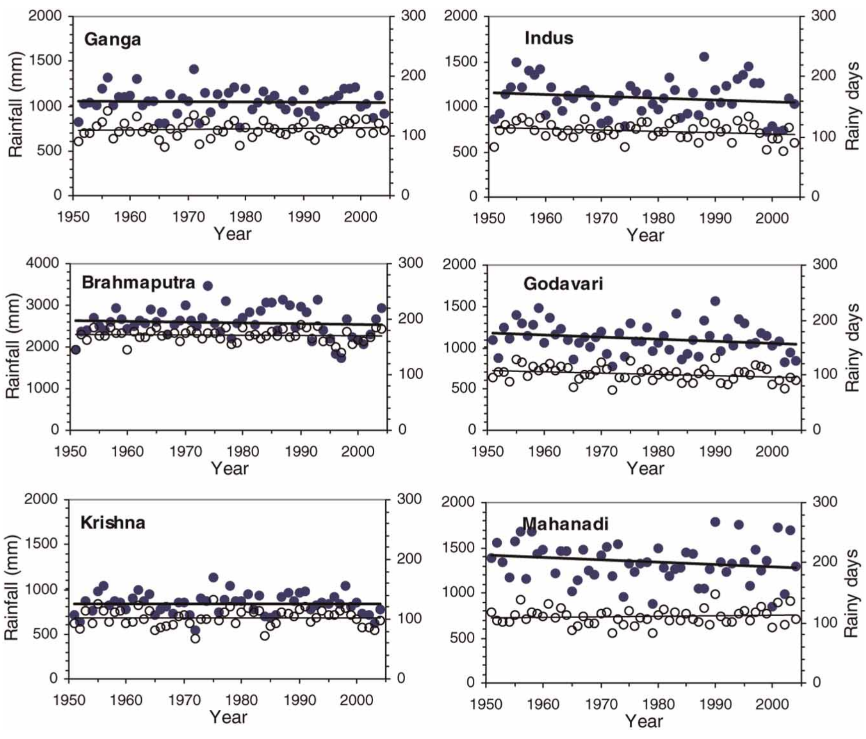

Figure 2 | Temporal variation of annual rainfall and rainy days for some of the major river basins of India. Filled circles represent rainfall and empty circles represent rainy days. Thick and thin black lines are the linear trend line in rainfall and rainy days, respectively. Note the y-axis scale for Brahmaputra River.

Figure 2 shows the temporal variation of annual rainfall and annual rainy days for some of the major river basins. Least-square lines are also drawn in Figure 2 to illustrate a possible linear trend in the rainfall and rainy day data. As seen from this figure, rainfall in the Indus, Brahmaputra, Godavari and Mahanadi basins show a definite decreasing trend whereas in Ganga and Krishna basins, the trend is not visible. Similarly, rainy days indicate a decreasing trend in Indus, Brahmaputra, Godavari basins and an increasing trend in three other river basins. This figure also indicates varying amounts of trend in rainfall and rainy days over different river basins.

Figure 3 shows the spatial distribution of mean annual rainfall and rainy days for different river basins. This figure indicates that the WFR1 river basin receives more annual rainfall than Brahmaputra and Barak+ river basins, but experiences less rainy days. This implies that the intensity of rainfall in WFR1 basins is much larger than that in the Brahmaputra and Barak+ basins. This figure brings out the wide variation of annual rainfall over different river basins of India. Figure 4 shows the monthly mean rainfall at a few of the river basins and highlights the wide variation in monthly rainfall distribution in various river basins.

Rainfall amount

The magnitude of the trend in annual and seasonal rainfall as determined using Sen's estimator is given in Table 3. As expected, trends of rainfall variations show a large variability in the magnitude and direction from basin to basin.

As shown in Table 4, six river basins (namely BBS, Barak +, Cauvery, Pennar, EFR3 and EFR4) have shown an increasing trend in annual rainfall; 15 river basins (Indus, Brahmaputra, Luni +, Sabarmati, Mahi, Narmada, Tapi, Mahanadi, Godavari, Krishna, WFR1, WFR2, EFR1, EFR2 and EFR5) have shown the opposite trend and one river basin (Ganga) has shown no change.

No change in the annual rainfall of the Ganga basin may result from the fact that for this basin, average rainfall has been measured over a very large area (861,452+ km^2) and the positive and negative trends over different sub-basins may have nearly balanced, resulting in no trend for the Ganga basin as a whole. The increase in annual rainfall over the river basins varied between 0.45 mm a^{-1} (for EFR4 river basin) to 4.93 mm a^{-1} (for EFR3 river basin). Similarly, the decrease in annual rainfall is found to be a maximum for WFR1 river basin (–10.16 mm a^{-1}) and a minimum for Krishna river basin (–0.27 mm a^{-1}). All the three river basins (Brahmaputra, WFR1 and WFR2) which receive mean annual rainfall of more than 2500 mm have shown a decreasing trend in annual rainfall.

Seasonal analysis of rainfall trends shows that pre-monsoon rainfall increased over 9 river basins and decreased over 13 river basins; monsoon rainfall increased over 6 river basins and decreased over 16 basins; post-monsoon rainfall increased over 13 river basins and decreased over 8 basins; and winter rainfall increased over 18 river basins

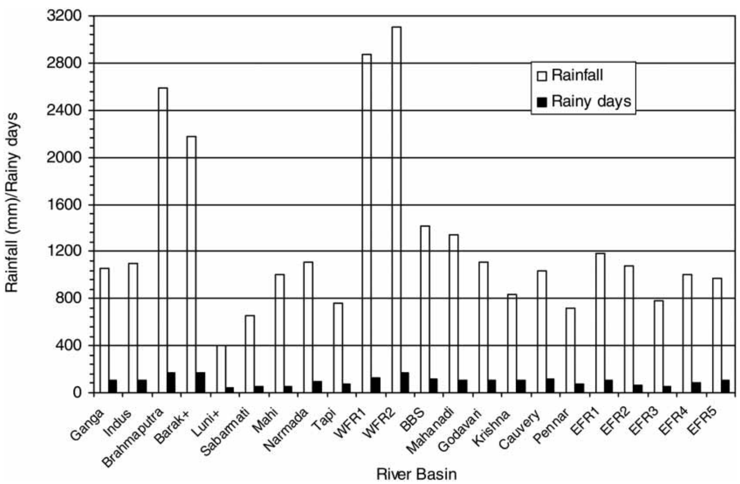

Figure 3 | Mean annual rainfall and rainy days for different river basins of India.

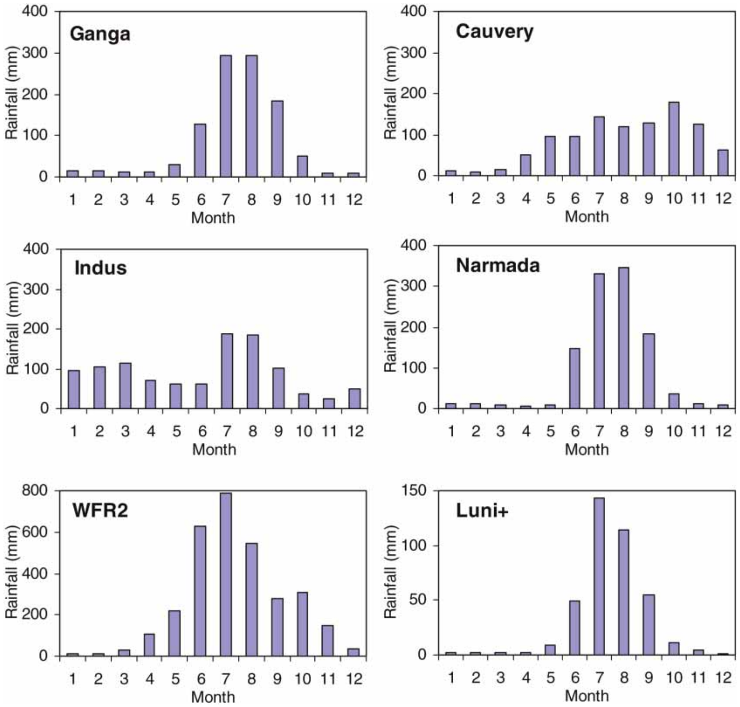

Figure 4 | Mean monthly rainfall at few selected river basins in India.

and decreased over 2 river basins. In the monsoon season, the maximum increase is of the order of 2.58 mm a^{-1} for EFR3 and the maximum decrease is for WFR1 (–8.47 mm a^{-1}) followed by the Indus (–3.16 mm a^{-1}). All the river basins except Ganga, Brahmaputra and EFR4 have shown the same direction of trend for annual and monsoon rainfall, perhaps because the monsoon season is the major contribution of annual rainfall. The Ganga basin, which has shown no change in annual rainfall, has experienced a small decreasing trend in the monsoon and post-monsoon season rainfall. On the basis of seasonal trends of rainfall, overall there appear to be early signs indicating weakening of summer (southwest) monsoon and strengthening of winter (north-east) monsoon.

Trends and magnitude of changes in annual rainfall in terms of the percentage of a mean per 100 years for all the river basins are reported in Table 3 and are depicted in Figure 5. The maximum increase in annual rainfall is of the order of 62.8% of the mean per 100 years for EFR3 and the maximum decrease is of the order of –35.4% of the mean per 100 years for WFR1. The Indus basin experienced the maximum decrease (–58.7%) and EFR3 experienced the maximum increase (71.9%) during the monsoon season. In general, west-flowing river basins seem to show a decreasing trend, while the small east-flowing river basins have an increasing trend (Figure 5).

The results of the Mann–Kendall test applied to annual and seasonal rainfall over different river basins (Table 3) indicates that the majority of river basins show neither an increasing nor decreasing significant trend in seasonal or annual rainfall. Out of the 22 river basins studied, the annual rainfall of only 2 river basins showed a significant trend. EFR4 showed a positive trend whereas WFR1 showed a significant negative trend. Monsoon rainfall indicated a negative significant trend in Indus and WFR1 river basins. Cauvery river basin in the post-monsoon season and two river basins (Krishna and EFR2) in winter season showed a positive significant trend in rainfall. In pre-monsoon season, three river basins (Godavari, Krishna and WFR2) experienced a negative significant trend.

Rainy days

The results of Sen's estimator and the Mann–Kendall test for rainy days for each river basin are given in Table 4 and

Table 3 | Sen's estimator of slope for rainfall (bold values indicate statistical significance at 95% confidence level as per the Mann–Kendall test)

		Annual		Pre-monsoon		Monsoon		Post-monsoon		Winter	
SN	Basin	mm a^{-1}	% of mean/ 100 yr	mm a^{-1}	% of mean/ 100 yr	mm a^{-1}	% of mean/ 100 yr	mm a^{-1}	% of mean/ 100 yr	mm a^{-1}	% of mean/ 100 yr
1	Ganga	0.000	0.0	0.341	60.4	–0.302	–3.4	–0.016	–2.8	0.081	21.0
2	Indus	–1.825	–16.6	0.880	35.4	**–3.160**	**–58.7**	–0.261	–40.9	0.864	35.1
3	Brahmaputra	–0.442	–1.7	–1.935	–36.0	0.570	3.2	–0.057	–3.2	0.146	18.8
4	Barak +	2.662	12.3	1.344	26.1	1.012	7.2	0.191	9.8	0.455	93.6
5	Luni +	–0.597	–15.0	0.109	78.8	–1.039	–28.8	0.028	17.5	0.057	90.3
6	Sabarmati	–0.990	–15.1	–0.006	–6.4	–1.242	–20.2	0.013	5.0	–0.014	–30.2
7	Mahi	–2.183	–21.8	0.003	3.8	–2.153	–22.7	0.000	0.0	0.000	0.0
8	Narmada	–2.409	–21.7	–0.030	–13.2	–2.394	–23.8	0.097	20.2	0.030	9.4
9	Tapi	–1.387	–18.1	–0.073	–42.0	–1.367	–20.5	0.379	57.7	0.000	0.0
10	WFR1	**–10.164**	**–35.4**	–0.318	–48.9	**–8.472**	**–32.1**	–0.515	–32.6	0.002	2.8
11	WFR2	–7.011	–22.6	**–2.482**	**–69.8**	–5.612	–25.0	0.926	20.4	0.050	8.9
12	BBS	2.222	15.7	0.728	60.5	1.026	8.9	–0.583	–52.5	0.056	14.3
13	Mahanadi	–2.905	–21.6	0.172	24.5	–3.130	–27.4	–0.091	–9.2	0.127	41.2
14	Godavari	–2.727	–24.6	**–0.400**	**–84.8**	–2.635	–28.0	0.209	21.7	0.166	76.1
15	Krishna	–0.271	–3.2	**–0.569**	**–81.3**	–0.827	–13.4	0.247	18.0	**0.155**	**129.6**
16	Cauvery	0.879	8.5	–0.563	–35.6	0.075	1.5	**1.748**	**57.4**	0.024	2.9
17	Pennar	1.257	17.5	–0.398	–47.4	1.040	27.1	0.114	5.2	0.023	6.9
18	EFR1	–1.231	–10.4	0.418	34.6	–1.156	–14.7	–1.391	–56.6	0.386	127.3
19	EFR2	–0.442	–4.1	0.525	79.0	–1.722	–24.6	–0.136	–4.9	**0.255**	**80.0**
20	EFR3	**4.928**	**62.8**	–0.630	–72.7	2.575	71.9	1.398	47.4	0.227	51.1
21	EFR4	0.445	4.4	–0.345	–35.0	–0.214	–5.1	0.659	17.8	0.197	17.8
22	EFR5	–0.950	–9.8	–0.800	–47.1	–0.500	–16.8	0.491	13.0	–0.246	–18.9

Figure 6. In the case of annual rainy days, 4 river basins (Ganga, Mahanadi, Krishna and EFR3) have shown an increasing trend, 15 river basins (Indus, Brahmaputra, Luni+, Sabarmati, Mahi, Narmada, Tapi, Barak +, Godavari, WFR1, WFR2, EFR1, EFR2, EFR4 and EFR5) have shown a decreasing trend and 3 river basins (BBS, Cauvery and Pennar) have shown no change in annual rainy days. The decrease in rainy days varies from –0.032 days per year to –0.375 days per year with the maximum decrease experienced by WFR2. The increase in rainy days varies from 0.024 days per year to 0.111 days per year with a maximum increase by Ganga and EFR3. The decreasing trend in Godavari, WFR2 and EFR5 river basins are found statistically significant at 95% confidence level whereas the increasing trends are not found statistically significant for any river basin.

Looking at the seasonal rainy days, 4 river basins each in pre-monsoon (Ganga, Mahanadi, BBS and EFR1), monsoon (Brahmaputra, Krishna, Cauvery and EFR3) and post-monsoon season (Tapi, Cauvery, Pennar and EFR3) and 2 river basins in winter season (Barak+ and EFR1) experienced an increasing number of rainy days. Note that 11 river basins in pre-monsoon, 3 in monsoon, 10 in post-monsoon and 19 river basins in winter have shown no change in rainy days. The river basins which have experienced a decreasing number of rainy days are Brahmaputra, WFR1, WFR2, EFR5, Pennar, EFR3 and EFR4 in pre-monsoon; Indus, Luni +, Sabarmati, Mahi, Narmada, Tapi, BBS, Barak +, Godavari, WFR1, WFR2, EFR1, EFR2, EFR4 and EFR5 in monsoon; Indus, Brahmaputra, BBS, Barak +, Godavari, WFR1, WFR2 and EFR1 in post-monsoon and EFR5 in winter season. In the monsoon season,

Table 4 | Sen's estimator of slope for rainy days

SN	Basin	Annual days per year	% of mean/ 100 yr	Pre–Monsoon days per year	% of mean/ 100 yr	Monsoon days per year	% of mean/ 100 yr	Post–Monsoon days per year	% of mean/ 100 yr	Winter days per year	% of mean/ 100 yr
1	Ganga	0.111	10.0	0.048	90.6	0.000	0.0	0.000	0.0	0.000	0.0
2	Indus	–0.182	–16.6	0.000	0.0	–0.167	–28.4	–0.045	–84.1	0.000	0.0
3	Brahmaputra	–0.064	–3.8	–0.025	–5.5	0.095	9.3	–0.061	–45.6	0.000	0.0
4	Barak +	–0.200	–11.8	0.000	0.0	–0.111	–10.4	–0.053	–35.6	0.042	84.6
5	Luni +	–0.104	–25.6	0.000	0.0	–0.125	–33.9	0.000	0.0	0.000	0.0
6	Sabarmati	–0.200	–40.3	0.000	0.0	–0.231	–50.3	0.000	0.0	0.000	0.0
7	Mahi	–0.138	–26.7	0.000	0.0	–0.139	–29.1	0.000	0.0	0.000	0.0
8	Narmada	–0.114	–12.2	0.000	0.0	–0.067	–8.2	0.000	0.0	0.000	0.0
9	Tapi	–0.167	–23.5	0.000	0.0	–0.139	–22.6	0.030	48.9	0.000	0.0
10	WFR1	–0.176	–13.8	–0.020	–29.5	–0.079	–7.5	**–0.111**	**–72.9**	0.000	0.0
11	WFR2	**–0.375**	**–21.5**	**–0.152**	**–48.8**	**–0.176**	**–17.1**	–0.032	–9.4	0.000	0.0
12	BBS	0.000	0.0	0.045	30.8	–0.034	–3.9	–0.079	–76.9	0.000	0.0
13	Mahanadi	0.053	4.8	0.029	37.4	0.000	0.0	0.000	0.0	0.000	0.0
14	Godavari	**–0.276**	**–26.9**	0.000	0.0	**–0.200**	**–23.5**	–0.031	–28.8	0.000	0.0
15	Krishna	0.024	2.3	0.000	0.0	0.026	3.4	0.000	0.0	0.000	0.0
16	Cauvery	0.000	0.0	0.000	0.0	0.028	5.1	0.050	17.2	0.000	0.0
17	Pennar	0.000	0.0	–0.027	–29.6	0.000	0.0	0.047	24.0	0.000	0.0
18	EFR1	–0.190	–17.6	0.053	41.5	–0.167	–22.3	–0.091	–53.7	0.034	98.7
19	EFR2	–0.044	–6.9	0.000	0.0	–0.125	–28.4	0.000	0.0	0.000	0.0
20	EFR3	0.111	22.5	–0.031	–65.6	0.070	26.0	0.038	25.3	0.000	0.0
21	EFR4	–0.032	–3.6	–0.032	–29.9	–0.047	–11.1	0.000	0.0	0.000	0.0
22	EFR5	**–0.333**	**–32.3**	**–0.143**	**–69.3**	–0.125	–34.1	0.000	0.0	–0.032	–26.7

a maximum increase in the number of rainy days is experienced within the Brahmaputra basin (0.095 days per year) whereas a maximum decrease is experienced within the Sabarmati basin (–0.231 days per year). The trend in the 2 river basins (WFR2 and EFR5) are found statistically significant at 95% level in pre-monsoon season and are significant at 2 river basins (Godavari, WFR2) in monsoon, 1 river basin (WFR1) in post-monsoon and no river basin experienced a statistical significant trend in the winter season.

DISCUSSION

Tables 3 and 4 and Figure 7 indicate that the direction of trend in rainfall and rainy days is similar for most river basins. For annual data, Mahanadi and Krishna have experienced a decreasing trend in annual rainfall and an increasing trend in rainy days, which means that droughts may become more recurrent in Krishna (which is a water-stressed basin). Barak+ and EFR4 have experienced increasing rainfall and decreasing rainy days, which implies that floods may become more intense in these basins. All the trends are non-significant and the magnitude of trend is small for Krishna and EFR4 river basin. Similarly, in the monsoon season, Barak+ and BBS (+ve trend in rainfall and –ve in rainy days) and Krishna (–ve trend in rainfall and +ve trend in rainy days) have experienced the opposite trend in rainfall and rainy days. Similar to annual data, these trends are non-significant.

Rainfall trends for different river basins (Figures 5 and 6) show that the neighbouring basins may frequently have opposite trends and, in some cases, these basins are

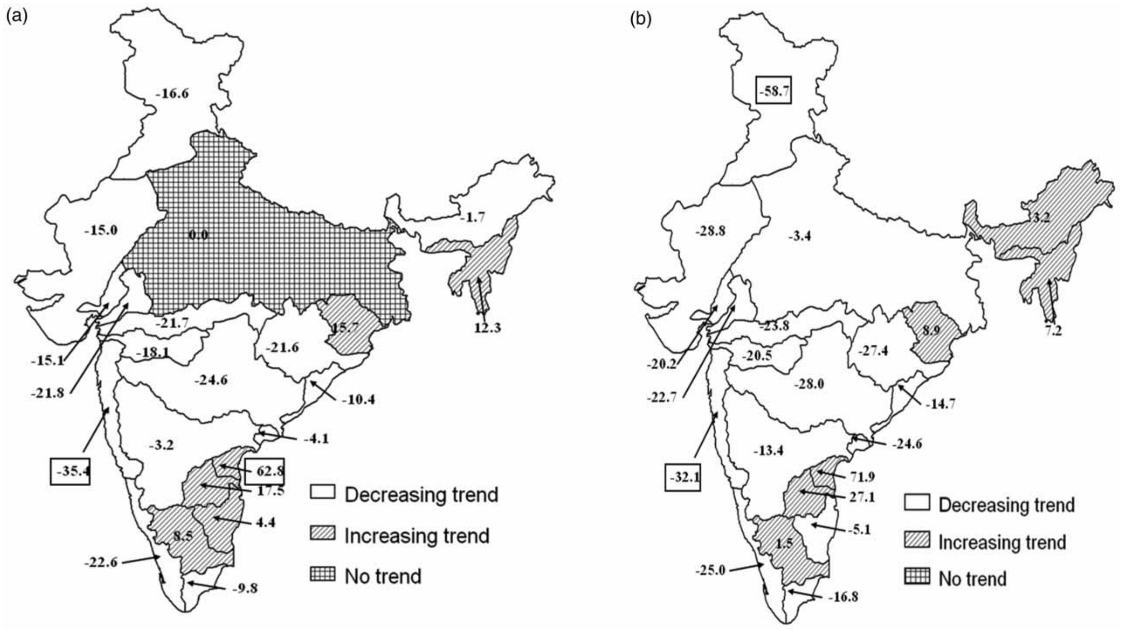

Figure 5 | (a) Trends and magnitude of changes in annual rainfall (% of mean/100 years) for different river basins in India. Significant trends are displayed in boxes. (b) Trends and magnitude of changes in monsoon rainfall (% of mean/100 years) for different river basins in India. Significant trends are displayed in boxes.

separated by ridges having low elevations. While analyzing flood data for detecting trends, Svensson *et al.* (2006) had noted that 'regional and global studies of trend analysis of high flows generally do not exhibit convincing and spatially coherent patterns of increases in flood magnitude … there may be several different reasons why trends in long-term records are … not displaying spatial coherence'.

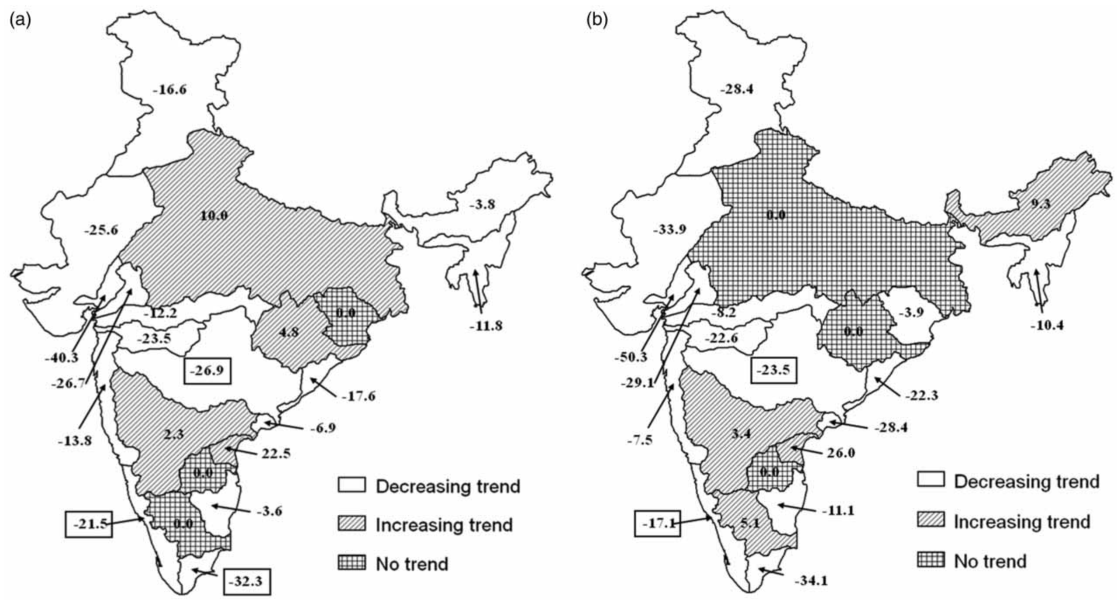

Figure 6 | (a) Trends and magnitude of changes in annual rainy days (% of mean/100 years) for different river basins in India. Significant trends are displayed in boxes. (b) Trends and magnitude of changes in monsoon rainy days (% of mean/100 years) for different river basins in India. Significant trends are displayed in boxes.

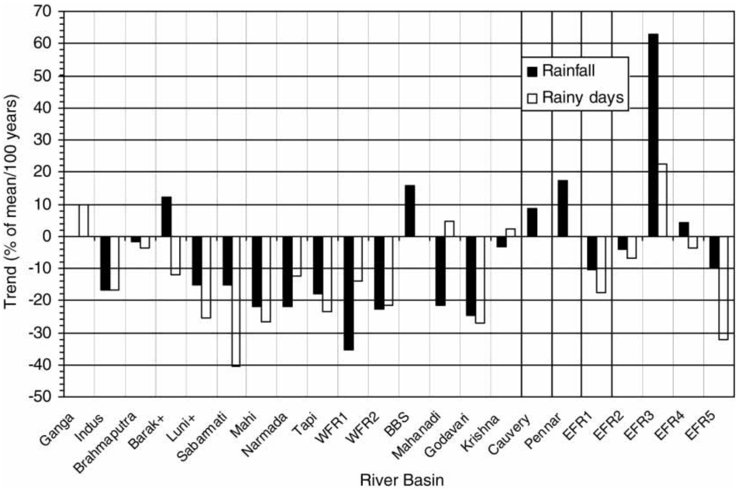

Figure 7 | Magnitude of changes in annual rainfall and rainy days (% of mean/100 years) for different river basins in India.

The observed trends in rainfall series are in conformity with the future projections made by Rajendran & Kitoh (2008) for some regions and are in disagreement for some regions. Similar is the case when the results of this study are compared with projections made sometime ago by Rupa Kumar *et al.* (2006).

There are different views in hydrologic literature about consideration of correlation while detecting trends in long hydro-climatic data series (Douglas *et al.* 2000; Bayazit & Onoz 2007). Cohn & Lins (2005) noted that the presence of long-term persistence (LTP) in a stochastic process can induce a significant trend result when no trend is present, if an inappropriate trend test is used. They also pointed out that 'statistical significance, sometimes cited to bolster scientific and political argument, is less certain because significance depends critically on the null hypothesis which in turn reflects subjective notions about what one expects to see … Trend tests which fail to consider LTP greatly overstate the statistical significance of observed trends when LTP is present. … from a practical standpoint, however, it may be preferable to acknowledge that the concept of statistical significance is meaningless when discussing poorly understood systems'.

Climate change is likely to impact all facets of life. Decreasing rainfall, as expected, will result in decreased water availability (Gosain *et al.* 2006). For India, the impacts on agriculture will be crucial. Based on experimentation at New Delhi, Aggarwal (2007) has reported that a 1°C rise in temperature throughout the growing period will reduce the wheat production by 5 million tons. Kalra *et al.* (2008) found that the yield of wheat, mustard, barley and chickpea show sign of stagnation or decrease following a rise in temperature in four northern states of India. Of course, the extent of decrease was different for crops as well as their locations. Bandyopadhyay *et al.* (2009) found a significant decreasing trend in grass reference evapo-transpiration all over India during 1971–2002.

A recent newspaper article (*The Tribune*, www.tribuneindia.com, 3 December 2009) reported 'Noted agricultural scientist M. S. Swaminathan says that an increase of 2 °C temperature is likely to decrease per ha yield of wheat by 0.45 MT and rice by 0.7 MT in India due to the shortening of crop life and certain physiological changes in plants. According to his estimates, just a 0.5 °C rise in temperature could reduce the yield of wheat by 10 per cent in states like Punjab, Haryana and Uttar Pradesh'. In view of such concerns, it will be important and timely to start adaptation and mitigation measures.

CONCLUSIONS

An understanding of the spatial and temporal distribution and changing patterns in rainfall is a basic and important requirement for the planning and management of water resources. The present study has examined trends in seasonal and annual rainfall and rainy days on the river basin scale for the period 1951–2004. Expectedly, the river basin rainfall trends show a large variability. Six river basins have experienced an increasing trend in annual rainfall in the range of 0.27 to 10.16 mm a^{-1} while 15 river basins have experienced decreasing annual rainfall in the range of 0.45 to 4.93 mm a^{-1}. Similarly, 4 river basins have shown an increasing trend in rainy days and 15 river basins have shown the opposite trend. The maximum increase was 0.11 day per year and the maximum decrease was 0.38 day per year.

Seasonal analysis shows that in the pre-monsoon season, rainfall has increased over 9 river basins and rainy days increased in 4 river basins; in monsoon season, rainfall increased over 6 river basins and rainy days in 4 river basins; in post-monsoon season, rainfall increased over 13 river basins and rainy days on 4 river basins; and in winter season, rainfall increased over 18 river basins and rainy days increased over 2 river basins. Rainfall decreased over 13 river basins in pre-monsoon season, over 16 basins in monsoon, over 8 basins in post-monsoon; and 2 river basins in winter season. Some of these are major and water-deficit river basins. The majority of river basins in pre-monsoon, post-monsoon and winter season have shown no change in rainy days.

A significance test showed that the majority of river basins show neither an increasing nor decreasing significant trend in seasonal rainfall and rainy days. The annual rainfall had a negative significant trend in the WFR1 river basin and an increasing significant trend only in EFR4 whereas annual rainy days have shown a significant decreasing trend in Godavari, WFR2 and EFR5 river basins. Thus the analysis of rainfall data for the period 1951–2004 does not indicate that the rainfall over the country is significantly changing. Absence of significant change in the number of rainy days shows that, at present, there is no indication of any major change in rainfall intensities.

While interpreting the results of trend analysis, recall the observations of Cohn & Lins (2005): 'that reported trends are real yet insignificant indicates a worrisome possibility: natural climatic excursions may be much larger than we imagine. So large, perhaps, that they render insignificant the changes, human-induced or otherwise, observed during the past century'.

ACKNOWLEDGEMENTS

The authors would like to convey their sincere thanks to two anonymous reviewers for their thoughtful and critical comments which have helped to significantly improve the quality of the paper.

REFERENCES

Aggarwal, P. K. 2007 Climate change: implications for Indian agriculture. *Hydrology Review* **22**, 37–46.

Bandyopadhyay, A., Bhadra, A., Raghuwanshi, N.S. & Singh, R. 2009 Temporal trends in estimates of reference evapotranspiration over India. *J. Hydrol. Eng. (ASCE)* **14**, 508–515.

Bayazit, M. & Onoz, B. 2007 To prewhiten or not to prewhiten in trend analysis? *Hydrol. Sci. J.* **52**, 611–624.

Bouwer, L. M., Aerts, J. C., Droogers, P. & Dolman, A. J. 2006 Detecting the long-term impacts from climate variability and increasing water consumption on runoff in the Krishna river basin, India. *Hydrol. Earth Syst. Sci.* **10**, 703–713.

Burn, D. H., Cunderlik, J. M. & Pietroniro, A. 2004 Hydrological trends and variability in the Liard river basin. *Hydrol. Sci. J.* **49**, 53–67.

Cohn, T. A. & Lins, H. F. 2005 Nature's style: naturally trendy. *Geophys. Res. Lett.*, **32**, L23402.

Dash, S. K., Jenamani, R. K., Kalsi, S. R. & Panda, S. K. 2007 Some evidence of climate change in twentieth-century India. *Climatic Change* **85**, 299–321.

De, U. S. 2001 Climate change impact: Regional scenario, *Mausam* **51**, 201–212.

Douglas, E. M., Vogel, R. M. & Knoll, C. N. 2000 Trends in flood and low flows in the United States: impact of spatial correlation. *J. Hydrol.* **240**, 90–105.

Gosain, A. K. & Rao, S. 2003 *Climate Change and India: Vulnerability Assessment and Adaptation* (ed. P. R. Shukla *et al.*), Universities Press (India) Pvt Ltd, Hyderabad p. 462.

Gosain, A. K., Rao, S. & Basuray, D. 2006 Climate change impact assessment on hydrology of Indian river basins. *Current Science* **90**, 346–353.

Goswami, B. N., Venugopal, V., Sengupta, D., Madhusoodanam, M. S. & Xavier, P. K. 2006 Increasing trends of extreme rain events over India in a warming environment. *Science* **314**, 1442–1445.

Helsel, D. R. & Hirsch, R. M. 1992 *Statistical Methods in Water Resources.* Elsevier, New York.

Hirsch, R. M., Helsel, D. R., Cohn, T. A. & Gilroy, E. J. 1993 Statistical treatment of hydrologic data. In: *Handbook of Hydrology*. (ed. D. R. Maidment), McGraw-Hill, New York, pp. 17.1–17.52.

IMD 2006, 2007 *Southwest Monsoon – end of season report for 2006 & 2007*. Published by India Meteorological Department, New Delhi (www.imd.ernet.in).

IPCC 2007 Summary for Policymakers. In: *Climate Change 2007: The Physical Science Basis* (ed. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, H. L. Miller). Cambridge University Press, UK.

ITC 2001 *ILWIS 3.0 Academic, User's Guide*. ILWIS Department, ITC, Enschede, The Netherlands.

Jain, S. K., Agarwal, P. K. & Singh, V. P. 2007 *Hydrology and Water Resources of India*. Springer, The Netherlands.

Kalra, N., Chakraborty, D., Sharma, A., Rai, H. K., Jolly, M., Chander, S., Kumar, P. R., Bhadraray, S., Barman, D., Mittal, R. B., Lal, M. & Sehgal, M. 2008 Effect of increasing temperature on yield of some winter crops in northwest India. *Current Science* **94**(1), 82–88.

Kendall, M. G. 1975 *Rank Correlation Methods*. Charles Griffin, London, UK.

Khan, T. M. A., Singh, O. P. & Sazedur Rahman, M. D. 2000 Recent sea level and sea surface temperature trends along the Bangladesh coast in relation to the frequency of intense cyclones. *Marine Geodesy* **23**, 103–116.

Kumar, V., Singh, P. & Jain, S. K. 2005 Rainfall trends over Himachal Pradesh, Western Himalaya, India. *Proceedings of 'Development of Hydro Power Projects – A Prospective Challenge', Shimla 20–22 April 2005*, (ed. G. N. Mathur, A. S. Chawla & R. L. Chauhan), Central Board of Irrigation and Power, and Himachal Pradesh State Electricity Board.

Kundzewicz, Z. W., Mata, L. J., Arnell, N. W., Döll, P., Jimenez, B., Miller, K., Oki, T., Şen, Z. & Shiklomanov, I. 2008 The implications of projected climate change for freshwater resources and their management. *Hydrol. Sci. J.* **53** (1), 3–10.

Lal, M. 2001 Climatic change: Implications for India's water resources. *J. Indian Water Resour. Soc.* **21**, 101–119.

Lal, M. 2003 Global climate change: India's monsoon and its variability. *J. Environ. Stud. Policy* **6**, 1–34.

Lettenmaier, D. P., Wood, E. F. & Wallis, J. R. 1994 Hydro-climatological trends in the continental United States 1948–88. *J. Climate* **7**, 586–607.

Mall, R. K., Gupta, A., Singh, R., Singh, R. S. & Rathore, L. S. 2006 Water resources and climate change: An Indian perspective. *Current Science* **90**, 1610–1626.

Mann, H. B. 1945 Nonparametric tests against trend. *Econometrica* **13**, 245–259.

Mehrotra, R. 1999 Sensitivity of runoff, soil moisture and reservoir design to climate change in central indian river basins. *Climatic Change* **42**, 725–757.

Min, S. K., Kwon, W. T., Park, E. H. & Choi, Y. 2003 Spatial and temporal comparisons of droughts over Korea with East Asia. *Int. J. Climatol.* **23**, 223–233.

Ministry of Environment and Forest (MOEF) 2004 *India's initial national communication to the United Nations framework convention on climate change*. Executive Summary, MOEF, New Delhi.

Mirza, M. Q. 1997 The runoff sensitivity of the Ganges river basin to climate change and its implications. *J. Environ. Hydrol.* **1**, 1–13.

Mirza, M. Q. 2002 Global warming and changes in the probability of occurrence of floods in Bangladesh and implications. *Global Environ. Chang* **12**, 127–138.

Mirza, M. Q., Warrick, R. A., Ericksen, N. J. & Kenny, G. J. 1998 Trends and persistence in precipitation in Ganges, Brahmaputra and Meghna river basins. *Hydrol. Sci. J.* **43**, 845–858.

Mooley, D.A. & Parthasarthy, B. 1984 Fluctuations of all India summer monsoon rainfall during 1871–1978. *Climatic Change* **6**, 287–301.

Mujumdar, P. P. & Ghosh, S. 2008 Modeling GCM and scenario uncertainty using a possibilistic approach: application to the Mahanadi River, India. *Water Resour. Res.* **44**, W06407. DOI: 10.1029/2007WR006137.

Partal, T. & Kahya, E. 2006 Trend analysis in Turkish precipitation data. *Hydrol. Process.* **20**, 2011–2026.

Rajeevan, M., Bhate, J., Kale, J. D. & Lal, B. 2005 Development of high resolution daily gridded rainfall data for the Indian region, India Meteorological Department. *Meteorol. Monograph Climatol.* **22**, 1–26.

Rajendran, K. & Kitoh, A. 2008 Indian summer monsoon in future climate projection by a super high-resolution global model. *Current Science* **95,** 1560–1569.

Ranade, A., Singh, N., Singh, H. N. & Sontakke, N. A. 2008 On variability of hydrological wet season, seasonal rainfall and rainwater potential of the river basins of India (1813–2006). *J. of Hydrological Research and Development* **23**, 79–108.

Rupa Kumar, K. & Ashrit, R. G. 2001 Regional aspects of global climate change simulations: validation and assessment of climate response of the Indian monsoon region to transient increase of greenhouse gases and sulphate aerosols. *Mausam* **52**, 229–244.

Rupa Kumar, K., Pant, G.B., Parthasarathy, B. & Sontakke, N. A. 1992 Spatial and sub seasonal patterns of the long term trends of Indian summer monsoon rainfall. *Int. J. Climatology* **12**, 257–268.

Rupa Kumar, K., Sahai, A. K., Kumar, K. K., Patwardhan, S. K., Mishra, P. K., Revadekar, J. V., Kamala, K. & Pant, G. B. 2006 High-resolution climate change scenarios for India for the 21st century. *Current Science* **90**, 334–345.

Salas, J. D. 1993 Analysis and modeling of hydrologic time series. In: *Handbook of Hydrology*. (ed. D. R. Maidment), McGraw-Hill, New York, pp. 19.1–19.72.

Sarker, R. P. & Thapliyal, V. 1988 Climate change and variability. *Mausam* **39**, 127–138.

Sen, P. K. 1968 Estimates of the regression coefficient based on Kendall's tau. *J. Am. Stat. Assoc.* **63**, 1379–1389.

Shrestha, A. B., Wake, C. P., Dibb, J. E. & Mayewski, P. A. 2000 Precipitation fluctuations in the Nepal Himalaya and its vicinity and relationship with some large scale climatological parameters. *Int. J. Climatol.* **20**, 317–327.

Singh, N., Sontakke, N. A., Singh, H. N. & Pandey, A. K. 2005 *Recent trend in spatiotemporal variation of rainfall over India-an investigation into basin-scale rainfall fluctuations*. IAHS Publication No. 296. pp. 273–282.

Singh, P. & Kumar, N. 1997 Impact assessment of climate change on the hydrological response of a snow and glacier melt runoff dominated Himalayan river. *J. Hydrol.* **193**, 316–350.

Singh, P., Arora, M. & Goel, N. K. 2006 Effect of climate change on runoff of a glacierized Himalayan basin. *Hydrol. Process.* **20**, 1979–1992.

Singh, P., Kumar, V., Thomas, T. & Arora, M. 2008a Changes in rainfall and relative humidity in different river basins in the northwest and central India. *Hydrol. Process.* **22**, 2982–2992.

Singh, P., Kumar, V., Thomas, T. & Arora, M. 2008b Basin-wide assessment of temperature trends in the north-west and central India. *Hydrol. Sci. J.* **53** (2), 421–433.

Sinha Ray, K. C. & Srivastava, A. K. 1999 *Is there any change in extreme events like droughts and heavy rainfall?* INTROPMET-97, IIT New Delhi, 2–5 December.

Sinha Ray, K. C. & De, U. S. 2003 Climate change in India as evidenced from instrumental records. *WMO Bulletin* **52**, 53–58.

Srivastava, H. N., Sinha Ray, K. C., Dikshit, S. K. & Mukhopadhaya, R. K. 1998 Trends in rainfall and radiation over India. *Vayu Mandal* **28**, 41–45.

Svensson, C., Hannaford, J., Kundzewicz, Z. W. & Marsh, T. J. 2006 Trends in river floods: why is there no clear signal in observations? *Frontiers in Flood Research*, IAHS Publication No. 305. pp. 1–18.

Thapliyal, V. & Kulshreshtha, S. M. 1991 Climate changes and trends over India. *Mausam* **42**, 333–338.

Yu, Y. S., Zou, S. & Whittemore, D. 1993 Non-parametric trend analysis of water quality data of rivers in Kansas. *J. Hydrol.* **150**, 61–80.

Yue, S. & Hashino, M. 2003 Temperature trends in Japan: 1900–1990. *Theor. Appl. Climatol.* **75**, 15–27.

Yue, S., Pilon, P. & Phinney, B. 2003 Canadian streamflow trend detection: impacts of serial and cross-correlation. *Hydrol. Sci. J.* **48**, 51–63.

First received 1 June 2009; accepted in revised form 20 April 2010