Trends in rainfall and peak flows for some river basins in India

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The aim of the present study is to examine the trends in magnitude and intensity of precipitation and peak floods of different magnitudes for seven major river basins in India. Data pertaining to daily flows for about 30-odd years and precipitation for 61 years (from 1951 to 2012) were analysed. Linear trends were calculated for the number of rainy days, rainfall intensity and occurrence of flood peaks for all basins. Using the Sen's slope estimator, it was found that annual peak rainfall increases for most of the basins in India. From the Mann–Kendall test and Sen's slope, it was found that the Cauvery and Brahamani and Baitarani basins show a rising trend in the number of rainy days, but the trend was falling for five other basins. When the basins were classified as mountains and plains, it was found that the number of daily rainfall events of different magnitudes was more in the mountains compared to the plains. The rivers which flow from west to east direction have more rainy days compared to those which flow towards the west. It was observed that in general the number of rainy days was falling while the number of intense events was increasing. The number of flood peaks of smaller magnitude in different decades showed slight falling trend. It was also found that there was falling or no trend for severe floods. Anthropogenic activities (construction of storage reservoirs, diversions, urbanization, land-use change, and soil and water conservation measures, etc.) have probably affected the generation of peak floods in the rivers of India. River regulation through storage reservoirs in the past 50 years has resulted in the reduction of peak flows. Hence with the same rainfall, the flood peaks would have increased under virgin conditions.

Keywords: Flood peaks, rainfall trends, river basins.

PRECIPITATION is a key component of the earth's hydrologic cycle, but it is also one of the most difficult hydrometeorological variables to measure and model accurately. Precipitation at a place is determined by large-scale as well as local processes, and therefore exhibits pronounced variability in a range of spatial and temporal scales. Among the climate variables, precipitation is the most important process for the water sector. It is a variable that drives the key natural resource process in a river basin. Therefore, it is most widely analysed in climate change impact studies.

Run-off from a river basin is the integrated outcome of climatic inputs and basin topography, land use/cover, and water management infrastructure. Therefore, a change in the precipitation and other relevant climatic variables, land use/land cover, and water utilization leads to a change in water yield from a catchment and its temporal distribution. It was found that river flow has strong natural variability and exhibits long-term persistence[1,2]. This behaviour can confound the results of trend and significance tests.

Global warming is unequivocal and is expected to be reflected in an increase in the magnitude and frequency of extreme precipitation events[2]. Due to their extensive and pervasive impacts on almost all aspects of environment and society, climate and its variability have drawn increasing attention of the scientific community, decision-makers and common people in recent years.

India is a vast country with geographical complexities and variabilities. In tandem with these, the climate of the country also has large spatial and temporal variations. The summer monsoon accounts for more than 80% of the annual rainfall and primarily regulates the hydrology of the Indian subcontinent. A small change in the monsoon rainfall can have profound economic and environmental impacts, since a large population in India depends on agriculture and allied sectors that are climate-dependent. Frequent occurrence of climatic extremes in recent years has given rise to questions and concerns on whether the characteristics of hydroclimatic variables are changing or not.

Thus it is pertinent to identify and deliberate on the changes in key hydroclimatic variables that will help in judicious management of water resources in India. Therefore, the objectives of this study are: (1) to analyse trend in annual rainfall, number of rainy days and rainfall intensity in some major Indian River basins, and (2) to study changes in flood peaks of different ranges in these river basins over the past several decades. The results of the analysis will improve our understanding of the risks under the changing environment in the selected Indian River basins.

Literature review – rainfall trends in India

A number of studies have been reported to detect trends in the rainfall in India and at and regional scales. Most of

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these studies have analysed annual and seasonal rainfalls for some specific stations or groups of stations. Some workers[2–4] studied changes in rainfall over India and found no substantial trend in average annual rainfall over the country. No clear trend was observed while analysing the long period monsoon rainfall data particularly on all India scale. Some studies identified pockets of significant long-term rainfall changes[2,5,6].

Ramesh and Goswami[7] analysed daily gridded observed rainfall data for the period 1951–2003 and found that the number of rainy days showed a decreasing trend. Analysis of seasonal rainfall showed a decreasing trend in the monsoon season over India and increasing tendency during the pre- and post-monsoon months. Dash *et al.*[5] and Kumar *et al.*[4] did not find any significant trend in annual, seasonal and monthly rainfall. Interestingly, they observed decrease in annual and monsoon rainfall, and an increase in pre-monsoon, post-monsoon and winter rainfall over the years, on trend analysis using rainfall data for the country for 135 years (1871–2005); however, maximum increase in rainfall was observed during the pre-monsoon period. Decrease in rainfall during the monsoon months (June–September) was observed, while there was an increasing trend in August on all-India basis. Moreover, while analysing rainfall of 30 sub-divisions, half of them were found to have increasing trend in annual rainfall, but the trend was statistically significant for only three sub-divisions, namely Haryana, Punjab and coastal Karnataka. Decreasing trend in annual rainfall was observed in 15 sub-divisions, while Chhattisgarh sub-division had significant decreasing trend.

India Meteorological Department (IMD) has divided the whole country into meteorological sub-divisions. IMD often processes climatic data according to these sub-divisions. Analysis from the long rainfall series[2,8,9] of 1476 rain-gauge stations for the period 1901–2003 revealed that there was significant decreasing trend during the monsoon period for three sub-meteorological divisions (Chhattisgarh, Jharkhand and Kerala), and significant increasing trend for eight sub-divisions (Jammu and Kashmir, west Uttar Pradesh, Gangetic West Bengal, Rayalseema, Madhya Maharashtra, Coastal Andhra Pradesh, Konkan and Goa, and north interior Karnataka). Subash *et al.*[10] reported that five meteorological sub-divisions from Central North East (NE) India showed significant decreasing trend for annual, seasonal and monthly precipitation data. The decreasing trend rate found to be 4.6 mm/year for Jharkhand and 3.2 mm/day for Central NE India during the period 1889–2008. A significant decreasing trend in rainfall for December in the recent past has been observed for all the meteorological sub-divisions of India, except Jharkhand. Pal and Al-Tabbaa[11] found decreasing trends during spring and monsoon periods and increasing trends during autumn and winter periods over India while analysing the rainfall data for 1954–2003.

Several studies in the past have analysed the trend and magnitude of rainfall on a basin-scale in India. Singh *et al.*[12] analysed the data of 316 rain-gauge stations and found that annual rainfall over many Central Indian basins (e.g. Sabarmati, Mahi, Narmada, Tapi, Godavari and Mahanadi) showed decreasing trend since the 1960s, while the main North Indian basins (Indus, Ganga and Brahmaputra), and Krishna and Cauvery basins showed an increasing trend. Ranade *et al.*[13] found no trend in onset and offset dates, duration and total rainfall of the wet season over different river basins of India. Singh *et al.*[12] have studied rainfall changes in nine basins of northwest and Central India over the last century. They estimated the rate of change of rainfall at each of the 43 stations by the slope of trend line. Increasing trends have been found in annual rainfall in the range 2–19% of the mean/100 years over eight river basins. Kumar and Jain[6] estimated trends in annual and seasonal rainfall and number of rainy days using daily rainfall data at 1° × 1° grids produced by IMD. They reported increasing trend in annual rainfall over 6 river basins, while 15 basins showed decreasing trend, but majority of the basins were found to show no trend (including Ganga basin). Analysis of annual rainy days revealed that 4, 15 and 3 river basins showed increasing, decreasing and no trend respectively. Godavari basin and some small rivers near the east and west coasts of peninsular India showed significant decreasing trend at 95% confidence level in annual rainy days.

Kumar and Jain[6] analysed seasonal rainfall trends over the Indian river basins. There was increasing trend in monsoon rainfall over 6 basins and decreasing trend over 16 basins. Similarly during post-monsoon period rainfall over 13 and 8 basins showed increasing and decreasing trends respectively. From the analysis of seasonal rainy days, increasing trend was observed in four, four, four and two river basins in pre-monsoon, monsoon, post-monsoon and winter season respectively. No change in the number of rainy days was observed for 11 river basins in pre-monsoon, 3 in monsoon, 10 in post-monsoon and 19 in winter season.

The SREX report[2] mentions the likelihood that the number of intense rainfall events has increased (statistically significant) in more areas than it has decreased. Further, it has been reported that there are no adequate studies to reinforce and impute variation in severe rainfall on seasonal or regional scale, though there are significant variations in trends in regional and sub-regional levels due to climate change. With regard to the ascription of observed changes in severe precipitation assessed in the SREX report, there is medium confidence about the anthropogenic effect on the intensification of extreme precipitation on the global scale. As stated before, the precipitation data show impacts of anthropogenic climate change which impact riverine floods. However, a substantial statistical connection between climate change due to anthropogenic causes and trends in the magnitude and frequency of floods could not be confirmed.

Studies of extreme rainfall trends in India

Many studies have reported that there is increase in frequency of intense rainfall events, but the total annual precipitation and the number of rainy days have decreased in many parts of Asia[5,14–19]. Increase in extreme rainfall events may have led to severe floods and landslides.

Sen Roy and Balling[20] analysed daily rainfall data for 1910–2000 at nearly 130 stations, and found that there was mostly increasing trend in a contiguous region over the northwestern Himalaya in Kashmir through most of the Deccan Plateau in the south and a decreasing trend in the eastern part of the Gangetic Plain. Joshi and Rajeevan[21] examined extreme precipitation indices for the period 1901–2000 for 100 stations in India and reported that most of the extreme precipitation indices for the southwest monsoon season and annual period showed significant increasing trend over the west coast and northwestern parts of the Peninsula. Using a 1951–2003 gridded daily rainfall dataset for India, Krishnamurthy *et al.*[22] reported that the frequency of extreme precipitation over many parts of India exhibited a decreasing trend.

Goswami *et al.*[19] suggested that the increase in maximum monsoon daily rainfall may be attributed to gradual increase in sea surface temperature (SST) in the tropical Pacific. They have reported that in spite of considerable year-to-year variability, there are significant increases in the frequency and the intensity of extreme monsoon rain events in central India over the past 50 years and the observed trends suggest enhanced risks associated with extreme rainfall over India in the coming decades. The findings of Ghosh *et al.*[23,24] were similar to those of Goswami *et al.*[19].

Lacombe and McCartney[25] found changes in rainfall pattern aligning with the geography of anthropogenic atmospheric disturbances and confirmed the paramount role of global warming in recent changes for daily gridded rainfall data (1951–2007). On analysing gridded rainfall data of 0.5° × 0.5° resolution for 1901–2012, Taxak *et al.*[26] reported an increasing trend in Wainganga river basin in Central India during 1901–1948, which was reversed during 1949–2012 resulting in decreasing rainfall trend.

Observed changes in high flows in rivers

Most rivers of the world are no longer in their natural state. Dams and diversions have resulted in large-scale changes in river flows and water use. Many dams are designed and operated to reduce flooding. These coupled with river engineering works have altered exceedance probability of flows of a given return period for many rivers. Extreme precipitation and flood events have been carefully investigated in many scientific studies in the past decade[2,27–30], because these have large impacts on the society and economies of the nations.

It has been reported that there is no substantial evidence of climate-related changes in the magnitude or frequency of floods in the United States and Canada during the 20th century and early 21st century[31–35]. Several studies dealing with climate-driven changes for rivers in Europe covering countries like Germany, Swiss Alps, France, Spain and the United Kingdom have been reported in the literature[36–39], but no trends have been found in flood magnitude and frequency on continental scale. Jiang *et al.*[40] found increasing trend in annual maximum floods in the lower Yangtze River for the 40 years of data studied. Analysis of the Mekong River showed that an average flood most likely decreased though there was an increase in the likelihood of extreme floods during the second half of the 20th century[41]. Bhutiyani *et al.*[42,43] reported increasing/decreasing trends over the last 40 years in four river basins of the northwestern Himalaya.

The Paraguay river basin, Amazon region South America, showed an increase in flood frequency[44,45]. Marengo *et al.*[46] reported that maximum flooding was recorded during 2009, while analysing 106 years of data for the Rio Negro at the Manaus gauge site. Di Baldassarre *et al.*[47] reported that African river basins have relatively less changes due to anthropogenic impacts and hence they provide an opportunity to study impacts of climate on floods that is not possible for other continents. However, they could not detect any significant trend in the magnitude of floods for African rivers during the 20th century.

Milly *et al.*[27,28] studied the changes in risk of great floods (those with discharge exceeding 100 years levels) for basins larger than 200,000 sq. km and found that the frequency of extreme floods had increased considerably during the 20th century. According to the authors, consequence of a statistically significant increasing trend in risk of extreme floods is an index indicating that the trend will continue. Milly *et al.*[27,28] used an ensemble of 12 climate models and found regional patterns of 20th century multi-decadal changes in discharge. These models projected 10–40% increase in run-off in eastern equatorial Africa, the La Plata basin and high-latitude North America and Eurasia, and 10–30% decrease in run-off in southern Europe, the Middle East, southern Africa, and mid-western North America by the year 2050.

Postel *et al.*[48] noted that if there is a change in intensity and reliability of the monsoon due to impact of climate change, it will affect both high and low flows. Immerzeel *et al.*[49] found that Brahmaputra is sensitive to reductions of flow. Discharge-weighted ensemble modelling was carried out by Gain *et al.*[50] using the outputs from a global hydrological model which was forced with 12 different global climate models (GCMs). They reported that extremely low flow conditions are likely to occur less frequently in the future, but predicted strong increase in peak flows.

Wu and Huang[51] studied changes in extreme rainfall and floods, and the causes of flood risk changes in the Beijiang basin, China, by analysing daily stream flow, peak flow and precipitation data of 1969–2011. Annual peak flows for this period showed no obvious trends, but large flood events have tended to become more frequent and intense in the past two decades. Devkota and Gyawali[52] used the Soil and Water Assessment Tool (SWAT) model to assess changes in the hydrological regime of the Koshi River basin due to climate change. They found that climate change does not pose a major threat to average water availability, but it is expected that temporal flow variations will increase in the future.

The above discussion on climate change impact on water resources indicates that there is no significant and considerable evidence of climate-driven observed changes in the magnitude or frequency of floods at the global scale level based on historical records. Therefore, there is skepticism regarding the variation and change in magnitude and frequency of the flood events. This is due to the availability of historical records of floods at the gauging stations being limited in space and time.

Possible causes for changes in flood behaviour

Many studies have reported that there were limited investigations on projected flood changes in rivers, especially at regional or continental scale when the IPCC Assessment Report 4 (AR4) was published. However, Kundzewicz *et al.*[1] and Bates *et al.*[53] have reported that due to occurrence of more frequent extreme rainfall events over most of the regions, the risk of rain-generated floods would be impacted. Further, effect of human-induced climate change in some variables that impact high flows, such as average and high precipitation was found[54]. However, we have not come across any statistical relation between anthropogenic climate change and its impact on the magnitude and occurrence of floods.

There are very few studies which have evaluated projected changes in floods on regional- or continental-scale. Employing daily river flow estimated from RCM or GCM yields and hydrological models, a few studies for Europe[55,56] and for the world[57] have found large-scale variations in frequency and/or magnitude of floods in the 21st century. Hirabayashi *et al.*[57] found that the frequency of floods in many regions of the world, except in North America and central and western Eurasia has increased.

In many places with cold climate including the Himalaya, seasonal snow storage and melt play an important role in annual run-off. As expected, the flow regime of rivers in such regions is impacted by changes in temperature. With increasing temperature, solid fraction of precipitation becomes smaller[57], which melts earlier in spring. Consequently, peak flow in the river takes place earlier. Projections of floods at global scale were prepared by Dankers *et al.*[58] and Hirabayashi *et al.*[57], using a number of GCMs from CMIP5. Outputs of GCMs were coupled with global hydrology and land surface models. Results showed flood hazards to be increasing over about half of the land area of the earth, but variability at the catchment scale was large. Schneider *et al.*[59] evaluated the impact of climate change on river flow regimes in Europe and found that on the European scale, climate change can be expected to significantly modify flow regimes, especially in the Mediterranean and boreal climate zone. Strongest impacts on flow timing for both high and low flows were found for the boreal climate zone. Flow magnitudes are likely to be predominantly altered in the Mediterranean and the Northern climates.

The literature has limited studies dealing with the influence of anthropogenic climate change on peak flows because the required data are not widely available. Although climate change has impacted processes such as precipitation and snowmelt that impact river flows, including peaks, there are no definite conclusions regarding the resultant changes in the magnitude and frequency of floods. Kundzewicz *et al.*[1] observed that in spite of the fact that extreme precipitation-based signals have been found and these have possible link to changes in flood patterns, so far no evidence (based on measured data) could be detected showing a climate-driven, globally widespread change in the magnitude and/or frequency of floods during the last decades.

Data used

In this study, data of selected major river basins in India were analysed. These river basins are: Krishna, Godavari, Mahanadi, Narmada, Cauvery, Sabarmati, and Brahamani and Baitarani, IMD has prepared gridded rainfall data for the country for the years 1951–2011 at grid size of $1° \times 1°$. From the IMD database, data pertaining to

Table 1. Daily discharge data used in the present study

River basin	Gauging station	Years of data
Baitarani	Anandpur	1972–2012
Brahamani	Jenapur	1979–2012
Cauvery	Musiri	1971–2012
Godavari	Polavaram	1965–2011
Krishna	Vijayawada	1965–2012
Mahanadi	Tikapara	1971–2010
Narmada	Garudeshwar	1972–2013
Sabarmati	Vautha	1999–2013

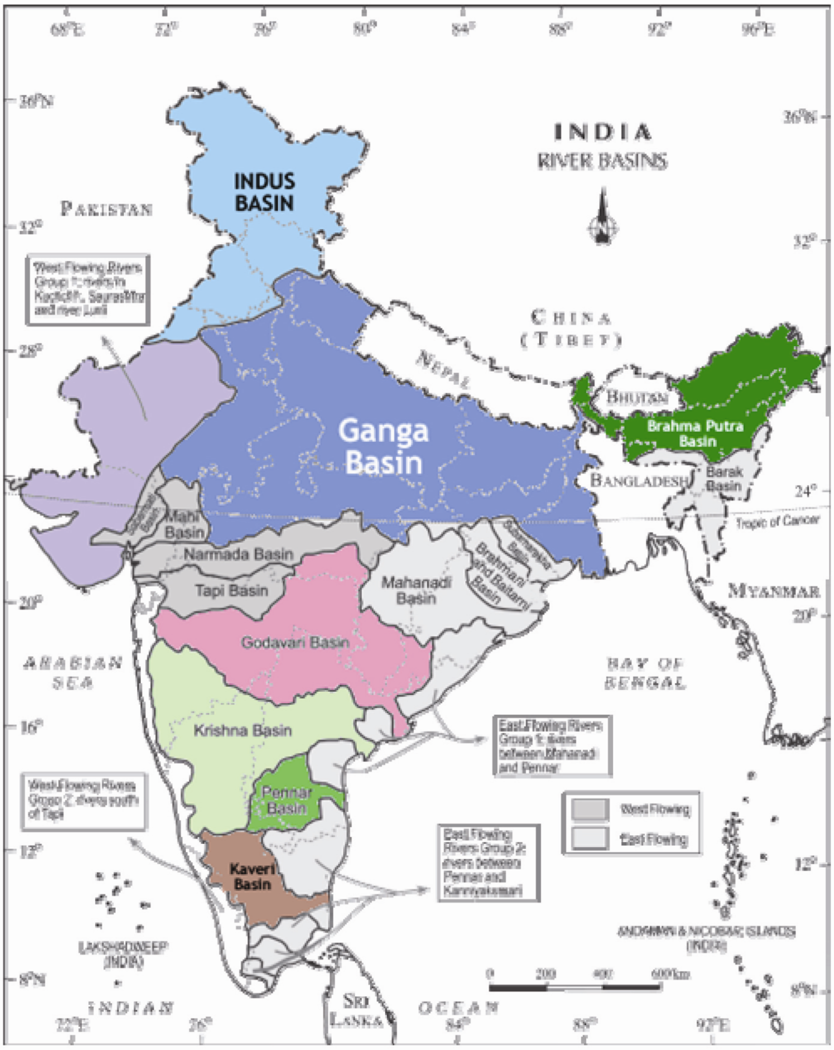

Figure 1. Map showing major river basins in India.

different basins were extracted. These were used to determine the daily average rainfall, yearly average rainfall and basin average rainfall for different years. In the present study, the term ‘rainy day’ has been used to denote a day on which a station has recorded rainfall of 0.1 mm or more. The term ‘rainfall intensity’ of a particular magnitude indicates that the 24-h rainfall has exceeded that amount. This assumption has been made since only daily data were available.

We have used the observed discharge data of gauging sites which are close to the mouths of the rivers. Daily discharge data were downloaded from the India-WRIS website (http://www.india-wris.gov.in/). Table 1 provides the details of discharge data used in the study and Figure 1 shows a map of the major basins. It may be seen that the series and around the years between 2010 and 2013, but the beginning years have a large range. We have not used the data of rivers of North India in this study because discharge data of these rivers (e.g. Indus, Ganga, and Brahmaputra) are classified. In the present study, Brahamani and Baitarani basins have been combined for computing average rainfall (since these are two small basins lying close to each other), but were treated separately for analysis of high flows. In addition, we also compiled data about the major storage projects completed in various river basins along with the year of completion and storage capacity. Using this, change in cumulative storage capacity with time was determined. Cumulative storage capacity can be considered to be a proxy of flood moderation in the upstream catchment which will impact the observed high flows.

Analysis and discussion

We discuss here the results of analysis of rainfall and discharge data for the period 1951–2012. For India, the first half of 1951–2012 was the period when there was small emission of carbon dioxide and other greenhouse gases due to industrial, energy and transport sectors. With growth of population and economic activities, the pace of LULC changes in the catchments and GHG emissions began to increase during the second half of this period.

Trend in average annual rainfall and annual peak rainfall

Average annual rainfall for the river basins was computed using gridded data and time-series plots were prepared. Figure 2 shows the time series of average annual rainfall for the Cauvery, Godavari, Krishna, Mahanadi, Narmada and Sabarmati river basins. Average rainfall for the different basins has also been plotted in the figure. In the present study, Mann–Kendall (MK) sign test and Sen's slope have been used to check the trend and slope available in the rainfall time-series data. Taylor and Loftis[60], and Burn *et al.*[61], have applied the non-parametric MK test to identify the trends in climatic variables. Details of the MK test are widely available in the literature and are not discussed here.

Results of trend analysis and inspection of plots (Figure 2) for average annual rainfall show that there is no significant trend at 95% confidence level for the period 1951–2012 for all basins. In this figure, the basin average rainfall (firm horizontal line) and linear trend plots (dotted line) are mostly overlapping. This indicates that there is no appreciable trend in average annual rainfall in most of the studied basins. In the time series that show a linear trend, the true slope (change per unit time) can be estimated by following a simple non-parametric procedure developed by Sen[62]. This involves computing slopes for all the pairs of points and the median of these slopes is used as an estimate of the overall slope. Sen's slope is insensitive to outliers and can be used to detect the trend in the data. The Brahamani and Baitarani, and Cauvery basins had high positive Sen's slope values for the study period (Table 2).

Trend analysis was also conducted for annual peak rainfall series representing maximum annual rainfall for seven basins in India. Using the MK sign test, positive trend was found for Cauvery and Narmada basins, but the trend was not significant at 95% confidence level. It is to be noted that *P*-value (probability) in the MK test is $<\pm 1.96$ for all basins, which indicates that there is no significant change in trend at 95% confidence level. From Table 2, it is seen that Sen's slope is positive (increasing) for most of the basins, except Brahamani and Baitarani basins. Though the slope is negative for these basins, it is not significant (the slope value is very close to zero). From this analysis, it can be concluded that there is no significant trend in average annual rainfall data, but Sen's slope exhibits small increasing value in annual peak rainfall for the studied river basins in India.

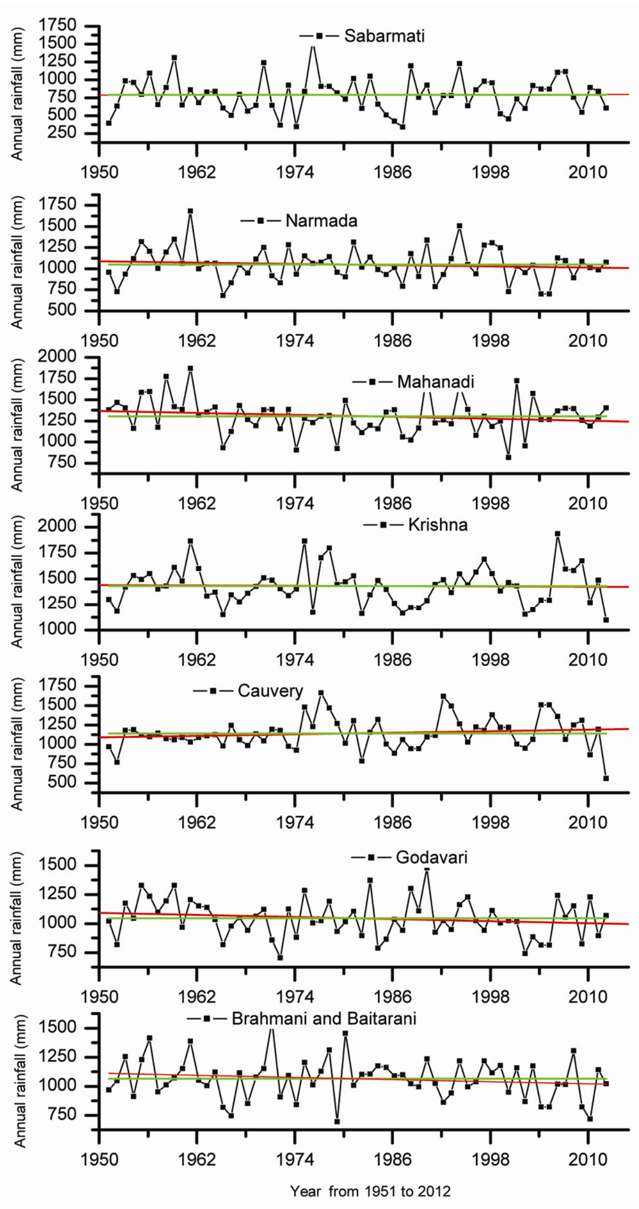

Figure 2. Trend in average annual rainfall for different river basins in India (trend- red line, basin average- yellow line).

Number of rainy days and rainfall of different intensities

From the rainfall data, the number of rainy days for each basin was determined. In order to check the variation of rainfall events, the number of rainy days was calculated. It can be observed from Figure 3 that the number of rainy days for most of the basins is decreasing over the years. In order to find the trend in number of rainy days, MK sign test was used and the results are presented in Table 3. From the sign test it is observed that Cauvery basin

Table 2. Trend in average annual rainfall and annual peak rainfall

River basin	Average annual rainfall			Annual peak rainfall		
	Sen's slope	*H*-value (MK)	*P*-value (MK)	Sen's slope	*H*-value (MK)	*P*-value (MK)
Brahamani and Baitarani	3.1425	0	0.1304	–0.0904	0	0.5782
Cauvery	1.7933	0	0.3013	0.3949	1	0.0001
Godavari	–1.7086	0	0.0654	0.1019	0	0.0834
Krishna	0.0115	0	0.9615	0.0346	0	0.4925
Mahanadi	–1.8259	0	0.2043	0.0929	0	0.2963
Narmada	–0.9217	0	0.4405	0.1542	1	0.0207
Sabarmati	0.1301	0	0.9661	0.2331	0	0.1642

Table 3. Maximum and minimum numbers and trends during rainy days for the river basins under study

River basin	Maximum (days)	Minimum (days)	River flow direction	Sen's slope	*H*-value (MK)	*P*-value (MK)	Rising/ falling (MK)
Brahamani and Baitarani	129	66	West to east	–1.1234	0	0.325	Falling
Cauvery	257	145	West to east	0.216	1	0.0477	Rising
Godavari	283	196	West to east	–0.333	1	0.0069	Falling
Krishna	307	229	West to east	–0.114	0	0.281	Falling
Narmada	212	136	East to West	–0.375	1	0.0038	Falling
Mahanadi	257	174	West to east	–0.219	0	0.0824	Falling
Sabarmati	134	71	East to West	–0.206	1	0.0577	Falling

MK, Mann–Kendall.

shows increasing trend in the number of rainy days, but falling trend is seen for the other basins. The results of Sen's slope test are similar to those of the MK test.

Table 3 presents the maximum and minimum number of rainy days for different basins. It can also be noted from Table 3 that the rivers which flow from west to east have more rainy days compared to those which flow towards the west. A possible reason is that the downstream parts of the rivers which flow into the ocean at the east coast receive rainfall during summer as well winter monsoon and hence more number of rainy days. It can also be noted that the Sabarmati basin lies in the arid part of India and has the lowest number of rainy days. Krishna basin has the highest number of rainy days among the basins studied. In this basin, the headwater zone receives very high rainfall (of the order of 4000–5000 mm/year), middle part receives less rainfall (about 400–600 mm/year) and the downstream part receives moderate rainfall (about 1000–1200 mm/year).

The number of rainfall events greater than different magnitudes (20, 30, 40 and 50 mm/day) was also determined from the data for different basins (Figures 4–10). For the Sabarmati and Cauvery basins (Figures 4 and 8), rainfall of all magnitudes is found to increase; the rise is more for the events of intensity of 50 mm/day or more. It is also seen that the Krishna basin has the highest number of intense rainfall events followed by Godavari, Cauvery, Mahanadi, Brahamani and Baitarani, Narmada and Sabarmati basins. In most of the basins, events having rainfall intensity of 50 mm/day or more were found to be increasing over the years, except for the Krishna basin (Figure 7). This basin has faced only one event of rainfall intensity more than 50 mm/day and that too in recent years. Cauvery basin (Figure 8) shows the sharpest rise in the number of rainy days. It may be noted that lowest number of intense rainfall events is experienced over Krishna basin and the highest number of intense rainfall (>20 mm) events is experienced over Mahanadi basin. Slope of linear trend for different intensities of rainfall over Godavari basin shows mild increase over the years, but not substantial compared to other basins. It is evident from the most of the plots that intense rainy days are increasing. Similarly, as the number of rainy days is decreasing, longer dry spells may prevail during crop growth. As a result, there may be decline in crop production in these basins.

Spatial variation of rainfall during concurrent period

In the present study, precipitation data of 61 years and flow data of 30 years were analysed. The trends of rainfall and flow data during the concurrent period (1971–2012) were also analysed. In the previous section, basin average rainfall used to detect trends in the number of rainy days, magnitude of different daily rainfall events and annual peak rainfall for seven major river basins in India. Precipitation often varies significantly over space and time, even within a basin. To compare precipitation variation within the basins, the areas of some basin were divided in head reaches and plain regions based on ground elevation. As discussed earlier, MK test and Sen's slope were used to detect trend in the mountain reaches and plain regions of the basins during the concurrent period.

The MK sign test could not detect any trend in the number of rainy days, average annual rainfall and annual peak rainfall in the mountain reaches and plain regions of the basins during the concurrent period. However, most of the basins showed negative slope in the number of rainy days using Sen's slope analysis. It was also found

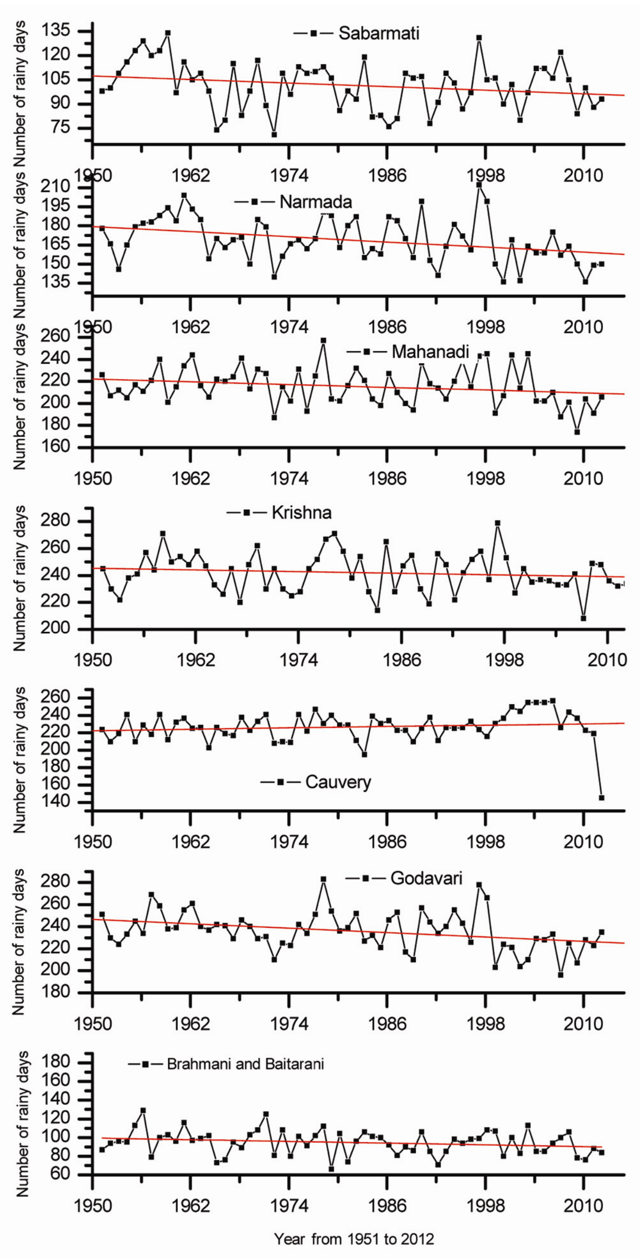

Figure 3. Number of rainy days for different years for the different river basins in India.

that average annual rainfall increased in the head reaches as well as plain regions of the basins, except in Cauvery basin, as evidenced by very high positive slope (using Sen's slope). It is interesting to note that peak annual rainfall decreases in the upstream areas of the basin, whereas plain areas of the basins shows an increase in peak annual rainfall, perhaps due to cyclonic events.

The magnitudes of daily rainfall were found to differ in different parts of the basins during the concurrent period. The number of events of different magnitudes of daily rainfall is more in the head reaches and plain regions of the basins, compared to the entire basins. Figure 11 shows that only a few events of daily rainfall of 50 mm or more are observed over Mahanadi basin, but spatial precipitation analysis shows that the number of events is quite large in the head reaches and at mouth of the basin. Similar results have been obtained for other basins.

From the analysis, it is observed that number of rainy days is very less when the average rainfall over the entire basin is considered, compared to the situation in which average rainfall over different regions (head reaches and

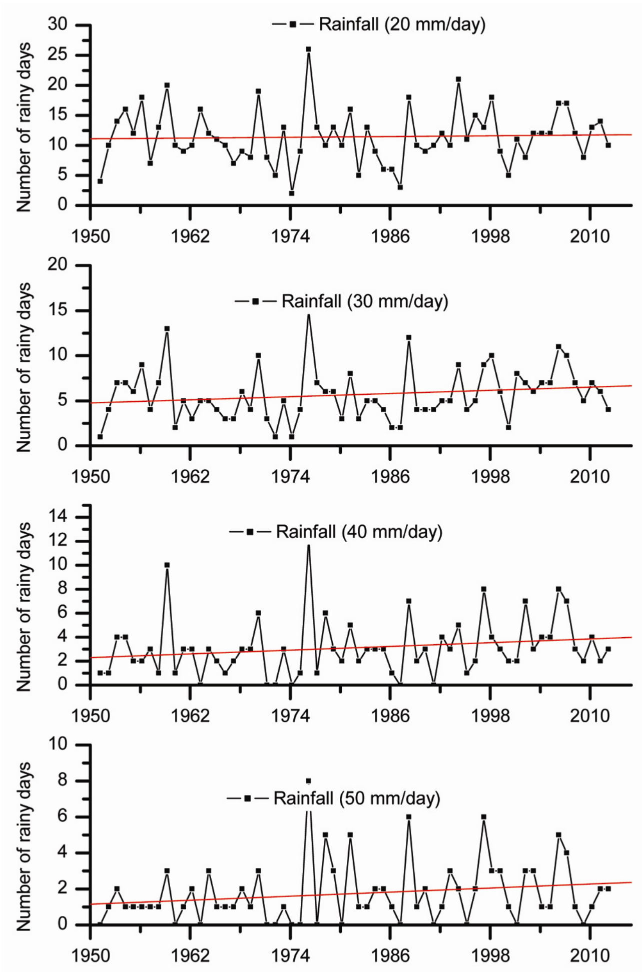

Figure 4. Number of rainy days having rainfall intensity of 20, 30, 40 and 50 mm/day or more for Sabarmati Basin.

plain regions) of the basins is considered. It may be noted that the number of rainfall grids ranges from 20 to 45 over different basins. When rainfall of small magnitude is divided by a large number of grids in many instances the average rainfall over the basin is less than 0.1 mm. Therefore, the number of rainy days is less compared to the analysis for the different regions. Similar observations are also found in the number of high-magnitude rainfall events. A comparison has been made between head reaches and plain regions in estimating events of high magnitude of rainfall. It is noteworthy to mention that the number of events is more in the plain-region compared to head reaches of the basins. There is minimum increase of 28% (year 1979) in 50 mm rainfall events in the Mahanadi basin and maximum increase of 236% during the period 2001 in the Cauvery basin.

Trends in high flows

The most common cause of floods in large river basins is intense and long-duration rainfall. A flood event is frequently characterized by its peak and duration. Peak flow of a flood event largely determines inundation and damage caused, and is the most important feature of a flood event. Discharge of a river at the outlet of a catchment is considered as the thumbprint of the catchment since it represents the integrated effect of all governing factors. In particular, the observed discharge at a site is greatly impacted by upstream storage and diversion. Hence, before studying the trends in discharge data, the observed data series should be naturalized to remove the impacts of upstream interventions. However, this would require information about each structure such as the location, year when the operation was commenced, the operation policy, and working tables. In India, most of this information is kept at the project offices and is not readily available at a centralized location. Further, for many projects, an operation policy has not been developed. Even for the projects where such a policy has been developed, it may not be rigorously followed. Computation of virgin flows during the monsoon season requires observed flows and working tables at (multi)hourly

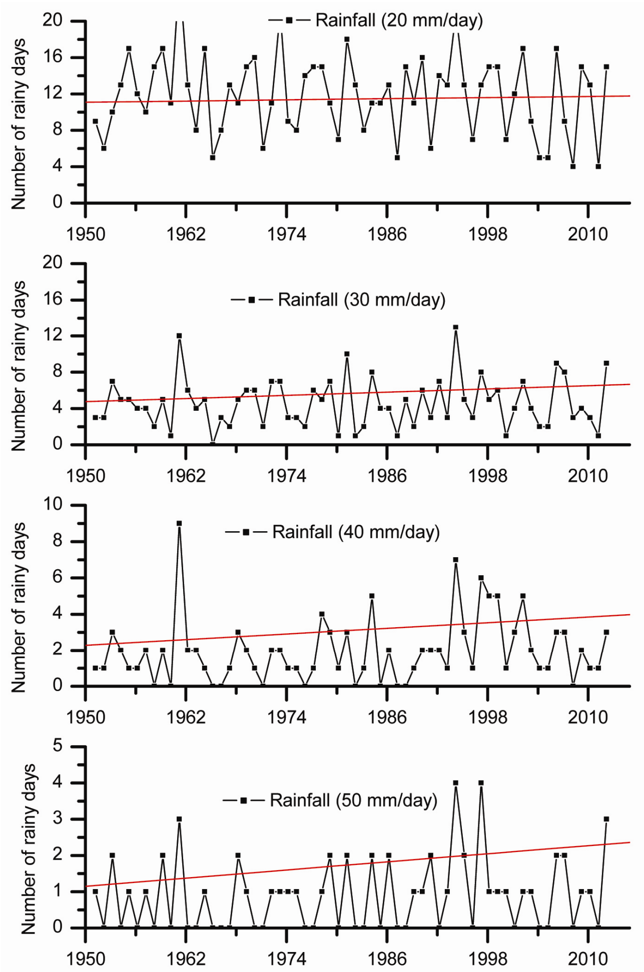

Figure 5. Number of rainy days having rainfall intensity of 20, 30, 40 and 50 mm/day or more for Narmada Basin.

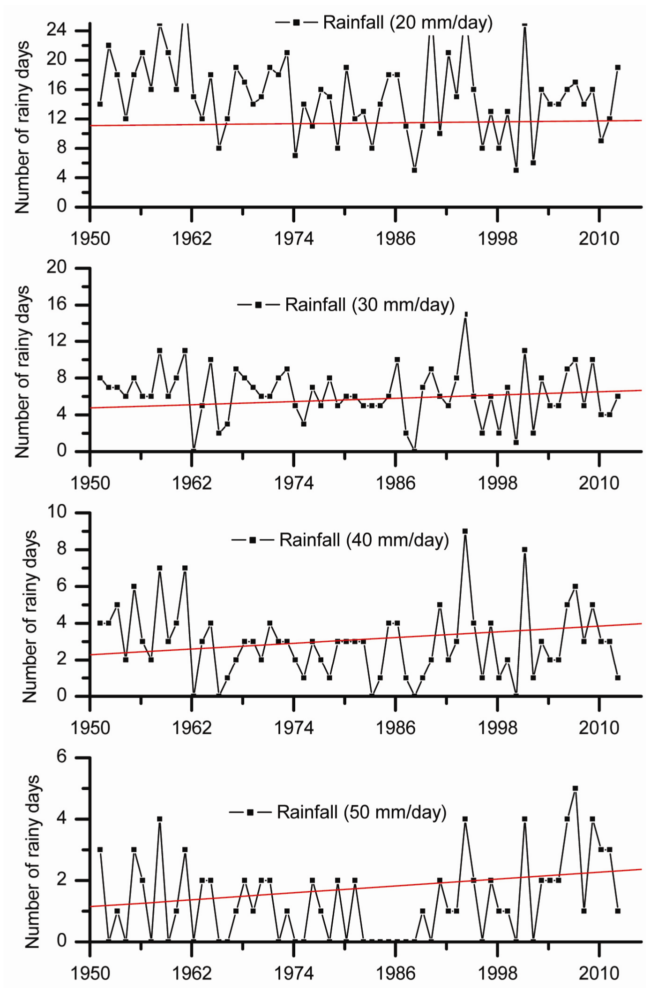

Figure 6. Number of rainy days having rainfall intensity of 20, 30, 40 and 50 mm/day or more for Mahanadi Basin.

time interval and these data are available at very few locations. In view of these constraints, it is difficult to compute virgin flows for large basins where a number of projects which have been constructed and have become operational at different times. We also note that the impact of storages on peak flows will progressively reduce as the peak of inflow hydrograph increases.

Keeping in view the objective of this study and the limitations highlighted earlier, we did not attempt to obtain short-term virgin flows for the various basins. Clearly, this is a limitation of the present study. However, we also believe that the inferences derived from observed data will not materially change the outcome of the analysis, particularly as we progressively focus on higher magnitude floods. Table 4 shows the mean annual flow, live storage capacity created and major storage projects in the river basins studied. Figure 12 represents plots showing the number of flood events of different magnitudes for various rivers in India.

In this study, we categorized the observed high flows into different ranges keeping in view the magnitude of flow for a basin. To understand the changes in the behaviour of flood peaks, we counted the number of flood peaks in different ranges of magnitude for different decades. Data were plotted showing the number of times floods of different magnitudes have occurred in different decadal periods. The results are summarized in Table 5.

In the Cauvery basin in peninsular India, several medium-sized storage projects were developed during 1930s and 1950s and a few projects in 1970s. Live storage capacity in the basin is about 41% of mean annual flow (MAF). Plots of the number of flood peaks of different magnitudes show that events of peaks 2000–4000 cumec had falling and rising trend, but peaks in the range 4000–8000 cumec did not show any discernible trend.

The Godavari basin in peninsular India occupies an area of more than 0.3 million sq. km. Several medium sized storage projects were developed in the basin during 1980s and 1990s, but there is no major storage development after 2001. Live storage capacity in the basin is about 38% of MAF. Plots of flood peaks of different magnitudes show that events with peak discharge in the

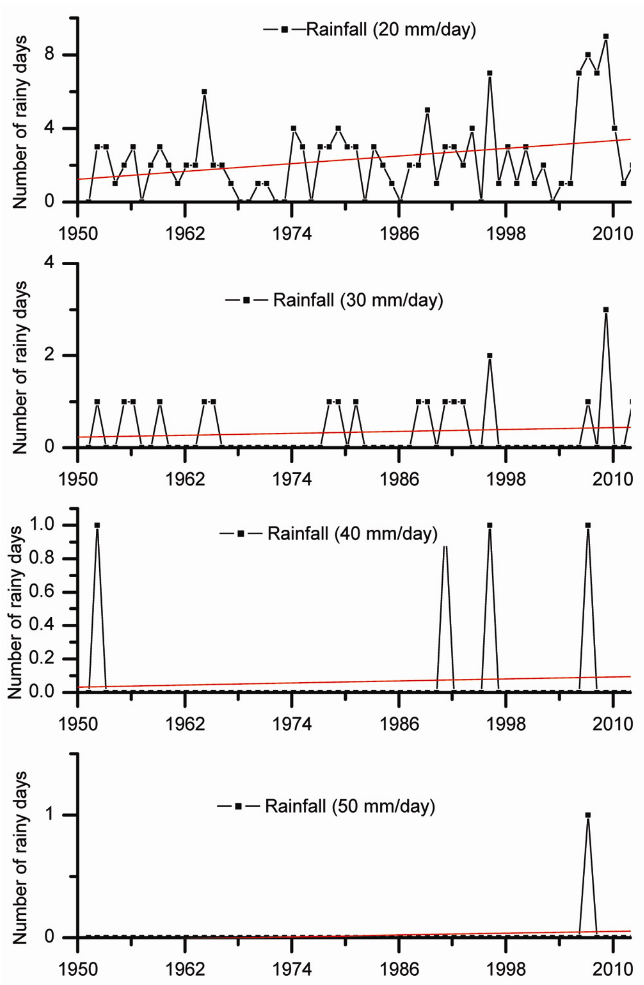

Figure 7. Number of rainy days having rainfall intensity of 20, 30, 40 and 50 mm/day or more for Krishna Basin.

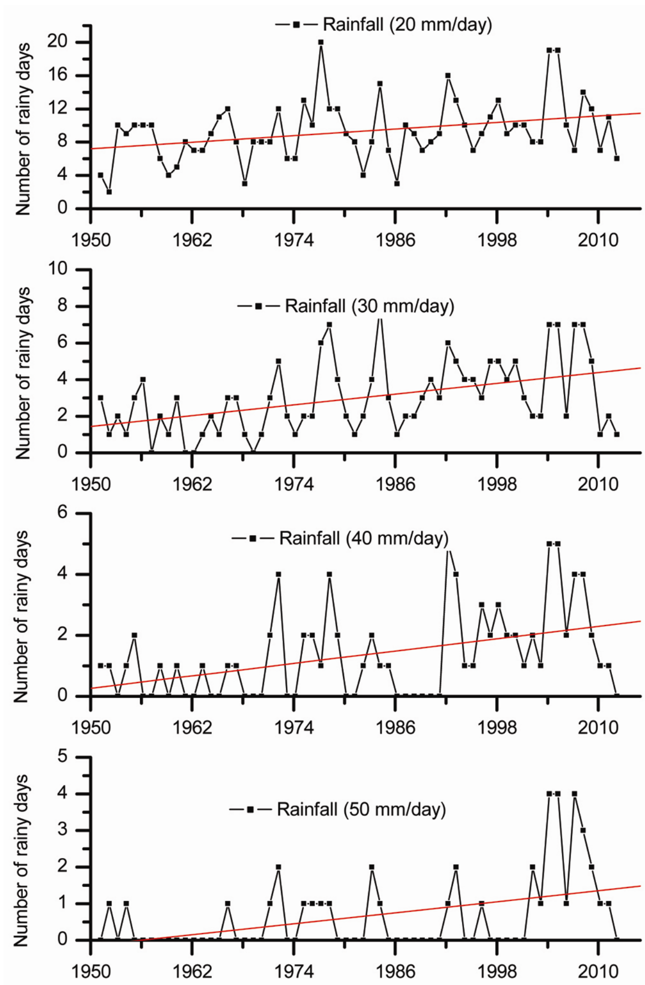

Figure 8. Number of rainy days having rainfall intensity of 20, 30, 40 and 50 mm/day or more for the Cauvery Basin.

range 10,000–20,000 and 20,000–30,000 cumec have a small falling trend. Occurrence of flood peaks higher than 30,000 cumec in different decades does not show any trend.

The Krishna river basin in South India spans an area of nearly 0.26 million sq. km in four states. Live storage capacity created in the basin is about 60% of MAF. Plots of flood peaks of different magnitudes show that the number of flood peaks of 5000–10,000 cumec depict a falling trend, but there is no trend in the peaks of larger magnitude.

The Mahanadi basin in east-central India occupies an area of more than 0.15 million sq. km. Mean annual flow computed from the observed data at Tikarpara is about 67 BCM. Hirakud dam, a major project with live storage of about 5.8 BCM was completed in 1958. Thereafter, many projects of smaller size were developed; the live storage capacity in the basin is about 25% of MAF. All the flow data used in this study have been impacted by Hirakud dam. Inspection of flood peaks of different magnitudes shows that there is no distinct pattern in the flood peaks of different ranges of flow.

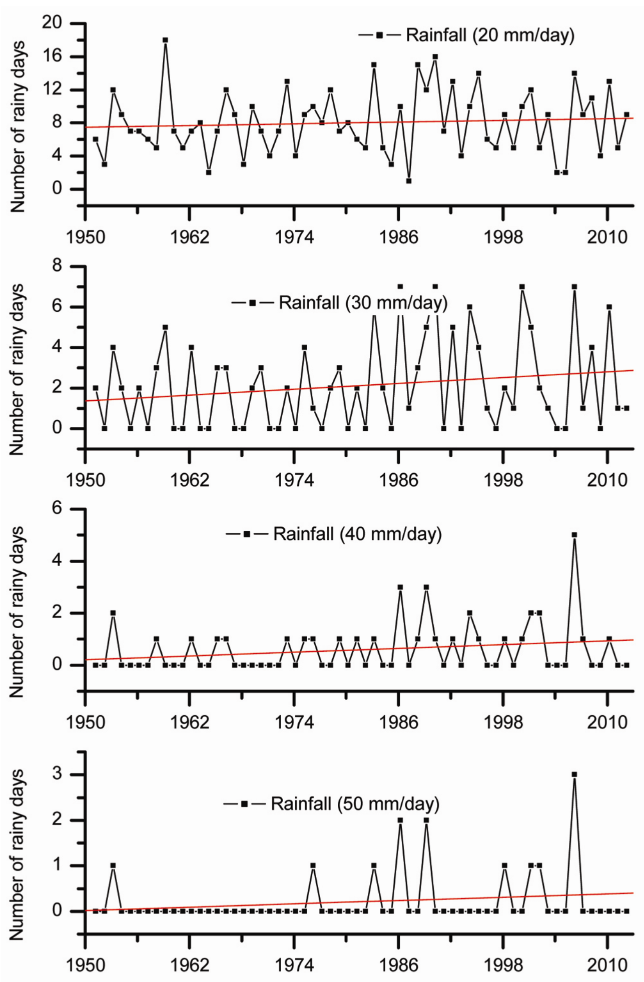

Figure 9. Number of rainy days having rainfall intensity of 20, 30, 40 and 50 mm/day or more for the Godavari Basin.

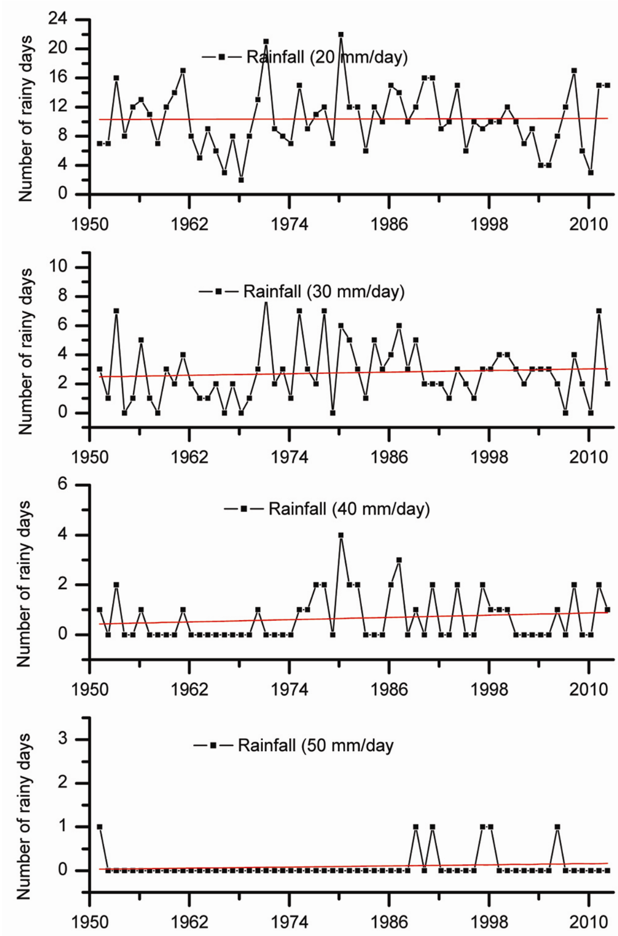

Figure 10. Number of rainy days having rainfall intensity of 20, 30, 40 and 50 mm/day or more for the Brahmani and Baitarani Basins.

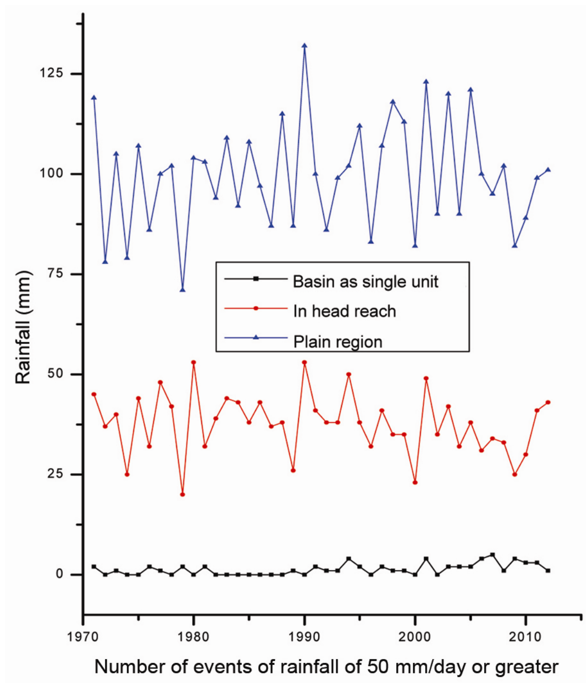

Figure 11. Number of events of rainfall of 5 mm/day or greater in different regions and whole Mahanandi basin.

Table 4. Mean annual flow, live storage capacity created and major storage projects in the river basins under study

River basin	Catchment area (sq. km)	Computed average annual rainfall (mm)	Mean annual flow (MCM)	Total live storage capacity (MCM)	Major storage projects with year of completion and live storage capacity (MCM)
Brahamani and Baitarani		1433	28,480	7,006	Salandi (1965, 556), Rengali (1984, 3414), Mandira Dam (1993, 311)
Cauvery	81,155	1142	21,360	8,788	Krishnarajasagar Dam (1931, 1276), Mettur Dam (1934, 2647), Lower Bhavani Dam (1955, 908), Kabini Dam (1974, 453), Hemavathy Dam (1979, 927)
Godavari	312,812	1045	110,540	42,403	Jayakwadi-I (1976, 2170), Sriram Sagar (1977, 2555), Muran (1981, 1456), Balimela (1988, 2676), Indrawati (1996, 1485)
Krishna	258,948	926	78,120	46,562	Koyna (1964, 2836), Bhadra (1965, 1785), Nagarjuna Sagar (1974, 5733), Hidkal (1977, 1387), Ujjani (1980, 1521), Narayanapura (1982, 863), Srisailam (1984, 7166), Almatti (2000, 861)
Mahanadi	141,589	1305	66,880	16,513	Hirakud Dam (1957, 5818), Pairi Dam (1977, 420), Ravishankar Sagar (1979, 765), Minimata Dam (1990, 3046), Badubandha Dam (1992, 540), Lower Indra Dam (2012, 314)
Narmada	98,796	1050	45,640	32,266	Barna Dam (1977, 456), Tawa Dam (1978, 1944), Karjan Dam (1987, 581), Bargi Dam (1988, 3238), Indira Sagar Dam (2006, 9750), Omkareshwar Dam (2007, 299)
Sabarmati	21,674	792	3,810	1700	Dharoi (1976, 776), Watrak (1983, 154), Mazam (1984, 37), Hathmati (1989, 149), Guhai (1990, 57)

Table 5. Occurrence of flood peaks of the magnitudes in different river basins under study

River basin	Behaviour of flood peaks (cumec)
Brahamani and Baitarani	Floods with peak 2k–4k, Falling; 4k and larger, No trend
Cauvery	2k–4k, Falling and then rising; 4k–8k, No trend
Godavari	10k–20k, Falling; 20–30k, Falling, >30k, No trend
Krishna	5k–10k, Falling, >10k, No trend
Mahanadi	No trend in flood peaks
Narmada	10k–20k, Falling; 20k–30k, Falling; >30k, Small falling trend
Sabarmati	All floods have falling trend

Narmada is a west-flowing river in central India and Narmada basin occupies an area of nearly 0.1 million sq. km. Its mean annual flow is 46 BCM and the basin has storage of 32 BCM (about 71% of MAF). Several medium-sized storage projects were developed in the basin during 1980s and 1990s. Plots of flood peaks of different magnitudes show that the occurrence of peaks of 10,000–20,000 cumec and 20,000–30,000 cumec is falling, but there is no distinct trend in floods of higher magnitudes.

The Sabarmati basin in west India occupies area of about 21,700 sq. km. Its mean annual flow is 3.8 BCM and the basin has storage of 1.70 BCM or 44% of MAF. Being located in the arid area, the high flow events are not frequent in the basin. Nevertheless, the number of flood peaks of different magnitudes shows a declining trend.

It can be concluded from the above analysis that the number of flood peaks of smaller magnitude in different decades shows slight falling trend. This can be attributed to the development of upstream storage capacities which are progressively increasing. Human activities (including urbanization and construction of check-dams, soil and water conservation measures, land-use change, etc.) are also affecting the generation of peak floods. At the same time, diversion of water by small projects and lift irrigation schemes (water is lifted or pumped from the rivers) is also increasing. Water storage projects in India typically follow a distinct drawdown–refill cycle. Usually storages are near their lowest levels before the beginning of the monsoon season (end of May) and are filled up by the end of the monsoon season (September or October). October till May forms the drawdown period. It is seen from the data that most high peaks are experienced during

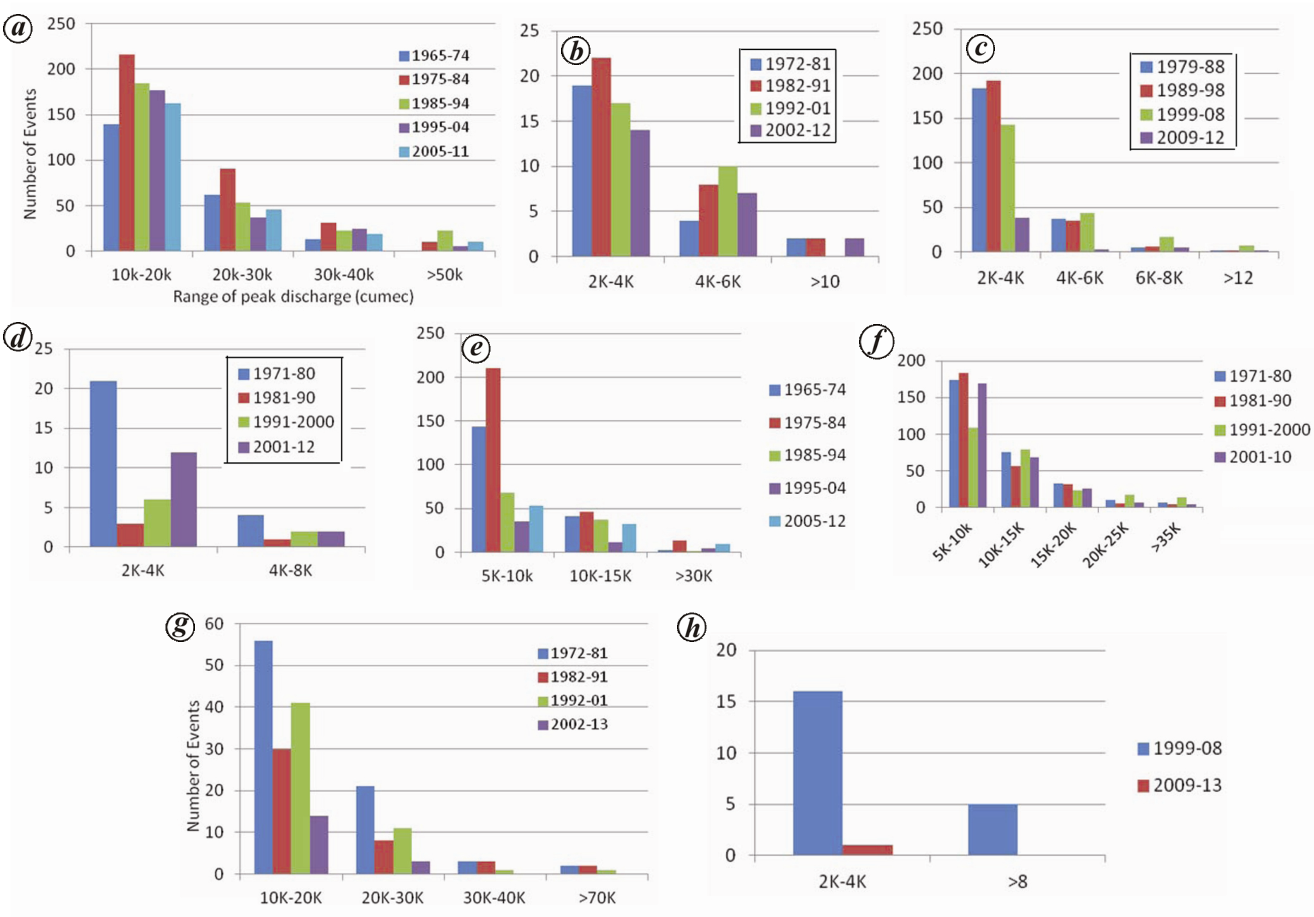

Figure 12 ***a*–*h*.** Plots showing the number of flood events of different magnitudes for various rivers in India. Number of flood events of different magnitudes: ***a***, Godavari; ***b***, Baitarni at Ananadpur; ***c***, Brahamani at Jenapur; ***d***, Cauvery at Musiri; ***e***, Krishna at Vijayawada; ***f***, Mahanadi and Tikapara; ***g***, Narmada at Garudeshwar; ***h***, Sabarmati at Vautha.

July and August. Due to the characteristic drawdown–refill cycle, peaks of the high flows that occur in the early part of the monsoon season have high chances of moderation.

According to the observed (regulated) data, there is a small rising trend or no trend in the flood peaks of higher magnitude. If the above analysis of flows is combined with the analysis of rainfall data which clearly shows increasing rainfall intensities, it can be concluded that the flood peaks under virgin conditions (if there were no upstream diversion or regulation) would show a rising trend. This is consistent with the increasing trend in high-intensity rainfall. From the analysis it can be observed that high magnitude of rainfall events is increasing in the plain region. As a result there may be an increase in food events in tributaries of different basins which do not have regulating structures. Detailed analysis is required to reinforce this conclusion.

Conclusion

In this study, we have determined the changes in heavy precipitation and peak flood for seven major river basins in India. The trends for the number of rainy days, annual average rainfall and annual peak rainfall series of different intensities were analysed by the MK trend test and Sen's slope. Among the river basins studied, there does not seem to be any trend in the average rainfall. However, the number of rainy days is falling across the basins and rainfall intensities are seen to be increasing. During the concurrent period annual peak rainfall is seen to decrease in the upstream areas of the basin, whereas plain areas of the basins show increasing annual peak rainfall. The number of different magnitudes of daily rainfall events is more in the head reaches and at mouth of the basins, compared to the whole basins. Floods of small magnitude show a falling trend, possibly due to higher upstream water use and development of storages which trap (a part of) high flows and release the water later. Floods of high magnitude have almost no appreciable trend in the studied basins at the gauged locations downstream. Considering the impact of upstream utilization and regulation by reservoirs, the peaks would have been rising if there were no major storages upstream. Increasing rainfall intensities and decreasing number of rainy days indicate that the country should urgently initiate adequate measures for extreme events in the water sector.

1. Kundzewicz, Z. W. *et al.*, Trend detection in river flow time series: 1. Annual maximum flow. *Hydrol. Sci. J.*, 2005, **50**(5), 797–810.
2. IPPC, IPCC (2012): *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* (eds Field, C. B. *et al.*), Cambridge University Press, Cambridge, 2013, p. 582.
3. Sinha Ray, K. C. and De, U. S., Climate change in India as evidenced from instrumental records. *WMO Bull.*, 2003, **52**(1), 53–59.
4. Kumar, V., Jain, S. K. and Singh, Y., Analysis of long-term rainfall trends in India. *Hydrol. Sci. J.*, 2010, **55**(4), 484–496.
5. Dash, S. K., Jenamani, R. K., Kalsi, S. R. and Panda, S. K., Some evidence of climate change in twentieth-century India. *Climatic Change*, 2007, **85**, 299–321.
6. Kumar, V. and Jain, S. K., Trends in rainfall amount and number of rainy days in river basins of India (1951–2004). *Hydrol. Res.*, 2010, **42**(4), 290–306.
7. Ramesh, K. V. and Goswami, P., The shrinking Indian summer monsoon. Research Report RR CM 0709, CSIR Centre for Mathematical Modelling and Computer Simulation, Bengaluru, 2007.
8. Rajeevan, M., Bhate, J., Kale, J. D. and Lal, B., High resolution daily gridded rainfall data for the Indian region: analysis of break and active monsoon spells. *Curr. Sci.*, 2006, **91**(3), 296–306.
9. Guhathakurta, P. and Rajeevan, M., Trends in the rainfall pattern over India. *Int. J. Climatol.*, 2008, **28**(11), 1453–1469.
10. Subash, N., Sikka, A. K. and Ram Mohan, H. S., An investigation into observational characteristics of rainfall and temperature in Central Northeast India – a historical perspective 1889–2008. *Theor. Appl. Climatol.*, 2010; doi: 10.1007/s00704-010-0299-2.
11. Pal, I. and Al-Tabbaa, A., Assessing seasonal precipitation trends in India using parametric and non-parametric statistical techniques. *Theor. Appl. Climatol.*, 2010; doi:10.1007/s00704-010-0277-8.
12. Singh, N., Sontakke, N. A., Singh, H. N. and Pandey, A. K., Recent trend in spatiotemporal variation of rainfall over India – an investigation into basin-scale rainfall fluctuations. IAHS Publication No. 296, 2005, pp. 273–282.
13. Ranade, A., Singh, N., Singh, H. N. and Sontakke, N. A., On variability of hydrological wet season, seasonal rainfall and rainwater potential of the river basins of India (1813–2006). *J. Hydrol. Res. Develop.*, 2008, **23**, 79–108.
14. Khan, T. M. A., Singh, O. P. and Rahman, M. S., Recent sea level and sea surface temperature trends along the Bangladesh coast in relation to the frequency of intense cyclones. *Mar. Geodesy*, 2000, **23**(2), 103–116.
15. Shrestha, A. B., Wake, C. P., Dibb, J. E. and Mayewski, P. A., Precipitation fluctuations in the Nepal Himalaya and its vicinity and relationship with some large scale climatological parameters. *Int. J. Climatol.*, 2000, **20**, 317–327.
16. Mirza, M. Q., Global warming and changes in the probability of occurrence of floods in Bangladesh and implications. *Global Environ. Change*, 2002, **12**, 127–138.
17. Lal, M., Global climate change: India's monsoon and its variability. *J. Environ. Stud. Policy*, 2003, **6**, 1–34.
18. Min, S. K., Kwon, W. T., Park, E. H. and Choi, Y., Spatial and temporal comparisons of droughts over Korea with East Asia. *Int. J. Climatol.*, 2003, **23**, 223–233.
19. Goswami, B. N., Venugopal, V., Sengupta, D., Madhusoodanam, M. S. and Xavier, P. K., Increasing trends of extreme rain events over India in a warming environment. *Science*, 2006, **314**, 1442–1445.
20. Sen Roy, S. and Balling, R. C., Trends in extreme daily precipitation indices in India. *Int. J. Climatol.*, 2004, **24**, 457–466.
21. Joshi, U. R. and Rajeevan, M., Trends in precipitation extremes over India. Research Report No: 3/2006, National Climate Centre, India Meteorological Department, Pune, 2006.
22. Krishnamurthy, C. K. B., Lall, U. and Kwon, Hyun-Han, Changing frequency and intensity of rainfall extremes over India from 1951 to 2003. *J. Climate*, 2009, **22**, 4737–4746.
23. Ghosh, S., Das, D., Kao, S. C. and Ganguly, A. R., Lack of uniform trends but increasing spatial variability in observed Indian rainfall extremes. *Nature Climate Change*, doi:10.1038/Nclimate1327
24. Ghosh, S., Luniya, V. and Gupta, A., Trend analysis of Indian summer monsoon rainfall at different spatial scales. *Atmos. Sci. Lett.*, 2009, **10**, 285–290.
25. Lacombe, G. and McCartney, M., Uncovering consistencies in Indian rainfall trends observed over the last half century. *Climatic Change*, 2014, **123**, 287–299.
26. Taxak, A. K., Murumkar, A. R. and Arya, D. S., Long term spatial and temporal rainfall trends and homogeneity analysis in Wainganga basin, Central India. *Weather Climate Extremes*, 2014, **4**, 50–61.
27. Milly, P. C. D., Wetherald, R. T., Dunne, K. A. and Delworth, T. L., Increasing risk of great floods in a changing climate. *Nature*, 2002, **415**, 514–517.
28. Milly, P. C. D., Dunne, K. A. and Vecchia, A. V., Global pattern of trends in streamflow and water availability in a changing climate. *Nature*, 2005, **438**, 347–350.
29. Petrow, T. and Merz, B., Trends in flood magnitude, frequency and seasonality in Germany in the period 1951–2002. *J. Hydrol.*, 2009, **371**(1–4), 129–141.
30. Kay, A. L., Davies, H. N., Bell, V. A. and Jones, R. G., Comparison of uncertainty sources for climate change impacts: flood frequency in England. *Climatic Change*, 2009, **92**(1–2), 41–63.
31. Wilhelma, B. *et al.*, 1400 years of extreme precipitation patterns over the Mediterranean French Alps and possible forcing mechanisms. *Quater. Res.*, 2012, **78**(1), 1–12.
32. Douglas, E. M., Vogel, R. M. and Knoll, C. N., Trends in flood and low flows in the United States: impact of spatial correlation. *J. Hydrol.*, 2000, **240**, 90–105.
33. McCabe, G. J. and Wolock, D. M., A step increase in streamflow in the conterminous United States. *Geophys. Res. Lett.*, 2002, **29**; doi:10.1029/2002GL015999.
34. Cunderlik, J. M. and Ouarda, T. B. M. J., Trends in the timing and magnitude of floods in Canada. *J. Hydrol.*, 2009, **375**(3–4), 471–480.
35. Villarini, G. F. *et al.*, On the stationarity of annual flood peaks in the continental United States during the 20th century. *Water Resour. Res.*, 2009, **45**, W08417; doi:10.1029/2008WR007645.
36. Benito, G., Barriendos, M., Llasat, C., Machado, M. and Thorndycraft, V., Impacts on natural hazards of climatic origin. Flood risk. In *A Preliminary General Assessment of the Impacts in Spain Due to the Effects of Climate Change* (ed. Moreno, J. M.), Ministry of Environment, Spain, 2005, pp. 507–527.
37. Yiou, P., Ribereau, P., Naveau, P., Nogaj, M. and Brazdil, R., Statistical analysis of floods in Bohemia (Czech Republic) since 1825. *Hydrol. Sci. J.*, 2006, **51**, 930–945.
38. Renard, B. *et al.*, Regional methods for trend detection: assessing field significance and regional consistency. *Water Resour. Res.*, 2008, **44**, W08419.
39. Allamano, P., Claps, P. and Laio, F., Global warming increases flood risk in mountainous areas. *Geophys. Res. Lett.*, 2009, **36**, L24404.
40. Jiang, T., Kundzewicz, Z. W. and Su, B., Changes in monthly precipitation and flood hazard in the Yangtze River Basin, China. *Int. J. Climatol.*, 2008, **28**(11), 1471–1481.

41. Delgado, J. M., Apel, H. and Merz, B., Flood trends and variability in the Mekong River. *Hydrol. Earth Syst. Sci.*, 2009, **6**(3), 6691–6719.
42. Bhutiyani, M. R., Kale, V. S. and Pawar, N. J., Changing streamflow patterns in the rivers of northwestern Himalaya: implications of global warming in the 20th century. *Curr. Sci.*, 2008, **95**(5), 618–626.
43. Bhutiyani, M. R., Kale, V. S. and Pawar, N. J., Long-term trends in maximum, minimum and mean annual air temperatures across the Northwestern Himalaya during the twentieth century. *Climatic Change*, 2007, **85**(1-2), 159–177.
44. Camilloni, I. A. and Barros, V. R., Extreme discharge events in the Paraná River and their climate forcing. *J. Hydrol.*, 2003, **278**(1–4), 94–106.
45. Barros, V. B., Chamorro, L., Coronel, G. and Baez, J., The major discharge events in the Paraguay River: magnitudes, source regions, and climate forcings. *J. Hydrometeorol.*, 2004, **5**, 1161–1170.
46. Marengo, J. A., Tomasella, J., Soares, W., Alves, L. and Nobre, C., Extreme climatic events in the Amazon basin. *Theor. Appl. Climatol.*, 2011; doi:10.1007/s00704-00011-00465-00701.
47. Di Baldassarre, G., Montanari, A., Lins, H. F., Koutsoyiannis, D., Brandimarte, L. and Blöschl, G., Flood fatalities in Africa: from diagnosis to mitigation. *Geophys. Res. Lett*., 2010, **37**, L22402; doi:10.1029/2010GL045467.
48. Postel, S. L., Daily, G. C. and Ehrlich, P. R., Human appropriation of renewable fresh water. *Science*, 1996, **271**, 785–788.
49. Immerzeel, W. W., van Beek, L. P. and Bierkens, M. F. P., Climate change will affect the Asian water towers. *Science*, 2010, **328**, 1382–1385.
50. Gain, A. K., Immerzeel, W. W., Sperna Weiland, F. C. and Bierkens M. F. P., Impact of climate change on the stream flow of the lower Brahmaputra: trends in high and low flows based on discharge-weighted ensemble modeling. *Hydrol. Earth Syst. Sci*., 2011, **15**, 1537–1545.
51. Wu, C. and Huang, H., Changes in heavy precipitation and floods in the upstream of the Beijiang River basin, South China. *Int. J. Climatol*., 2015, **35**, 2978–2992.
52. Devkota, L. P. and Gyawali, D. R., Impacts of climate change on hydrological regime and water resources management of the Koshi River Basin, Nepal. *J. Hydrol.: Reg. Stud*., 2015, **4**, 502–515.
53. Bates, B. C. *et al.*, Climate change and water. Technical paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, 2008.
54. Barnett, T. P. *et al*., Human-induced changes in the hydrology of the western United States. *Science*, 2008, **319**(5866), 1080–1083.
55. Lehner, B. *et al.*, Estimating the impact of global change on flood and drought risks in Europe: a continental, integrated analysis. *Climatic Change*, 2006, **75**(3), 273–299.
56. Dankers, R. and Feyen, L., Flood hazard in Europe in an ensemble of regional climate scenarios. *J. Geophys. Res. – Atmos.*, 2009, **114**, D16108.
57. Hirabayashi, Y., Kanae, S., Emori, S., Oki, T. and Kimoto, M., Global projections of changing risks of floods and droughts in a changing climate. *Hydrol. Sci. J.*, 2008, **53**(4), 754–772.
58. Dankers, R. *et al*., A first look at changes in flood hazard in the ISI-MIP ensemble. *Proc. Natl. Acad. Sci*., 2013; doi:10.1073/pnas.1302078110.
59. Schneider, C., Laize, C. L. R., Acreman, M. C. and Florke, M., How will climate change modify river flow regimes in Europe? *Hydrol. Earth Syst. Sci.*, 2013, **17**, 325–339; doi:10.5194/hess-17-325-2013.
60. Taylor, C. H. and Loftis, J. C., Testing for trend in lake and groundwater quality time series. *J. Am. Water Res. Ass.*, 1989, **25**(4), 715–726.
61. Burn, D. H., Cunderlik, J. M. And Pietroniro, A., Hydrological trends and variability in the Liard river basin. *Hydrol. Sci. J.*, 2004, **49**, 53–67.
62. Sen, P. K., Estimates of the regression coefficient based on Kendall's tau. *J. Am. Statist. Assoc*., 1968, **63**, 1379–1389.

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