Analysis of monsoon rainfall variability over Narmada basin in central India: Implication of climate change

T. Thomas, S. S. Gunthe, N. C. Ghosh and K. P. Sudheer

ABSTRACT

Daily rainfall of 23 high resolution ($1^{\circ} \times 1^{\circ}$) grid cells covering the Narmada basin has been analyzed to investigate the trend in extreme rainfall events. The trend analysis of the 1-day maximum rainfall series showed a significant positive trend at 95% significance level with the Mann–Kendall test statistic value of $z = 3.66$ over the entire basin. The analysis further suggested that there has been an increasing trend in the magnitude of 1-day maximum rainfall over the basin with more areas in the basin experiencing high intensity storms, which was more prominent in the most recent 20 years. Drought duration estimated by the standardized precipitation index for the periods 1951–1970 and 1989–2008 indicated that the entire basin has experienced frequent droughts during the recent two decades, with the middle zone of the basin being more prone to droughts. The analysis also suggested that appropriate measures may be proposed for better management of the water resources in the basin, and also for mitigation of floods and droughts, considering the increased risk of the high intensity storms as well as the increased frequency of drought occurrence during the recent two decades.

Key words | climate change, drought, extreme events, ISMR, trend analysis

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INTRODUCTION

The changing climate is a matter of growing concern worldwide, particularly about its impacts on various vital segments including major components of the hydrological cycle and consequently its effects on water resources and management. The rise in surface air temperature and subsurface ocean temperature, which are perceived to be the primary cause of sea level rise resulting from a continuously warming climate and increased moisture content associated with expected higher rainfall amounts, are considered to be strongly affecting the temporal (Goswami *et al.* 2006; Dash *et al.* 2011 and references therein) and spatial pattern of Indian Summer Monsoon Rainfall (ISMR). Climate change in the Indian context has caused an increase in surface temperature at the rate of 0.2 °C per decade from 1971 to 2007 (Kothawale *et al.* 2010). Such an increase in temperature is expected to bring out a change in the hydrological cycle mainly due to an increase in average evaporation, water vapor, and precipitation. Recently an increase in the intensity and frequency of extreme rainfall events has been reported over central India (where the basin is located), which makes these areas susceptible to flash floods and drought at the same time (Goswami *et al.* 2006; Schiermeier 2006; Rajeevan *et al.* 2008; Krishnamurthy 2011).

The ISMR is the major source of water for most of the regions in India (Dash *et al.* 2011). The agriculture, forestry, wetlands, and fisheries sectors, which are the main livelihood of the majority of the Indian population, are strongly subjected to the water-based ecosystems that primarily depend on ISMR, which thus is the primary driving force of the Indian economy (Kumar *et al.* 2006). It had been reported that the seasonal mean of ISMR over the past century has not exhibited any statistically significant trend and strong variability despite the steady rise in the global mean temperature (Goswami *et al.* 2006; Rajeevan *et al.* 2008). On the other hand, Kothawale *et al.* (2008) observed that the ISMR decreased at 1.5 mm/year over the period

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1971–2002. It has also been reported that the intra-seasonal variability of ISMR has weakened since the 1970s (Kulkarni *et al.* 2009; Kulkarni 2011). Nonetheless, the extreme rainfall events associated with the increasing trend of sea surface temperatures and latent heat flux over the Indian Ocean have been increasing over central India (Rajeevan *et al.* 2008). In addition, studies on long-term trends of ISMR indicated the absence of any trend due to the consideration of rainfall being random over an all-India scale (Mooley & Parthasarthy 1984; Guhathakurtha & Rajeevan 2006) despite the existence of strong trends on spatial scales (Parthasarathy 1984; Rupa Kumar *et al.* 1992).

An analysis of the rainfall pattern, its distribution, and trend on a seasonal and an intra-seasonal scale resulting from the implication of changing climate is important to evaluate uncertainties associated with the availability and management of water resources. Such analysis may be helpful to policy-makers to explore appropriate strategies for efficient water resource management. A number of studies (Ghosh *et al.* 2009; Preethi *et al.* 2010; Pai *et al.* 2011; Ghosh *et al.* 2012) have analyzed the ISMR variability in the Indian context considering the country as a single unit with most of them reporting ISMR variability in space and time. However, they did not explicitly investigate the spatial and temporal variability of rainfall (especially extreme events) on local watersheds. It is to be noted that with any analysis when performed on a larger scale, the variability at the small scale (local) may be neutralized. Therefore, it is imperative to analyze rainfall data at local (basin) scale to understand the effect of climate change in a basin. In addition, increasing anthropogenic aerosol concentrations associated with rapid industrialization over India is known to perturb the cloud properties on a local scale (Rosenfeld *et al.* 2008). Such perturbations can cause suppression of rainfall at the early developmental stage resulting in greater overturning and convection with intense and enhanced rainfall. Various basins in central India have experienced both droughts and floods in recent years.

One of the major basins in central India is the Narmada basin, which caters for the needs of water for irrigation and hydroelectric power generation. The water resources development plans in the Narmada basin include more than 30 major multi-purpose reservoirs and also a large number of moderate and minor projects. These projects are well distributed over the basin, and consequently the effectiveness of these developments largely depends on the consequential effects of changing climate and its hydrologic variability. Keeping this in view, in the present study we comprehensively analyzed the spatial and temporal pattern of monsoon rainfall over the Narmada basin.

STUDY AREA

The Narmada basin in India lies between 72.53 °E–81.75 °E and 21.33 °N–23.75 °N and extends over an area of 98,796 km^2 with a maximum length of around 953 km and a maximum width of around 234 km (Figure 1). It is bounded by the mountains of Vindhya to the north, the Maikal range to the east, Satpuras to the south, and the Arabian Sea to the west. The Narmada River, which is a snow-free perennial Indian river, originates at the Amarkantak Plateau (22°40′N and 81°45′E) of the Maikal range in the Shahdol district of Madhya Pradesh at an elevation of 1,057 m above msl. The river drains into the Arabian Sea after traversing through a channel length of around 1,312 km. The basin lies in three states viz. Madhya Pradesh, Maharashtra, and Gujarat with an aerial extent of 86, 2, and 12%, respectively, in each state.

The basin has three distinct physiographic zones, namely, the upper zone comprising of the hilly region covering the districts of the Shahdol, Mandla, Balaghat, Seoni, Jabalpur, Narsinghpur, Sagar, and Damoh; the middle zone, comprising of a plains region covering the districts of Chhindwara, Hoshangabad, Betul, Raisen, Sehore, and Khandwa; and the lower zone comprising of the lower hilly and lower plains region covering the districts of East and West Nimar, Dewas, Indore, Dhar, and Jhabua in Madhya Pradesh, Dhule in Maharashtra, and Bharuch and Vadodara in Gujarat. The basin mainly experiences a humid and tropical climate with an average annual rainfall of 1,178 mm mostly received (about 90%) during the southwest monsoon months (June–September). Alluvial deposits are also found on the banks of the major tributaries of the river Narmada. The net sown area in the basin is about 45% with an average cropping intensity of 135%, while about 32% of the basin is forested.

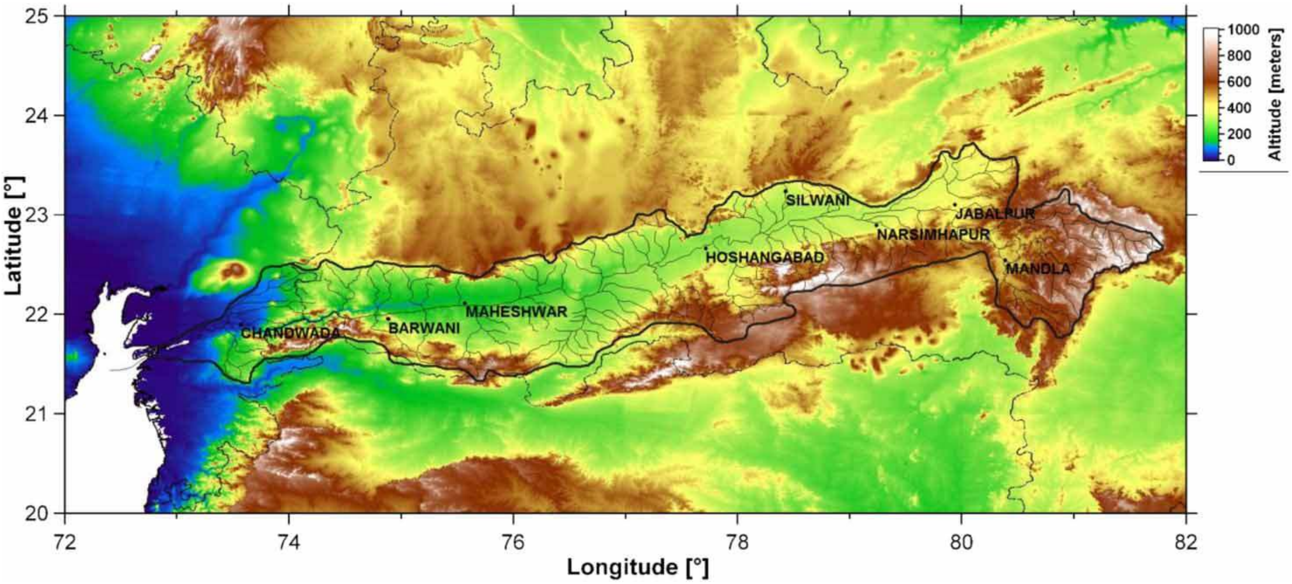

Figure 1 | Base map of the Narmada basin.

DATA AND METHODOLOGY

The $1^\circ \times 1^\circ$ daily gridded rainfall data prepared by the India Meteorological Department (IMD) for the Indian land mass (6.5°N–38.5°N and 66.5°E–100.5°E) have been used in the present study (Rajeevan *et al.* 2006). A total of 1,803 rain gauge stations with a minimum data availability of 90% for the period 1951–2008 have been used for preparation of this gridded data set. The data interpolation is based on the Shepard (1968) method, wherein the weighted sum of the observations at surrounding rain gauge stations falling within the predefined radius of influence is considered. The rainfall data have been interpolated into rectangular (35×32) grid cells. It is worth mentioning that the gridded data, which is obtained by interpolating and smoothing the measurements from rain gauges, may underestimate the variance of point rain gauge data. However, for a basin-wide analysis, it is apparently difficult to obtain sufficient number of rain gauges evenly distributed over the basin. In such cases, analysis may be performed on the gridded data, though they are smoother than the individual station data because of the averaging over a $1^\circ \times 1^\circ$ box.

Nevertheless, to validate the possibility and usefulness of data used in the present study we compared daily gridded interpolated rainfall data with direct observation for grids where rain gauge data are available (in this case Jabalpur) and the scatter plot prepared between the station and gridded rainfall data to investigate any significant variations do not portray considerable bias between the gridded and station rainfall data. The R^2 between the gridded and station rainfall data appeared to be moderate to very strong (0.45–0.81). Moreover, more than one rain gauge station exists in most of the grid cells falling over the Narmada basin. The Narmada basin is covered by 23 grid cells $(1^\circ \times 1^\circ)$ as per the IMD interpolated information, of which the lower zone (72°E–76°E and 21°N–24°N) constitutes seven grid cells, the middle zone (76°N–79°N and 21°N–24°N) eight grid cells, and the upper zone (79°E–82°E and 21°N–24°N) eight grid cells as shown in Figure 2. The additional details about data collection, interpolation techniques, and methodology can be found in Rajeevan *et al.* (2005). The historic data on precipitation in Narmada basin have been analyzed for three different hydrologic characteristics: (i) extreme rainfall events which cause flood; (ii) change in frequency of occurrence of extreme rainfall; and (iii) drought occurrence.

To investigate the possible trends in the extreme rainfall patterns during the last six decades, grid cell-wise analysis of the rainfall characteristics, which could potentially be responsible for extreme rain events in the basin, have

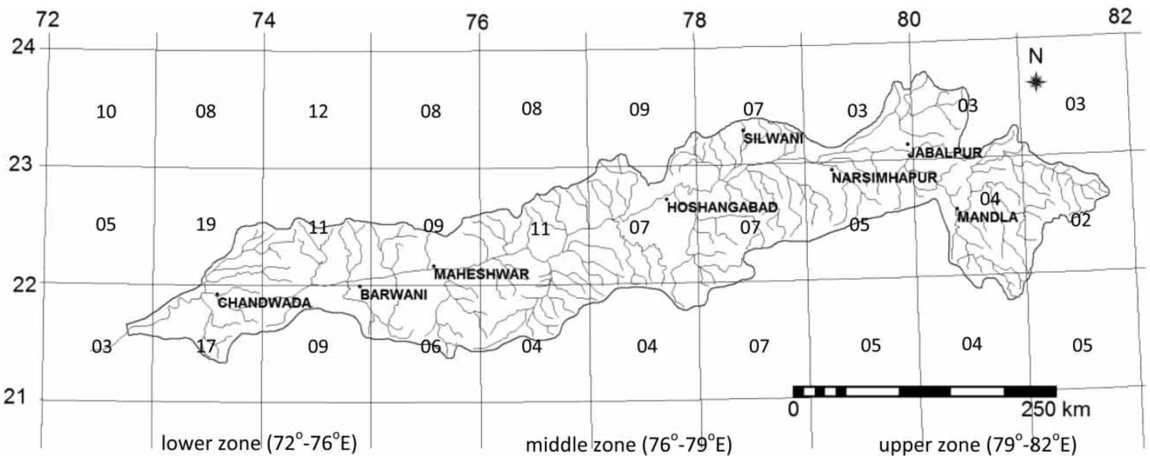

Figure 2 | Grid and rain gauge station information of the Narmada basin.

been carried out. From the time series of yearly rainfall data (daily gridded values), the maximum 1-day and maximum 2-day rainfall have been extracted for each year, as these are indicators of the flood potential in various parts of the basin. Based on the total rainfall received in any given day, the rainfall events have been classified into various categories. Even though a fixed threshold of defining extreme events is not appropriate over regions where the mean climate has large spatial variability, fixed thresholds have been used to define the extreme events over the Narmada basin, as the seasonal mean and the daily variability is reasonably homogeneous over central India. Different threshold values had been used by various researchers (Goswami *et al.* 2006; Sen & Balling 2004; Stephenson *et al.* 1999) for classifying the rainfall. This study considers the threshold values as follows: extreme rainfall (>200 mm/day); very heavy rainfall (>150 mm/day); and heavy rainfall (>100 mm/day). A day that receives rainfall less than 2.5 mm has been considered to be a dry day. As our major focus is to analyze the extreme events, rainfall between 2.5 and 100 mm on one day has been considered as a moderate event. Time series for each of the above categorization has been prepared from the available gridded data for further analysis.

To assess whether there is any change in the magnitude of rainfall associated with different recurrence intervals, frequency analysis of 1-day maximum rainfall series has been performed for each grid. The spatial variability of 5-year and 10-year return period rainfall has been analyzed to assess the regions with potential for flooding. The trend analysis of the extracted time series corresponding to the above probability analysis has been carried out using the Mann–Kendall (MK) test (Mann 1945; Kendall 1975). It has been reported by previous researchers that under a changing climate scenario, due to anthropogenic activities, the intensity and frequency of extreme rainfall events have increased in the recent two decades (Goswami *et al.* 2006). Accordingly, to demonstrate the impact of climate change driven by anthropogenic activities, the data for each of the initial and latest 20 years in this study were analyzed separately. This division of the data period in this study was also based on the preliminary analysis over the entire 58 years data, which indicated that the rainfall variability in the initial and the latest 20 year period are plausibly the best representation of contrasting scenarios to efficiently demonstrate the effect of changing climate on extreme rainfall events. The precipitation has therefore been analyzed for the total period of 58 years during 1951–2008, and also by considering two classes of 20 years each, 1951–1970 and 1989–2008. Accordingly, the data during 1971–1988 was deselected to capture the contrast in the trend in extreme events during the two distinct time periods 1951–1970 (past) and 1989–2008 (present). However, there is no specific reason not to include the deselected data (analysis performed but not shown) depending upon the objective of the study and region. In addition, the major change in land use pattern might have taken place in the basin with the construction of major reservoirs after 1988.

In the Narmada basin, nearly 90% of the annual rainfall is received during the five monsoon months from June to September, and 60% is received during the 2 months of July and August. The rainfall nominally is heavy in the upper hilly and upper plains areas of the basin. It gradually decreases toward the lower plains and the lower hilly areas and thereafter increases toward the coast and south western portions of the basin. In the upper hilly areas, the annual accumulated rainfall is more than 1,400 mm whereas in the upper plains from Jabalpur to the Punasa dam site, the annual rainfall decreases from around 1,000 mm to less than 650 mm around Barwani, and this area represents the most arid part of the Narmada Basin. Therefore, Narmada basin is prone to drought occurrence in addition to the occurrence of flood. Consequently, the drought analysis has been performed in the various zones of Narmada basin based on the monthly rainfall time series using the drought indicator approach. The standardized precipitation index (SPI) by McKee *et al.* (1993) has been used for this analysis. The trend in the time series of SPI has been evaluated by the MK test.

MANN–KENDALL TEST

MK test (Mann 1945; Kendall 1975), which is a non-parametric statistical procedure, is commonly used to identify trends in time series of variables including temperature, precipitation, and streamflow in the context of climate change (Taylor & Loftis 1989; McLeod *et al.* 1991; Yu *et al.* 1993; Douglas *et al.* 2000; Burn *et al.* 2004; Lindström & Bergström 2004; Xiong & Guo 2004) data series. Before applying the MK test, the testing for serial correlation for identifying the auto-correlation is required. The MK test can be applied to the original data series ($x_1, x_2, \ldots, x_n$) if the lag-1 auto-correlation (r_1) is not significant at the 95% confidence level, else the test has to be applied to the pre-whitened series obtained as ($x_2 – r_1 \times 1$, $x_3 – r_1 \times 2, \ldots$, $x_n – r_1 x_{n-1}$) (Von Storch & Navarra 1995; Partal & Kahya 2006)

$$E(S) = 0 \mathrm{var}(S) = \frac{N(N-1)(2N+5) - \sum_{k=1}^{n} t_k(t_k-1)(2t_k+5)}{18}$$
$$Z = \frac{S-1}{\sqrt{\mathrm{var}(S)}} = \frac{S+1}{\sqrt{\mathrm{var}(S)}} \tag{1}$$

The null hypothesis that there is no trend in the times series is rejected if the test statistic satisfies the conditions, either $Z > +1.96$ or $Z < -1.96$ (at 95% significance level).

STANDARDIZED PRECIPITATION INDEX

The SPI developed by McKee *et al.* (1993) is a widely used index for assessing drought severity, and it has the advantages of statistical consistency. The SPI allocates a single numeric value varying between −3 and +3 to the precipitation, which can be compared across different climatic regions. The SPI allows determining the occurrence probability of dry or wet events at different time scales varying from 3 to 24 months, and monthly rainfall data for a minimum of 30 years is required for the analysis (Hayes 1999).

$$G(x) = \frac{1}{\alpha^{\beta}\Gamma\beta}\int_0^x x^{\beta-1}e^{-x/\alpha}dx\frac{x}{\alpha} \tag{2}$$

$$G(x) = \frac{1}{\Gamma\beta}\int_0^{t\alpha} t^{\beta-1}e^{-t}dt \tag{3}$$

$$H(x) = q + (1-q)G(x) \tag{4}$$

$$Z = \mathrm{SPI} = -\left[t - \frac{C_{0+}C_1 t + C_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right] \tag{5}$$

$$Z = \mathrm{SPI} = +\left[t - \frac{C_{0+}C_1 t + C_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right] \tag{6}$$

$$t = \sqrt{\ln\left\{\frac{1}{(H(x))^2}\right\}} \tag{7}$$

$$t = \sqrt{\ln\left\{\frac{1}{(1.0 - H(x))^2}\right\}} \tag{8}$$

where $c_0 = 2.51552$, $c_1 = 0.80285$, $c_2 = 0.01033$, $d_1 = 1.43279$, $d_2 = 0.18927$, and $d_3 = 0.00131$. A drought event occurs during the period when the SPI is continuously negative with an intensity of −1.0 or less. The drought characteristics including frequency, duration, intensity, and magnitude have been calculated with the estimated SPI based on the values of SPI as given in Table 1 (Hayes 1999).

RESULTS AND DISCUSSION

Analysis of extreme rainfall events

The statistical characteristics of the annual rainfall over the Narmada basin (across the zones) are presented in Table 2. A considerable variation in the average rainfall in all three zones of the Narmada basin is evident, as the average annual rainfall varies between 1,286.2 mm in the upper zone and 902.2 mm in the lower zone accounting for a difference of about 40% (Table 2). The inter-annual variability of rainfall is high in the lower zone compared to the other two zones as indicated by a high value of coefficient of variation. The results presented (Table 2) clearly illustrate the significant spatial variation of rainfall over the basin.

The 1-day maximum rainfall extracted from each of the 23 grids covering the Narmada basin for the entire period (1951–2008) exhibited a variation from 135.4 to 473.0 mm. The temporal variation of the 1-day maximum rainfall is shown in Figure 3, and it can be observed that the magnitude of the 1-day maximum rainfall has increased steadily over the last 58 years and is found to be more prominent in the last two decades. The trend analysis of the 1-day maximum rainfall series showed a positive trend at 95% significance level with the MK test value of $z = 3.66$. The strength of the test statistic confirms that the number of events of 1-day maximum rainfall over the basin has increased considerably.

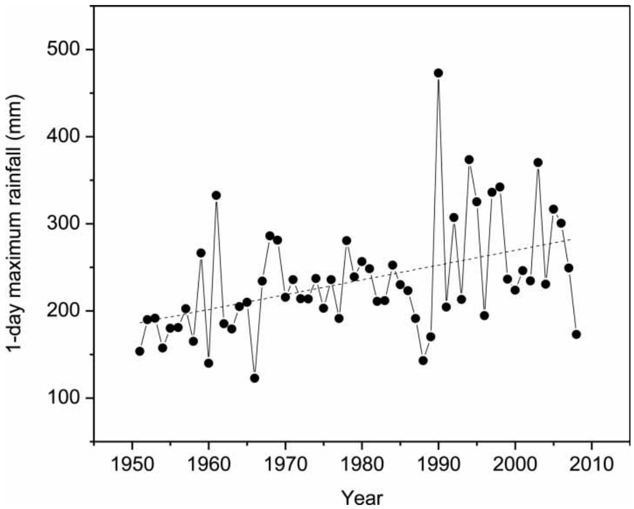

Figure 3 | Temporal variation of amount of 1-day maximum rainfall in the basin (MK test z statistic $= 3.66$; $p = 0.003$).

The time series of the 1-day maximum rainfall has further been analyzed to identify the variation in the initial 20-year period (1951–1970) and the recent 20-year period (1989–2008), and the results are given in Table 3. These results show that the average 1-day maximum rainfall has increased significantly from 203.9 mm during 1951–1970 to 275.9 mm during the recent 20-year period. A positive

Table 1 | Drought severity classification based on standardized precipitation index

S. No.	Drought severity class	SPI range
1	Extreme drought	Z = <− 2.00
2	Severe drought	−2.00 < Z = <− 1.50
3	Moderate drought	−1.50 < Z = <− 1.00
4	Near normal	−1.00 < Z = <+ 1.00

Table 2 | Statistical characteristics of annual rainfall in different zones of Narmada basin

S. No.	Parameter	Upper zone	Middle zone	Lower zone
1	Average annual rain (mm)	1,286.2	1,059.1	902.2
2	Coefficient of variation (%)	18.4	19.7	28.4

Table 3 | Comparison of the characteristics of 1-day maximum rainfall during the periods 1951–1970 and 1989–2008

S. No.	Statistical parameters	1951–1970	1989–2008
1	Average of 1-day maximum rain (mm)	203.9	275.9
2	Maximum of 1-day maximum rain (mm)	332.6	472.9
3	Minimum of 1-day maximum rain (mm)	122.6	170.3
4	Number of events with rainfall >300 mm	1	9
5	Number of events with rainfall >200 mm	8	17

upward shift has been observed in the minimum (and maximum as well) of the 1-day maximum rainfall series when compared between the first two decades (of the analysis) and the last two decades, which indicates that the magnitude of rainfall has potentially increased in the later parts of the last 58 years. It is further observed that nine events of 1-day rainfall greater than 300 mm occurred during the latter 20-year period as compared to only one event during 1951–1970. Similarly, 17 events of 1-day rainfall greater than 200 mm occurred during the later 20-year period as compared to only eight events during 1951–1970. To ascertain whether the means from the two time periods (initial and later 20 years) are significantly different, a *t*-test has been conducted on the time series of 1-day maximum rainfall. The obtained *t*-statistic value of 3.39 indicated that the mean of the current 20-year period and the first 20-year period are significantly different at the 95% significance level. These results clearly demonstrate that the magnitude of 1-day maximum rainfall over the basin has increased during the last two decades, which plausibly indicates an impending climatic change.

In order to investigate whether more areas in the basin have experienced high intensity rainfalls in recent years (change in spatial variability), temporal distribution of high intensity rainfall for different grids, have been analyzed. It is observed (Figures 4–6) that the number of grids experiencing extreme, very heavy, and heavy rainfall has increased over the last 58 years. The results of the MK test (Table 4) for these three time series suggested a significant positive trend of increase in the number of grids experiencing high intensity rainfalls. This indicates more areas in the basin may likely experience high intensity storms in coming years under continuously changing climatic conditions.

There is no significant trend of change in the average annual rainfall in the Narmada basin. However, there could be changes in the moderate and the high intensity

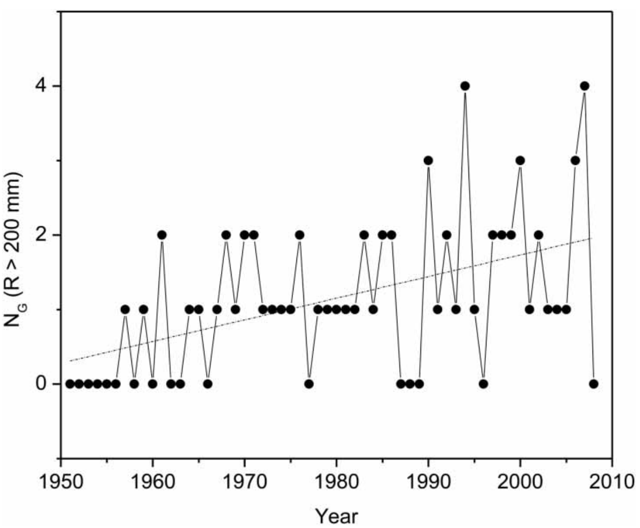

Figure 4 | Temporal variation of number of grids with extreme rainfall events (MK test *z* statistic = 3.704; *p* = 0.0005).

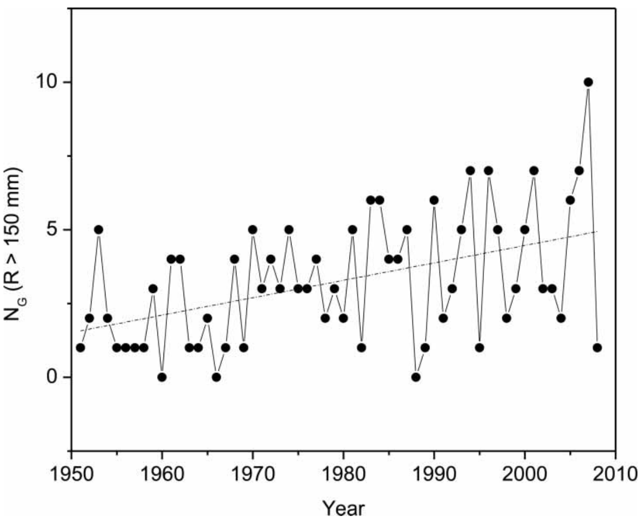

Figure 5 | Temporal variation of number of grids with very heavy rainfall events (MK test *z* statistic = 3.351; *p* = 0.0009).

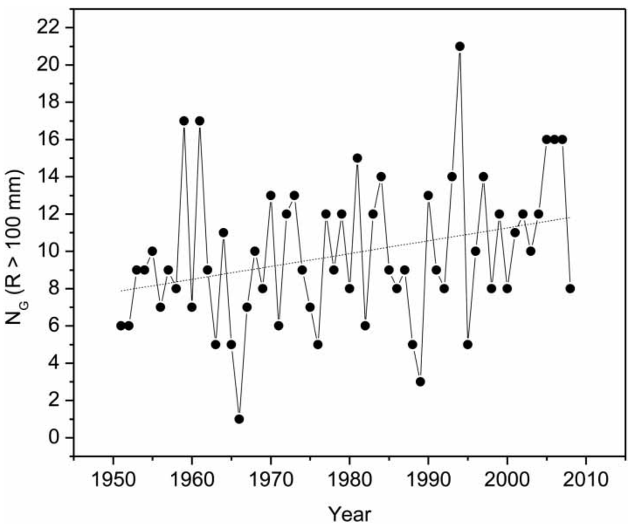

Figure 6 | Temporal variation of number of grids with heavy rainfall events (MK test *z* statistic = 2.321; *p* = 0.02).

Table 4 | Mann–Kendall test statistic for high intensity rainfall categories in Narmada basin

	Extreme rainfall	Very heavy rainfall	Heavy rainfall	Moderate rainfall
Test statistic (z)	3.704	3.351	2.321	−1.913
Coefficient of variation	0.89	0.67	0.39	0.15
p value	0.0005	0.0009	0.02	0.06
Inference	Positive	Positive	Positive	No trend

storm events contributing to the annual rainfall. Number of days with moderate rainfall (Figure 7) in the basin is found to be decreasing over the period. However this did not exhibit any significant negative trend at the 95% significance level according to MK test. The contribution of moderate rainfall events to the total annual average rainfall is found to be decreased from 83% (in the initial 20 years) to 79% in the recent 20 years. The contribution of the annual average rainfall from heavy rainfall events was 17% in the initial 20 years, and had increased to 21% in the recent 20 years. This plausibly confirms the earlier inference that there is an increase in the number of rainy days with high rainfall magnitude.

The variation in the number of occurrences of heavy and extreme rainfall (more than 100 mm and more than 150 mm, respectively) during the periods between 1951–1970 and 1989–2008 is given in Figures 8 and 9. The number of rainy days with more than 100 mm rain showed a significant falling trend for the period 1951–1970 and an increasing trend (though not significant at the 95% significance level) for the period 1989–2008 (Figure 8). The events with rain >150 mm (Figure 9) showed a significant

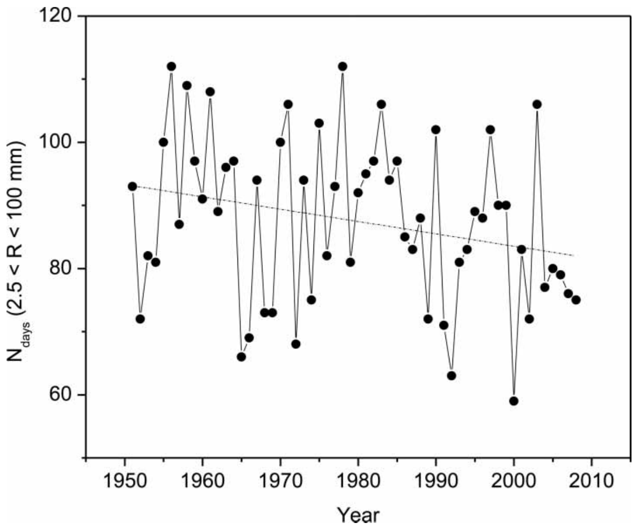

Figure 7 | Temporal variation of number of days with moderate rainfall events (MK test z statistic = −1.913; p = 0.06).

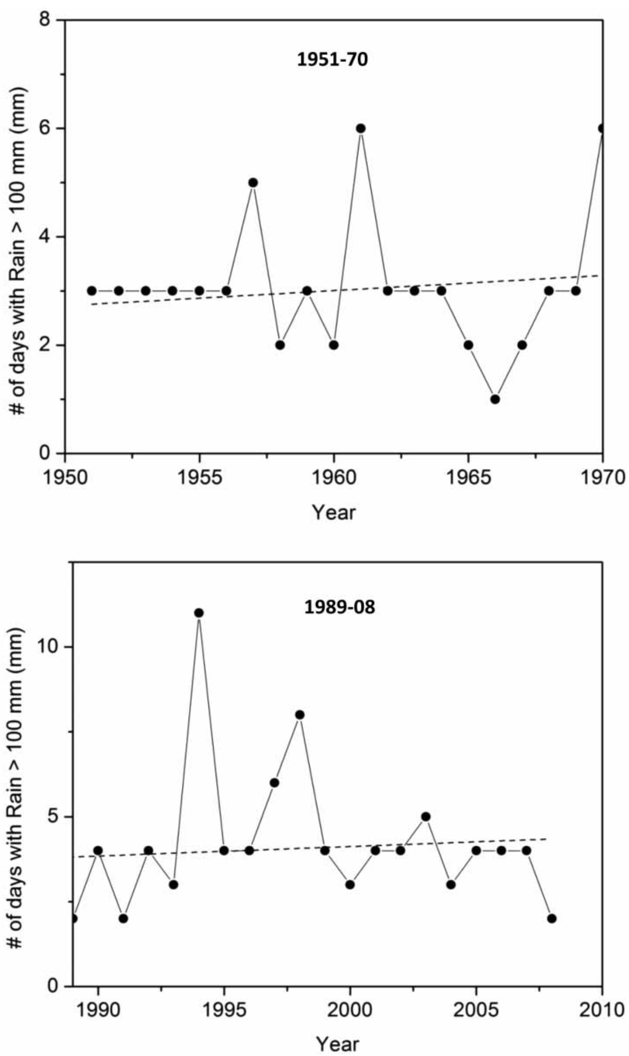

Figure 8 | Variation of number of days with rainfall greater than 100 mm with time.

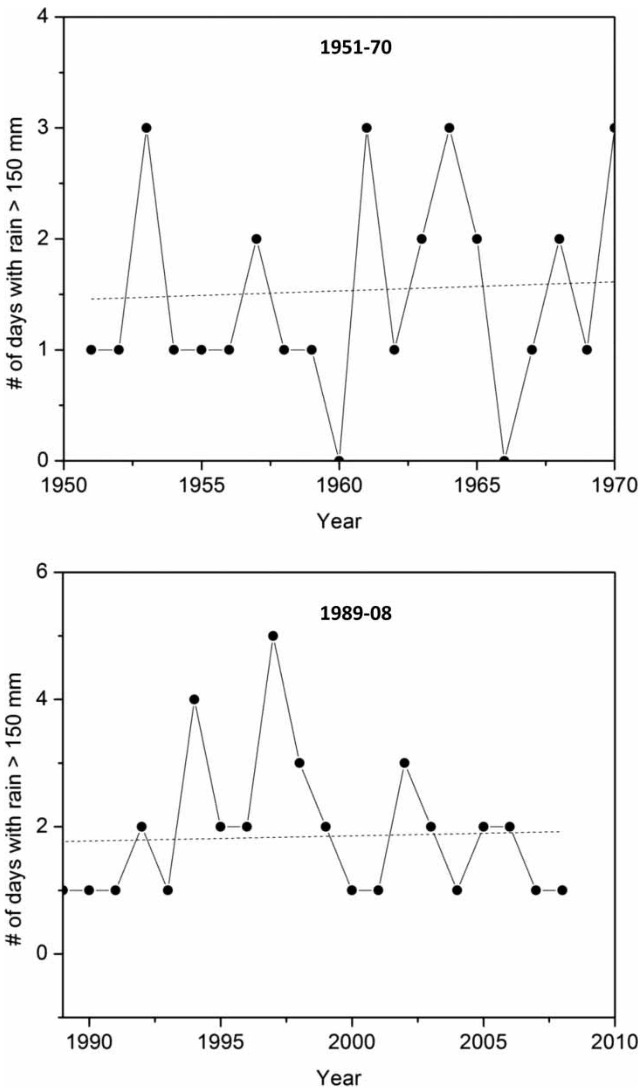

Figure 9 | Variation of the number of days with rainfall greater than 150 mm with time.

rising trend at 95% significance level in both periods. Considering the earlier results that the magnitude of high intensity rainfall has increased in the recent 20 years, it can be inferred that the high intensity rainfall amounts, as well as number of occurrences, have increased over the Narmada basin in the last 20 years.

Frequency analysis of extreme rainfall events

Considering the estimated increased trends in the occurrences of high intensity rainfall over the basin, 5 and 10-year return period rainfall for each zone have been computed to establish their trend. This information will be vital for the design and management of storm sewers in the urban cities falling in the basin. The n-year return period rainfall has been computed considering a moving window of 30 years. Subsequently, the 5 and 10-year return period rainfall have been computed for each of the 30-year moving windows, which gave a time series of 29 values for each moving window of 30 years. Thereafter, the MK test was applied to each of the time series of 5 and 10-year return periods to detect the trend. The spatial variation of the MK-test statistic for the 5-year return period rainfall (Figure 10) showed a significant increasing trend for most of the regions except three grid cells in the middle zone. A similar trend is also observed for the 10-year return period (Figure 11) of rainfall. These results clearly indicate that there is a need to re-examine the design aspects of the storm water drains in urban areas of the basin particularly in the context of the expected increase in high intensity storms in the future.

El Niño which has been known to be one of the most important forcing factors of the ISMR variability (Sikka 1980; Pant & Parthasarthy 1981; Rasmusson & Carpenter 1983; Webster *et al.* 1998), has apparently weakened in the last two decades of the 20th century (Kumar & Cane 1999; Kripalani & Kulkarni 1999; Slingo & Annamalai 2000; Ashok *et al.* 2001). A strong positive Indian Ocean Dipole (IOD) event witnessed in 1983 and 1997 has weakened the El Niño southern oscillation (ENSO)–monsoon relationship (Saji & Yamagata 2003; Ashok *et al.* 2004). The El Niño events apparently cause a significant deficit in rainfall (at 90% confidence level) over most of the country whereas the IOD events have a positive impact around the monsoon trough areas and a few parts of the west coast. However, IOD events have been very few in the last decades (Saji & Yamagata 2003) and therefore the extreme events over the Narmada basin are not a direct result of the natural inter-annual variability. Moreover, Goswami *et al.* (2006) have shown an increase in intensity and frequency of extreme events even though no change in seasonal mean of rainfall is observed.

Drought occurrence

Analysis of drought events for the three zones including their duration has been carried out for the initial 20-year

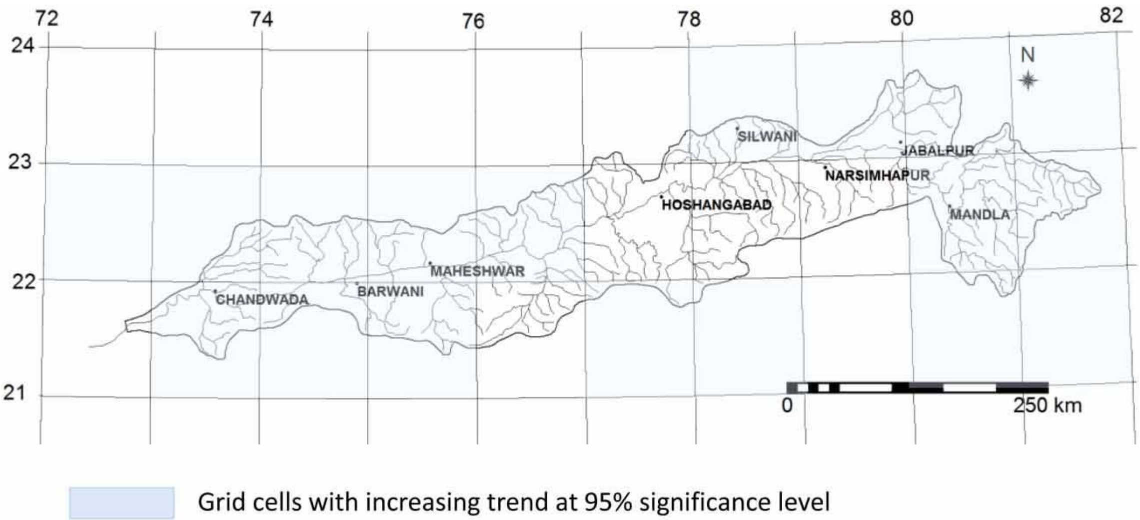

Figure 10 | Grid cells with significant increasing trends in 5-year return period rainfall.

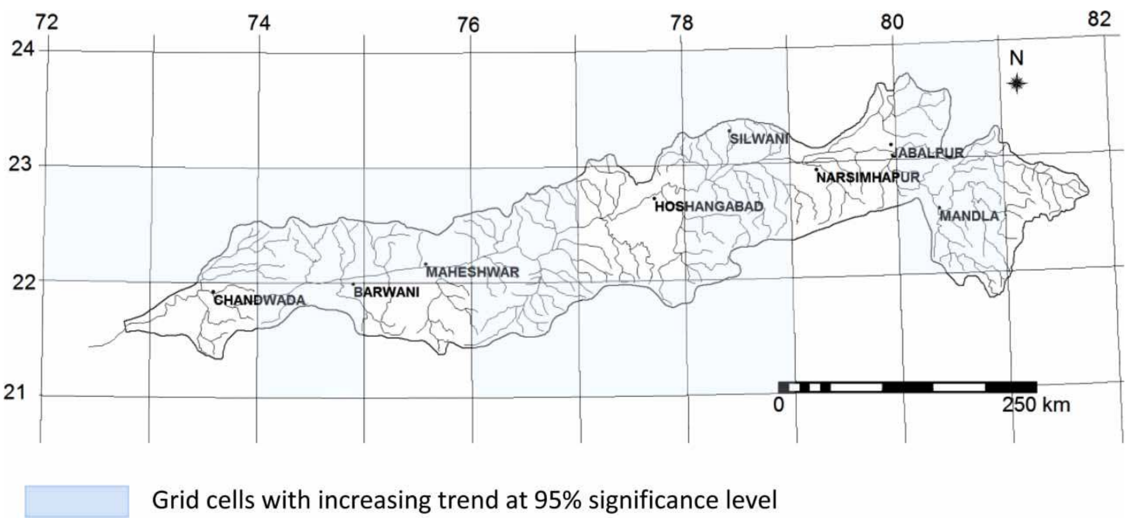

Figure 11 | Grid cells with significant increasing trends in 10-year return period rainfall.

period (1951–1970) and the recent 20-year period (1989–2008). Three time scales have been considered for analysis; 3-month SPI, which is indicative of soil moisture conditions in the basin 6-month SPI that represents surface water availability conditions and 12-month SPI, which is indicative of long-term storage including ground water availability. The SPI has also been computed with the station rainfall data and the resulting values of the SPI are not significantly different from the SPI values obtained from the gridded rainfall data. The comparison of the duration of drought months for the SPI value below -1.0 is given in Figure 12.

Figure 12 indicated that the middle zone is more prone to droughts because the drought duration in this zone has always been highest between 35 months for 3-m SPI and 52 months for 12-m SPI compared to other two zones. The comparison of the drought duration for the periods of 1951–1970 and 1989–2008 clearly indicated that all the three zones had experienced more droughts during the period 1989–2008 as compared to the period 1951–1970. This eventually suggests that the occurrence of the droughts over the basin during the last 20 years (1980–2008) has also been increased, along with the increase of

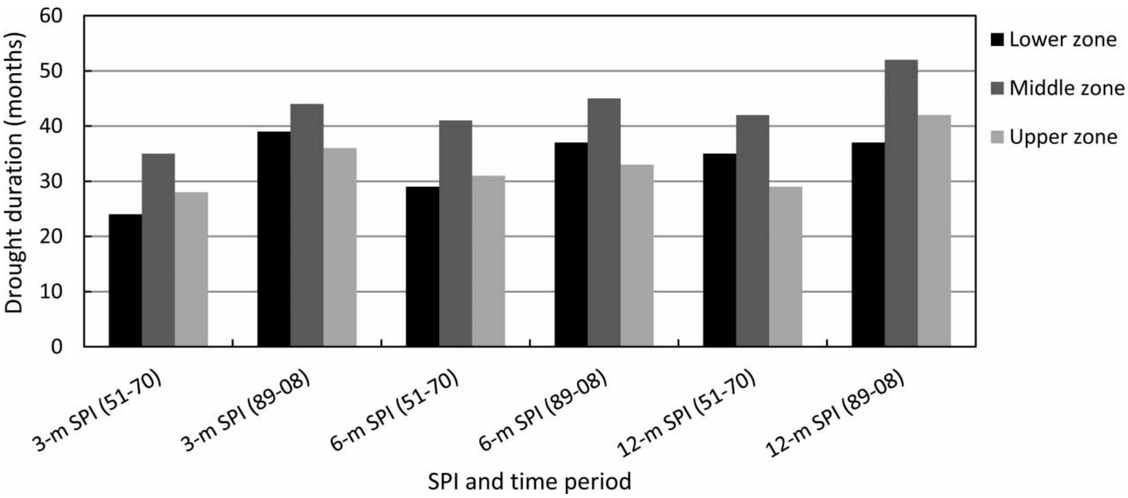

Figure 12 | Duration of droughts of different in various zones of Narmada basin.

high intensity storms. The comparison of the number of drought events that occurred with a duration of more than four consecutive months estimated based on the 12-m SPI showed that for the period 1951–1970 such events occurred twice in the lower and middle zone and only once in the upper zone, while during the period from 1989–2008, such events occurred four times in the upper and middle zone and only twice in the lower zone. This indicated that the frequency of drought events has remained more pronounced in the middle and upper zones. This information is significantly important with respect to agricultural activities in the Narmada basin. A prolonged drought may affect the sowing operations or completely destroy the standing crops and can thereby cause problems regarding food security in the region. Moreover, the increase in the drought duration in the upper zone that receives the highest rainfall, and maintains the sustainability of the river flow during the non-monsoon season, may lead to the dry condition of river flow downstream.

The analyses thus lead to the inference that the high intensity storms including the 1-day maximum rainfall, extreme, very heavy, and heavy rainfall and the occurrence of the drought events coexist in the basin. The characteristics of these two extremes can simultaneously be increased despite a reduction in the days of moderate rainfall events over the basin.

SUMMARY AND CONCLUSIONS

Daily rainfall of 23 high resolution ($1^\circ \times 1^\circ$) grid cells covering the Narmada basin have been analyzed to investigate the change in extreme rainfall events considering those as indicative of the climate change phenomenon. The trend analysis of the 1-day maximum rainfall series for a period of 58 years showed a significant positive trend at 95% significance level with the MK test statistic value of $z = 3.66$ over the entire basin. It was observed that the mean rainfall of the two time periods varies significantly at 95% significance level according to *t*-test. There has been an increase in the magnitude of 1-day maximum rainfall over the basin during the recent two decades. The analysis also indicated that more areas (spatially) in the basin are experiencing high intensity storms, and this was more prominent in the recent 20 years. The number of rainy days with more than 100 mm rain has decreased during 1951–1970, whereas the same has increased during 1989–2008. Further, the number of high intensity rainfall days is experienced more in the more recent 20 years. A significant increasing trend in the magnitude of 5, 10, and 25-year return period rainfall has been observed in most of the regions in the basin. The comparison of the drought duration estimated by the SPI, for the periods 1951–1970 and 1989–2008, indicated that the entire basin has experienced more droughts during the recent 20-year period. The middle zone has been found to be more prone to droughts.

The trends of extreme events indicate that the possibility of rain-related extremes are going to increase over the Narmada basin. The extreme rainfall events generally results in flash floods and crop damages that have major impacts on society, economy, and environment for which disaster preparation must be enhanced. Although prediction of such extreme events is still fraught with uncertainties, a proper assessment of the likely future trends would help in disaster management and evolving adaptation mechanisms. In closing, the increase of the high intensity storms as well as the increased frequency of drought occurrence during the recent 20-year spell suggests that appropriate measures should be considered for better management of the water resources in the basin, and also for mitigation of floods and droughts. We further believe that increasing temperature due to increasing anthropogenic activities may not be viewed as the only reason for increase in intensity and frequency of extreme events over the basin. A deeper understanding is needed to emphasize the role of land use changes, increase in greenhouse gases, etc., and their consequent effect on rainfall variability over the basin. We believe that high resolution dynamic modeling supplemented by a high resolution network of observational data will help in better understanding the implication of climate change on rainfall variability.

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