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ORIGINAL PAPER

Climate change indications in short-period rainfall records from coastal India using trend analysis: a proposed framework

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Abstract

Climate change has reportedly resulted in higher magnitude and frequency of extreme weather variables in many parts of India. Such studies pertaining to rainfall were based on long-period records, gridded rainfall data, or climate model projections, which have inherent uncertainties. As long-period records might not be available for many locations, gridded data or climate model analysis could be supplemented with the examination of short-period observations (<20 years) for climate change effects. Detecting climate change effect from short-period high-resolution data has not yet been reported in the literature. For such exercise, this study proposes a framework based on trend analysis along with a demonstration case at a coastal site in India. Using the proposed analysis, indications of climate change are identified in short-period (January 1997 to December 2013: 17 years) high-resolution (hourly) rainfall data, which are subsequently corroborated with results from long-period (60-year) annual data from the site. This proof-of-concept study opens up an intriguing possibility of detecting climate change indications from short-period data, subject to validation on a larger scale with observations from more weather stations. The results could aid judicious decision-making regarding safety margins required in hydraulic design, to account for climate change effects. The methodology, if corroborated with more studies, might prove useful for detecting climate change effects from other short-period hydro-meteorological data as well.

Keywords Climate change · Indian monsoon · Rainfall records · Sen's Innovative Method · Short-period data · Trend analysis

Introduction

Intergovernmental Panel on Climate Change (IPCC) reported that the twenty-first century would be much warmer than earlier, due to rapid urbanisation, deforestation, greenhouse gases, and global warming—resulting in climate change effects varying over space and time (IPCC 2014). For India, the effects of climate change have been reported as an increase in frequency and intensity of extreme rainfall events in several sub-divisions while the trend is decreasing in a few (Guhathakurta and Rajeevan 2008). The increase in the number and intensity of extreme point rainfall events are reported for India (Khaladkar et al. 2009), notably for peninsular, east, and north east India (Guhathakurta et al. 2011). Such weather extremes resulting from global warming and climate change would have adverse socio-economic impacts in India—owing to the unique climatic regime, large population and rapid growth therein, and advancing urbanisation (Rathore et al. 2016). The in situ weather observational network maintained by Indian Meteorological Department (IMD), analysis forecast products, early warning, and disaster preparedness in place for India were discussed (Kumar et al. 2016). The adverse effects of climate change on agriculture in India have been highlighted (Bhardwaj et al. 2022; Baig et al. 2022; Kulanthaivelu et al. 2022). The effects of climate change on groundwater hydrology have been investigated (Swain et al. 2022). The negative impact of deforestation and climate change on the biodiversity in North-Eastern India has been identified and remedial measures have been suggested (Gogoi and Lahon 2022). Such studies bear sufficient indications that the manifestation of climate change would be happening across India, though the effect and intensity could be spatially varying.

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Studies on the trend of rainfall and temperature in India and the associated implications of climate change are aplenty (Thapliyal and Kulshrestha 1991; Mehrotra and Mehrotra 1995; Kothyari and Singh 1996; Naidu et al. 1999; Stephenson et al. 2001; Lal and Singh 2001; De 2001; Wilk and Hughes 2002; Kumar et al. 2006, 2010; Dash and Hunt 2007; Dash et al. 2007; Krishnamurthy et al. 2009; Pal and Al-Tabbaa 2009, 2010; Krishnakumar et al. 2009; Bhan 2010; Guhathakurta et al. 2011; Auffhammer et al. 2012). For brevity, the present discussion is limited to few articles from the last decade.

Conducting an extensive review of the trend of rainfall and temperature in India, Jain and Kumar (2012) reported inconclusive results. Ghosh et al. (2012) examined the trend of Indian rainfall using extreme value theory and reported a lack of spatial uniformity, a feature that highlights the importance of site-specific evaluation. Kumar et al. (2013) presented downscaled climate change projections for South Asia and India, wherein all three regional climate models yielded similar results. The warming over India was projected as 1.5 °C by end of 2050 and 3.9 °C by the end of the century with rainfall increasing in peninsular India and remaining unchanged or decreasing inland. Salvi et al. (2013) presented statistical downscaling of daily rainfall projection data from climate models at 0.5° resolution for India and indicated a possible increase of rainfall over western coasts and north-east India along with a decrease in south-eastern coast, northern India, and western India. Trend analysis of 141-year (1871–2011) rainfall records over 30 sub-divisions of India revealed decreasing annual and monsoon rainfall in most of the sub-divisions as the net impact of climate change (Mondal et al. 2015).

Analysing 1901–2014 data, Radhakrishnan et al. (2017) reported a significant negative trend for Indian rainfall over the last 30 years. Coupled Model Intercomparison Project Phase 6 (CMIP6) offered improvements over the predecessor CMIP5, as reported by Gusain et al. (2020), particularly for the identification of the spatiotemporal pattern of rainfall in the Western Ghats and Himalayan foothills. The present-day global warming of 0.6 °C over Indian landmass was found to be consistent with the changes in annual maximum daily precipitation (multi-model average) in CMIP6. Using a regional climate model, Rai et al. (2020) evaluated the change and variability of rainfall in rainfall-homogenous regions in India, for mid-future (2030–2060) and far-future (2070–2099), with 1976–2005 data as a reference. Mean precipitation was observed to increase by over 50% for several meteorological subdivisions, with the north-west, north-east, and hilly regions having increased rainfall and peninsular India having less in mid-future and far-future. The projected trends appear to be contradictory to the other studies based on observational data or downscaled data, particularly for peninsular India (Guhathakurta et al. 2011; Kumar et al. 2013; Salvi et al. 2013). This could possibly be due to the particular regional climate model or the representative concentration pathway considered in the analyses. Trend analysis of rainfall in meteorological divisions of India (1901–2015) revealed an increasing trend of overall rainfall before the 1950s, and decreasing thereafter, affecting the availability of freshwater resources.

Variation in the long-term trend was observed for the state of Odisha, India from the analysis of 135-year (1871–2006) rainfall data, when considered on annual, seasonal, or monthly scales (Patra et al. 2012). Rainfall trend during pre-monsoon and post-monsoon was increasing, whereas the monsoon season, except August, had decreasing trend. Annual rainfall data from 62 years (1949–2010) of Sagar and 65 years (1945–2010) of Damoh districts of the Bundelkhand region of central India revealed decreasing long-term trend (Rai et al. 2014). Trend analysis of gridded daily precipitation data over the Narmada basin in India reported climate change being evident as more frequent droughts during 1989–2008, with 1951–1970 as the reference level (Thomas et al. 2015).

The impact of climate change on the precipitation and intensity–duration–frequency relationship for Roorkee, India, was analysed using an observed and ensemble of five general circulation models, revealing increasing rainfall intensities (Singh et al. 2016). A similar study was reported for Jorhat, Assam wherein autoregressive time series models were developed on 35-year data (1965–2000), tested on 8-year data (2001–2008), applied for obtaining projections till 2050 and finally concluded the absence of any significant trend (Dabral et al. 2016). Analyses of 100-year data (1901–2000) for rainfall for 236 districts in Ganga basin revealed that 39 districts displayed a significant negative trend, attributable to climate change (Bera 2017). Another study with 111-year rainfall data (1901–2011) for Madhya Pradesh reported decreasing rainfall trends for all seasons, particularly monsoon (Kundu et al. 2017).

Being majorly an agriculture-dependent country, variations in rainfall due to climate change would impact Indian economy. Mishra et al. (2013) demonstrated improved irrigation efficiency based on short-period rainfall forecast with a field study in Kharagpur, India. Public perceptions and sensitivities towards local weather changes affect the proactive adaptation measures taken and could impact the vulnerability of a community towards climate change (Howe et al. 2014). Changes in rainfall for drought-prone districts, Balangir and Nuapada in Odisha state, India was investigated, correlating with farmers' perception of climate change (Panda 2016). Analysis of 30-year data from 230 villages in India revealed that the farmers responded to rainfall shocks with non-farm wage jobs, suggesting increasing vulnerability in future, particularly for places with historically less variable weather (Chuang 2019). A recent study highlighted the variations of long-term and (recent) short-term rainfall records for many of the sub-divisions in India, attributable to the effects of climate change (Gangarde et al. 2022). Such findings make the analyses of site-specific data more significant for critical and important infrastructure.

Evaluation of the effects of climate change on critical infrastructure has been taken up in the last decade, but the studies were mostly limited to bridges. Though climate change has been indicated as a potential concern for the safe hydraulic design of bridges, a specific guideline for addressing the risk has not been provided by the US Department of Transportation (USDT 2012). A study indicated that increased imperviousness due to urbanisation/development upstream greatly increased the risk of freeboard reduction due to rising water levels and bridge flooding (Bhatkoti et al. 2016). The effect of projected climate change on bridge reportedly resulted in an increase of 0.85 m in water level, 0.3 m/s in water velocity, and cascading effects such as an increase in scour depth, forces, and moments (for piers) due to a 100-year storm (Ifelola 2017). Overtopping and scour depth were identified as the prime concerns for bridges under future climate change scenarios (Akhter 2018). A recent review article by Nasr et al. (2020) summarized the potential climate change effects on bridge infrastructure and suggested possible adaptation options, applicable in part or whole, for other critical infrastructure as well. Notably, such climate change impact studies targeted towards Indian inland infrastructure are missing from the literature. The findings of such research studies need to be distilled into guidelines for addressing climate change effects for important and sensitive infrastructure. Such specific guidelines are presently scarce in the literature.

From the foregoing discussion, it can be concluded that the effect of climate change on precipitation in India has been firmly established. The extremes (high rainfall leading to flooding or low rainfall leading to droughts) would affect agriculture, livelihood, and the general economy. Whereas information on both extremes over larger areas would be of interest for agriculture and water resources planning, evaluations of the higher extremes would become pertinent for flood risk assessment, particularly for critical infrastructure and densely populated urban localities. For the safety of important infrastructure such as long-span bridges, sea links, power plants, large dams, nuclear facilities, or chemical refineries, evaluation of climate change effects on the point specific extreme (high) rainfall would be necessary. The importance of probabilistic knowledge of climate change and integration of the same in the formulation of inclusive climate policies has been elucidated by Narain (2022). To that extent, climate change and global warming effects were incorporated into the forecast of Indian summer monsoon rainfall with a series of dynamic and physical climate networks (Fan et al. 2022) and these generalized forecast products would be useful for planning agriculture or water resources. On the contrary, for safety evaluation of existing important and critical infrastructure such as dams, bridges, or power plants, or for factoring possible climate-change effects into the design of new ones, more specific products would be necessary. Whereas for rivers, long-term water level records and precipitation records might be available and can be used for evaluation of the safety of dams or bridges, in other cases such as upcoming refinery or nuclear facilities, the rainfall data available from the specific site observation could be limited to a few years.

The general and specific guidelines for India are provided by the Bureau of Indian Standards (BIS) in various codes and standards. However, such guides in India generally lack any specific stipulation for incorporating climate change effects in the estimation of extreme storm events (surface drains: BIS 1978; drainage of building basement: BIS 1987; hydraulic design of barrages and weirs: BIS 1989; storm analysis: BIS 2003; cyclonic resistance of buildings: BIS 2004; wind load calculations including cyclones: BIS 2015). Codes applicable for flood evaluation for nuclear facilities in India are provided by Atomic Energy Regulatory Board (AERB) and these suggest the use of a safety margin to address climate change and global warming issues (AERB 2002, 2014). In order to incorporate changes arising from recent observations and updated knowledge, such estimations are subject to periodic review once in ten years (AERB 2002). Being away from population centres, the weather monitoring generally starts after the identification of the site for nuclear facilities, and therefore, observed data could be limited from 10 to 15 years at the design stage. A similar scenario might exist for other critical or hazardous infrastructures as well. Thereby evaluation of climate change in any of these cases would not be possible by adopting conventional methods.

In trend analysis and climate change literature, records of 30 or more years are considered as a ‘climate’ such that the transient variations do not influence/suppress valid inferences. The general practice is to evaluate some variable (say, maximum rainfall for a particular probability of exceedance, or the slope of the trend line of the variable) for two sets of data: the first 30 (or more) years defining the past (present) climate; the latter 30 (or more) years defining the present (future) climate; and subsequently comparing the results. This conventional approach would not be useful for application on short-period data. The majority of the studies employed observed rainfall data for this purpose (Jain and Kumar 2012; Patra et al. 2012; Rai et al. 2014; Mondal et al. 2015; Panda 2016; Rathod et al. 2016; Radhakrishnan et al. 2017; Kundu et al. 2017; Bera 2017; Praveen et al. 2020). Gridded rainfall data (Thomas et al. 2015) or climate change general circulation model (GCM) results (Salvi et al. 2013; Kumar et al. 2013; Singh et al. 2016; Rai et al. 2020; Gusain et al. 2020) can be adopted for the past and future climate to project climate change effects.

However, because of large uncertainties associated with climate projections, for estimating site-specific precipitation, regenerated or projected rainfall data is recommended to be supplemented with site-specific observations, particularly for sensitive structures such as nuclear facilities (Kumar et al. 2013; Song et al. 2020; Salimian et al. 2021). As indicated earlier, observational data at new nuclear sites are generally limited between 10 and 15 years at the time of finalization of designs. Presently, evaluation of climate change effect from short-period rainfall record is not readily available in the literature, with all studies with recorded rainfall considering 30 years data (or more) as 'climate' for analysis. The hydraulic designer, consequently, is left with the little technical basis for deciding upon the safety margin that would be required to account for climate change for the nuclear structures, or other critical structures (AERB 2002, 2014). This suggests that a novel approach would be necessary to evaluate such short-period data for the impact of climate change, similar to the improvised methodology for extreme value analysis of rainfall data, along with the clock hour correction factor, performed for this site earlier (Dauji 2022a, b).

The present study proposes a novel conceptual framework for examining short-period (in the present study, 17 years: January 1997 to December 2013) high-resolution (in the present study, hourly) rainfall data for evaluation of climate change effects. This is proposed to be performed with analyses of the trend of several chosen rainfall variables (both frequency and magnitude) using Sen's Innovative Trend Analysis (Sen 2012, 2017). Climate change effects are generally indicated by an increase in extremes reflected in both magnitude and frequency. Therefore, it is postulated that the proportion of increasing trends observed for these variables (evaluated from the short-term data) would indicate the probability of the extreme rainfall events at the site being affected by climate changes. Such inferences might be later corroborated with the trend analysis of long-period rainfall data, as and when available from the site. However, this proof-of-concept study should be supported by many similar studies across India and the world for gaining wider acceptance and recognition by hydraulic designers. The probability of climate change affecting extreme rainfall for the particular site estimated in the proposed approach from short-period site-specific records could be useful as a scientific basis for the selection of design margins to accommodate climate change effects (AERB 2002, 2014; USDT 2012). This framework may be considered by the regulators (BIS, AERB, USDT, or others) for later incorporation into the codes.

Novelty of the proposed framework

As indicated in the short review of climate change studies on rainfall data presented earlier, the conventional approach requires long-term rainfall records from a site. Owing to the fact that climate change effects have high spatial variability, site-specific inferences become necessary for critical infrastructure. For some important and sensitive infrastructure, site records might be limited to ten or fifteen years, rendering this conventional approach unsuitable for site-specific inferences regarding climate change effects. However, the method for evaluation of climate change effects from short-length data is not available in the literature. The novelty of the proposed framework is that by adopting this concept, short-period high-temporal resolution rainfall data can be examined for pieces of evidence of climate change. The framework is based on the analysis of the trend of selected magnitude and frequency rainfall variables for a given site using Sen's Innovative Trend Analysis (Sen 2012). The proof-of-concept study needs corroboration with short-period rainfall records from many other locations for broader acceptability by hydraulic designers. This approach may be extended for spatial applications with rainfall records from multiple weather stations or other hydro-meteorological variables as well.

After the introduction to the topic in this section, the remainder of the article is arranged as follows. The description of the methodology and the data employed for the study is provided in the subsequent section: Methods and Data. The results obtained from the analyses, interpretation, and detailed discussion of the results follow in the 'Results and Discussion' section. The salient findings of the study are summarised and future directions are indicated in the final section, 'Conclusions.'

The objective of the article is to propose a statistical framework for identifying the climate change effects from short-period meteorological data (say, rainfall) from the site of some critical infrastructure. The result obtained from this framework would be the probability that a particular meteorological variable at the given site would be affected by climate change. This probability would form a scientific basis for the design engineers to ascertain the safety margin that can be adopted to factor in the future climatic effects in the hydraulic design of the critical infrastructure. As explained in the foregoing discussion, such framework for identification of climate change effect from short-period data or any basis for fixing the climate-change safety margin for critical infrastructure is presently missing from the literature. The numbers obtained in this study could provide a scientific basis for the safety margins to be adopted for hydraulic design for critical or hazardous establishments in the locality, particularly industrial and nuclear facilities.

Methods and data

Site description

Hourly rainfall records obtained from a captive weather station located on the eastern coast of the Arabian Sea, around 150 km north of Mumbai would be used in this study. The site on the Konkan belt is one of the highest rainfall zones in India, with heavy monsoon rainfall occurring during the period from June to September.

Data

Continuous hourly rainfall data of the site was available for the period 1997–2013, termed as short-period data throughout this article. The data was examined for quality and was reported to be of high quality (Harshanth et al. 2021). Lower temporal resolution (annual) data was available from the site spanning 60 years, termed as long-period data throughout the article. This data can be analysed for climate change effects using the conventional method. The annual data was available for four variables: annual total rainfall; monthly maximum rainfall; daily maximum rainfall; and hourly maximum rainfall for the period of 1961–2020.

Sen's innovative trend analysis methodology

The limitations of conventional trend analysis could include less power for small sample size or for data with serial correlation; deviations of data from normal probability distributions, possible skewness of data; and requirement of pre-whitening of data before application, among others. Sen's innovative trend analysis and slope estimation overcame these limitations (presence of trend: Sen 2012; slope estimation: Sen 2017). Application of this method has found numerous applications in hydro-meteorological time series (rainfall and runoff: Sen 2012; Dabanli et al. 2016, temperature: Sonali and Kumar 2013; Sen 2014; Dabanli et al. 2016, relative humidity: Dabanli et al. 2016, droughts: Malik et al. 2020). As it involved short-period data, this method was deemed suitable for this study. Basically, this method involved a graphical interpretation of the presence of trend (Sen 2012; Dabanli et al. 2016). Formulations are available for estimation of the slope and intercept of the trend line, reproduced as Eq. 1 and Eq. 2 respectively (Sen 2017).

$$s = \frac{2(\overline{y}_2 - \overline{y}_1)}{n} \tag{1}$$

where $\overline{y}_1$ and $\overline{y}_2$ are the arithmetic averages of the first and the second halves of the dependent variable, y, and n is the total number of data.

$$a = \overline{y} - \frac{2(\overline{y}_2 - \overline{y}_1)}{n} \times \overline{t} \tag{2}$$

where $\overline{y}$ and $\overline{t}$ are the arithmetic average of dependent variable and time sequence respectively and n, $\overline{y}_1$, and $\overline{y}_2$ are as listed for Eq. 1.

For further details of the method and application aspects of Sen's innovative trend analysis, interested readers are directed to the literature (Sen 2012, 2017; Dabanli et al. 2016). An interesting normalization procedure was proposed by Dauji (2021) for the comparison of the trend of two or more datasets with absolute values in different ranges (or different orders of magnitude) and was demonstrated with COVID-19 data from India. This method would be useful in comparing Sen's innovative trend for the first and second halves of the long-period rainfall data in a single scatter plot.

Proposed framework

Generally, the climate is considered for weather data belonging to 30 or more years. Due to the paucity of long-period hourly data, identification of climate change for a given site might be required to be performed based on high-resolution short-period data. The proposed framework for achieving this target is as follows. It is postulated that occurrences of higher (or lower) magnitude events in short-period high-resolution data, both in terms of frequency as well as absolute magnitude (as enumerated in Table 1), would indicate the manifestation of climate change for this location.

The selection of the variables (fixing of the percentiles, for instance) was performed such that the number of non-zero entries was more than half of the total duration of 17 years; that is, there were 9 or more entries. As listed in Table 1, the number of variables was 154 and 222 for magnitude and frequency respectively. For other locations, variable selection can be different. Short-period data was available for 17 years (1997–2013) and Sen's (2012) innovative trend analysis was applied on the same to identify whether the trend was increasing or decreasing, for each of the variables. In Sen's (2012) innovative method, the presence of a trend is analysed graphically. In addition to the graphical interpretation, the positive value of estimated slope (Eq. 1) of the trend line (Sen 2017) would indicate an increasing trend, whereas a negative value would indicate a decreasing trend.

It is further postulated that the number of variables with increasing trend expressed as a percentage of the total number of variables (magnitude, frequency, and combined) would indicate the probability that climate change effects are manifested in the short-period data, in this case of 17 years.

Table 1 Variables examined for climate change effects: Short-period records (17 years: 1997–2013)

Variable	Period	Total numbers
Magnitude variables		
Total rainfall (mm)	June, July, August September, October, JJAS#, OND$, Annual	8×3=24
Daily maximum rainfall (mm)		
Hourly maximum rainfall (mm)		
[1 h; 2 h; 3 h; 4 h; 5 h; 6 h; 24 h] [Maximum; 99 percentile; 95 percentile; 90 percentile]	June, July, August, September	7×4×4=112
[6 h] [Median]	July, August	2
[24 h] [Median]	June, July, August, September	4
[1 h; 2 h; 3 h] Max;	OND$	3
[4 h; 5 h; 6 h] [Max; 99 percentile]	OND$	3×2=6
[24 h] [Max; 99 percentile; 95 percentile]	OND$	3
Total magnitude variables		154
Frequency variables		
Rainfall days	June, July, August September, October, JJAS#, OND$, Annual	8
Rainfall hours		8
No-rain days	JJAS#, OND$, Annual	3
No-rain hours	JJAS#, Annual	2
Weeks of rain	-	1
Weeks > median (46 mm)	-	1
Days > 85 percentile (45.5 mm)	-	1
Hours > 95 percentile (15.6 mm)	-	1
Number of weeks with rainfall (mm) in different ranges	Zero; 1 to 10; 10 to 20; 20 to 50; 50 to 100; 100 to 200; 200 to 400; > 400	8
[1 h; 2 h; 3 h; 4 h; 5 h; 6 h; 24 h] [< 10 percentile; < 20 percentile]	MAM*	7×2=14
[1 h; 2 h; 3 h; 4 h; 5 h; 6 h; 24 h] [< 10 percentile; < 20 percentile; > 60 percentile; > 70 percentile; > 80 percentile;]	OND$	7×5=35
[1 h; 2 h; 3 h; 4 h; 5 h; 6 h; 24 h] [< 20 percentile; < 50 percentile; > 80 percentile; > 90 percentile; > 95 percentile;]	June, July, August, September	7×5×4=140
Total frequency variables		222
Total short-period (magnitude and frequency) variables		154+222=376

*MAM, March–April-May; #JJAS: June-July–August-September;

$OND, October–November-December

Analysis of longer rainfall records would definitely improve the reliability of the inferences. Therefore, Sen's innovative trend analysis is performed for four available long-period variables recorded at the site: annual total rainfall; monthly maximum rainfall; daily maximum rainfall; and hourly maximum rainfall (Table 2). Readers may note that all these four variables happen to be magnitude variables. Analysis for trends using the same tool (Sen's Innovative Trend Analysis) would produce results comparable to the proposed method for the short-period data. The inference from the results of trend analysis applied to long-period data and short-period data would indicate the viability of the proposed framework. The simplicity of the method: Sen's

Table 2 Variables examined for climate change effects: Long-period records (60 years: 1961–2020)

Variable	Period	Total numbers
Total rainfall (mm)	Annual	1
Monthly maximum rainfall (mm)		1
Daily maximum rainfall (mm)		1
Hourly maximum rainfall (mm)		1
Total Long-period (Magnitude) Variables		4

Innovative Trend Analysis (Sen 2012) enables the completion of the analyses in Microsoft Excel software.

Results and discussion

In this section, first, the data statistics for both short-period and long-period data used for the study are briefly discussed. Thereafter, the results of trend analysis with Sen's innovative method are discussed in detail for some sample cases with short-period data. Subsequently, the summary of all results obtained for short-period data are examined for trend, and pieces of evidence of the effects of climate change are investigated. Finally, results of trend analysis of long-period records, the entire 60 years, as well as the first and second 30-year periods are compared for the pieces of evidence of the effects of climate change. The pieces of evidence from short-period data and long-period data are compared thereafter.

Statistics of rainfall data

Few salient statistics of short-period data are summarised in Table 3 (magnitude: Table 3; frequency: Table 4) and the same for the long-period magnitude data are listed in Table 5 for the rainfall observations from the site. A comparison of Table 3 and Table 5 reveals that whereas the total annual and maximum monthly rainfall occurred earlier to the short period considered here, the maximum daily and maximum hourly rainfall happened during the short period under consideration. The variability of the total annual rainfall is almost 1.5 times for the long-period data (Table 5), when compared to the short-period data (Table 3); and for maximum monthly rainfall also the long-period variability is slightly higher. However, for the maximum daily and maximum hourly rainfall, the short-period variability (Table 3) is higher than the long-period one (Table 5). Despite less annual rainfall, maximum daily rainfall and maximum hourly rainfall having higher values, coupled with higher variability would

Table 3 Descriptive statistics of short-period (17 years: 1997–2013) rainfall magnitude data

Statistic	Annual rainfall	Maximum monthly rainfall	Maximum daily rainfall	Maximum hourly rainfall
Maximum (mm)	2937	1438	713	168
Minimum (mm)	1566	495	98	36
Mean (mm)	2067	845	255	66
Standard deviation (mm)	366	264	145	31
Coefficient of variation	0.18	0.31	0.57	0.46

Table 4 Descriptive statistics of short-period (17 years: 1997–2013) rainfall frequency data

Statistic	Number of annual weeks of rain	Number of annual rain-days	Number of monsoon rain-days	Number of annual rain-hours
Maximum	24	103	96	734
Minimum	17	71	66	462
Mean	20	95	88	558
Standard deviation	2.14	8.71	7.88	76.85
Coefficient of variation	0.11	0.09	0.09	0.14

Table 5 Descriptive statistics of long-period (60 years: 1961–2020) rainfall magnitude data

Statistic	Annual rainfall	Maximum monthly rainfall	Maximum daily rainfall	Maximum hourly rainfall
Maximum (mm)	3665	1601	713	168
Minimum (mm)	874	336	93	25
Mean (mm)	1938	817	220	60
Standard deviation (mm)	568	277	112	24
Coefficient of variation	0.29	0.34	0.51	0.40

indicate short intense rainstorms at the location during the short period under consideration (1997–2013), a typical signature of climate change effect on rainfall. The variability observed for the frequency variables (short-period data: Table 4) is relatively less ranging between 0.14 for the number of annual rainfall hours and 0.09 for rain days (annual or monsoon).

Trend for total rainfall

Sen's innovative trend plots are depicted in Fig. 1a for total annual rainfall and Fig. 1b for total monsoon rainfall. A monotonic and increasing trend is observed for the total annual rainfall, but for total monsoon rainfall, the trend appears to depart slightly from being monotonic, though it is conclusively increasing. Both these magnitude variables have an increasing trend.

Trend for number of weeks, days, and hours of rainfall

Figure 2a displays the annual weeks of rainfall to be non-monotonically decreasing, whereas Fig. 2b demonstrates that the monsoon rainfall days have a weak non-monotonic increasing trend. In contrast, the monsoon rainfall hours depict non-monotonic increasing trend in Fig. 2c. Out of these three frequency variables, one is decreasing and the other two are increasing, however weak.

Trend of number of weeks with different rainfall ranges

The number of annual weeks with moderately high rainfall (100–200 mm) as well as high rainfall (200–400 mm) clearly show non-monotonic increasing trend in Fig. 3a and Fig. 3b respectively. Hence these two frequency variables are both displaying an increasing trend.

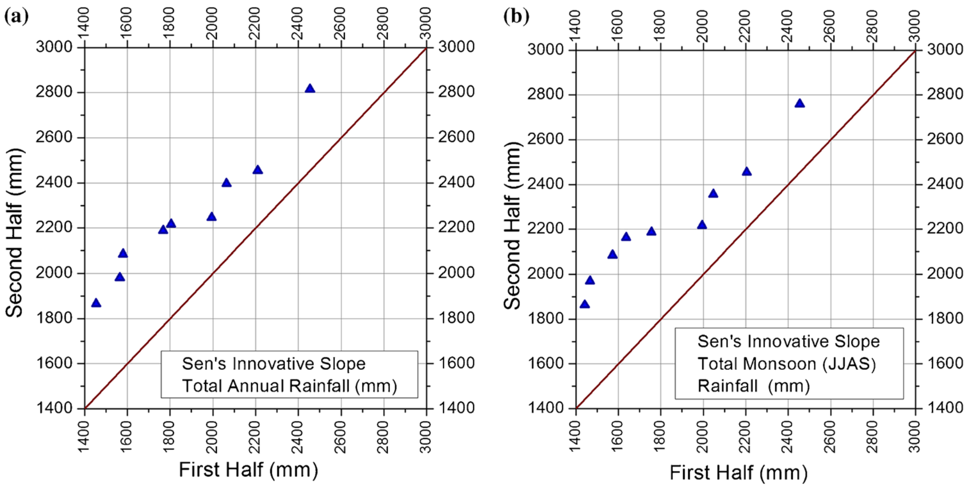


Fig. 1 Trend analysis of short-period data: **a** Total annual rainfall; **b** Total monsoon rainfall

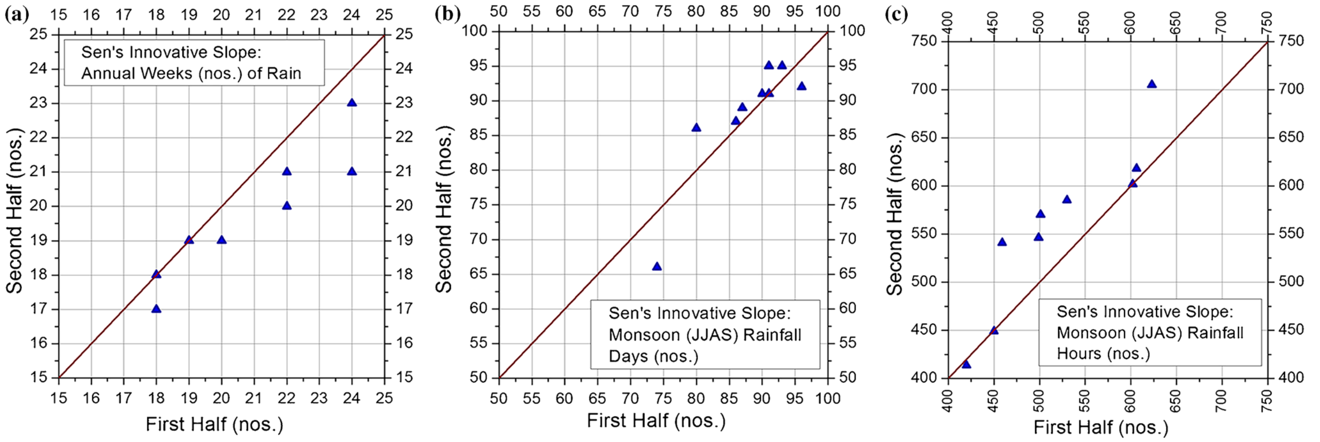


Fig. 2 Trend analysis of short-period data: **a** Annual weeks of rain; **b** Rainfall days in monsoon; **c** Rainfall hours in monsoon

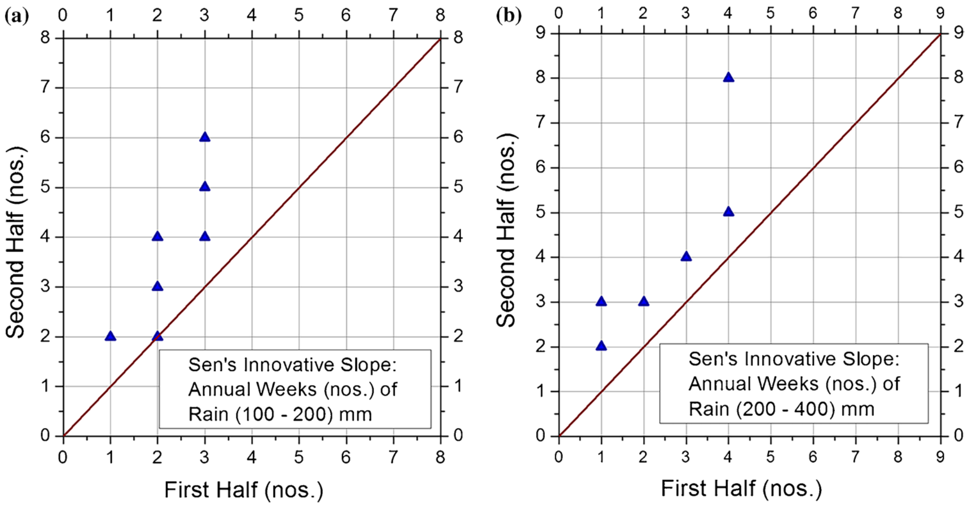


Fig. 3 Trend analysis of short-period data: **a** Annual weeks with rain between 100 and 200 mm; **b** Annual weeks with rain between 200 and 400 mm

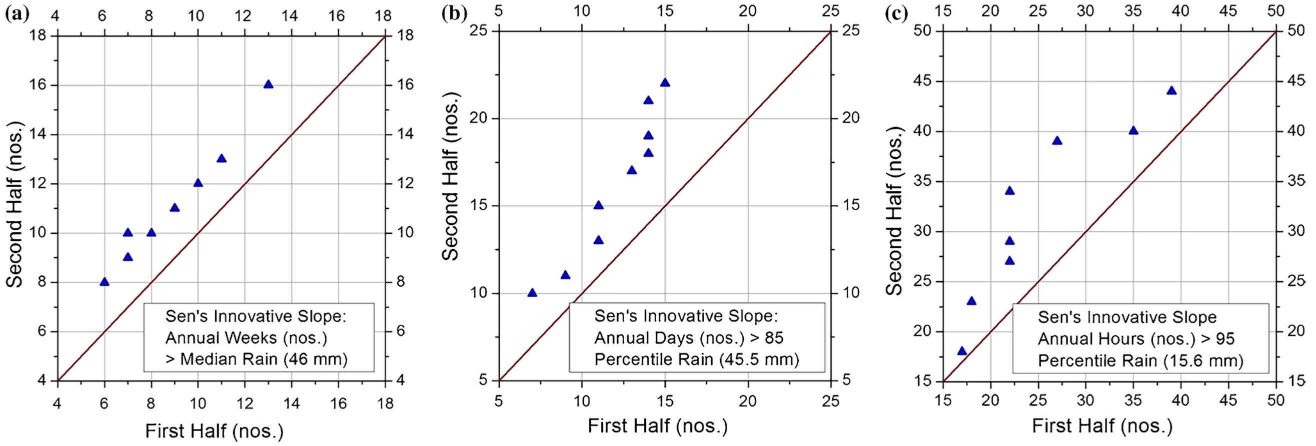


Fig. 4 Trend analysis of short-period data: **a** Annual weeks with rainfall higher than median weekly rainfall (46 mm); **b** Annual days with rainfall higher than 85 percentile daily rainfall (45.5 mm); **c** Annual hours with rainfall higher than 95 percentile daily rainfall (15.6 mm)

Trend of frequency of some extremes

The annual weeks having greater than the median weekly rainfall (46 mm) display a clear monotonic increasing trend (Fig. 4a), whereas the annual days (Fig. 4b) with greater than 85 percentile daily rainfall (45.5 mm) as well as the annual number of hours (Fig. 4c) having greater than 95 percentile hourly rainfall (15.6 mm) depict non-monotonic but increasing trends. All these three frequency variables have increasing trends, monotonic or otherwise.

Trend of magnitude of some extremes

The scatter plots for the maximum daily (Fig. 5a) and maximum hourly (Fig. 5b) trend, which happen to be the same for monsoon or annual, depict that considering the high values (≥ 400 mm daily or ≥ 100 mm hourly) are having decreasing trend. For daily maximum rainfall (< 400 mm) the trend is weakly and non-monotonically increasing, whereas, for the hourly maximum (< 75 mm), it can be inferred that there is a very weak non-monotonic decreasing trend.

Evidence of climate change from exhaustive trend analysis of magnitude and frequency of extremes from short-period data

As explained in the section: Methodology, a total of 154 magnitude variables and a total of 222 frequency variables (Table 1) from 17-year hourly rainfall records for the site were examined for possible climate change effects with trend analysis. The summary of the trends observed for magnitude variables is presented in Fig. 6 and the same for frequency variables is depicted in Fig. 7. The combined results from trend analysis of the magnitude and frequency variables are listed in Fig. 8, where it can be observed that there is 65% probability that the 17-year rainfall record displays evidence

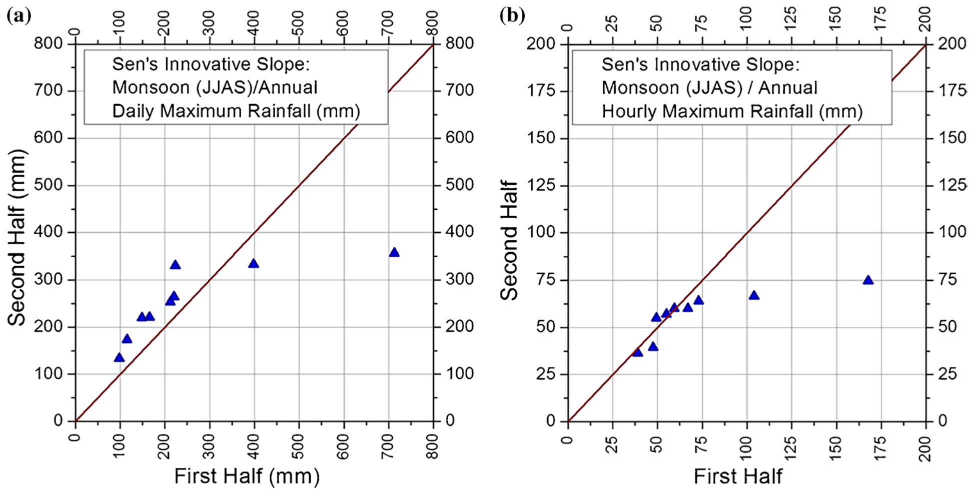


Fig. 5 Trend analysis of short-period data: **a** Maximum hourly rainfall (annual / monsoon); **b** Maximum hourly rainfall (annual / monsoon)

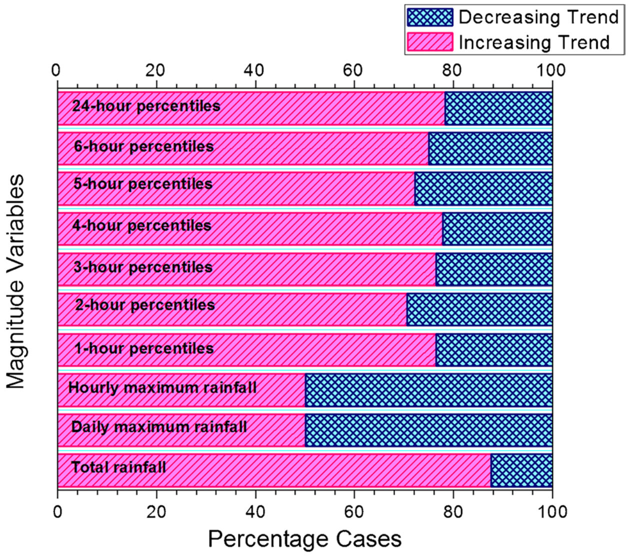


Fig. 6 Summary of trend analysis of magnitude variables for climate change effects

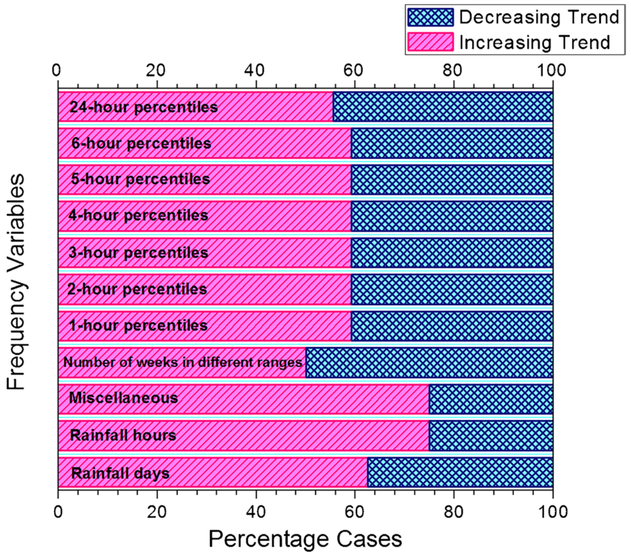


Fig. 7 Summary of trend analysis of frequency variables for climate change effects

of possible increasing effects of global warming and climate change. Considered separately, the probability of possible climate change effects increasing the magnitudes of extreme rainfall events work out as 73.4% and the probability of possible climate change effects in increasing the frequency of extreme rainfall events comes to a relatively lower value: 59.4%. This is a typical result wherein the magnitude of heavy rainfall is affected more than the frequency, though both are increasing due to possible climate change effects. The stormwater drainage system for small urban watersheds would generally be designed for storm periods ranging from 15 min to 2-h (BIS 2003), whereas the 24-h rainfall might be important for regional drainage (BIS 1978). Therefore, considering the fact that the probability of the magnitude of high rainfall event being affected by climate change effects stands at 73.4%, and that the 1-h, 2-h, and 24-h percentiles have respective probabilities of 76.5%, 70.6%, and 78.3% of increasing possibly due to climate change effects, the margin in hydraulic design values considered for critical infrastructure in the locality should be considered accordingly.

Evidence of climate change from trend analysis of long-period data

The data statistics for the long-period data were discussed earlier. Presently, the box plots of the same, split into 20 years each, would be examined in Fig. 9a–d for the climate change effect. The present approach of comparison of 20-year statistics is favoured over the regular 30-year approach for the purpose of highlighting the changes in

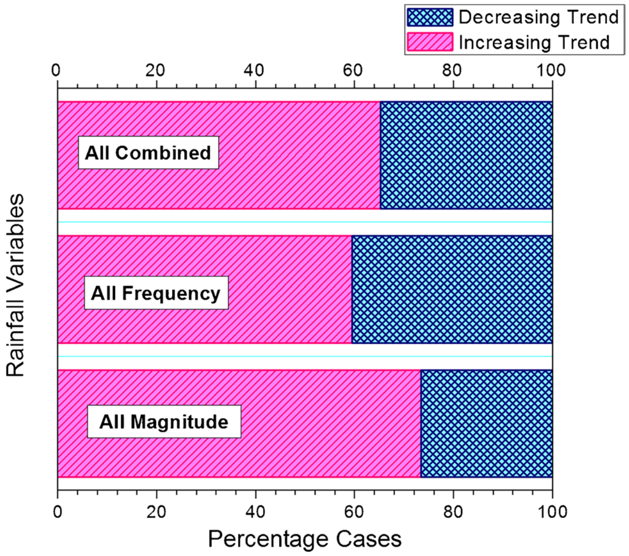


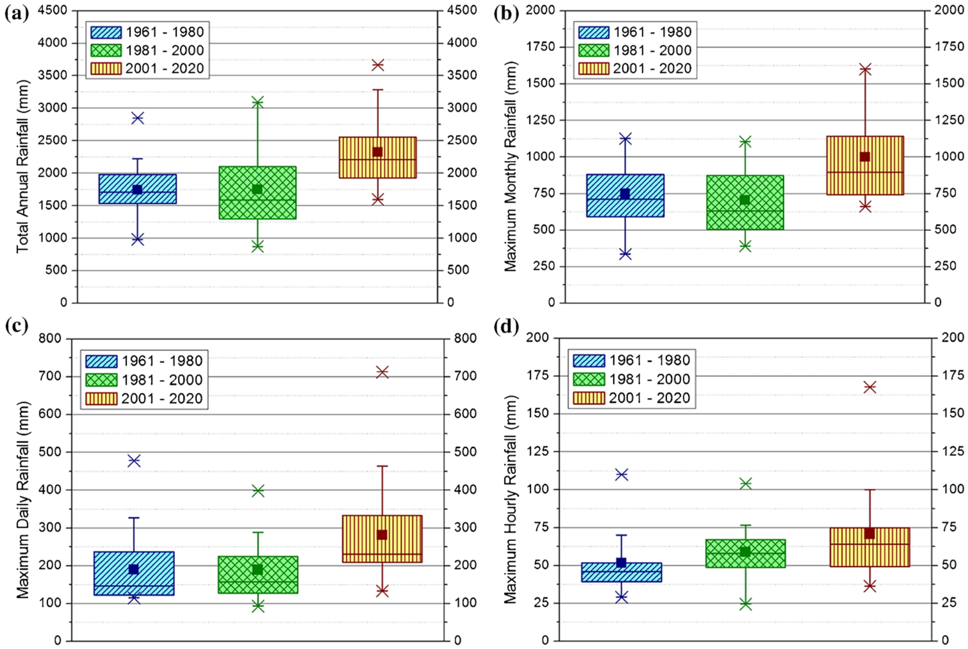
Fig. 8 Summary of trend analysis of combined variables (magnitude and frequency) for climate change effects

these variables in the recent (last 20) years. From the plots (Fig. 9a–d), it can be seen that the mean and median both have increased for all four variables (1.2 times to 1.5 times) in the last 20 years, compared to the earlier two 20-year periods. The figures also show a substantial increase in the range of variation (around 1.6 times) for the hourly maximum rainfall and daily maximum rainfall in the last 20 years. These observations indicate that the rainfall variables are increasing in magnitude and intense rainfall (daily or hourly) is displaying more variability in recent years. These would be correlated with the trend analysis in the next paragraph.

All three trends, total 60 years, first 30 years, and second 30 years, are reflected in the combined scatter plots (Fig. 10a–d), normalized as suggested in the literature (Dauji 2021). Whereas it can be concluded that the trend of the total annual rainfall is monotonically increasing when the entire 60-year record is considered, it is non-monotonically decreasing in the first 30 years and non-monotonically increasing in the second (Fig. 10a). In cases of maximum monthly rainfall (Fig. 10b) and maximum daily rainfall (Fig. 10c), the trend is non-monotonic; increasing considering the entire duration and second 30 years, and decreasing in the first. Considering the hourly maximum rainfall (Fig. 10d), the trend can be inferred as non-monotonic increasing for the entire duration. However, when the first and second 30 years are considered, the trends of lower and higher values are decreasing and of the middle range values are increasing (Fig. 10d). The slope of the trend line evaluated with Sen's innovative method for long-period data is presented in Table 6.

In Table 6, all four variables show a higher slope of the trend line in the second half (the value is positive: increasing) as compared to the slope of the trend line in the first half (the value is negative: decreasing). The trend of the total 60-year data for the four variables confirms the overall increasing trend, with all slopes having positive values. These results would indicate that climate change could be affecting the precipitation variables at the site in later 30 years, manifested in the increasing magnitude of the extreme rainfall events. It can therefore be concluded that the analysis of the trend in the proposed approach with short-period 17-year hourly rainfall data provided similar inference as the analysis of the trend of the long-period 60-year

Fig. 9 Box and whisker plots for long-period data: **a** Total annual rainfall; **b** Maximum monthly rainfall; **c** Maximum daily rainfall; **d** Maximum hourly rainfall



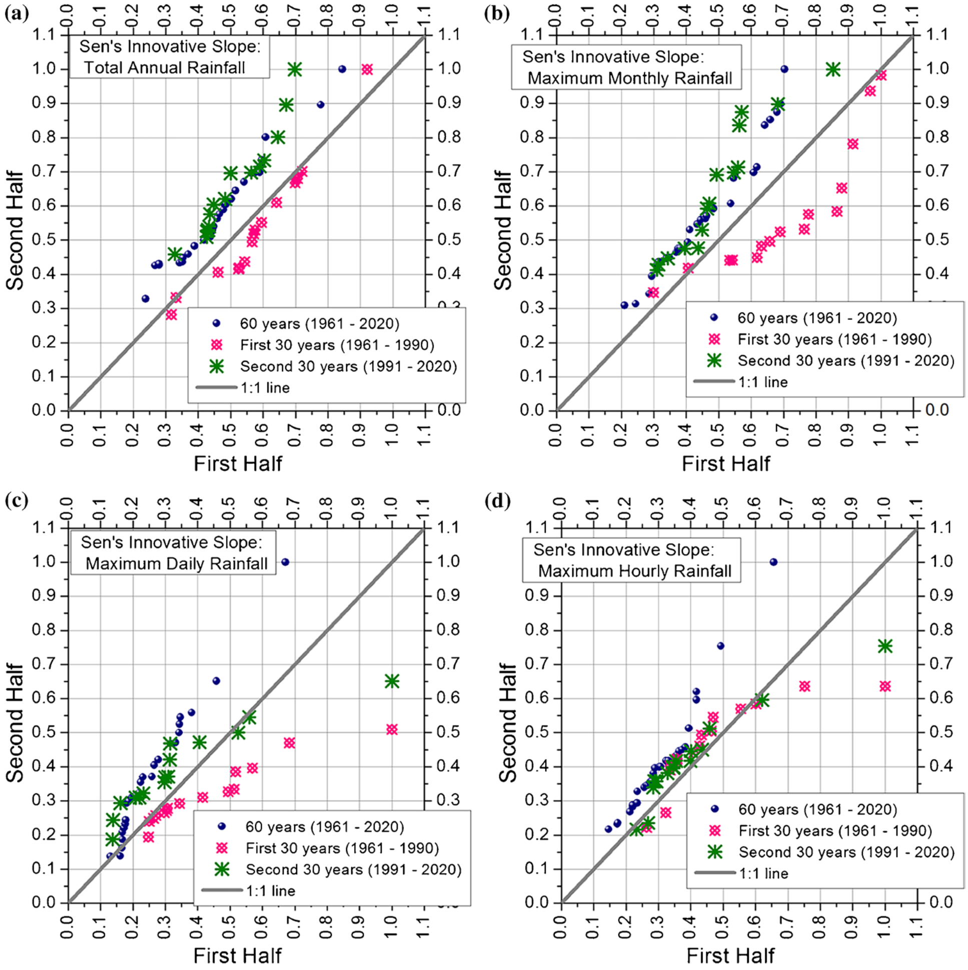


Fig. 10 Trend analysis of long-period data for climate change effects: **a** Total annual rainfall; **b** Maximum monthly rainfall; **c** Maximum daily rainfall; **d** Maximum hourly rainfall

Table 6 Slope of the trend line using Sen's innovative method: Long-period records (60 years: 1961 – 2020)

Variable	Slope of trend line			Remarks
	Total 60 years	First 30 years	Second 30 years	
Total annual rainfall	14.06	– 8.92	36.23	Increasing trend
Monthly maximum rainfall	6.47	– 9.48	15.90	Increasing trend
Daily maximum rainfall	2.68	– 3.59	2.21	Increasing trend
Hourly maximum rainfall	0.58	– 0.04	0.17	Increasing trend

rainfall records. This finding imparts more confidence in the applicability of the framework with short-period data proposed in this article.

Application of proposed concept for adaptation to climate change and hydraulic safety

It is a possibility that the results of this proof-of-concept study, that is, climate change indications from the short-period record being corroborated by long-period records, could be incidental. Therefore, before the proposed approach can be accepted by the hydrologic community, it needs to be corroborated with similar studies with short-period and long-period records from many other locations. However, if and when this is established as a valid approach, it would benefit the hydraulic design of the civil structures for the important and critical infrastructure facilities by providing a basis for judicious selection of the safety margins (presently missing from the design codes and standards) to account for the climate change effects even from short-period site observations. Improved hydraulic safety would help to reduce the risk of inundation and flooding of the facilities and keep the infrastructure functioning smoothly through heavy storm/precipitation events.

Conclusions

In this study, a novel framework has been proposed for examining short-period data for climate change, which was hitherto missing from the literature. This method would serve as a scientific basis for the judicious selection of the safety margins needed to be applied to the flooding studies for critical infrastructure to account for climate change. As a demonstration, short-period hourly rainfall data of 17 years from a high-rainfall coastal location in India has been examined for evidence of climate change effects, employing Sen's Innovative Trend Analysis for magnitude and frequency variables. Based on the general philosophy that climate change effects are manifested in the extreme events increasing in number (frequency) as well as absolute magnitude, the short-period rainfall records of the site revealed that there was around 73% probability that the magnitudes of extreme rainfall events were being affected by climate change; and that there was around 59% probability that the frequency of extreme rainfall events was affected by climate change; and considered in totality, there was around 65% probability that the rainfall at the study location was impacted by climate change. Similar analysis with long-period data (60 years: 1961–2020) revealed that the increasing trend of four rainfall variables over the second 30 years was higher than the first thirty. Consequently, higher magnitude rainfall events may be expected to increase in frequency as well as magnitude in the future at the site, and therefore, the margin to account for climate change effects should be judiciously selected for the hydraulic design of stormwater drainage systems and structures, particularly for sensitive facilities.

The reliability of the inferences from short-period data would definitely improve with the availability of data belonging to longer duration. However, it is a possibility that similar inferences from short-period and long-period data for the site could be incidental. Therefore, similar studies for other locations of different rainfall regimes would be desired for establishing this proof-of-concept study as a viable option. The results obtained in the proposed framework could be compared with those obtained from analysis of gridded rainfall data or global/regional circulation model data for better insights into the climate change impacts on meteorological variables. If corroborated by other similar studies, this conceptual framework might be extended for evaluating the effects of climate change on other short-period hydro-meteorological variables as well.

The proposed framework would particularly be extremely handy in examining short-period rainfall data from new sites in India for nuclear facilities or other hazardous installations for possible climate change effects, and therefore, could provide a scientific basis for deciding upon the safety margin to be adopted in hydraulic design to account for climate change according to the AERB (2002, 2014) guidelines. On a broader scale, for critical infrastructure sites in India or abroad, this approach can help judicious selection of the safety margins for the hydraulic design, to account for climate change, based on short-period high-resolution meteorological data.

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Data Availability The author received the data for limited research purposes only and is not authorized to share the data.

Declarations

Conflict of interest The author declares that he has no competing interests.

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