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RESEARCH ARTICLE

60 YEAR TREND ANALYSIS OF EXTREME RAINFALL INDICES OVER BANGLADESH

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ABSTRACT

This study investigated the patterns of extreme daily rainfall indices over eight meteorological stations in Bangladesh from 1961 to 2020, utilizing monthly and seasonal data sets. The climate change-related indicators comprised frequency-based indices: R10mm, R20mm, CDD, CWD and Intensity-based indices: RX1day, RX5day, R95p, R99p, PRCPTOT, SDII. The amplitude of trends in extreme rainfall indices time series was estimated using the nonparametric Sen's slope estimator method, and the statistical significance of the trends was assessed using the Mann–Kendall test. The result shows that rainfall in pre-monsoon has an increasing trend except for Dhaka station, with an increasing trend for monsoon Chittagong, Barisal, Maymensingh, and Rangpur, oppositely decreasing trend in the dry season for Dhaka, Barisal, Rangpur and Sylhet with the none-significant trend for any season. Frequency Indices had a significant increasing trend in Mymensingh, Rajshahi, and Rangpur stations, where Intensity Indices are followed by Rangpur station. Seasonal RX1 day and RX5 days there were no significant increases or decreases with time. Overall, rainfall trend analysis is critical in a variety of sectors, including water resource management, agriculture, climate change research, disaster risk reduction, and ecosystem management. It contributes to sustainable development and environmental preservation by providing essential information for planning and decision-making.

KEYWORDS

Extreme Rainfall, Trend Analysis, Significant, Frequency indices, Intensity indices

1. INTRODUCTION

Global environmental changes are significantly altering precipitation patterns worldwide, yielding profound ecological, social, and economic repercussions within local communities (Seneviratne, And Zhang, 2021). Among the notable shifts, the frequency and intensity of extreme precipitation events stand out, amplifying the risks of climate-related damages in various regions (Seneviratne, And Zhang, 2021). These alterations in precipitation dynamics are critical facets of the changing climate, impacting flood occurrences, drought conditions, water resources, and agricultural productivity (Jain and Kumar, 2012; Rahman, 2012). The repercussions of global air warming are evident in the modification of the water cycle, significantly affecting agricultural and economic development across regions (Rahman et al., 2012). Therefore, the assessment of precipitation variability, extreme precipitation events, and their concomitant climatic changes is presently a matter of considerable concern (Chattopadhyay and Edwards, 2016; Zhang et al., 2014). Studies examining environmental parameters reveal a transition in precipitation patterns from coherent spatial structures to highly regionalized designs (Jain, and Kumar, 2012; Chattopadhyay and Edwards, 2016; Zhang et al., 2014). The mean, mean maximum and mean minimum temperatures increased at rates of 0.103, 0.091, and 0.097°C per decade, respectively, for the rainfall period 1958–2007 in Bangladesh. Compared to other seasons, winter saw more warming (Islam et al., 2014; Shahid, 2011). Previous research on observed increases in extreme climate in Bangladesh has relied entirely on station data (Ahmed et al., 2017; Caesar et al., 2015). A few stations across the nation were insufficient for studying the spatial patterns of changes in extreme climate across the country due to the huge distances between stations and the high number of missing data (Khan et al., 2019). However, examined trends in daily extreme rainfall indices across Bangladesh from 1958 to 2007, finding significant increases in annual and pre-monsoon rainfall, as well as an increase in heavy precipitation days (2.2 days per decade) and a decrease in consecutive dry days (2.8 days per decade) (Shahid, 2011). Furthermore, (Shahid et al., 2012) examined a station dataset from 1961 to 2008 in Bangladesh and discovered a rising trend in maximum and minimum temperatures of 0.11 C and 0.15 C per decade, respectively.

Various investigations have explored Bangladesh's precipitation trends across distinct regions and seasons, highlighting diverse patterns (Ahmed et al., 2017; Shahid and Khairulmaini, 2009; Basher et al., 2018; Bari et al., 2017). These studies reveal a nuanced picture, indicating increases in certain types of rainfall while noting decreases in others across different parts of the country (Cerón, et al., 2022; Sa'adi et al., 2023; Kalita et al., 2023). Notably, these trends manifest variations in extreme rainfall indices, signaling potential alterations in flood patterns and intensities (Imran et al., 2023). Given the region-specific nature of precipitation patterns, there's a critical need for high-quality scientific data tailored to specific regions to aid in adapting to these changes (Moss et al., 2013). Consequently, this paper aims to analyze forty years of precipitation data (1961–2000) across diverse regions in Bangladesh to assess the extent of regional changes in extreme precipitation events. While global trends in precipitation patterns align broadly with those observed in Bangladesh, regional variations necessitate a deeper understanding (Mondal et al., 2013). Hydrological changes emerge as primary consequences of environmental shifts in Bangladesh, highlighting water resources as a chief

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concern in the face of climate change (Rahman et al., 2012). Notably, studies have noted varying precipitation trends in different parts of the country, affected by factors like relative humidity and localized storm systems (Mondal et al., 2013; Deka et al., 2013).

This study builds upon prior research efforts by incorporating a comprehensive dataset from the Bangladesh Water Development Board (BWDB) and Bangladesh Meteorological Department (BMD) (Wu et al., 2016). By spanning the timeframe of 1960–2000, consistent with previous investigations, this study aims to discern the frequency and trends of precipitation and extreme weather events, aligning these patterns with global observations. Moreover, the impact of precipitation on food security, food policies, and disaster relief measures in Bangladesh has been a subject of investigation (Ara and Ostendorf, 2017; Hossain and Paul, 2018). Understanding the relationship between precipitation events and their consequences remains pivotal for devising effective strategies to mitigate risks and enhance resilience in the face of changing climatic patterns.

2. METHODOLOGY

2.1 Study Area

Geographically, Bangladesh stands on the northern shoreline of the Bay of Bengal, extending between 20°34′–26°38′ N latitude and 88°01′–92°41′ E longitude. The area has a tropical monsoon climate characterized by heavy seasonal rainfall, high temperatures, and high humidity. The area has a tropical monsoon climate characterized by heavy seasonal rainfall, high temperatures, and high humidity (Rajib et al., 2012). In general, maximum summer temperatures range between 38 and 41 °C, while winter temperatures in most parts of the country vary between 16 and 20 °C (Rakib, 2018). Monsoon months June and July typically receive the most rainfall, 442 mm and 481 mm, respectively, on average across the country. The average annual relative humidity ranges from 70.5% to 78.1% over the country. Land elevations of the northeast region vary mostly between 21 and 30 m, while those in the southeast parts are mostly above 40 m. In this paper, trend analysis has been performed for rainfall indices at Dhaka (23.81° N, 90.41° E), Chittagong (22.33° N, 91.82° E), Sylhet (24.54° N, 91.52° E), Barisal (22.75° N, 90.41° E), Mymensing (24.74° N, 90.39° E), Rangpur (25.75° N, 89.24° E) and Rajshahi (24.37° N, 88.59° E) for 1999-2018 time frame.

The rainy season from June to October is hot and humid in this region, with heavy showers and thunderstorms. Nearly 355 mm of the average rainfall occurs between June and October, and the annual average rainfall all over 7 stations is 189 mm. On the other hand, the annual total rainfall average is 2627 mm, 2029 mm, 1967 mm, 2063 mm, 1307 mm, 2021 mm and 3910 mm at Chittagong, Barisal, Dhaka, Mymensing, Rajshahi, Rangpur and Sylhet, respectively. Figure 1 shows the selected stations for analysis.

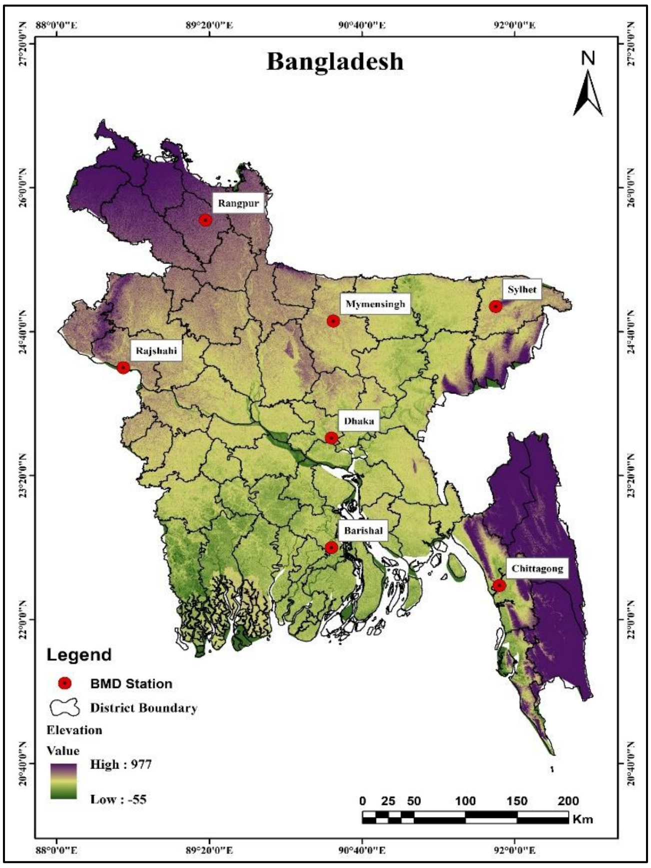

Figure 1: Selected Meteorological Stations

2.2 Dataset

Daily rainfall data were obtained from the Bangladesh Meteorological Department (BMD). To maintain data quality, a month was considered as having complete data if there were less than or equal to 5 missing days, and a year was considered complete if all months were complete according to the above criteria (Rajib et al., 2012; Rakib, 2013).

2.3 Rainfall Indices

The extreme precipitation indices are presented in Table 1. Frequency-based indices include the annual count of days when rainfall is greater than 10 mm and 20 mm, consecutive dry days (CDD), and consecutive wet days (CWD), and the intensity-based indices consist of monthly maximum 1-day precipitation, monthly maximum consecutive 5-day precipitation, annual total precipitation in wet days, and Simple Daily Intensity Index (SDII).

A day with a minimum rainfall of 1 mm is considered a wet day. The CDD is calculated as the largest number of consecutive days where daily rainfall is less than 1 mm, while the CWD is the largest number of consecutive days where rainfall is greater than 1 mm. For the percentile-based indices, R95p and R99p, the 95th and the 99th percentile of the rainfall on wet days in the observation period (1961–2020) is obtained, and the total daily rainfall greater than the 95th and the 99th percentile value is calculated. The daily intensity, SDII, is the ratio of the total precipitation amount on wet days to the number of wet days.

2.4 Data Quality Control

Twenty years of daily precipitation data (1961–2020) were used to calculate the precipitation indices. The precipitation series were tested first for homogeneity using the 'RHtests_dlyPrcp' package, maintained by the Climate Research Division at the Atmospheric Science and Technology Directorate of Canada. This software package can be used to detect and adjust for multiple change points (shifts) that could exist in a data series that may have first-order autoregressive errors (Wang, and Feng, 2014). It is built on the principle of the penalized maximal t-test and the penalized maximal F-test.

Table 1: Extreme Precipitation Indices

Index	Definition	Unit
Frequency indices		
R10mm	Annual count of days when rainfall ≥ 10 mm	days
R20mm	Annual count of days when rainfall ≥ 20 mm	days
CDD	Maximum number of consecutive days with rainfall < 1 mm	days
CWD	Maximum number of consecutive days with rainfall ≥ 1 mm	days
Intensity indices		
RX1day	Monthly maximum 1-day precipitation	mm
RX5day	Monthly maximum consecutive 5-day precipitation	mm
R95p	Annual total rainfall when rainfall > 95th percentile	mm
R99p	Annual total rainfall when rainfall > 99th percentile	mm
PRCPTOT	Annual total precipitation on wet days	mm
SDII	Average precipitation amount on wet days	mm/day

2.5 Trend Detection and Characterization

The trend is the significant change of random variables over time, which can be detected using statistical parameters and non-parametric procedures. To detect trends in the time series of climatic variables, non-parametric statistical procedures were applied in this study. The magnitude of the trend in the time series was determined using the non-parametric method called Sen's estimator, and the Mann-Kendall test (MK) was used to analyze the statistical significance of the trend (Kendall, 1948; Mann, 1945). The MK test compares the relative size of the data, not the value of the data itself (Gilbert, 1987). The advantage of this test is that the data do not need to fit any statistical distribution. In this test, each data value in the time series is compared to all subsequent values. The statistics MK and S of the x series are given by:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(x_j - x_i)$$

Where sgn is the signum function, the variance associated with S is calculated from:

$$V(s) = \frac{n(n-1)(2n+5) - \sum_{k=1}^{m} t_k(t_k-1)(2t_k+5)}{18}$$

Where m is the number of tied groups, and tk is the number of data points in group k. In cases where the sample size n > 10, the test statistic Z(S) is calculated from:

$$Z(S) = \begin{cases} \frac{S-1}{\sqrt{V(S)}}, & if\ S > 0 \\ 0, & if\ S = 0 \\ \frac{S+1}{\sqrt{V(S)}}, & if\ S < 0 \end{cases}$$

Positive values of $Z(S)$ Indicate increasing trends, while negative $Z(S)$ Values reflect decreasing trends. Trends are considered significant if $|Z(S)|$ are greater than the standard normal deviate $Z_{1-\alpha/2}$ for the desired value of α.

Sen's approach was used in this study to quantify the significant linear trends in the time series. Widely used for determining the magnitude of trend in hydro-meteorological time series [4], [39], Sen's slope has the advantage over the regression slope in the sense that it is not affected by gross data errors and outliers. The slope, Q, between any two values of a time series x can be estimated from:

$$Q = \frac{x_k - x_j}{k - j}, \qquad k \neq j$$

For a time series x having n observations, there are possible N = n(n − 1)⁄2 values of Q that can be calculated. According to Sen's method, the overall estimator of the slope is the median of these N values of Q. The overall slope estimator Q* is given by:

$$Q^* = \begin{cases} Q_{(N+1)/2}, & N\ is\ odd \\ \frac{Q_{N/2} + Q_{(N+2)/2}}{2}, & N\ is\ even \end{cases}$$

The confidence interval of the slope is calculated from the same array of ordered slopes. Q_i using indexes M_1 and M_2. The lower and upper limits of the confidence interval are the $M_1 th$ and $(M_2+1)th$ largest of the N-ordered slope estimates Q_i, indices M_1 and M_2 are determined from:

$$M_1 = (N - C_\propto)/2$$

$$M_2 = (N + C_\propto)/2$$

where

$$C_\propto = Z_{1-\propto/2}\sqrt{Var(S)}$$

Where S is the MK test statistic, and $C_\propto$ is the confidence interval. Using tabulated Z values for cumulative normal distribution, the 95% confidence interval is calculated using. $Z_{1-0.05/2} = 1.96$. The confidence band of a time series depends on the sample size and variance of the data. A time series with very low variance and a higher sample size may result in a narrow confidence interval. In general, the narrower the interval (at a given confidence level), the less uncertainty there is about the results.

3. Results

3.1 Rainfall Trends

Annual total rainfall in the northeast region is the highest in the country, ranging from 2586 mm to 5944 mm, with an average of 3910 mm at the Sylhet station from 1961 to 2020. For the same time frame, the annual total rainfall at Chittagong varied between 1586 mm and 4108 mm, with a mean of 2627 mm. The annual precipitation total ranged from a low of 1277 mm to a high of 2877 mm at the Barisal station located in the southern region, with a mean of 2019 mm from 1961 to 2020. Similarly, Dhaka has a range from 1169 mm to 3028 mm with an average of 1967 mm, Mymensing has a range from 1368 mm to 3312 mm with an average of 2063 mm, Rajshahi has a range from 792 mm to 2241 mm with an average of 1307 mm, and Rangpur has the range from 763 mm to 3748 mm with the average of 2021 mm.

The annual rainfall amount in the mid-eastern region is relatively lower than in the northeast and southeast regions. The standard deviation of annual rainfall at Dhaka, Chittagong, Barisal, Mymensing, Rajshahi, Rangpur and Sylhet stations were 541 mm, 931 mm, 459 mm, 644 mm, 518 mm, 692 mm and 997 mm, respectively, indicating that rainfall at Chittagong and Sylhet is more variable than other regions. Station-wise monthly and seasonal average rainfall quantities are presented in Tables 2 and 3.

Monsoon (June–October) season receives a majority of the rainfall at these stations: 85.68% at Chittagong, 82.03% at Barisal, 80.64% at Dhaka, 80.12% at Mymensing, 82.76% at Rajshahi, 82.56% at Rangpur and 79.37% at Sylhet. The Dry (November–February) season receives a minority of the rainfall at these stations: 1.67% at Chittagong, 2.45% at Barisal, 2.14% at Dhaka, 1.75% at Mymensing, 2.01% at Rajshahi, 0.97% at Rangpur and 1.9% at Sylhet. Pre-monsoon (June–October) season receives an annual rainfall of: 16.55% at Chittagong, 16.4% at Barisal, 21.5% at Dhaka, 23.71% at Mymensing, 18.01% at Rajshahi, 21.2% at Rangpur and 28.65% at Sylhet.

In the Monsoon period, Rangpur has the highest temperature fluctuations than the others. In the Pre-Monsoon period, Sylhet had the highest temperature fluctuations than the others. In the Dry period, Chittagong has the highest temperature fluctuations than the others.

Table 2: Monthly precipitation trend detection and characterization, 1961–2020														
Month	**Dhaka**		**Chittagong**		**Barisal**		**Mymensing**		**Rajshahi**		**Rangpur**		**Sylhet**	
	Mean (mm)	Sen's Q (mm/decade)	Mean (mm)	Sen's Q (mm/decade)	Mean (mm)	Sen's Q (mm/decade)	Mean (mm)	Sen's Q (mm/decade)	Mean (mm)	Sen's Q (mm/decade)	Mean (mm)	Sen's Q (mm/decade)	Mean (mm)	Sen's Q (mm/decade)
January	5	0.00	6	0.00	8	0.00	7	0.00	9	0.00	7	0.00	8	0.00
February	20	0.00	16	0.00	21	0.00	16	0.03	12	0.00	10	0.00	41	0.00
March	51	0.00	43	0.00	46	0.00	33	0.14	22	0.20	26	0.05	115	0.22
April	136	0.24	107	0.58	102	0.56	124	1.50	57	0.70	99	1.50	363	2.36
May	277	-0.33	257	2.38	209	0.23	305	1.44	125	1.92	266	1.25	541	3.69
June	345	-0.65	567	-0.47	393	-0.53	382	1.04	227	-0.50	400	0.46	777	-1.14
July	371	1.19	688	-0.31	408	1.30	421	0.70	292	-0.50	430	0.96	759	-1.96
August	308	1.31	488	-0.13	348	-0.32	320	0.46	226	-0.63	324	0.62	619	-0.40
September	282	-1.00	247	0.94	285	0.06	294	1.00	233	0.20	335	2.88	503	1.09
October	167	-0.06	196	0.63	184	-0.32	174	0.52	107	0.43	145	0.74	214	0.47
November	28	0.00	48	0.04	49	0.00	15	0.00	11	0.00	7	0.00	27	0.00
December	10	0.00	10	0.00	10	0.00	7	0.00	7	0.00	5	0.00	10	0.00

Table 3: Seasonal precipitation trend detection and characterization, 1961-2020														
Month	**Dhaka**		**Chittagong**		**Barisal**		**Mymensing**		**Rajshahi**		**Rangpur**		**Sylhet**	
	Mean (mm)	Sen's Q (mm/decade)	Mean (mm)	Sen's Q (mm/decade)	Mean (mm)	Sen's Q (mm/decade)	Mean (mm)	Sen's Q (mm/decade)	Mean (mm)	Sen's Q (mm/decade)	Mean (mm)	Sen's Q (mm/decade)	Mean (mm)	Sen's Q (mm/decade)
Pre-monsoon	391	-0.40	408	2.73	357	0.91	462	2.55	204	2.52	391	2.90	1019	6.32
Monsoon	1634	-3.43	2185	5.00	1618	0.67	1591	1.80	1085	-6.15	1634	6.20	2871	-1.81
Dry	30	-0.05	79	0.13	88	-0.35	45	0.18	39	0.09	30	-0.05	85	-0.05

3.2 Rainfall Indices Trend

Time series analysis for climatic parameters is significant in climate predictions. Rainfall is becoming one of the essential climatic aspects in today's worry for future projections; hence, numerous scholars study the data series to identify probable rainfall trends. Figures 2a to 2h show the precipitation indices for Dhaka, Chittagong, Barishal, Mymensingh, Rajshahi, Rangpur, Sylhet and Khulna stations, respectively, from 1961 to 2000, along with the calculated trend slope and 95% confidence limits on the slope. Table 4 summarizes the magnitude and statistical significance of these trends. The slope of a trend line with a negative sign indicates a decline, while a positive sign indicates a rise.

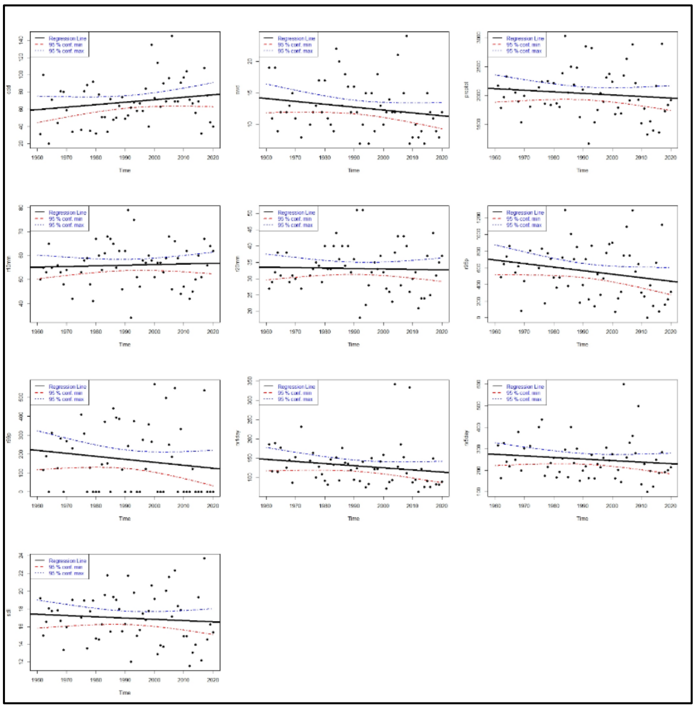

Figure 2a: Precipitation indices trends at Dhaka station, 1961–2020. Solid straight lines indicate the linear trend and dashed straight lines indicate the 95% confidence limits estimated with Sen's Slope estimator method

3.2.1 Frequency Indices

R10mm, R20mm, consecutive dry days (CDD), and consecutive wet days (CWD) are the frequency indices. R10mm and R20mm were designated by Yazid and Humphries as the number of days with heavy rainfall and very heavy rainfall, respectively (Rakib, 2013). The annual frequency of the heavy rainfall day (R10mm) index ranges between 34 and 83 days per year. The lowest number of heavy rainfall days occurred at Rajshahi, while the highest number of heavy rainfall days occurred at Sylhet. All of the stations showed positive trends except Khulna and whole stations ranging from -0.091 to 0.222 days per decade. Rajshahi and Rangpur had a significant positive trend.

Rajshahi station had the lowest annual frequency of very heavy rainfall days (R20mm) (20 days/year), whereas Sylhet experienced very heavy rainfall of 56 days per year. Rajshahi had no negative trend in the R20mm and was statistically significant. Rangpur, on the other hand, showed significant positive trends for R20mm. The fact that R10mm and R20mm have a similar trend. The decrease in the number of days with very heavy rainfall (20 mm) may be contributing to the station's declining annual rainfall trend. The consecutive dry days (CDD) index in Bangladesh ranged between 53 and 74 days. The Chittagong station had the lowest CDD frequency whereas Khulna had the heights. The CDD trend was positive at all seven stations. At a 95% confidence level, the positive trend in all stations where Mymensingh, Rajshahi, Rangpur and Sylhet were statistically significant. In the selected stations, the regional pattern of the consecutive wet days (CWD) index showed a range of 8-23 days per year. All stations showed positive CWD trends ranging from -0.00 to 0.125 days per decade. All eight stations had positive, and Barishal, Mymensingh and Rajshahi had significant trends at a 95% confidence level. Both CDD and CWD have an increasing trend, which has a positive impact on the appropriate rainfall happening in the concerned region.

3.2.2 Intensity Indices

PRCPTOT, R95p, R99p, RX1day, RX5day, and SDII are the intensity indices. Table 4 shows the mean climatology of daily maximum rainfall (RX1day) in the area, which ranges from 94 to 164 mm. Mann-Kendall and Sen's Slope trend analysis revealed that all stations had positive RX1day trends, except for Dhaka, which had a negative slope for RX1day. None of these trends, however, were statistically significant, but Rangpur. The mean climatology of the 5-day maximum rainfall (RX5day) was similar in pattern to RX1day. The higher intensity of five-day maximum rainfall ranges from 170 to 357 mm. RX5day has a positive trend for all stations, which has a similarity with RX1day but Dhaka. Chittagong, Mymensingh, Rangpur and Khulna had positive and statistically significant trends at a 95% confidence level.

The mean climatology of the annual wet-day rainfall total (PRCPTOT) varies from 1118 mm at Rajshahi to 3435 mm at Sylhet, and both stations had a positive trend. For PRCPTOT, all the assigned station has a positive trend, whereas Chittagong, Mymensingh and Rangpur showed significant changes with a 95% confidence level. The mean climatology of very wet days (R95p) and extremely wet days (R99p) ranged from 315 to 841 mm and 99 to 251 mm, respectively. The resulting patterns of both R95p and R99p indices were similar beyond Dhaka station. Mann–Kendall and Sen's Slope trend analysis revealed a statistically non-significant positive trend for all stations but Dhaka for R95p. There was no statistically significant trend for R95p indices, whereas only Rangpur had a significant trend for R99p indices. Including all the stations had a positive trend for R99p. The Simple Daily Intensity Index (SDII) is an index representing extreme precipitation to evaluate the intensity of rainfall. It depends on the annual rainfall amounts and annual rainy days, meaning trends of both annual rainfall amounts and annual rainy days have impacts on the trend of SDII. The SDII ranges from 12 mm/day at Rajshahi to 22 mm/day at Sylhet. Such highly intensive rainfall has high erosion potential that can lead to long-term flooding events in the Sylhet region. Trends analysis of SDII displays increasing trends for all stations. Of these trends, Sylhet, Chittagong and Rangpur were statistically significant at a 95% confidence level.

3.2.3 RX1 and RX5 Trend Detection

Further analyses of the RX1day and RX5day indices were conducted on a monthly and seasonal basis. Results of the Mann-Kendall trend test and the Sen's Slope estimator test for the monthly and seasonal RX1day and RX5day indices from 1961 to 2020 at the chosen stations in Bangladesh are shown in Tables 5 and 6. The RX1day and RX5day monthly trends follow a pattern that is consistent with the monthly precipitation trends previously displayed in Table 2.

Both RX1day and RX5day showed decreasing trends during monsoon months (June–October) at Dhaka, Rajshahi and Sylhet, but none of them was statistically significant at a 95% confidence level. Again, Mymensingh and Rajshahi have an increasing trend but are non-significant at a 95% confidence interval both for RX1day and RX5day. Rangpur has a positive trend both for RX1day and RX5day except for June (RX1day), where there was a significant positive trend for the months of September at RX1day. Sylhet has a negative non-significant trend for the months of June and July, having a positive trend for the months of August, September and October at RX1daya and RX5day. Khulna station shows a nonsignificant positive trend both for RX1daya and RX5day, except for October. Rajshahi Station has a positive, significant increasing trend both for RX1daya and RX5day in the months of March to May. Rangpur and Mymensingh have a significant positive trend at RX1day in the months of April but a non-significant trend at RX5day. November months has a non-significant negative trend for all stations at RX5day but a non-significant positive trend in December inversely. On the Other hand, three stations, namely Chittagong, Mymensingh and Sylhet, have a non-significant positive trend for the months of November among RX1day. December has a non-significant positive trend for all stations except Rangpur. In the months of January, Dhaka, Barishal and Rajshahi had a non-significant positive trend and vice versa for the remaining months, both for RX1day and RX5day. Similarly, during February, Mymensingh, Rajshahi and Rangpur have a non-significant positive trend and vice versa for the remaining months (Except Sylhet station) both for RX1day and RX5day. With respect to seasonal trends, the Dry period shows negative and nonsignificant trends for Dhaka, Chittagong, Barishal, Rangpur, Sylhet and Khulna stations. Both for RX1 and RX5 day rest are positive trends but similarly nonsignificant. For the period of Pre-Monsoon Season, Only Dhaka and Khulna have nonsignificant and negative trends both for RX1 and RX5 days. The rest of the station shows a nonsignificant positive trend both for RX1 and RX5 days, but Rajshai shows a significant trend at a 95% confidence level. In the Monsoon season, none of the stations shows a significant trend, namely Chittagong, Rangpur and Khulna, both for RX1 and RX5 days.

Table 4: Precipitation indices trend detection and characterization, 1961-2020

Index	Dhaka		Chittagong		Barisal		Mymensing		Rajshahi		Rangpur		Sylhet		Khulna	
	Mean(mm)	Sen's Q (mm/decade)	Mean(mm)	Sen's Q (mm/decade)	Mean(mm)	Sen's Q (mm/decade)	Mean(mm)	Sen's Q (mm/decade)	Mean(mm)	Sen's Q (mm/decade)	Mean(mm)	Sen's Q (mm/decade)	Mean(mm)	Sen's Q (mm/decade)	Mean(mm)	Sen's Q (mm/decade)
Frequency Indices																
R10mm (days)	51.508	0.147	43.328	0.208	52.295	0.069	51.918	0.189	34.164	0.194*	47.738	0.222*	83.410	0.219	54.129	-0.091
R20mm (days)	30.410	0.090	29.951	0.207	31.393	0.066	31.311	0.214*	19.475	0.111*	30.672	0.208*	56.066	0.217	29.774	0.138
CDD (days)	63.180	0.713	53.098	0.800	66.311	0.635	65.180	0.915*	58.131	0.879*	66.410	0.868*	55.639	0.837*	74.161	0.222
CWD (days)	11.656	0.000	10.230	0.047	13.557	0.112*	11.984	0.125*	7.721	0.071*	11.361	0.000	22.934	0.117	14.419	0.000
Intensity Indices																
PRCPTOT (mm)	1866.426	1.022	2085.279	12.523*	1869.443	2.679	1884.689	10.560*	1181.311	2.780	1931.951	10.196*	3434.475	12.818	1811.645	4.955
R95p (mm)	514.525	-0.710	648.902	6.271	488.230	2.988	483.197	4.424	314.541	1.578	557.230	3.831	841.492	6.490	478.807	5.667
R99p (mm)	156.262	0.000	223.525	0.000	166.738	0.000	150.049	0.000	98.820	0.000	187.279	0.017*	251.918	0.000	156.000	2.696
RX1day (mm)	118.475	-0.377	163.295	0.473	131.148	0.322	123.623	0.559	94.295	0.730	154.705	1.473*	163.443	0.436	126.516	1.250
RX5day (mm)	231.377	0.000	354.262	2.625*	241.869	1.017	227.213	1.607*	169.721	1.031	297.639	2.512*	356.623	1.375	243.387	3.250*
SDII (mm/day)	15.577	0.016	17.559	0.119*	15.697	0.001	15.537	0.026	12.398	0.011	17.973	0.073*	21.561	0.071*	15.868	0.083

Sen's slope estimates are per decade, Significance: * for $p < 0.05$

Table 5: Monthly and seasonal RX1day (mm) trend detection, 1961-2020.

Month/Season	Dhaka		Chittagong		Barisal		Mymensing		Rajshahi		Rangpur		Sylhet		Khulna	
	MK-Z	Sen's Q	MK-Z	Sen's Q	MK-Z	Sen's Q	MK-Z	Sen's Q	MK-Z	Sen's Q	MK-Z	Sen's Q	MK-Z	Sen's Q	MK-Z	Sen's Q
January	0.44	0.00	-0.78	0.00	0.17	0.00	-0.49	0.00	0.01	0.00	-0.04	0.00	-0.77	0.00	-1.21	0
February	-0.53	0.00	-0.89	0.00	-0.41	0.00	1.72	0.06	1.12	0.00	0.42	0.00	-0.56	-0.04	-0.79	-0.23
March	-0.04	0.00	-0.10	0.00	0.19	0.00	1.72	0.12	2.90	0.17*	0.46	0.01	0.51	0.10	-0.66	-0.16
April	0.00	0.00	0.29	0.02	1.05	0.17	1.89	0.29*	2.67	0.31*	2.71	0.40*	0.77	0.20	0.96	0.3
May	-0.41	-0.08	1.17	0.45	0.61	0.15	-0.49	-0.10	3.12	0.60*	1.39	0.30	1.14	0.45	-1.00	-0.33
June	-0.37	-0.10	-0.68	-0.33	-0.47	-0.15	1.04	0.40	0.94	0.30	-0.29	-0.10	-1.21	-0.51	1.05	0.86
July	-0.27	-0.06	-1.17	-0.72	-0.34	-0.09	0.79	0.29	0.17	0.02	0.68	0.32	-0.54	-0.20	0.40	0.29
August	-0.45	-0.11	-0.63	-0.25	-0.69	-0.10	0.69	0.21	0.00	0.00	0.49	0.23	0.03	0.00	0.61	0.25
September	-1.32	-0.38	-0.37	-0.10	-0.32	-0.08	0.08	0.00	1.19	0.33	2.26	0.98*	0.11	0.03	0.39	0.26
October	-0.03	0.00	0.03	0.00	-0.34	-0.08	1.01	0.29	1.07	0.20	1.46	0.45	-0.11	-0.04	-0.41	-0.34
November	-0.47	0.00	0.38	0.00	-0.24	0.00	0.45	0.00	-0.07	0.00	-1.87	0.00	0.50	0.00	-0.42	0
December	0.65	0.00	0.78	0.00	0.21	0.00	0.57	0.00	0.17	0.00	-0.20	0.00	1.33	0.00	0.84	0
Dry	-0.006	0	-0.30	-0.02	-0.44	-0.09	0.88	0.14	0.65	0.07	-0.42	-0.04	-0.05	0	-0.47	-0.38
Pre-Monsoon	-1.39	-0.53	0.65	0.36	0.76	0.37	0.80	0.35	3.08	1.03	1.88	0.58	1.19	0.77	-0.32	-0.33
Monsoon	-1.85	-1.41	-0.21	-0.24	-0.52	-0.36	0.47	0.38	-0.40	-0.29	1.40	1.90	-0.24	-0.25	1.13	2.66

Sen's slope estimates are per decade, Significance: * for $p < 0.05$

Table 6: Monthly and seasonal RX5day (mm) trend detection, 1961-2020

Month/Season	Dhaka		Chittagong		Barisal		Mymensing		Rajshahi		Rangpur		Sylhet		Khulna	
	MK-Z	Sen's Q	MK-Z	Sen's Q	MK-Z	Sen's Q	MK-Z	Sen's Q	MK-Z	Sen's Q	MK-Z	Sen's Q	MK-Z	Sen's Q	MK-Z	Sen's Q
January	0.05	0.00	-0.58	0.00	0.15	0.00	-0.36	0.00	0.06	0.00	-0.85	0.00	-0.66	0.00	-1.45	0
February	-0.24	0.00	-0.84	0.00	-0.43	0.00	1.32	0.05	1.26	0.05	0.39	0.00	0.04	0.00	-1.35	-0.64
March	0.58	0.10	0.59	0.00	-0.16	0.10	2.17	0.26	2.71	0.20*	1.00	0.08	0.10	0.03	-0.10	0
April	0.36	0.14	-0.42	-0.10	0.85	0.31	1.37	0.47	2.87	0.54*	1.84	0.56	1.90	1.27*	0.87	0.55
May	-0.70	-0.23	1.10	0.84	0.91	0.43	0.02	0.00	2.97	0.75*	0.99	0.45	1.31	1.00	-0.51	-0.38
June	-0.68	-0.30	-0.10	0.00	-0.06	-0.02	0.81	0.67	0.72	0.40	0.19	0.07	-0.57	-0.49	1.10	1.75
July	0.69	0.45	-0.70	-0.70	-0.18	-0.08	0.94	0.67	0.27	0.15	0.02	0.00	-0.34	-0.33	0.15	0.19
August	-1.18	-0.50	-0.77	-0.80	0.48	0.19	0.54	0.22	0.28	0.09	0.68	0.67	0.24	0.18	0.19	0.21
September	-1.21	-0.51	-0.23	-0.14	-0.29	-0.13	0.31	0.12	0.72	0.34	1.59	1.29	0.46	0.45	0.29	0.35
October	-0.30	-0.11	-0.01	0.00	-0.59	-0.36	0.22	0.09	0.98	0.32	1.03	0.61	0.17	0.14	-0.42	-0.44
November	-1.28	-0.05	-0.32	0.00	-0.33	0.00	-0.45	0.00	-0.08	0.00	-1.65	0.00	-0.10	0.00	-0.48	0
December	0.55	0.00	0.91	0.00	0.40	0.00	0.44	0.00	0.39	0.00	0.28	0.00	1.16	0.00	1.14	0
Dry	-0.51	-0.16	-0.51	-0.16	-0.66	-0.30	0.33	0.04	0.95	0.16	-0.66	-0.08	-0.29	-0.09	-0.91	-0.8
Pre-Monsoon	-0.63	-0.41	0.69	0.75	1.18	0.81	0.84	0.56	3.05	1.58*	1.79	1	1.47	1.98	-0.05	-0.06
Monsoon	-1.21	-2.06	0.41	1.16	0.08	0.1	0.40	0.77	-0.52	-0.86	1.10	2.90	-0.12	-0.27	0.86	4.9

Sen's slope estimates are per decade, Significance: * for $p < 0.05$

3.3 Trend of Indices

Figure 3 presents a comparative view of weather trends across different stations, highlighting whether specific weather indices are on the rise or decline. Among the stations examined, Chittagong shows an overall upward trend in most indices, indicating increased cooling degree days, more frequent cold wave occurrences, and a rise in days with significant rainfall over 10mm and heavy rainfall over 20mm. Conversely, Dhaka experiences an increase in cooling degree days and days with more than 10mm of rain but witnesses a decrease in cold wave days and days with over 20mm of rainfall. Mymensigh exhibits an increase in cooling degree days, cold wave occurrences, and heavy rainfall over 20mm, yet a decrease in days with 10mm of rain. Sylhet displays an increase in cooling degree days and heavy rainfall over 20mm but a decrease in cold wave days and days with over 10mm of rainfall. Barishal, Rajshahi, and Rangpur demonstrate mixed trends across the indices. This comparative data offers insights into evolving weather patterns in distinct regions, enabling comprehensive climate analysis and forecasting.

On the other hand, the intensity indices in Figure 4 show various precipitation indices across different stations, aiming to elucidate the trends in precipitation characteristics. Barishal, Dhaka, and Sylhet exhibit predominantly decreasing trends across most indices, signifying declining patterns in daily heavy precipitation, total precipitation, intensity, and frequency of extremely heavy rain events. Chittagong (City) showcases an intriguing mix with increasing total precipitation and intense rainfall occurrences despite a general decrease in other metrics, suggesting localized variations in precipitation patterns. Mymensigh demonstrates a similar declining trend in most indices, except for an increase in total precipitation. In contrast, Rangpur consistently displays an upward trajectory across all indices, indicating a notable increase in various precipitation characteristics. These findings contribute valuable insights into regional precipitation trends, emphasizing potential shifts in rainfall patterns and intensity, which are essential for understanding and predicting local climate variations.

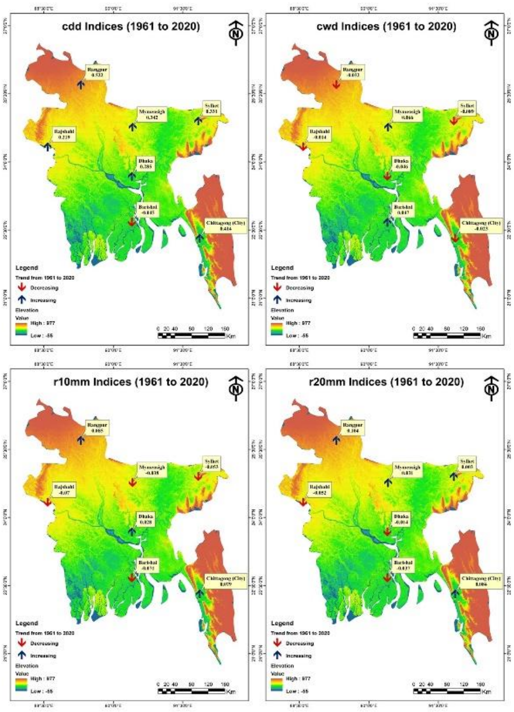

Figure 3: Trend of Frequency Indices.

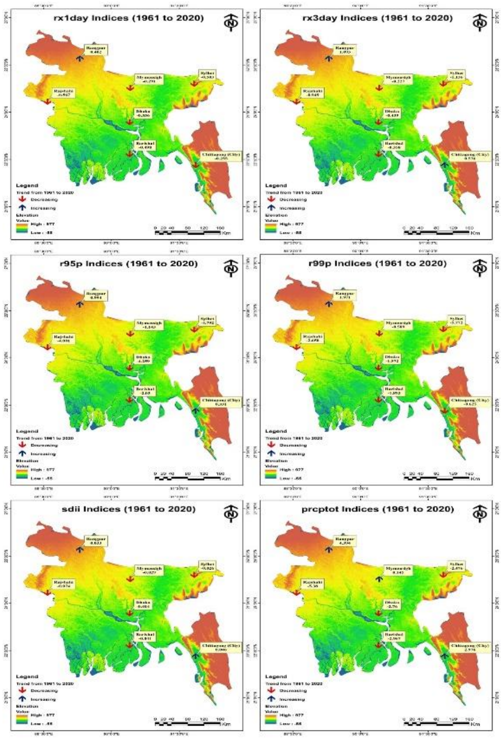

Figure 4: Trend of Intensity indices

4. Discussion

Results of the trend test showed that average yearly rainfall in the Mymensingh and Rangpur areas has grown over time and has dropped for the remaining six regions for monthly computation. However, these trends were not significant. Although statistically non-significant positive trends were discovered for seasonal rainfall in the pre-monsoon, Monsoon and Post monsoon seasons was seen. More crucially, the temporal distribution of rainfall patterns looked to become more varied in the monsoon season. Historically, these months have received most of the annual rainfall in this region. As monsoon rainfall becomes more erratic, local crops will begin to face failure, and systemic changes in agricultural resource allocation and planning will be required (Rakib, Z., 2018). The increase in daily temperatures and cutting down trees may be responsible for the decrease in rainfall during the monsoon (Rakib, 2013). The rainfall variability in the southeastern hilly region during the early post-monsoon may be connected with the depressions or cyclone rain effects, which have been growing in recent decades, making the rainfall more variable (Rahman and Lateh, 2017). Analysis of trends in the extreme rainfall indices indicated very regional patterns. The frequency of severe rainfall days indicated statistically non-significant increasing trends largely beyond Mymensingh, Rajshahi and Rangpur stations. This may be contributing to the declining yearly rainfall pattern at Dhaka, Chittagong, Barisal Sylhet and Khulna. The patterns of intensity-based indexes were found to be quite regional in nature. For example, all the indices showed a strong positive trend, whereas other stations have generally growing trends with a mix of significant and non-significant trends.

Overall, eastern Bangladesh's extreme rainfall patterns and variability are consistent with those of the adjacent areas. For instance, noted trends of between 8.5 and 11.2 days per decade for CDD, between 14.9 and 11.6 days per decade for CWD, between 7.4 and 5.4 days per decade for R10mm, between 4.5 and 2.9 days per decade for R20mm, between 6.7 and 1.1 mm per decade for RX1day, between 13.9 and 22.3 mm per decade for RX5day, and between 0.7 and 0.9 mm per day (Vietnam, Thailand, Myanmar, Cambodia, Laos, parts of Malaysia, China, Bangladesh, and India) (Yazid and Humphries, 2015). In the northeastern region of Bangladesh, (Basher et al.,2018). reported trends of 1.9 to 2.0 days per decade for CDD, 3.3 to 0.4 days per decade for CWD, 76.4 to 43.2 mm per decade for PRCPTOT, 11.7 to 2.5 mm per decade for RX1day, 25.4 to 2.7 mm per decade for RX5day, and 2.4 to 1.5 mm per day per decade for SDII. To reported a tendency of 0.3 to 0.5 days per decade for days with significant rainfall (R10mm) over India's main river basins (Deshpande et al., 2016). As a reported trends of between 12.4 and 2.5 millimeters per decade for RX1day, 5.7 to 4.4 millimeters per decade for RX5day, 1.4 to 0.5 millimeters per day per decade for SDII, 1.5 to 0.5 days per decade for R10mm, 0.4 to 0.7 days per decade for R20mm, 5.5 to 1.8 days per decade for CDD, 0.8 to 4.3 days per decade for CWD.

5. Conclusion

In this paper, rainfall data over a 40-year period (1961–2020) from eight meteorological stations in Bangladesh were analyzed to evaluate the magnitude of regional changes in rainfall and extreme rainfall temporally. Analysis of extreme rainfall at annual, seasonal and monthly scales was based on frequency-based and intensity-based indices recommended by ETCCDI. The magnitude of trends of these rainfall indices was determined using the nonparametric Sen's slope estimator method, while the statistical significance of the trends was analyzed using the Mann–Kendall test. The study investigated extreme daily rainfall patterns over eight meteorological stations in Bangladesh, and the outcomes showed an increasing trend in rainfall during the pre-monsoon season, except for the Dhaka station, while the monsoon season saw increasing trends in Chittagong, Barisal, Mymensingh, and Rangpur. Conversely, the dry season showed a decreasing trend in rainfall for Dhaka, Barisal, Rangpur, and Sylhet, with a non-significant trend for any season. Frequency-based indices had a significant increasing trend in Mymensingh, Rajshahi, and Rangpur stations, while intensity-based indices followed by the Rangpur station. There was no significant increase or decrease in seasonal RX1 days and RX5 days over time. Overall, the study highlights the importance of rainfall trend analysis in various sectors, including water resource management, agriculture, climate change research, disaster risk reduction, and ecosystem management. The findings of the study provide valuable information for planning and decision-making, contributing to sustainable development and environmental preservation.

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Article Highlights

Analyzed trends and indices related to climate change using statistical techniques and examined patterns of extreme rainfall across eight meteorological sites in Bangladesh between 1961 and 2020.

Varied trends have been observed, including growing pre-monsoon rainfall (apart from Dhaka), rising monsoon trends in some areas, and declining dry-season rainfall in Dhaka, Barisal, Rangpur, and Sylhet.

Highlighted notable increases in the frequency indices at the stations in Mymensingh, Rajshahi, and Rangpur, as well as rising intensity indices, which were mostly seen at Rangpur.

APPENDIX

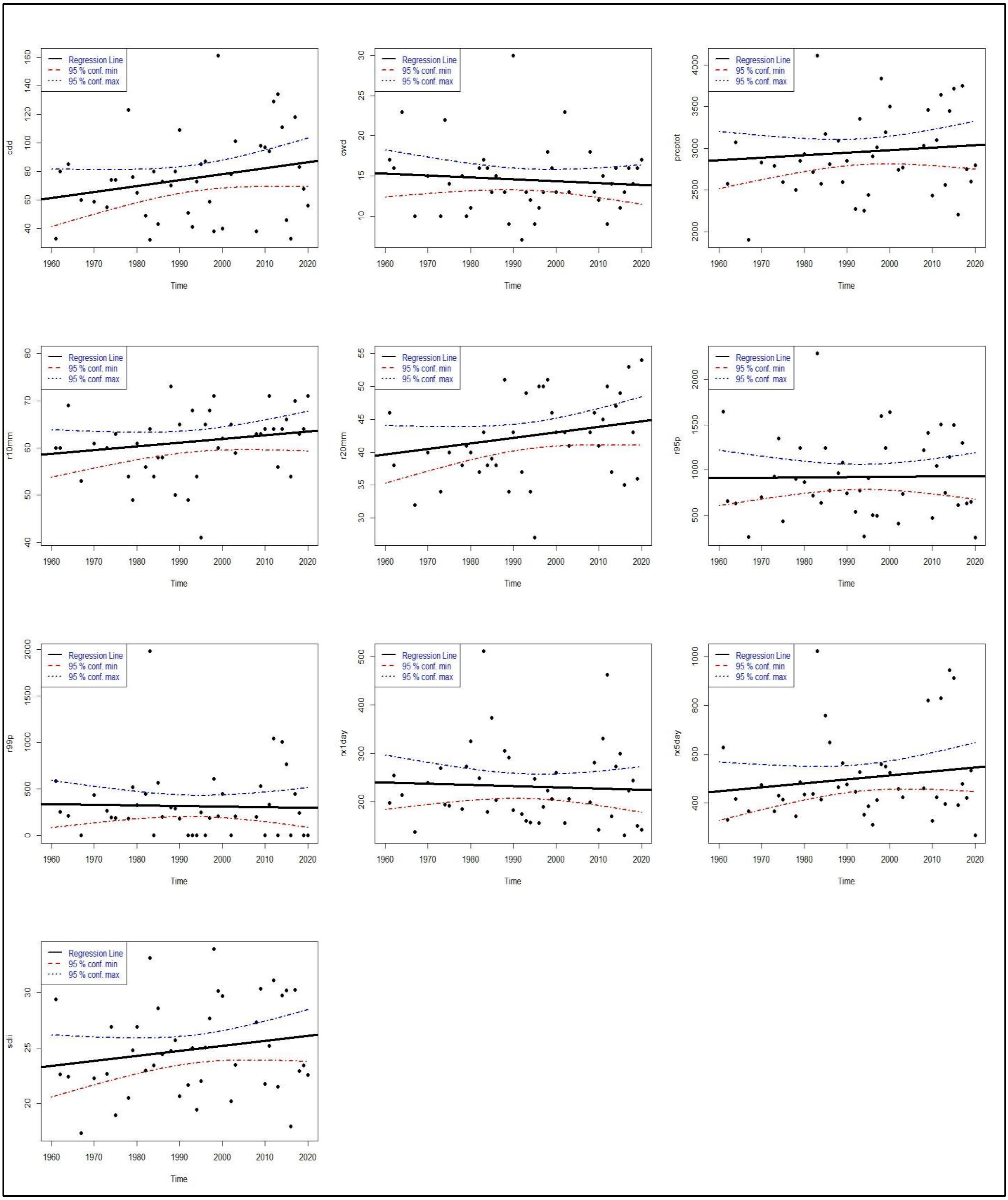

Figure 2b: Precipitation indices trends at Chittagong station, 1961–2020. Solid straight lines indicate the linear trend and dashed straight lines indicate the 95% confidence limits estimated with Sen's Slope estimator method

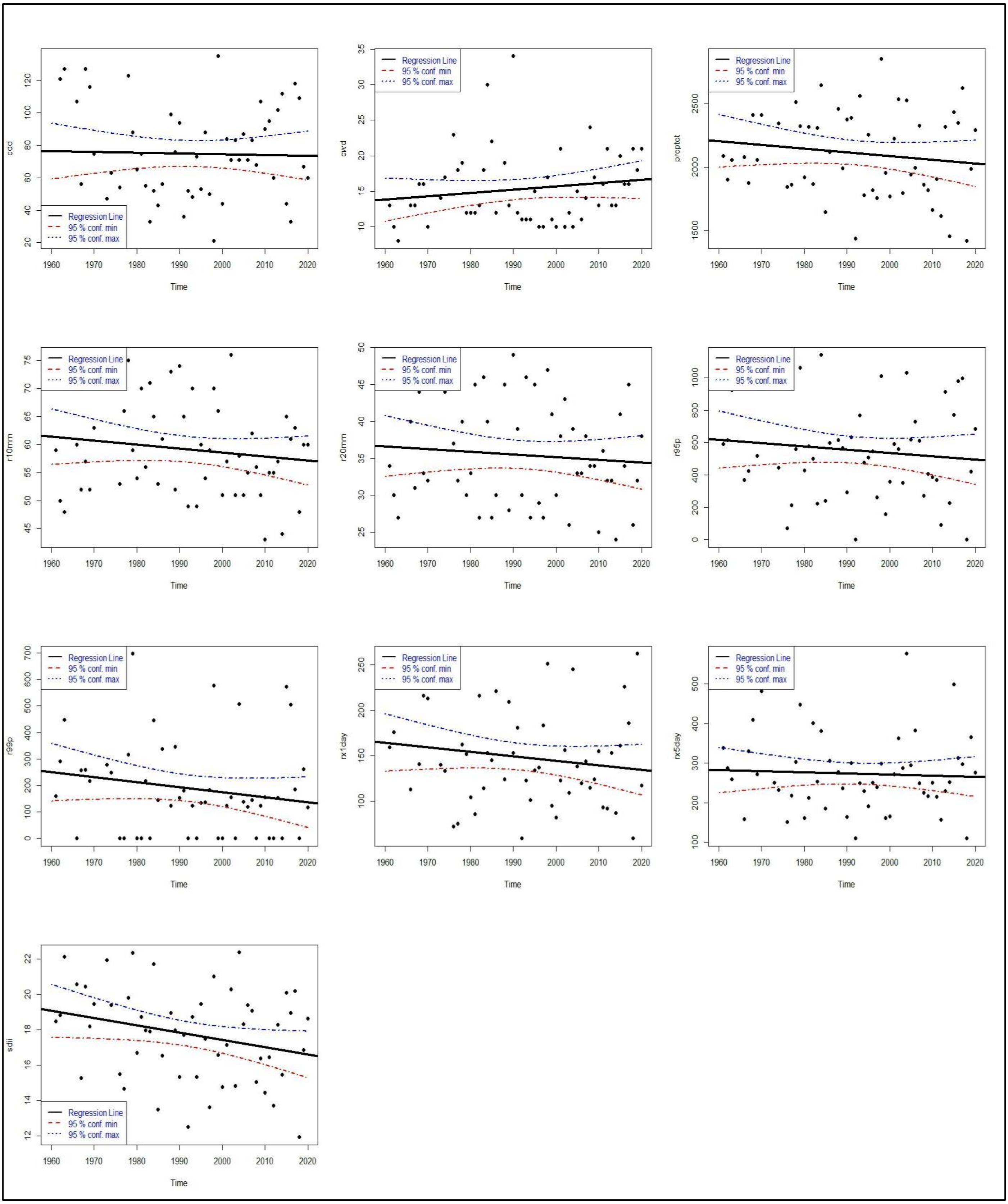

Figure 2c: Precipitation indices trends at Barishal station, 1961–2020. Solid straight lines indicate the linear trend and dashed straight lines indicate the 95% confidence limits estimated with Sen's Slope estimator method

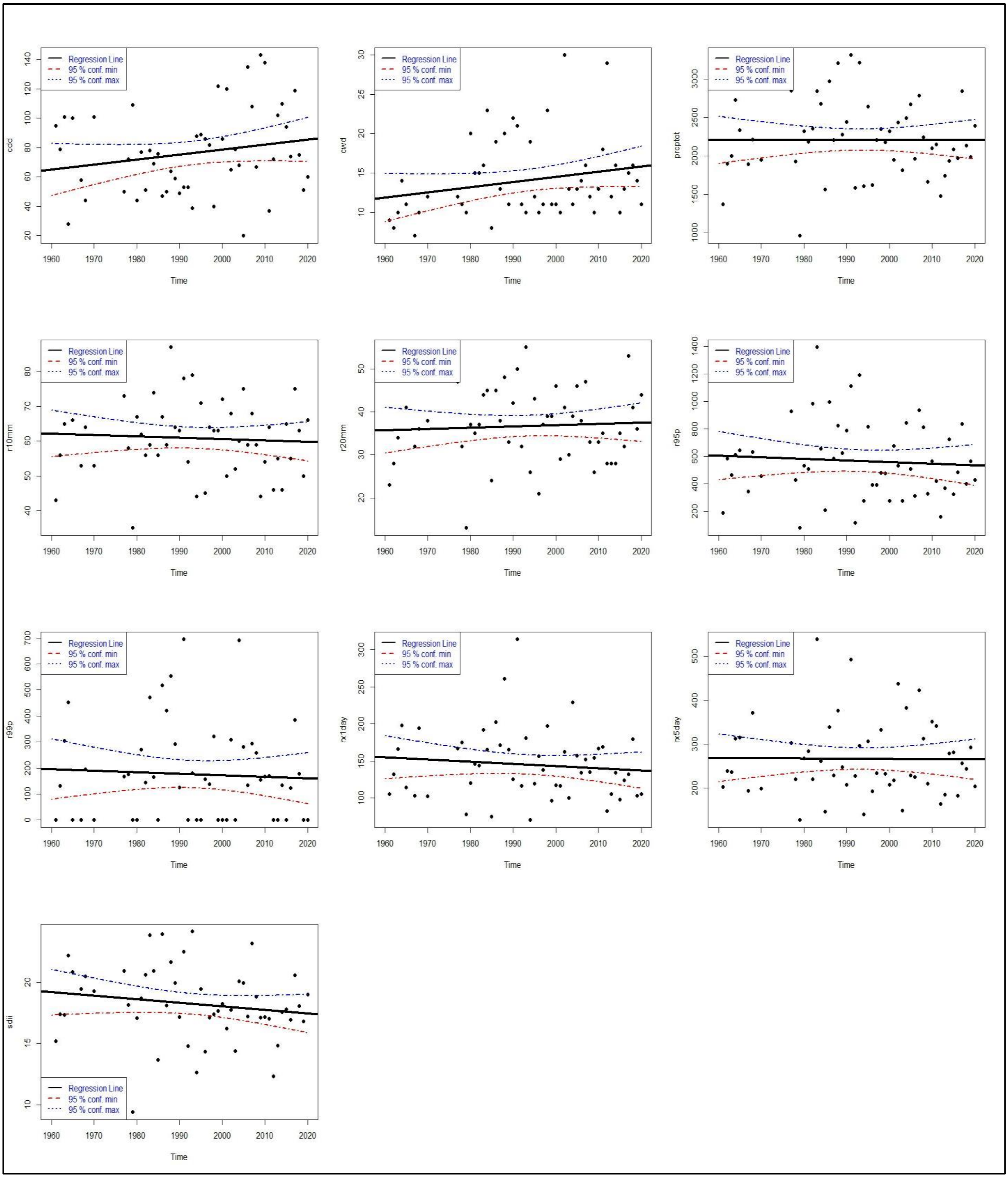

Figure 2d: Precipitation indices trends at Mymensingh station, 1961–2020. Solid straight lines indicate the linear trend and dashed straight lines indicate the 95% confidence limits estimated with Sen's Slope estimator method

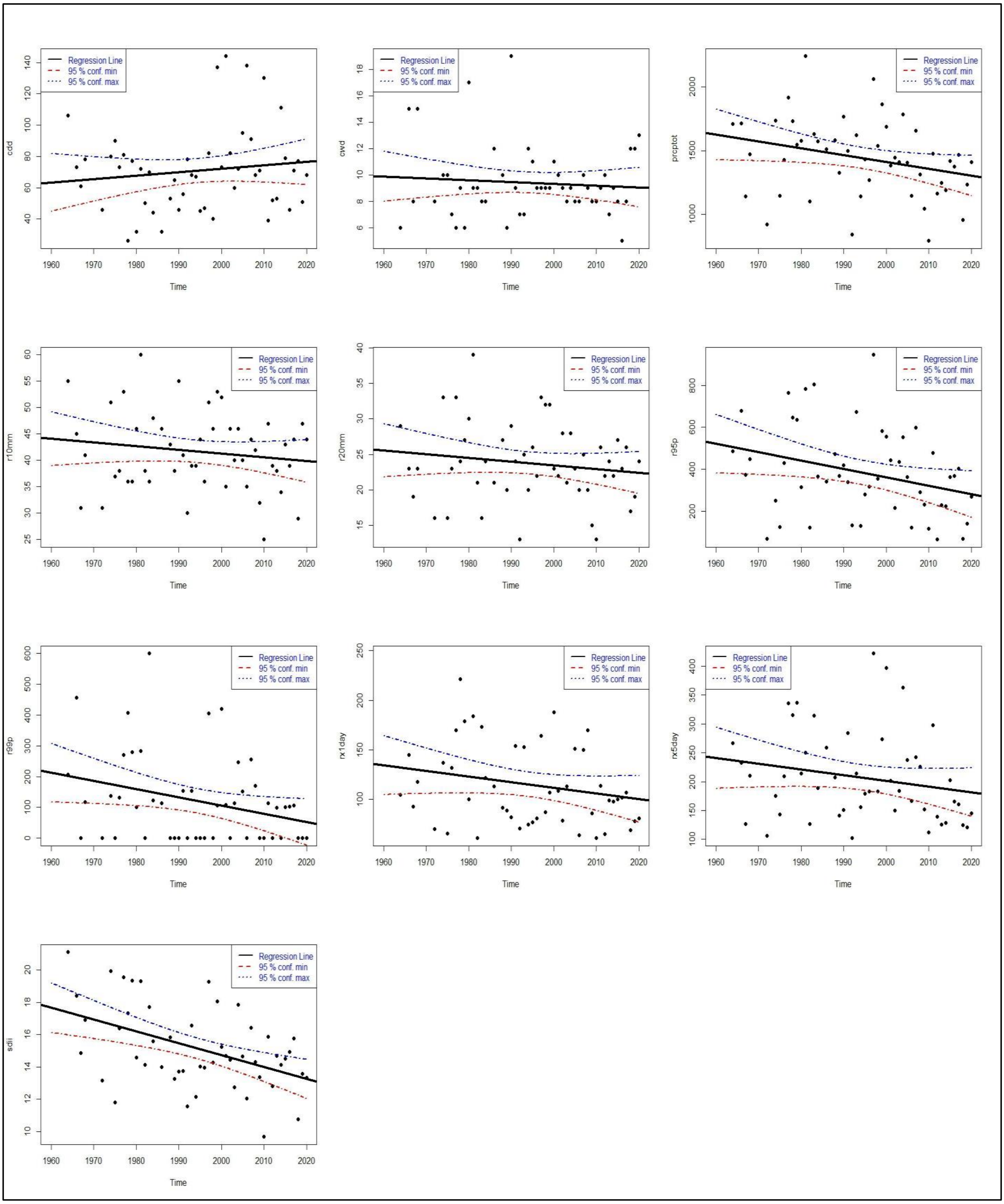

Figure 2e: Precipitation indices trends at Rajshahi station, 1961–2020. Solid straight lines indicate the linear trend and dashed straight lines indicate the 95% confidence limits estimated with Sen's Slope estimator method

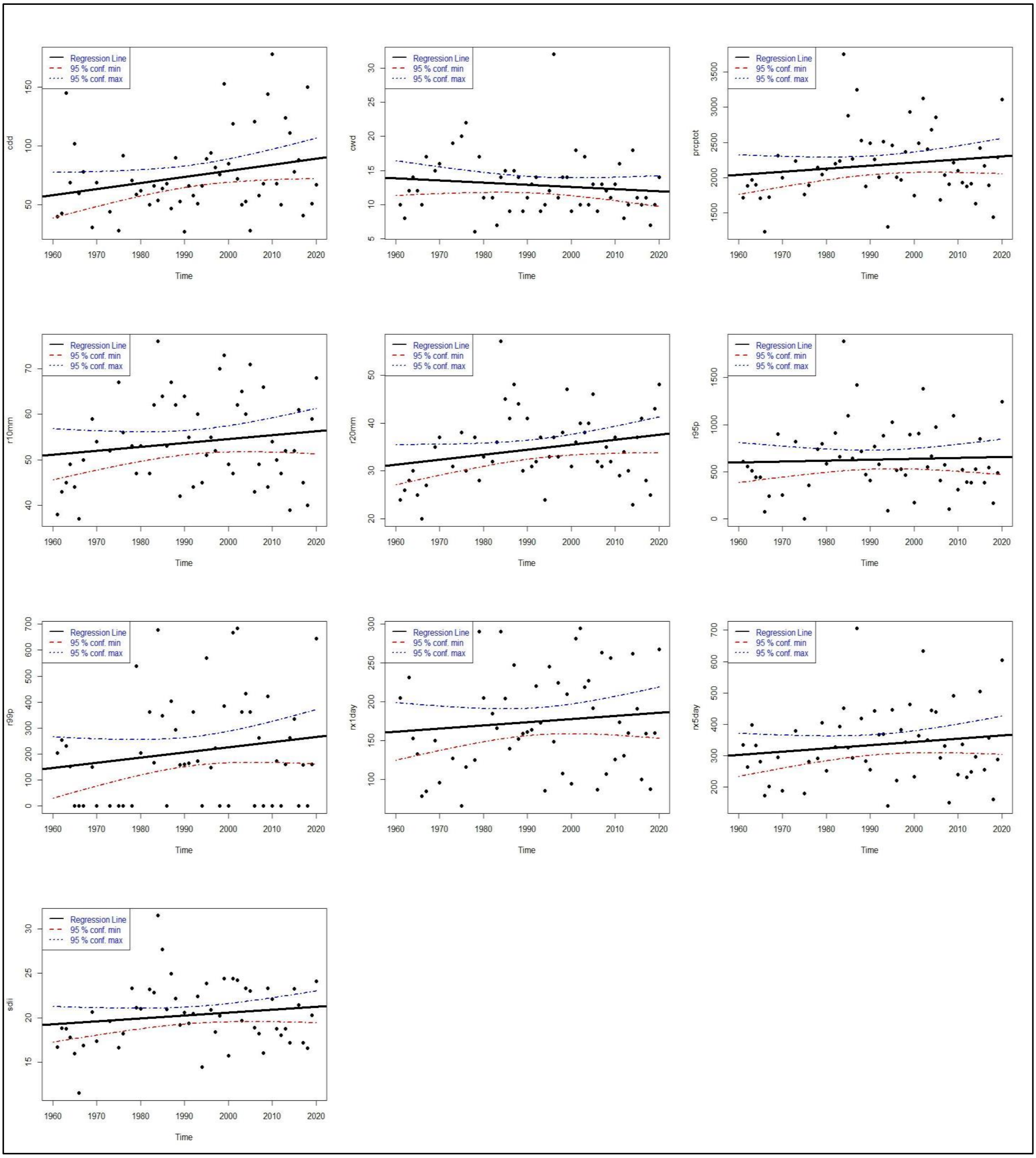

Figure 2f: Precipitation indices trends at Rangpur station, 1961–2020. Solid straight lines indicate the linear trend and dashed straight lines indicate the 95% confidence limits estimated with Sen's Slope estimator method

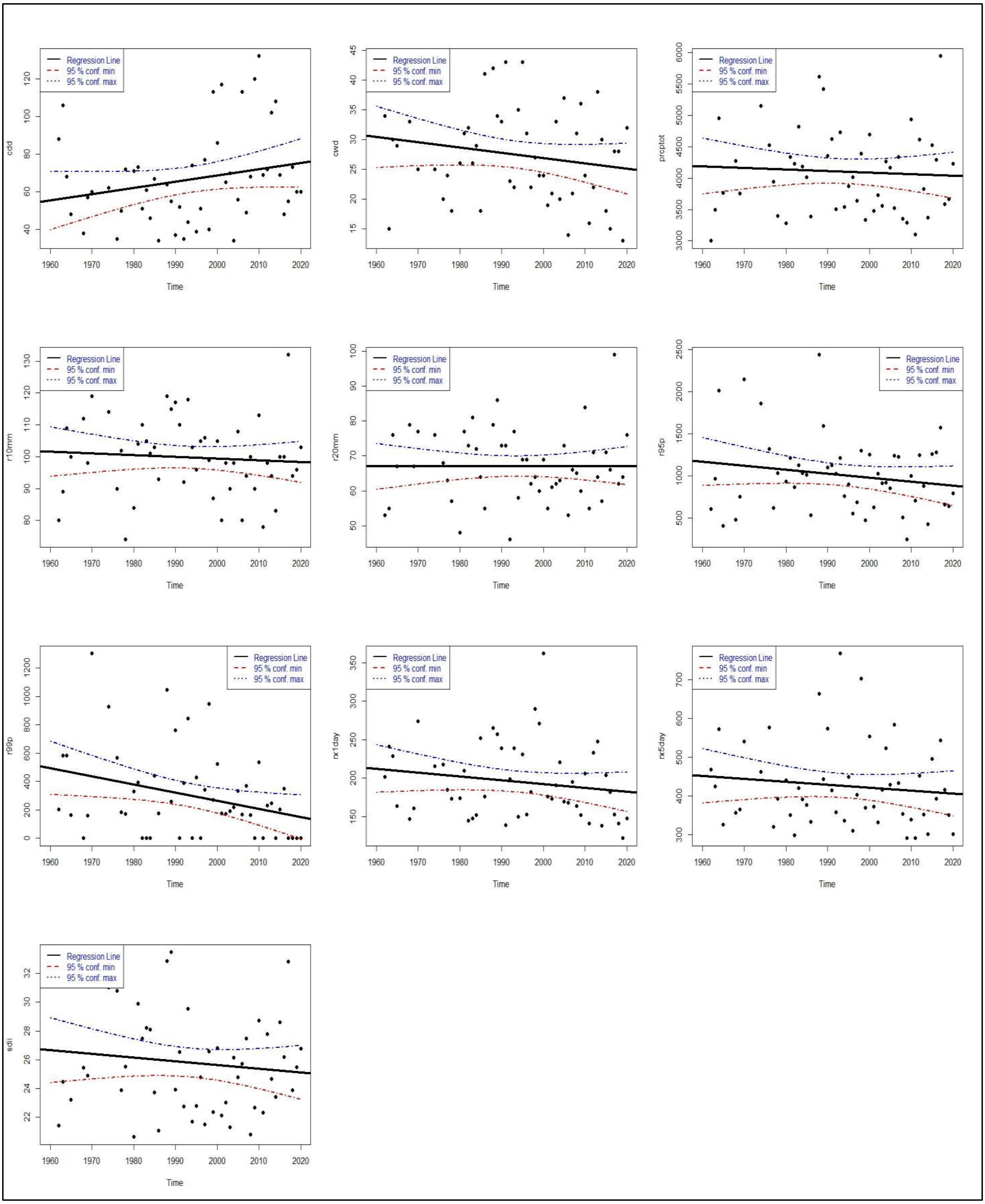

Figure 2g: Precipitation indices trends at Sylhet station, 1961–2020. Solid straight lines indicate the linear trend and dashed straight lines indicate the 95% confidence limits estimated with Sen's Slope estimator method

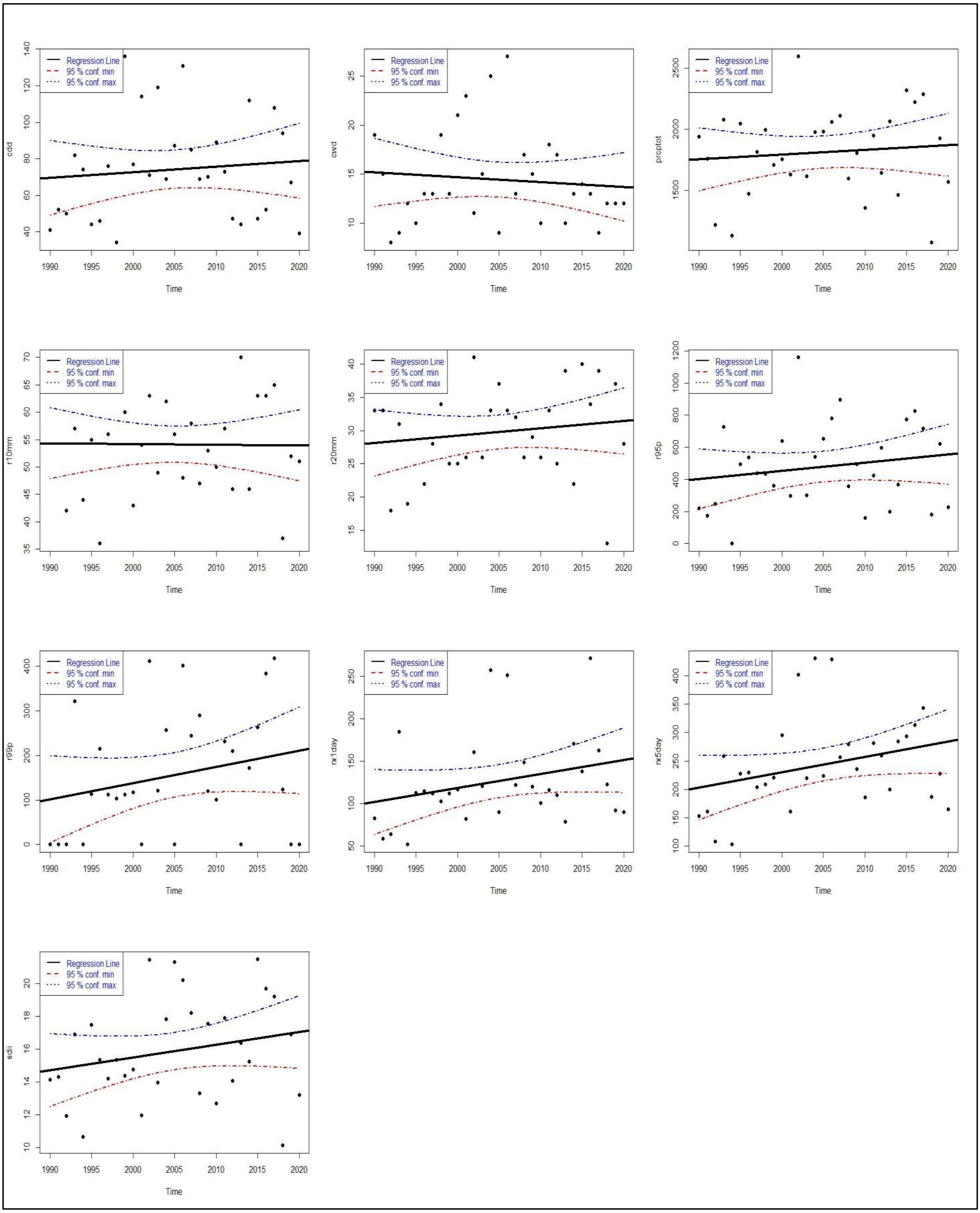

Figure 2h: Precipitation indices trends at Khulna station, 1990–2020. Solid straight lines indicate the linear trend and dashed straight lines indicate the 95% confidence limits estimated with Sen's Slope estimator method