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Assessment of extreme rainfall through statistical process control-I chart

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This study demonstrated the use of statistical process control (SPC)-I chart as a tool to estimate extreme rainfall. This study was conducted in the tropical dry zone of Sri Lanka. Rainfall data (1971–2017) from 19 meteorological stations were used to make SPC-I charts. The probability of having extreme rainfall in a particular month was modelled with the binary time series mixed model using the GLIMMIX procedure. Results showed a significantly different probability of occurrence of extreme rainfall in base and test periods in the dry zone. A higher number of extreme rainfall was recorded at all the rainfall stations during the test period. Monthly changes in occurrence of extreme rainfall were also observed. Comparing the results of the study with the existing results, it is found that SPC-I charts can be used as a tool to explore extreme rainfall. Compared to climate-related extreme assessment methods, SPC-I chart is simple and can accommodate even monthly rainfall data. The result of the study is useful in agricultural planning in the dry zone, Sri Lanka.

Keywords. BTSM model; extreme rainfall; SPC-I charts; Sri Lanka; dry zone.

1. Introduction

Extreme precipitation is expected to intensify with global warming over large parts of the globe. Some global climate models indicated that the increases in extreme precipitation would be larger than increases in mean precipitation (Tabari 2020) and are expected to further intensify in the future under the changing climate (Min *et al.* 2011). Those events increase the possibility of flood conditions or drought conditions (Nowbuth 2010) and are often associated with severe impacts on society and the environment. The degree of geographical extent, severity, and duration of extreme events vary from region to region (Bhatti *et al.* 2020).

World Meteorological Organization suggests maximum one-day precipitation, maximum five-day precipitation, and precipitation due to very wet days (>95 percentile; >99 percentile) (Klein Tank *et al.* 2009) to describe the extreme rainfall events. Zin *et al.* (2012) used eight different indices to assess extreme events. The eight indices were: extreme dry spells, extreme sum of rainfall, extreme wet-day intensities at 95th and 99th

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percentiles, proportion of extreme rainfall amount to the total rainfall amount at 95th and 99th percentiles, and frequency of extreme wet-days at the 95th and 99th percentiles. Researchers use various methods to assess extreme rainfall events. However, when the applied techniques are sophisticated, they become computationally expensive and less used in resource-poor countries. This study attempted to use a simple technique, Statistical Process Control (SPC)-I chart, as a tool to estimate extreme rainfall in the dry zone of Sri Lanka. Although the SPC method was incepted for the manufacturing process, it was understood that it could be applied for any process (Begic-Hajdarevic *et al.* 2016). SPC methods are supposed to monitor production processes, healthcare, software processes, statistical inference at work, and others. Vucijak *et al.* (2014) also showed that it could effectively be applied to water management or related hydrological studies. To the best of our knowledge, we could not observe the comprehensive analysis of extreme rainfall using the SPC-I chart. Thus, we used SPC-I chart to assess the extreme rainfall status in the dry zone of Sri Lanka.

Small island countries are more vulnerable to extreme rainfall than other parts of the world, as they are smaller in size, surrounded by ocean, and have limited coping capacities (Leal Filho *et al.* 2021). Sri Lanka, a small tropical island, is frequently affected by the disastrous effects of extreme rainfall hazards. Cyclones witnessed it and subsequent flooding, landslides, and droughts, causing catastrophic losses to human life, economy, and natural ecosystem within a short period. The most common hazards in Sri Lanka are seasonal and localized flooding and landslides, followed by cyclones, storm surges, droughts, and high winds. Based on the rainfall variations in Sri Lanka, four seasons have been identified and are the North East Monsoon (NEM) from December to February, South West Monsoon (SWM) from May to September, First Inter-Monsoon (FIM) from March to April, and Second Inter-Monsoon (SIM) from October to November (Nisansala *et al.* 2019). Extreme rainfall events caused by tropical cyclones are slow-moving tropical lows from the Bay of Bengal, active and onset phases of the SWM and the NEM seasons, and local-scale thunderstorms during the inter-monsoon seasons (Thevakaran *et al.* 2019). According to the climate risk and adaptation country profile of Sri Lanka (2020), the number of extreme rainfall-related hazards has increased. Global Climate Risk Index (2019) also showed that Sri Lanka is one of the countries most affected by extreme weather events, along with Puerto Rico and Dominica.

Few studies have been conducted about climate change variability and extreme weather condition in Sri Lanka. Thevakaran *et al.* (2019) studied the trends in extreme rainfall events using data from 13 rainfall stations from 1961 to 2010. They considered the extreme events as the 99th percentile of daily rainfall and the number of dry days was also calculated, and the extreme events were subjected to trend analysis. According to their findings, extreme rainfall events during the period were without coherent increasing or decreasing trends. Moreover, Jayawardena *et al.* (2018) studied the long-term trends of extreme rainfall using 1980–2015 recorded data of 19 meteorological stations in the country. They have used a number of precipitation indices such as annual total precipitations from wet days, average precipitation on wet days, the maximum number of consecutive wet days, etc. According to their findings, nearly 65–75% of stations showed increasing trends of extreme precipitations in the country.

Based on the average annual rainfall, Sri Lanka has been divided into three major climatic zones: namely wet (>2,500 mm), intermediate (2,500–1,750 mm), and dry zones (1750–900 mm) (Karunaweera *et al.* 2014). Dry zone is affected by variations in air temperature, rainfall, soil moisture, and intensity and frequency of extreme events (Secretariat, C.C. 2016). It is recorded that the dry and intermediate zones of the country were seriously affected by drought in 2001, while the *Hambantota* region in the dry zone experienced prolonged severe drought between 2001 and 2002. Abeysingha and Rajapaksha (2020) found that the frequency of occurrence of drought is higher in the dry zone than in the wet and intermediate zones of Sri Lanka. A dry zone is a water-stressed area experiencing erratic seasonal water availability (Secretariat, C.C. 2016). It causes drinking water scarcity among people. Agriculture is the primary source of income for people living in the dry zone. Data collection survey on the disaster risk reduction sector in Sri Lanka (2017) reported that people affected by both flood and drought are larger in northern and eastern dry zone regions. The report also indicated that the regions face the problem of heavy rainfall during rainy and less rainfall in the dry seasons.

The primary objectives of this study were to: (i) demonstrate the use of Statistical Process Control (SPC)-I chart as a tool to estimate extreme rainfall and (ii) analyze the extreme rainfall variations in the dry zone, Sri Lanka using a simple method to assist policymakers in the planning process.

2. Materials and methods

2.1 *Study area*

The dry zone covers about 70% of the total land area in Sri Lanka (Dharmasiri and Jayarathna 2021) and encompasses the lowland of the island's north, east, north-central, and southeast. However, since the historical time of the island, the dry zone has been the major agricultural region of the country. Thus, rainfall patterns and trend identification are very useful for rain-fed crop production. The annual average rainfall is <1750 mm in the dry zone (Punyawardena 2010), and it gets high intense rain during inter monsoon season. Also, there is a distinct dry period from May to September (Abeysekera *et al.* 2015) in the dry zone of Sri Lanka. The dry zone gets more rain, mostly during NEM and SIM.

2.2 *Description of data*

Monthly rainfall data for 25 stations were collected from the meteorology department of Sri Lanka for 47 years, from 1971 to 2017. The department of meteorology is the legally responsible administration for data collection and quality checking. Data were preprocessed and screened for missing values and homogeneity using the Pettit test. Data series of more than 5% missing values and inhomogeneous were excluded from the analysis. Finally, the study was limited to 19 meteorological stations located in the dry zone of Sri Lanka for analysis. Figure 1 shows the geographic distribution of weather stations used to obtain the data.

2.3 *Methods of analysis – Theory*

SPC-I chart was used for analysis. A small discussion is provided for readers to briefly explain the method used in the analysis.

The SPC chart is widely used in production processes as an effective monitoring technique. It is also increasingly used in non-manufacturing sectors in the decision-making process. Walter Shewhart invented the basic theory of SPC during the early 1920s (Vucijak *et al.* 2014). The SPC seeks to identify whether the process is in control and the extent of the process variability (Begic-Hajdarevic *et al.* 2016).

The main principle of SPC is to distinguish the causes of the process variation where random variations are inherent to the process, and they can only be removed by changing the entire process. The other causes of variation, relatively large in magnitude and identifiable, are conveniently classified as 'assignable' 'special' causes. When such causes of variation are present, the process is classified as 'unstable' or 'out of statistical control.' These 'unstable' or 'out of statistical control' status are considered extreme events, which are considered extreme rainfall in this study. Seven quality tools are introduced in SPC (Abtew *et al.* 2018). These quality tools are Pareto chart, cause-and-effect sheet, scatter diagram, flow chart, histogram, check sheets, and control charts.

Control charts are graphical techniques that help manage processes and make it easy to recognize points and processes that are out of control. According to the procedure proposed by Walter Shewhart, first, the centerline (CL) is placed at the mean of past performances. Then, two action lines, upper action line (UAL) and the lower action line (LAL) are drawn (figure 2). UAL and the LAL are placed at three standard deviations (std dev) from the centerline (figure 2). The warning lines (upper warning line (UWL) and lower warning line (LWL)) are placed at two standard deviations from the sample means (X). If the process is stable, it may be expected that most of the individual values lie within the range $X \pm 3$ standard deviations, based on the assumption of the normal data distribution (Vucijak *et al.* 2012). Thus, 99.74% of the population is at three standard deviations from the mean on both sides if the process has a normal distribution. It means that there is only a 0.26% chance of getting a value beyond the three standard deviations. This criterion can be used to assess if the process has either been modified or become unstable (Vucijak *et al.* 2014). The SPC-I chart considers this an extreme event (**first condition**).

The process is in a normal distribution if 95.44% of the population is under two standard deviations from the mean on both sides. It has a 4.56% chance of having a value above the two standard deviations, whereas such a chance is only 0.21%. Then one measured value beyond the two standard deviations can be detected as a warning signal for greater attention. At the same time, the two

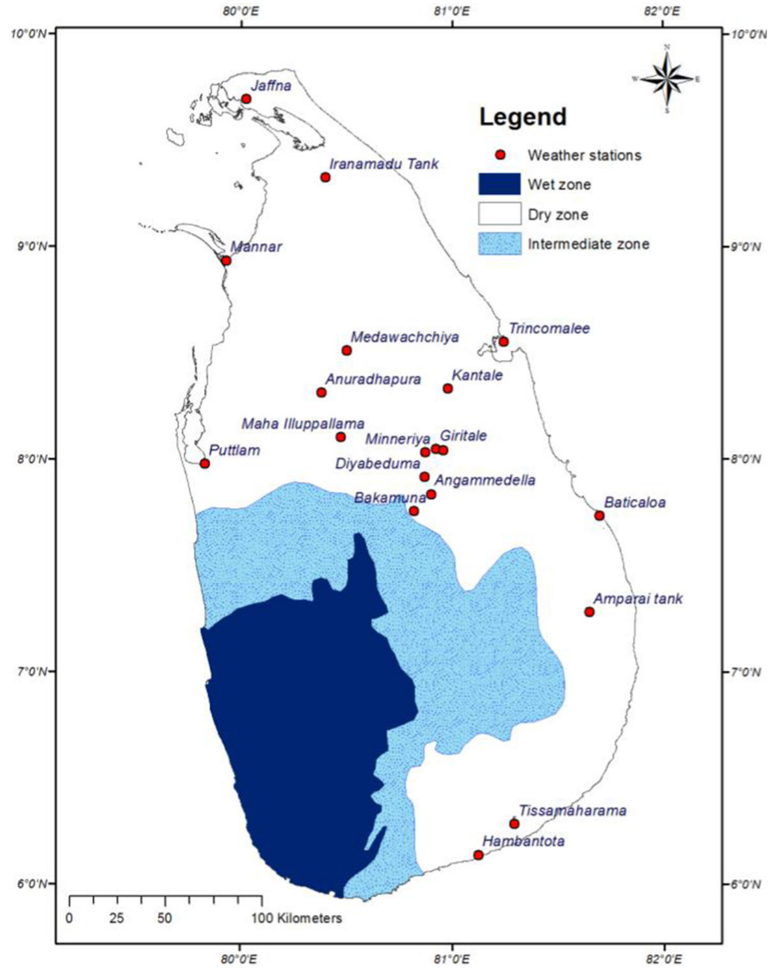

Figure 1. Geographical distribution of the 19 weather stations used in the study in the dry zone of Sri Lanka.

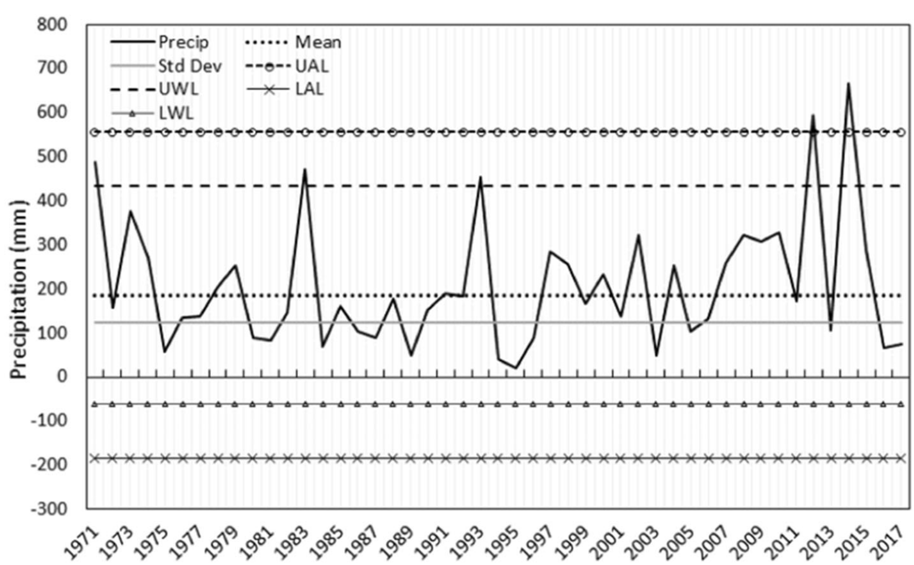

Figure 2. Sample of SPC-I chart for rainfall.

consecutive values beyond the two standard deviations indicate that the process has either shifted or become unstable. Thus, two out of three successive points outside the two standard deviation limits can be considered extreme events (**second condition**). In addition, if eight points in a run are always on one side of the mean, that can also be considered an extreme event in SPC-I chart (**third condition**).

2.4 *Methods of analysis – Procedure followed*

The available data was divided into 1971–2000 as the base period and 2001–2017 as the observed or test period. Twelve data sets were established for each period based on the total monthly precipitation (mm). Analysis was carried out in two phases: phase I and phase II.

2.4.1 *Phase I*

The arithmetic means (X), standard deviations (std dev), upper action line (UAL), lower action line (LAL), upper warning line (UWL), lower warning line (LWL) parameters were calculated for each of the months of the base period, 1971–2000. Extreme rainfalls were assessed using the three methods as indicated under the theory of SPC-I chart for the same period.

2.4.2 *Phase II*

Control charts were prepared for the 2001–2017 test period based on phase I parameters (1971–2000). Then, extreme events were identified and assessed whether they were still 'under control' using all three conditions in SPC-I chart.

2.5 *Statistical analysis*

The numbers of extreme qualifying for the first rule, the points lying beyond the UAL at all the rainfall stations, were extracted from the SPC-I charts, considering the test and base periods. Similarly, counts were extracted for the second condition.

The probability of having an extreme rainfall event in a particular month (ith month) was modelled with the binary time series mixed (BTSM) model (Hung *et al.* 2008) using the GLIMMIX procedure of Statistical Analysis Software (SAS) software. The periods (base and test), season, month nested with the season, and rainfall station were used as covariates. The interaction terms: period∗season, period∗month within the season, and period∗stations were also included in the model. The correlation between observations was modelled using first-order autoregressive (AR-1) correlation structure. The fitted model is given in equation (1).

Relative risk was calculated to quantify the risk of extreme rainfall events in the test period compared to the base period.

$$\begin{aligned}\mathrm{Log}\left(\frac{pr(y_t=1)}{1-pr(y_t=1)}\right) &= \mu + period_i + season_j \\ &+ period * season_{(ij)} + month_{k(j)} \\ &+ period * month_{(ik(j))} + station_l \\ &+ period * station_{(il)} + y_{t-1} + e_{ijklt}, \qquad (1)\end{aligned}$$

where μ is the conditional mean, $period_i$ is the effect of ith period, $season_j$ is the effect of jth, season, $period * season_{(ij)}$ is the interaction between ith, period and jth season, $month_{k(j)}$ is the effect of kth month nested within the jth season, $period * month_{(ik(j))}$ is the interaction between ith period and kth month nested within jth season, $station_l$ is the effect of lth station, $period * station_{(il)}$ is the interaction between ith period and lth season, y_{t-1} is the effect of extremes in the previous month, and e_{ijklt} is the random residual.

Chi-square test probability was used to compare the occurrence of extreme rainfall events between the base and test periods. Relative risk was calculated to quantify the risk of extreme rainfall occurring in the test period compared to the base period using SAS.

3. Results and discussion

Figure 3(a and b) shows control I charts of monthly rainfall for different months at Anuradhapura rainfall station during the study period (1971–2017). However, arithmetic mean in CL, std. dev, UAL, LAL, UWL, and LWL were calculated for the base period (1971–2000) and used the same for even the test period (2001–2017) as indicated in the methodology. Similarly, the study calculated all these statistics for all 19 weather stations and relevant counts satisfying the three conditions separately. As observed in Anuradhapura station, the dry zone gets more rain during the months of September, October, November, and December (figure 3a and b).

We noted that points for the first two conditions in all stations were in the upper section of the graph, indicating that extreme events are mostly wet or flood-causing events. However, extremes fulfilling the third condition (i.e., eight points in a

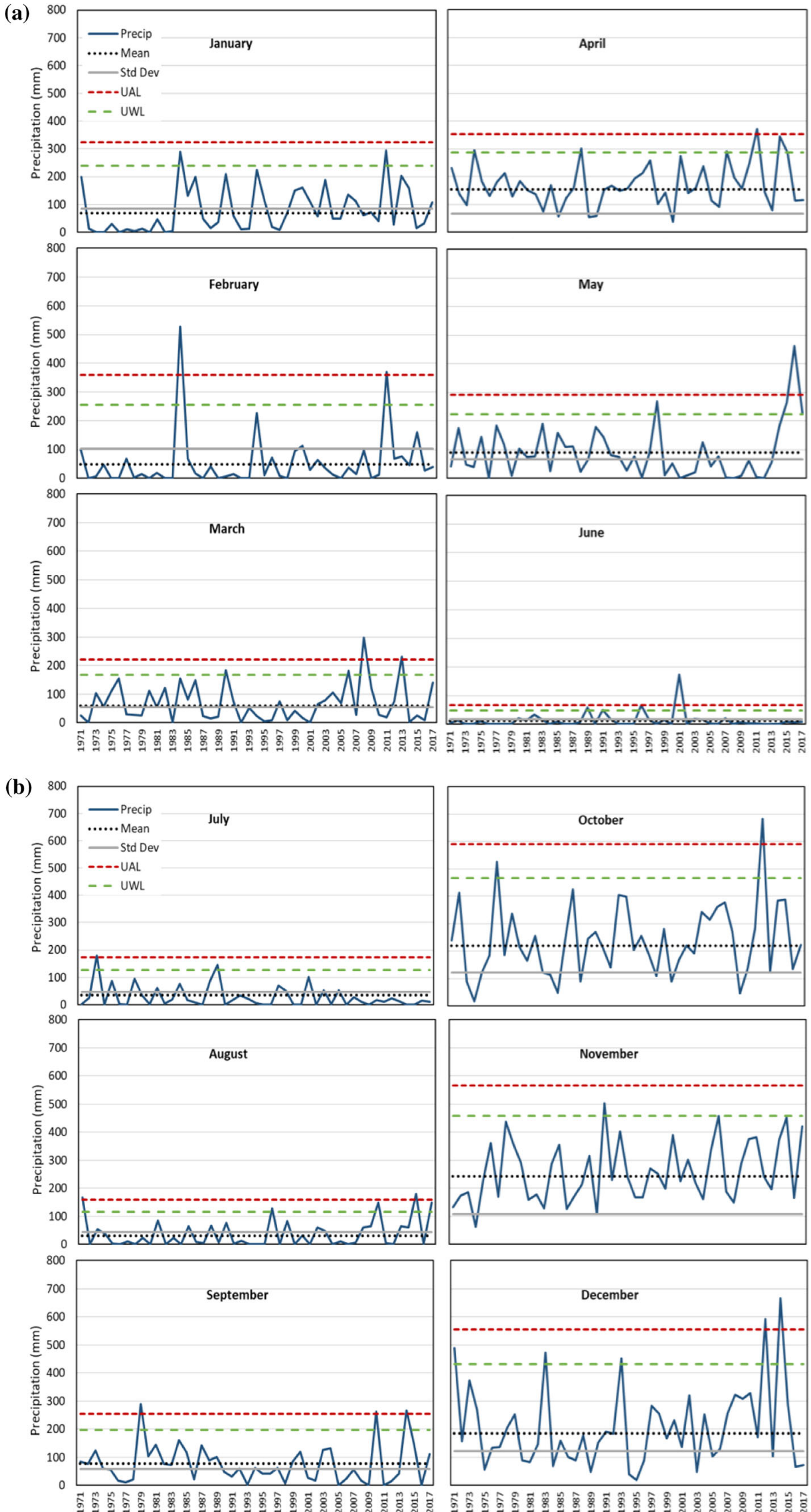

Figure 3. Control I chart for Anuradhapura station (**a**) from January to June (1971–2017) and (**b**) from July to December (1971–2017).

run on one side of the mean) were at both upper and lower (separated by the mean line) sections. Therefore, in order to run the BTSM model, we used only the points of the first two conditions. The third condition was not considered as it had both wet and dry extremes.

The results of the BTSM model are discussed first. The results of the different stations of the dry zone matching the three conditions separately for extreme rainfall are discussed subsequently.

3.1 *Results of the BTSM model*

Extreme event counts were extracted, satisfying at least one condition out of the first two conditions for BTSM model. Then, the model was run and the results are presented in table 1.

The results revealed that the probability of occurrence of extremes rainfall in base and test periods are significantly different ($p < 0.0001$); however, there is no significant difference between seasons ($p = 0.2705$) or no significant interaction between periods (test and base periods) and seasons ($p = 0.1235$) (table 1). Figure 4 shows the interaction plot between periods and seasons. It also indicates that the test period has a higher probability of occurring extreme wet events in both cropping seasons.

It is worth noting that both the *Yala* and *Maha* cropping seasons receive approximately the same probability of occurrence of extreme rainfall occurrence as the seasonal effect is non-significant. The BTSM results further revealed that the probability of extreme rainfall occurrence is significantly different in different months within the season ($p = 0.0105$) (table 1). There is a significant interaction between periods (test and base) and months within the season ($p < 0.0001$), the *Yala* and *Maha* (table 1). Figure 5 shows the scatter plot of the probability of occurrence of extreme rainfall in different months for the base and test periods. The blue circles indicate extremes in different months during the base period, and the red-coloured dots indicate that for the test period. There is a higher probability of having extreme events during the months of April, May, August, September, October, November, December, January, and March during the test period than in the base periods. Out of these months, March, April, May, and August to October exhibited comparatively higher probabilities of extreme rainfall during the test period, which are considered with the intermonsoon rain. In contrast, February, June, and July indicated a higher probability of occurrence of extreme rainfall during the base period. These results infer that there is a significant change in the occurrence of extreme rainfall events from the base period to the test period, probably due to climate change.

Significant interactions were observed among stations and periods ($p = 0.0502$) (table 1). This indicates that extremes at different stations have changed from the base period to the test period (figure 6). As shown in figure 6, Madawachchiya, Kanthalai, and Jaffna stations recorded higher probabilities during the test period than during the base period. For instance, there was a low probability of occurrence of extreme rainfall at Madawachchiya station during the base period. Still, that station manifests the highest probability during the test period among the stations.

Table 1. *The results of BTSM model.*

Effect	*F* value	*P* value
Period	32.70	<.0001
Season	1.22	0.2705
period*season	2.38	0.1235
Month (season)	2.35	0.0105
period*month (season)	5.30	<0.0001
Station	1.34	0.1603
Station*period	1.63	0.0502

Period: Base and test periods; Season: Yala and Maha cropping seasons.

3.2 *First condition: UAL and LAL in different stations*

The number of extreme events qualifying the first rule, the points lying beyond the UAL at all the rainfall stations, were extracted from the SPC-I charts considering the test and base periods and presented in table 2. It is interesting to know that all the extremes were observed and counted in the upper action line indicating wet events that might have caused flood-like conditions. It is clear that the extreme count per year as a % is higher in the test period than in the base period.

Table 3 shows the relative risk of extreme rainfall in each station compared to the base period considering the events recorded in UAL. Relative risk value expresses the likelihood of extreme during the test period compared to the base period, and the confidence limit (95%) indicates the

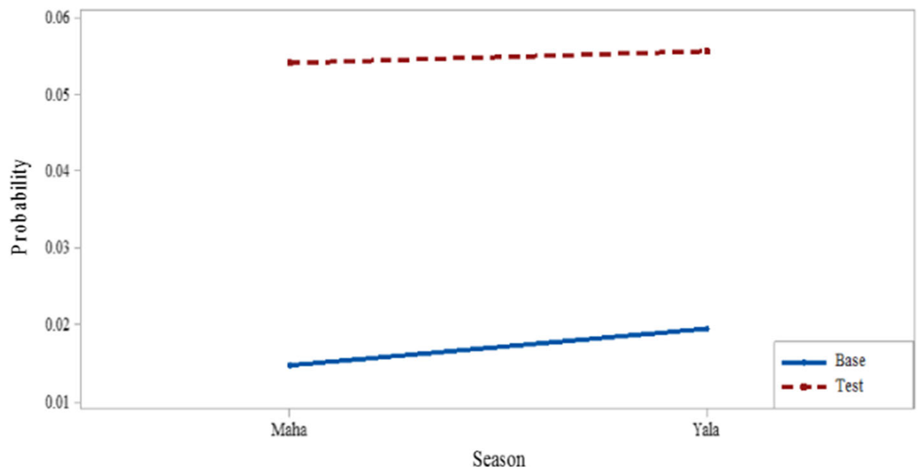

Figure 4. Interaction plot of different cropping seasons and the test and base periods.

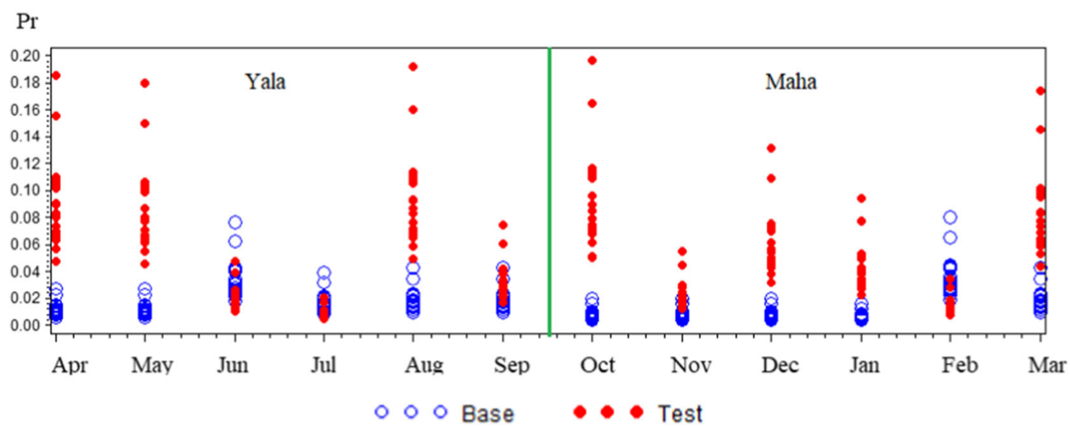

Figure 5. Scatter plot showing the probabilities of extreme rainfall events in different months (qualifying at least one condition out of the first two conditions). Pr: Probability.

variability of relative risk. Five stations out of 19 showed significantly higher extreme counts ($p <$ 0.05) during the test period. The stations are Anuradhapura, Batticaloa, Kantalai tank, Madawachchiya, and Tissamaharama. Table 2 also shows the same stations indicating considerably higher extreme count per year as a percentage. These significantly increased extreme rainfall with reference to the base period might be due to climate change.

Moreover, the relative risk of extreme rainfall occurring in the test period for Anuradhapura was 4.23 (95% CI 1.51–11.85) (table 3). This indicates that the likelihood of an extreme event in the test period is four times higher than in the base period. However, this can be varied from 1.5 and 11.8, as indicated by a 95% confidence interval. The highest risk of extreme rainfall occurring is recorded from Madawachchiya and it is 8.3 (95% CI 2.8–24.3) (table 3). At present and even in future periods, there is a risk of monthly rainfall of 4.2, 3.3, 5.3, 8.4, and 4.7 times higher than that of the base period (1971–2000) at Anuradhapura, Batticaloa, Kantalai tank, Madawachchiya, and Tissamaharama, respectively.

3.3 *Variability of extreme events beyond upper action line (UAL) in different months in the Yala and Maha seasons*

Tables 4 and 5 present the extreme rainfall counts expressed as a per cent per year according to the counts above UAL in different months at different rainfall stations during the Yala and Maha seasons, respectively, in the dry zone. The test periods of both seasons showed higher counts than the base periods. This is prominent in April, May, and September months in the Yala season and October, December, March, and January months in the Maha season. It is further observed that the highest value (35.3%) is recorded at Madawachchiya rainfall station in August during the Yala season, and Kantalai tank recorded the highest (23.5%) in October during the Maha season.

3.4 *Variability of extreme events in two out of three successive points outside the two standard deviations limits in different stations (2nd condition)*

Table 6 shows the extreme count and count % satisfying the second condition of SPI-I chart during test and base periods. All the extreme counts of all the rainfall stations were observed at UWL, indicating extreme conditions are wet, leading to flooding. Considerably higher counts are detected during the test period than during the base period. Significant higher values were recorded in Amparai tank, Anuradhapura, Hingurakgoda, Iranamadu, Jaffna, Kantalai tank, MahaIlluppallama, Mannar, Madawachchiya, and Minneriya tank stations. Their relative risk is also shown in table 7, which infers that climate change probably improves the wet conditions at the stations associated with the dry zone, Sri Lanka. Relative risks are not shown when there is no count for the base period.

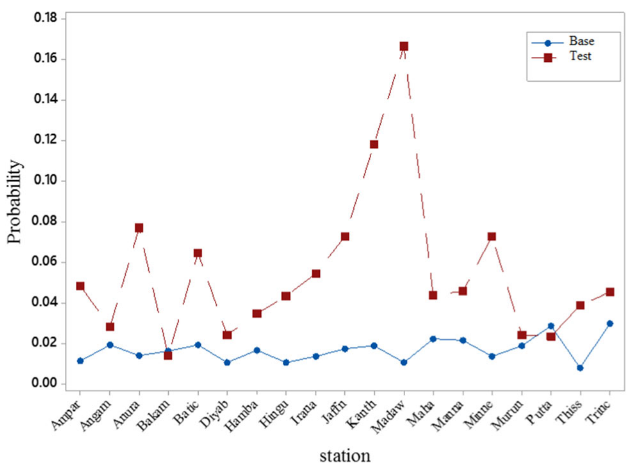

Figure 6. Interaction plot of probabilities of occurrence of rainfall in different months at different stations considering both seasons.

3.5 *Variability of extreme events in consecutive eight points on one side of the mean line in different stations*

If eight points in a run are always on one side of the mean, that can also be considered an extreme condition in the SPC-I chart (table 8). The study calculated such events in both periods, and the values were subjected to a chi-square probability test to find the significant difference ($p < 0.05$) (table 9). Unlike other conditions, we could observe

Table 2. *Extreme rainfall and non-extreme rainfall counts beyond the UAL at different stations using monthly rainfall (first condition).*

	Base period (1971–2000)			Test period (2001–2017)		
Stations	Extreme counts	Extreme counts per year (%)	Nonextreme counts	Extreme counts	Extreme counts per year (%)	Nonextreme counts
Amparai tank	4	13.3	356	6	35.3	198
Angamedilla	5	16.7	355	4	23.5	200
Anuradhapura	5	16.7	355	12	70.6	192
Bakamoona	4	13.3	356	3	17.6	201
Batticaloa	7	23.3	353	13	76.5	191
Diyabeduma	4	13.3	356	5	29.4	199
Hambantota	4	13.3	356	5	29.4	199
Hingurakgoda	4	13.3	356	5	29.4	199
Iranamadu	5	16.7	355	5	29.4	199
Jaffna	6	20.0	354	9	52.9	195
Kantalai tank	5	16.7	355	15	88.2	189
MahaIlluppallama	8	26.7	352	6	35.3	198
Mannar	8	26.7	352	6	35.3	198
Madawachchiya	4	13.3	356	19	111.8	185
Murunkan	5	16.7	355	3	17.6	201
Minneriya tank	5	16.7	355	7	41.2	197
Puttalam	8	26.7	352	3	17.6	201
Tissamaharama	3	10.0	357	8	47.1	196
Trincomalee	5	16.7	355	7	41.2	197

Table 3. *Results of chi-square test on extreme and non-extreme rainfall counts beyond the UAL in different stations using monthly rainfall (first condition).*

Stations	Chi-square probability	Relative risk		
		Value	95% confidence limits	
Amparai tank	0.1136	2.64	0.75	9.27
Angamedilla	0.6025	1.41	0.38	5.19
Anuradhapura	0.0027	4.23	1.51	11.85
Bakamoona	0.7110	1.32	0.29	5.85
Batticaloa	0.0063	3.27	1.32	8.08
Diyabeduma	0.2224	2.20	0.60	8.12
Hambantota	0.2224	2.20	0.60	8.12
Hingurakgoda	0.2224	2.20	0.61	8.12
Iranamadu	0.3584	1.76	0.51	6.02
Jaffna	0.0516	2.65	0.95	7.33
Kantalai tank	0.0002	5.29	1.95	14.35
MahaIlluppallama	0.5980	1.32	0.46	3.76
Mannar	0.5980	1.32	0.46	3.76
Madawachchiya	<0.0001	8.38	2.89	24.30
Murunkan	0.9372	1.05	0.25	4.38
Minneriya tank	0.1063	2.47	0.79	7.68
Puttalam	0.5351	0.66	0.17	2.46
Tissamaharama	0.0106	4.70	1.26	17.54
Trincomalee	0.1063	2.47	0.79	7.68

points both in the upper and lower sections of the graphs. We can observe that eight points consecutively in the upper part of the mean are lower than the lower part of the graph both in the test and base periods. This infers that there is approximately the same chance of occurrence of drought both in the test and base periods. As shown in table 9, there is no significant difference between base and test periods on the 3rd condition of SPI-I chart.

4. Discussion

Extreme events are defined in statistics using extreme value theory and its variants (Coles 2001) and are complicated in analysis. Expert team on climate change detection, monitoring and indices (ETCCDMI) (Alexander *et al.* 2006) introduced 11 rainfall indices to calculate extreme rainfall using daily rainfall data. In addition, Gu *et al.* (2022) reviewed the literature on seven aspects of extreme rainfall detection in China. Still, scientific debates are in progress regarding selecting the best methods of assessing extreme rainfall events, and when the techniques become so complex, their implementation is computationally expensive. In addition, the input data requirements, such as daily rainfall, restrict the use of such computationally sophisticated daily data-driven models in data-sparse developing countries. In such instances, 'control I charts' is a better option for analysis of extreme rainfall where the method is simple and can accommodate daily, weekly or monthly rainfall data as well as any variable defined by the user, such as cumulative sum or average of three or five consecutive days. ETCCDMI proposed extreme indices are divided into five categories: percentile based, absolute, threshold, duration, and other indices (Alexander *et al.* 2006) and 'control I charts' is a threshold index since we count the events using the mean and standard deviation. We suggest using SPC-I chart along with the 11 indices to achieve robust decisions over climate change assessment of extreme rainfall.

It is shown that the South Asian monsoon rainfall extremes have become relatively frequent (Yao *et al.* 2008; Baidya *et al.* 2008; Shrestha *et al.* 2017). Bandara *et al.* (2013) showed that extreme rainfall has increased in the coastal region of Sri Lanka, considering three extreme indices. An increase in precipitation has been revealed in the southeastern region, which is a part of the dry zone of Sri Lanka (Karunathilaka *et al.* 2017). Moreover, Sanjeewani and Manawadu (2017), utilizing some extreme rainfall indices, pointed out that the southwestern,

Table 4. *Extreme rainfall count expressed as % per year according to the counts above UAL in different months at different rainfall stations in the dry zone of Sri Lanka – the Yala season.*

	April		May		June		July		August		September	
Station	Base	Test	Base	Test	Base	Test	Base	Test	Base	Test	Base	Test
Amparai Tank	3.33	5.88	3.33	0.00	3.33	5.88	0.00	0.00	0.00	5.88	0.00	0.00
Angamedilla	0.00	0.00	0.00	5.88	3.33	5.88	3.33	0.00	3.33	0.00	0.00	0.00
Anuradhapura	0.00	5.88	0.00	5.88	3.33	5.88	3.33	0.00	3.33	5.88	3.33	11.76
Bakamoona	0.00	0.00	3.33	0.00	3.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Batticaloa	0.00	11.76	0.00	11.76	3.33	0.00	3.33	0.00	3.33	5.88	3.33	5.88
Diyabeduma	3.33	0.00	0.00	5.88	3.33	0.00	0.00	0.00	0.00	0.00	3.33	0.00
Hambantota	3.33	5.88	3.33	0.00	0.00	0.00	3.33	0.00	0.00	5.88	3.33	5.88
Hingurakgoda	0.00	0.00	0.00	0.00	6.67	5.88	0.00	0.00	0.00	0.00	3.33	0.00
Iranamadu	0.00	0.00	0.00	5.88	3.33	0.00	0.00	0.00	0.00	0.00	3.33	0.00
Jaffna	3.33	23.53	3.33	17.65	3.33	0.00	0.00	0.00	0.00	0.00	0.00	5.88
Kantalai tank	0.00	11.76	0.00	11.76	3.33	0.00	3.33	0.00	3.33	5.88	0.00	0.00
MahaIlluppallama	3.33	0.00	0.00	5.88	3.33	5.88	3.33	0.00	0.00	0.00	3.33	0.00
Mannar	0.00	11.76	3.33	5.88	3.33	0.00	0.00	0.00	3.33	5.88	3.33	0.00
Madawachchiya	3.33	5.88	0.00	0.00	3.33	0.00	0.00	0.00	0.00	35.29	0.00	0.00
Murunkan	0.00	5.88	0.00	5.88	0.00	0.00	0.00	0.00	3.33	0.00	3.33	0.00
Minneriya tank	0.00	0.00	0.00	5.88	3.33	0.00	3.33	0.00	3.33	0.00	3.33	0.00
Puttalam	3.33	0.00	0.00	5.88	0.00	0.00	3.33	5.88	3.33	0.00	3.33	0.00
Tissamaharama	0.00	0.00	3.33	0.00	0.00	0.00	0.00	0.00	3.33	0.00	0.00	11.76
Trincomalee	0.00	11.76	3.33	5.88	3.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 5. *Extreme rainfall count expressed as % per year according to the counts above UAL in different months at different rainfall stations in the dry zone of Sri Lanka – the Maha season.*

	October		November		December		January		February		March	
Station	Base	Test	Base	Test	Base	Test	Base	Test	Base	Test	Base	Test
Amparai Tank	0.00	0.00	0.00	0.00	0.00	11.76	0.00	0.00	3.33	0.00	0.00	5.88
Angamedilla	0.00	5.88	0.00	0.00	0.00	5.88	0.00	0.00	3.33	0.00	3.33	0.00
Anuradhapura	0.00	5.88	0.00	0.00	0.00	11.76	0.00	0.00	3.33	5.88	0.00	11.76
Bakamoona	0.00	5.88	0.00	0.00	0.00	11.76	0.00	0.00	3.33	0.00	3.33	0.00
Batticaloa	3.33	5.88	3.33	0.00	0.00	11.76	0.00	11.76	3.33	5.88	0.00	5.88
Diyabeduma	0.00	5.88	0.00	0.00	0.00	5.88	0.00	5.88	3.33	0.00	0.00	5.88
Hambantota	0.00	0.00	0.00	0.00	0.00	5.88	0.00	5.88	0.00	0.00	0.00	0.00
Hingurakgoda	0.00	11.76	0.00	0.00	0.00	5.88	0.00	0.00	3.33	0.00	0.00	5.88
Iranamadu	0.00	0.00	3.33	5.88	0.00	0.00	0.00	0.00	3.33	0.00	3.33	17.65
Jaffna	0.00	0.00	0.00	5.88	0.00	0.00	0.00	0.00	3.33	0.00	6.67	0.00
Kantalai tank	0.00	23.53	0.00	0.00	0.00	5.88	0.00	5.88	3.33	5.88	3.33	17.65
MahaIlluppallama	0.00	5.88	3.33	0.00	3.33	5.88	0.00	5.88	3.33	0.00	3.33	5.88
Mannar	3.33	0.00	0.00	5.88	3.33	0.00	3.33	0.00	3.33	0.00	0.00	5.88
Madawachchiya	0.00	11.76	0.00	11.76	0.00	5.88	3.33	17.65	3.33	5.88	0.00	17.65
Murunkan	0.00	0.00	0.00	0.00	3.33	0.00	0.00	0.00	3.33	0.00	3.33	5.88
Minneriya tank	0.00	11.76	0.00	0.00	0.00	5.88	0.00	5.88	3.33	5.88	0.00	5.88
Puttalam	0.00	0.00	0.00	0.00	0.00	5.88	3.33	0.00	6.67	0.00	3.33	0.00
Tissamaharama	0.00	5.88	0.00	0.00	0.00	17.65	0.00	5.88	3.33	0.00	0.00	5.88
Trincomalee	3.33	11.76	0.00	5.88	0.00	0.00	3.33	5.88	3.33	0.00	0.00	0.00

eastern, and north-eastern parts of the country are highly exposed to these extreme events-related hazards. It is worth noting southwestern, eastern, and north-eastern parts of the country belong to the dry zone of Sri Lanka. The present study using 'control I charts' also showed that rainfall extremes are relatively higher at present than in the years before 2000 in the dry zone of Sri Lanka. The

Table 6. *Extreme and non-extreme counts of two out of three successive points outside the two standard deviations limits in different stations (2nd condition).*

Stations	Base period (1971–2000)		Observed period (2001–2017)	
	Extreme count	Extreme count per year (%)	Extreme count	Extreme count per year (%)
Amparai tank	0	0	4	23.53
Angamedilla	2	6.67	2	11.76
Anuradhapura	0	0	4	23.53
Bakamoona	2	6.67	0	0
Batticaloa	0	0	0	0
Diyabeduma	0	0	0	0
Hambantota	2	6.67	2	11.76
Hingurakgoda	0	0	4	23.53
Iranamadu	0	0	6	35.29
Jaffna	0	0	6	35.29
Kantalai tank	2	6.67	9	52.94
MahaIlluppallama	0	0	3	17.65
Mannar	0	0	3	17.65
Madawachchiya	0	0	15	88.23
Murunkan	2	6.67	2	11.76
Minneriya tank	0	0	8	47.05
Puttalam	2	6.67	2	11.76
Tissamaharama	0	0	0	0
Trincomalee	6	20	2	11.76

Table 7. *Results of chi-square test on extreme events and non-extreme event counts in two out of three successive points outside the two standard deviations limits in different stations using monthly rainfall.*

Stations	Chi-square probability	Relative risk		
		Value	95% confidence limits	
Amparai tank	0.0077	–	–	–
Angamedilla	0.5635	1.76	0.25	12.43
Anuradhapura	0.0077	–	–	–
Bakamoona	0.2862	–	–	–
Batticaloa	–	–	–	–
Diyabeduma	–	–	–	–
Hambantota	0.5635	1.76	0.25	12.43
Hingurakgoda	0.0077	–	–	–
Iranamadu	0.0011	–	–	–
Jaffna	0.0011	–	–	–
Kantalai tank	0.0015	7.94	1.73	36.40
MahaIlluppallama	0.0211	–	–	–
Mannar	0.0211	–	–	–
Madawachchiya	<0.0002	–	–	–
Murunkan	0.5635	1.76	0.25	12.43
Minneriya tank	0.0002	–	–	–
Puttalam	0.5635	1.76	0.25	12.43
Tissamaharama	–	–	–	–
Trincomalee	0.5078	0.58	0.11	2.88

results of the use of 'control I charts' are thus comparable to the results of the previous studies. Jayawardena *et al.* (2018) analyzed the rainfall extreme indices using the daily rainfall data (1980–2015) at 19 meteorological stations in Sri Lanka and showed increasing trends of rainfall over

Table 8. *Extreme count and non-extreme counts of consecutive eight points on one side of the mean line in different stations.*

	Base period (1971–2000)				Test period (2001–2017)			
Stations	Upper extreme count	Lower extreme count	Total extreme count	Extreme count per year (%)	Upper extreme count	Lower extreme count	Total Extreme event count	Extreme count per year (%)
Amparai tank	–	3	3	10	–	–	–	–
Angamedilla	–	5	5	16.67	–	1	1	5.88
Anuradhapura	–	3	3	10	–	3	3	17.65
Bakamoona	–	3	3	10	–	1	1	5.88
Batticaloa	–	1	1	3.34	–	–	–	–
Diyabeduma	–	1	1	3.34	–	1	1	5.88
Hambantota	–	1	1	3.34	–	–	–	–
Hingurakgoda	1	5	6	20	–	3	3	17.65
Iranamadu	–	5	5	16.67	–	1	1	5.88
Jaffna	1	9	10	33.34	–	4	4	23.53
Kantalai tank	–	1	1	3.34	–	–	–	–
MahaIlluppallama	–	2	2	6.67	–	2	2	11.76
Mannar	1	6	7	23.34	–	2	2	11.76
Madawachchiya	–	5	5	16.67	1	–	1	5.88
Murunkan	2	12	14	46.67	–	7	7	41.17
Minneriya tank	–	3	3	10	–	1	1	5.88
Puttalam	–	1	1	3.34	–	2	2	11.76
Tissamaharama	–	5	5	16.67	1	2	3	17.65
Trincomalee	–	3	3	10	–	2	2	11.76

Table 9. *Results of chi-square test on extreme events and non-extreme event counts in consecutive eight points on one side of the mean line in different stations.*

		Relative risk		
Station	Chi-square probability	Value	95% confidence limits	
Amparai tank	0.1911	–	–	–
Angamedilla	0.3175	0.35	0.04	3.00
Anuradhapura	0.4784	1.76	0.35	8.66
Bakamoona	0.6408	0.58	0.06	5.61
Batticaloa	0.4512	–	–	–
Diyabeduma	0.6834	1.76	0.11	28.06
Hambantota	0.4512	–	–	–
Hingurakgoda	0.8583	0.88	0.22	3.49
Iranamadu	0.3175	0.35	0.04	3.00
Jaffna	0.5490	0.70	0.22	2.22
Kantalai tank	0.4512	–	–	–
MahaIlluppallama	0.5635	1.76	0.25	12.43
Mannar	0.3800	0.50	0.10	2.40
Madawachchiya	0.3175	0.35	0.04	3.00
Murunkan	0.7827	0.88	0.36	2.15
Minneriya tank	0.6408	0.58	0.06	5.61
Puttalam	0.2704	3.52	0.32	38.68
Tissamaharama	0.9372	1.05	0.25	4.38
Trincomalee	0.8579	1.17	0.19	6.98

80% of the stations. Out of the stations, most of the significant trends were observed in the dry zone stations. Moreover, analyzing the rainfall trends over five decades (1961–2010) pointed out more rainfall trends in Sri Lanka during the recent decade (2001–2010) than in other older four decades.

They showed increasing annual rainfall at Jaffna, Manner, Trincomalee, Anuradhapura, Maha-Illuppallama, and Batticaloa stations located in the dry zone (Naveendrakumar *et al.* 2018). The present study also showed significantly increasing rainfall at Anuradhapura and Batticaloa compared to the base period considering the first two conditions of SPC-I chart. These results (Jayawardena *et al.* 2018; Naveendrakumar *et al.* 2018) further corroborate the findings of present study, the use of control I charts in analyzing the extreme rainfall.

Abeysingha (2022) reviewed published 15 manuscripts on rainfall trends of Sri Lanka and pointed out the increasing tendency of annual rainfall over Sri Lanka. Nisansala *et al.* (2019) analyzed the rainfall trend in Sri Lanka using the Mann–Kendall (MK) test and innovative trend analysis techniques. They found that rainfall in the dry zone of Sri Lanka is increasing and further pointed out that the increased rainfall amount of some stations is mainly due to the increased rainfall events. The present study also confirms that there is an increase in extreme rainfall events in the dry zone based on the two conditions of the SPC-I chart. This analysis also showed the higher probability of occurrence of extremely high rainfall events both in the Maha and Yala cropping seasons during the present and in the future compared to the baseline scenarios, probably due to climate change. First and second conditions of SPC-I chart showed significant wetting conditions at Anuradhapura station. Similarly, a significant increasing trend in very wet days and extreme rainfall days have been observed in the same station by Jayawardena *et al.* (2018), evidencing the increase of precipitation in extreme events at dry zone locations. From this evidence, we can assure that SPC-I chart is a possible good index to find extreme rainfall events.

It is reported that the temperature of most of the stations increased in Sri Lanka (Naveendrakumar *et al.* 2018). According to the thermodynamic Clausius–Clapeyron relationship, the increase of water vapour in proportion to the saturation concentrations at a rate of about 6–7% per degree rise in temperature results in the proliferation of extreme precipitations (Ingram 2016). High moisture contents in the atmosphere in the context of global warming lead to an increase in the frequency and intensity of extreme rainfall (Wentz *et al.* 2007; Li *et al.* 2018). Thus, the rise of temperature during the recent past in the dry zone area of the country due to climate change might have resulted in a higher occurrence of extreme rainfall, especially from the convective mechanism.

Nisansala *et al.* (2019) presented an increasing rainfall trend in the dry zone, especially in the eastern and southeastern parts of the country. They further showed that most of the stations with an increasing trend had increased high rainfall values through the innovative trend analysis approach. When analyzing the present finding with Nisansala *et al.* (2019), we can further infer that stations that showed increasing rainfall trends in their study are due to high-intensity rainfall events. In addition, it reveals that extreme rainfall events notably influence total annual and seasonal rainfall in the dry zone. Even though rainfall amount would be in the increasing trend, the effective utilizable rainfall for crop production may not be increased in the dry zone. As discussed in the results, considering the third condition of SPC-I charts, there is approximately the same chance of occurrence of drought both in the test and base periods. Therefore, policymakers can decide on the optimum use of extremely high rainfall by enhancing rainfall harvesting storage and mechanisms in the dry zone of Sri Lanka. Moreover, the results of the BTSM model, particularly seasonal changes of extreme rainfall events, are useful for water management in the dry zone area. Results of chi-square test probability given for different stations can be used as indices to act on relative disaster risk reductions in those areas because extreme high precipitation events accompany damages due to floods and landslides. The changes in the occurrence of extreme seasonal rainfall events, trends, and relative risk detected from this study can be considered when making decisions and plans by disaster management and other relevant authorities. More importantly, the results can be used for agricultural planning and management in the dry zone of Sri Lanka.

5. Conclusions

This article investigates the use of the SPC-I chart as a tool to assess the extreme rainfall in the dry zone of Sri Lanka. Comparing the findings of the present method with the existing studies, it can be concluded that the SPC- I charts can be used to explore extreme rainfall analysis.

SPC-I charts and the application of BTSM model confirm that the probability of occurrence of extreme rainfall in base and test periods in the dry zone of Sri Lanka is significantly different and is higher during the test periods. Significant interactions among the months of the seasons in the occurrence of extreme rainfall are observed, and extremes in different stations have changed from base period to test period symbolizing the effect of climate change.

Notably, five stations out of 19 showed significantly higher extreme counts ($p < 0.05$) during the test period. It can further be suggested that extreme rainfall events influence total increased annual and seasonal rainfall in the dry zone.

Author statement

N S Abeysingha and A M K R Bandara generated the concept based on the experience and the literature survey, and K M Kularathna is the student and did the analysis part under the supervision of N S Abeysingha and A M K R Bandara. The model was developed by A M K R Bandara. Main writer of the manuscript is N S Abeysingha. Ram L Ray helped to check the manuscript's overall quality, prepare graphs, and improve figures.

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