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Research Article

Spatio-Temporal Rainfall Variability and Concentration over Sri Lanka

Uttam Pawar,[1] **Pasindu Karunathilaka**,[2] **and Upaka Rathnayake**[2]

[1]*Department of Geography, HPT Arts and RYK Science College, Nashik 422 005, Maharashtra, India*
[2]*Department of Civil Engineering, Faculty of Engineering, Sri Lanka Institute of Information Technology, Malabe, Sri Lanka*

Correspondence should be addressed to Upaka Rathnayake; upaka.r@sliit.lk

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Changes in precipitation patterns significantly affect flood and drought hazard management and water resources at local to regional scales. Therefore, the main motivation behind this paper is to examine the spatial and temporal rainfall variability over Sri Lanka by Standardized Rainfall Anomaly Index (SRAI) and Precipitation Concentration Index (PCI) from 1990 to 2019. The Mann–Kendall (MK) trend test and Sen's slope (SS) were utilized to assess the trend in the precipitation concentration based on PCI. The Inverse Distance Weighting (IDW) interpolation method was incorporated to measure spatial distribution. Precipitation variability analysis showed that seasonal variations are more than those of annual variations. In addition, wet, normal, and dry years were identified over Sri Lanka using SRAI. The maximum SRAI (2.27) was observed for the year 2014 for the last 30 years (1990–2019), which shows the extremely wet year of Sri Lanka. The annual and seasonal PCI analysis showed moderate to irregular rainfall distribution except for the Jaffna and Ratnapura areas (annual scale-positive changes in Katugastota for 21.39% and Wellawaya for 17.6%; seasonal scale-Vavuniya for 33.64%, Trincomalee for 31.26%, and Batticaloa for 18.79% in SWMS). The MK test, SS-test, and percent change analyses reveal that rainfall distribution and concentration change do not show a significant positive or negative change in rainfall pattern in Sri Lanka, despite a few areas which experienced significant positive changes. Therefore, this study suggests that the rainfall in Sri Lanka follows the normal trend of precipitation with variations observed both annually and seasonally.

1. Introduction

Rainfall is the most significant element of weather and climate that directly affects agriculture, water resources, and more importantly, the socioeconomic situation of the society [1, 2]. Rainfall variability and concentration under the changing climate scenario causes extreme droughts and flood conditions in various regions around the world [3]. Several studies have reported a considerable reduction in rainy days and a sizeable upturn in rainfall intensity in many countries, including China and America [4–6]. Climate change induces variations not limited to rainfall intensity, magnitude, and rainfall pattern but also to the total amount of precipitation [7–9] Moreover, the regularity and magnitude of disastrous climatic events such as droughts and floods have seen fluctuations as a result of climate change [10–15]. Consequently, it is vital to study spatial and temporal rainfall fluctuations and precipitation concentration (PC) that lead to flood and drought incidents for the sustainable consumption of available freshwater resources and water conservation [14, 16]. Natural resources such as water are under increased stress and thereby enhance the vulnerability to drought [17]. Nevertheless, global warming alongside the El Niño-Southern Oscillation (ENSO) phenomenon has increased drought events all over the world, namely, in North America, East Africa, East Asia, and Australia [18–21].

Numerous scholars have constructed and used different indices to understand drought situations, such as the standardized precipitation index (SPI), standardized precipitation evapotranspiration index (SPEI), rainfall anomaly index (RAI), standardized hydrological index (SHI), standardized runoff index (SRI), and Palmer drought severity index (PDSI) [22–24]. On the other hand, the spatial and temporal behavior of precipitation concentration was analyzed by several indices in the literature including precipitation concentration period (PCP), precipitation concentration degree (PCD), monthly precipitation concentration index (MPCI), and the daily precipitation concentration index (DPCI) [25–28]. These indices were used on different spatial and temporal scales in various regions around the world. The rainfall anomaly index (RAI) was introduced by Van Rooy [29] and it features a ranking system to categorize negative and positive precipitation irregularities [30]. In addition to the above-stated indices, Olukayode Oladipo [31] investigated historical drought events in North America using the Bhalme and Mooley drought index (BMDI). However, the Palmer drought index (PDI) and RAI were also used to assess the droughts. Their results suggested that all three indices performed equally well in identifying meteorological drought events, but the RAI was the least complicated index of them.

Furthermore, many researchers found out that the precipitation concentration index (PCI) has merits to analyze the seasonal precipitation variations and understanding the seasonal fluctuations in rainfall [32]. De Luis et al. [33] investigated deviations in precipitation using rainfall data from 1946 to 2005 in Spain. Their findings suggested that variations in PCI are complicated while also being linked to global atmospheric characteristics as well as local factors influencing precipitation deviations.

In addition, nonparametric tests like the Mann–Kendall (MK) trend test and Sen's slope estimator test were comprehensively applied in many scholarly works in numerous regions [34, 35] to verify the presence of spatio-temporal rainfall trends and account for their significance. The combination of these tests with precipitation and drought indices showcased a comprehensive view of the rainfall and drought variabilities.

In addition, Muhire et al. [36] investigated the relationship between seasonal rainfall anomalies and El Niño-Southern Oscillation (ENSO) events from 1935 to 1992 in Rwanda. They observed that even though El Niño and La Niña took place within the same year, there were no correlations with rainfall anomalies. Nevertheless, ENSO events were more correlated with positive long rain anomalies and negative short rain anomalies. Additionally, several studies have characterized the effect of ENSO events on the rainfall variation in Sri Lanka [37, 38] and observed that because of the strong seasonality in rainfall, correlations between Southern Oscillation (SO) events and rainfall fluctuations show positive and negative values in time and space.

Some drought investigations conducted in Sri Lanka have concentrated solely on the dry zones [39, 40]. However, Abeysingha and Rajapaksha [41] assessed the status of droughts in Sri Lanka by mainly utilizing SPI on monthly precipitation data from 1970 to 2017 from 54 weather stations. In addition, Alahacoon et al. [42] used SPI, RAI, and Vegetation Health Index (VHI) to investigate long-term drought occurrences and assess drought hazards at the district level in Sri Lanka. Furthermore, Herath et al. [43] explored month-wise precipitation data utilizing SPI to monitor probable drought circumstances on the entire island for the year 2015. However, studies that attempt to comprehensively investigate drought trends on a national scale using multiple drought indicators are rather unfound in Sri Lanka, and therefore, the authors were motivated to conduct this research study. According to Zhang et al. [44] SRAI is most suitable for the analysis of meteorological drought in the monsoon-dominated environment where the rainfall is significantly seasonal and periodic. Besides, the PCI is a powerful indicator for spatio-temporal rainfall distribution and is also very useful for the analysis of seasonal changes in rainfall [45]. Therefore, the objectives of this study are: (1) to investigate the rainfall distribution characteristics in Sri Lanka using SRAI and PCI indices, respectively; and (2) to study patterns of precipitation concentration by utilizing the MK trend test and rate of change in PCI at annual and seasonal timescales. These objectives are to bring up a comprehensive view of the spatio-temporal rainfall variability and concentration over Sri Lanka. The outcomes of this study will offer better strategies for water resource management and agricultural planning while aiding the development of drought mitigation strategies for the entire country. According to Karbasi et al. 46, prediction of drought plays a vital role in the effective management of water resources and agriculture by managing drought conditions.

2. Study Area and Data Used

Sri Lanka is a tropical island in the southeastern region of the Indian Ocean between latitudes of 5°N to 10°N and longitudes of 79°E to 82°E. The island happens to be encircled by the Indian Ocean, the Gulf of Mannar, and the Bay of Bengal (refer to Figure 1). The total geographical area of Sri Lanka is 65,610 km^2. The country can be separated into three main climatic zones, i.e., the wet zone, the intermediate zone, and the dry zone based on rainfall characteristics [47]. In addition, the mean annual temperature in lowlands and highlands varies between 26.5–28.5°C and 14.7–17.1°C, respectively. Further, the climate of the country is characterized by high relative humidity, generally ranging between 75% and 95% [48]. Generally, a tropical climate is to be expected in Sri Lanka, and the wettest part of the island is the southwestern region.

Annual and monsoon rainfall characteristics of Sri Lanka were examined using rainfall data from the 15 rain gauge stations (refer to Figure 1 and Table 1). The rainfall stations were selected carefully according to rainfall data quality and their good distribution in the territory. The monthly rainfall data (from 1990 to 2019) were purchased from the Department of Meteorology, Sri Lanka. In addition, this study mainly focuses on annual and monsoon rainfall variation and concentration. Two main monsoon seasons are active in Sri Lanka, the southwest monsoon season (SWMS) taking place between May to September and the northeast monsoon season (NEMS) which occurs between December to February, the monthly rainfall data were categorized accordingly to these seasons.

3. Methodology

3.1. Overall Methodology. The monsoonal (SWMS and NEMS) and annual rainfall characteristics of Sri Lanka were studied by fundamental statistical techniques such as mean, standard deviation (SD), and coefficient of variance (CV). Additionally, the standardized rainfall anomaly index (SRAI) and precipitation concentration index (PCI) were used to present the annual and seasonal rainfall distribution characteristics. The nonparametric tests, Mann–Kendall trend test (MK) and Sen's slope (SS), and the magnitude of change analysis were carried out for PCI. The spatial distributions were showcased in maps using IDW interpolation method in ArcGIS.

3.2. Coefficient of Variation (CV). Coefficient of variation is used define rainfall variability into three categories based on its numerical value, including low ($CV < 20$), moderate ($20 < CV < 30$), and high ($CV > 30$) [49]. Annual and monsoonal rainfall variability over Sri Lanka was calculated using the following equation.

$$CV = \frac{\sigma}{\mu} \times 100, \qquad (1)$$

where, σ is the standard deviation and μ is the mean rainfall for annual and seasonal scales.

3.3. Standardized Rainfall Anomaly Index (SRAI). Annual precipitation data in Sri Lanka were investigated using SRAI which has grown in popularity for regional climate change studies [50]. The dry years and wet years within a span of time [51] can be found from in the following equation.

$$SRAI = \frac{X_i - \overline{X}}{\sigma}, \qquad (2)$$

where X_i, and $\overline{X}$ are the annual rainfall of the particular year and the long-term mean annual rainfall over a period of observation. The negative SRAI values present a drought while the positive values present a wet episode. McKee et al. [52] proposed the categorization of the SRAI values and presented in Table 2.

3.4. Precipitation Concentration Index (PCI). PCI indicates the monthly distribution of precipitation and has been widely used to indicate the disastrous hydrological events such as droughts and floods [53]. The PCI can be calculated annually and seasonally (for SWM and NEM) using the equations (3) and (4).

$$PCI_{annual} = \frac{\sum_{i=1}^{12} P_i^2}{\left(\sum_{i=1}^{12} P_i\right)^2} \times 100, \qquad (3)$$

$$PCI_{seasonal-SWM} = \frac{\sum_{i=1}^{12} P_i^2}{\left(\sum_{i=1}^{12} P_i\right)^2} \times 41.66, \qquad (4)$$

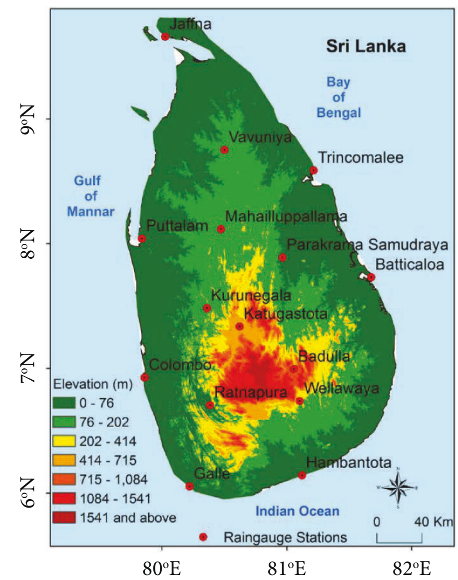

FIGURE 1: Locations of the rain gauge stations under review.

TABLE 1: Geographical information of rain gauge stations.

Stations	Latitude	Longitude	Elevation (m)
Jaffna	9° 40′ N	80° 01′ E	3
Vavuniya	8° 45′ N	80° 30′ E	98
Trincomalee	8° 34′ N	81° 15′ E	24
Puttalam	8° 01′ N	79° 49′ E	2
Mahailluppallama	8° 07′ N	80° 28′ E	117
Parakrama Samudraya	7° 54′ N	80° 58′ E	58
Batticaloa	7° 43′ N	81° 42′ E	8
Kurunegala	7° 28′ N	80° 22′ E	116
Katugastota	7° 19′ N	80° 37′ E	417
Badulla	6° 58′ N	81° 02′ E	670
Colombo	6° 54′ N	79° 52′ E	7
Ratnapura	6° 40′ N	80° 24′ E	86
Wellawaya	6° 43′ N	81° 05′ E	16
Galle	6° 01′ N	80° 13′ E	12
Hambantota	6° 07′ N	81° 07′ E	16

TABLE 2: Standardized rainfall anomaly index (SRAI) value and classes [52].

SRAI value	Category
2 and above	Extremely wet
1.5 to 1.99	Severely wet
1.0 to 1.49	Moderately wet
−0.99 to 0.99	Near normal
−1.0 to −1.4	Moderately dry
−1.5 to −1.99	Severely dry
−2 and less	Extremely dry

$$PCI_{seasonal-NEM} = \frac{\sum_{i=1}^{12} P_i^2}{\left(\sum_{i=1}^{12} P_i\right)^2} \times 25, \qquad (5)$$

where, monthly precipitation in month i is defined as P_i. The numerical value 100 in equation (3) is to account for the 12 months (100%) in the annum. Similarly, 41.66 are for

5 months of the year in SWM and 25 are for 3 months in the NEM season. The numerical value of PCI is used to classify the rainfall distribution. Uniform precipitation distribution (low precipitation concentration) is given by PCI less than 10. Moderate precipitation is given by PCI in between 11 and 15 while 16 to 20 give the irregular distribution. The PCI values greater than 20 showcase the strong irregularity of precipitation distribution (that is, high precipitation concentration). The classification can be found in Oliver [54].

3.5. The Mann–Kendall (M–K) Test and Sen's Slope Estimator. The MK trend test was frequently used to assess the trends in climatic factors. The test combined with Sen's slope estimator was used in a number of studies in Sri Lanka [41, 55]. The annual and seasonal trends of PCI for Sri Lanka were analyzed using these two tests. Equations (6)–(8) showcase the formulations for the Mann–Kendall test. More information about these formulations can be found in Mann [56] and Kendall [57].

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}\left(P_j - P_i\right), \tag{6}$$

where n, P_i, and P_j are the number of climatic data points and climatic data in the time series where $j > i$. The *sgn* function is defined in the following equation.

$$\operatorname{sgn}\left(P_j - P_i\right) = \begin{cases} +1, & \text{if } \left(P_j - P_i\right) > 0, \\ 0, & \text{if } \left(P_j - P_i\right) = 0, \\ -1 & \text{if } \left(P_j - P_i\right) < 0. \end{cases} \tag{7}$$

when n is greater than 10, S becomes a normal distribution with a mean of 0. The variance of this distribution is given in the following equation.

$$\sigma_s^2 = \frac{1}{18}\left[n\,(n-1)\,(2n+5) - \sum_t t\,(t-1)\,(2t+5)\right]. \tag{8}$$

where t is the extent of any given ties. The Mann–Kendall statistics Z_c is calculated as per in the following equation.

$$Z_c = \begin{cases} \dfrac{S-1}{\sigma_s}, & S > 0, \\ 0, & S = 0, \\ \dfrac{(S+1)}{\sigma_s}, & S < 0. \end{cases} \tag{9}$$

The positive and negative Z_c values indicate the positive and negative trends in the climatic time series. However, the significance of the trend depends on the null hypothesis. If the null hypothesis is rejected when $|\, Z_c \,| > Z_1 - \alpha/2$, then a significant trend appears in the time series. All the results are tested at $\alpha = 0.05$ ($Z_c = \pm 1.96$) significance level. The qualitative trend identification is presented in a numerical trend using the Sen's slope estimator (SS). The formulations for the Sen's slope estimator are given in the following equations [58].

$$Q_i = \frac{P_j - P_k}{j - k}, \quad i = 1, 2, \ldots N, \tag{10}$$

where j and k are time points in the climatic time series. More information can be found in Sen's slope estimator [58].

4. Results and Discussion

4.1. Descriptive Statistics and Rainfall Distribution. Annual and seasonal rainfall distribution characteristics of all selected rainfall stations are listed in Table 3. Annual and seasonal statistical analysis showed that annual average rainfall varied between 1064 mm (Hambantota) and 3682 mm (Ratnapura). The mean seasonal rainfall during SWM ranges between 224 mm (Jaffna) and 1782 mm (Ratnapura). Further, during the NEM season, mean seasonal rainfall fluctuates between 246 mm (Puttalam) and 890 mm (Batticaloa) (refer to Table 3).

The station-wise descriptive statistics showed a maximum annual rainfall deviation (542 mm) for Batticaloa and the lowest deviation in annual rainfall for Hambantota (232 mm). The maximum deviation (376 mm) in SWM rainfall was observed at the Ratnapura and minimum rainfall deviation (112 mm) for Batticaloa stations. In the case of the NEM season, rainfall deviated between 110 mm (Puttalam) and 423 mm (Batticaloa). Moreover, rainfall variability analysis denoted that at annual average rainfall varied between 14% (Ratnapura) and 29% (Batticaloa) (refer to Figure 2(a)).

In addition, Table 3 specified that the Vavuniya, Mahailluppallama, Kurunegala, Katugastota, Colombo, Ratnapura, and Galle stations' annual rainfall variability is low (below 20%), and reaming stations showed moderate annual rainfall variability (between 20% and 30%). In the case of the SWM season, rainfall varied between 21% (Ratnapura) and 61% (Mahailluppallama) (refer to Figure 2(b)). Nevertheless, seasonal rainfall (SWM) variability is moderate at Katugastota, Colombo, Ratnapura, and Galle. The NEM season rainfall variability is high (above 30%) at all stations under review (refer to Figure 2(c)). This clearly shows that seasonal rainfall variability is more than that of annual rainfall variability (refer to Figure 2). On the other hand, NEM rainfall showed more variability as compared to SWM (refer to Figures 2(b) and 2(c)).

4.2. Standardized Rainfall Anomaly Index (SRAI) and Rainfall Departure from Mean (%). The annual and seasonal (SWM and NEM) SRAI and rainfall departure from mean (%) analyses were executed for Sri Lanka to identify the rainfall trend at the national level from 1990 to 2019 (refer to Figure 3). The SRAI analysis showed that the years 2010, 2011, 2014, 2015, and 2019 were wet years while the years 1992, 1996, 2001, 2003, and 2016 were the dry years (refer to Figure 3(a)) for Sri Lanka during 1990–2019.

Table 3: Summary of the annual and seasonal rainfall of the Sri Lanka (1990–2019).

SN	Stations	Annual					SWMS					NEMS				
		Mean	Max	Min	SD	CV	Mean	Max	Min	SD	CV	Mean	Max	Min	SD	CV
1	Jaffna	1382	1965	903	318	23	224	565	28	123	55	373	976	81	201	54
2	Vavuniya	1433	2106	1038	238	17	311	588	144	126	40	438	838	216	174	40
3	Trincomalee	1648	2910	996	367	22	335	603	96	126	38	601	1619	205	252	42
4	Puttalam	1205	1734	819	263	22	256	539	48	134	52	246	579	83	110	45
5	Mahailluppallama	1480	2090	1011	272	18	292	848	53	178	61	390	748	104	167	43
6	Parakrama Samudraya	1790	2941	846	480	27	245	581	51	140	57	771	1532	294	313	41
7	Batticaloa	1870	3621	1010	542	29	247	500	30	112	45	890	2403	388	423	48
8	Kurunegala	1991	2737	1228	326	16	632	1119	334	203	32	283	719	57	142	50
9	Katugastota	1868	2666	1300	287	15	590	898	375	147	25	404	767	95	175	43
10	Badulla	1777	2525	1035	349	20	398	785	209	133	33	574	1354	250	217	38
11	Colombo	2402	3370	1774	371	15	1001	1703	639	243	24	326	582	102	120	37
12	Ratnapura	3682	4711	2801	499	14	1782	2508	1271	376	21	475	894	220	178	37
13	Wellawaya	1996	3158	1466	457	23	342	665	98	158	46	446	855	190	167	38
14	Galle	2335	3091	1537	406	17	1068	1590	471	296	28	333	586	136	127	38
15	Hambantota	1064	1734	649	232	22	304	734	78	125	41	258	466	73	113	44

SWMS = southwest monsoon season; NEMS = northeast monsoon season; Max = maximum; Min = minimum, SD = standard deviation; CV = coefficient of variability.

The annual rainfall of Sri Lanka was regularly less than its long-term annual average rainfall (1862 mm) between 1990 and 2019, as indicated by the rainfall departure from the mean (refer to Figure 3(a)). However, the annual rainfall in the years 2014 and 2015 was 24% and 18% more than the annual average rainfall in the country. In addition, the SWM rainfall was frequently below the average southwest monsoon rainfall (ASWMR) between 2000 and 2013 except in 2003, 2004, and 2010 (refer to Figure 3(b)). The SRAI computed for SWM rainfall denoted that 2002, 2005, 2011, and 2012 years were the severe drought years whereas, 1997 was severe wet year (refer to Figure 3(b)).

The highest negative rainfall departure (−37%) was observed in 2012, while the maximum positive rainfall departure was seen (+31%) in 1997. In the case of NEM, seasonal rainfall departure fluctuates between -51% (1992) and 81% (2011) (refer to Figure 3(c)). The SRAI showed 2011 and 2014 years were the extremely wet years of Sri Lanka during NEM. Although in the year 2014 SWM rainfall was very less, NEM rainfall was 62% more than that of an average northeast monsoon rainfall (ANEMR) and the SRAI value was 2.27 which caused 2014 years to be considered the extremely wet year of Sri Lanka during 1990–2019.

4.3. Spatio-Temporal Analysis of Wet and Dry Years. A station-wise wet and dry years were identified for all rainfall stations using SRAI for annual rainfall (refer to Table 4). Table 4 shows that 2011, 2014, and 2019 years were the wet years and 2016 was the dry year for most of the stations under review. Moreover, station-wise wet, normal, and dry years from 1990 to 2019 were depicted graphically to understand spatial rainfall variation (refer to Figure 4). Figure 4 remarkably shows that all stations received utmost normal rainfall (average 21 years) with an average of 5–5 years of wet and dry period respectively during 1990–2019. However, the analysis showed the highest (24 years) years of normal rainfall for Trincomalee and the lowest (18 years) years for Jaffna stations. The maximum dry years (6 years) were observed for the Jaffna, Mahailluppallama, Katugastota, Colombo, and Galle whereas, the lowest dry years (3 years) were identified for the Trincomalee and Ratnapura stations, respectively. This specified that in spite of spatial rainfall fluctuations in the wet and dry periods in the last 30 years (1990–2019), Sri Lanka received normal rainfall most frequently.

4.4. Precipitation Concentration Index (PCI) Analysis. Figure 5 illustrates the results of the analysis of the spatial distribution of the mean PCI values (annual and seasonal) for the 15 selected rain gauge stations. The spatial distribution of the PCI was depicted by using the IDW interpolation method.

Based on the PCI classification suggested by Oliver [49], only the Ratnapura station showed uniform rainfall distribution during SWM (refer to Tables 2 and 5). The average annual PCI varied from 11 (Ratnapura) to 21 (Jaffna) over the country (refer to Figure 5(a)). However, for the SWM rainfall PCI ranged between 10 (Ratnapura) and 19 (Puttalam and Mahailluppallama) whereas PCI varied between 11 (Ratnapura) and 16 (Jaffna) in the NEM (refer to Figures 5(b) and 5(c)). Besides, Vavuniya, Puttalam, Mahailluppallama, and Parakrama Samudraya showed irregular rainfall distribution on the annual and seasonal (SWM) scale (refer to Table 5). In addition, the mean annual PCI of the Jaffna is above 20 that specifying strong irregularity of precipitation distribution (refer to Table 5 and Figure 5(a)). Furthermore, during the NEM season, except for Jaffna, all rainfall stations denoted moderate rainfall concentration of rainfall. Overall, moderate rainfall concentration to irregular rainfall distribution was observed for the majority of the raingauge stations both annually and seasonally.

4.5. Trend Analysis and Percent Change of PCI. MK test was carried out to identify the mean annual and seasonal trend of

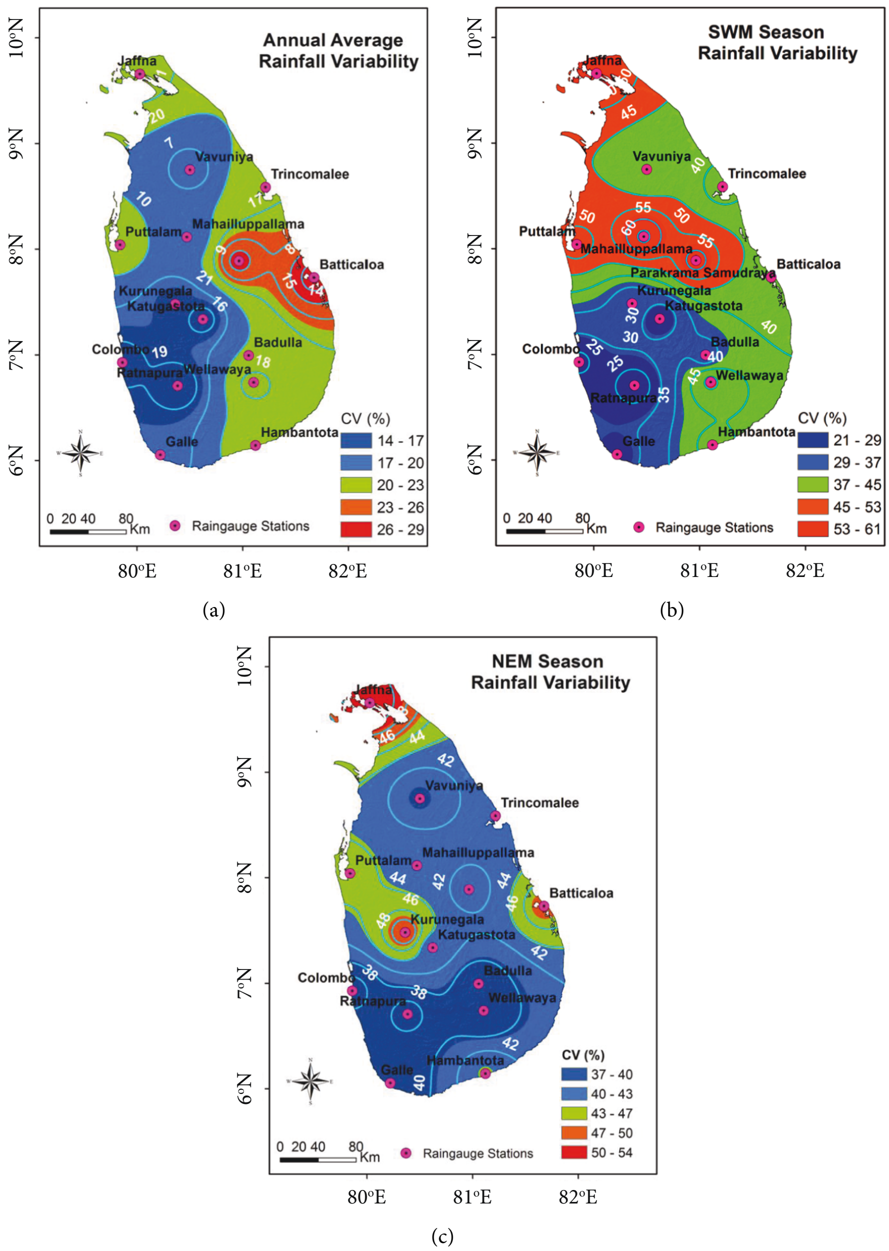

Figure 2: Spatial distribution of rainfall variability at annual and seasonal timescale. (a) For annual average. (b) For SWM season. (c) For NEM season.

PCI, and the spatial distribution map of these were prepared using IDW interpolation method in ArcGIS 10.1 (refer to Table 6 and Figure 6).

The MK trend analysis result showed that annual mean precipitation concentration significantly increased at Katugastota ($Z = 2.17$) and Wellawaya ($Z = 1.76$) stations at 0.05 and 0.10 levels of significance, respectively (refer to Figure 6(a)). A significantly increasing trend for the Vavuniya ($Z = 2.21$), Trincomalee ($Z = 2.20$), and Batticaloa ($Z = 1.69$) was observed during the SWM season (refer to Figure 6(b)). During the NEM season a significant increase in precipitation concentration was noted only for the Katugastota ($Z = 1.81$) at a 0.10 level of significance (refer to Figure 6(c)). However, Batticaloa (annual), Mahailluppallama (SWMS), and Badulla (NEMS) did not show any changes in the rainfall concentration during 1990–2019 (refer to Figures 6(a)–6(c)). The Mahailluppallama, Parakrama Samudraya, Ratnapura, Galle, and Hambantota stations showed insignificant decreasing trend in mean annual rainfall concentration (refer to Figure 6(a)). In the case of SWMS, only Kurunegala, Katugastota, and Galle stations revealed a decreased (insignificant) trend in the mean seasonal rainfall concentration (refer to Figure 6(b)). The Trincomalee and Colombo stations experienced an insignificant decreasing trend during NEMS (refer to Figure 6(c)).

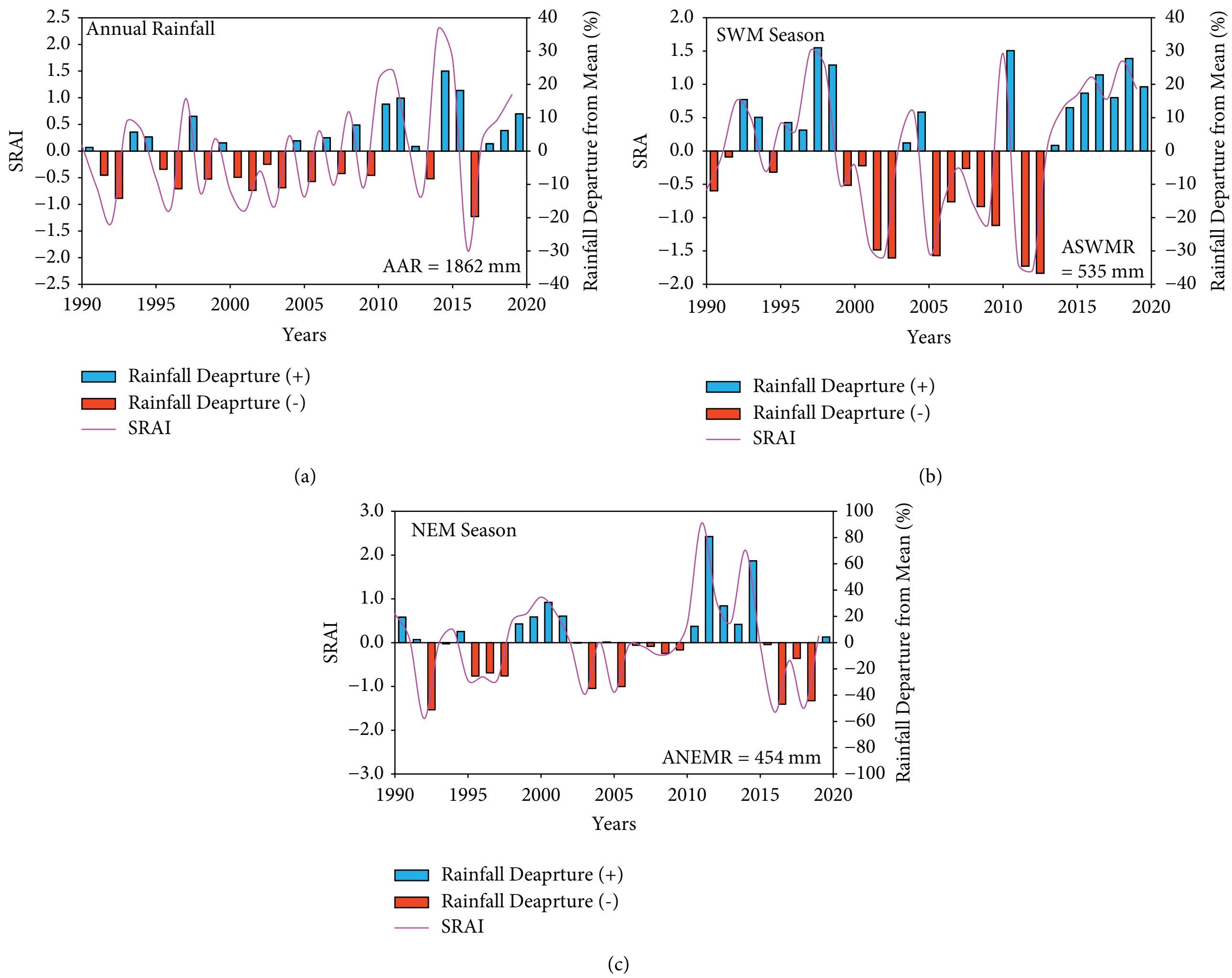

Figure 3: Plots of annual and seasonal SRAI and rainfall departure from mean (%) for Sri Lanka. (a) For annual rainfall. (b) For SWM season. (c) For NEM season.

Table 4: Station-wise wet and dry years observed in Sri Lanka based on SRAI (1990–2019).

Stations	Wet years	Dry years
Jaffna	1990, **1993**, **2001**, **2004**, 2008, **2015**	**1992**, 2006, 2012, 2016, 2000, 2013
Vavuniya	1993, 2000, **2011**, ***2014***, **2015**	1992, **1995**, 2005, 2006, 2016
Trincomalee	***2011***, 2015, 2018	1998, 2007, **2016**
Puttalam	2002, 2014, 2015, ***2019***	2007, 2011, 2013, 2017
Mahailluppallama	**1997**, 2002, ***2014***, 2015, **2019**	1992, **1998**, 2003, 2005, **2009**, 2013
Parakrama Samudraya	1990, 1994, 1997, ***2011***, **2015**	1995, **1996**, 1998, 2016, 2017
Batticaloa	1994, 2004, **2011**, 2014	1992, **1998**, 2005, 2006, 2016
Kurunegala	***1997***, 2006, 2008, 2010, ***2014***, 2018	2000, 2001,***2003***, 2007
Katugastota	1993, ***2010***, ***2014***	1998, 2003, 2004, **2016**, 2017, 2019
Badulla	**2006**, 2010, ***2011***, 2014, **2015**	1992, 1998, 2001, ***2016***
Colombo	1999, 2005, ***2010*** , 2015, 2019	2000, 2001, 2003, 2004, **2011**, 2013
Ratnapura	**1998**, 1999, **2010**, ***2014***, 2017	2007, ***2009***, ***2016***
Wellawaya	2015, ***2017***, **2018**, ***2019***	1993, 1999, 2001, 2002, 2003
Galle	**1999**, **2007**, **2010**, **2019**	1990, 2001, ***2002***, 2003, 2005, 2013
Hambantota	1997, 2006, 2015, ***2019***	***1992***, 2001, ***2016***, 2018
Sri Lanka	2010, **2011**, ***2014***, **2015**, 2019	1992, 1996, 2001, 2003, **2016**

SRAI = standardized rainfall anomaly index; bold value shows severe wet and dry years; bold and Italic value shows extremely wet and dry years.

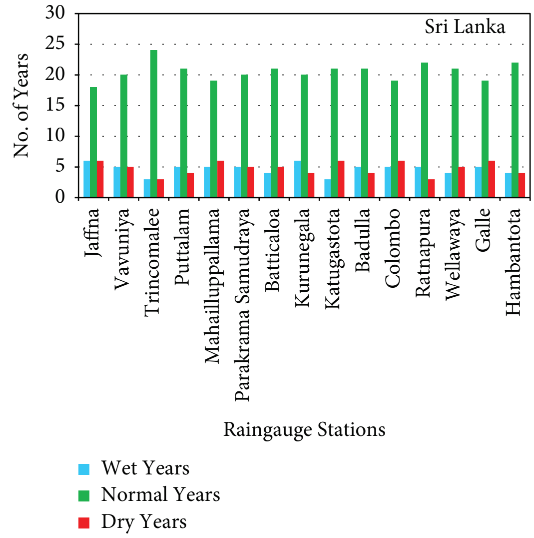

Figure 4: Plot of station-wise distribution of wet, normal, and dry years.

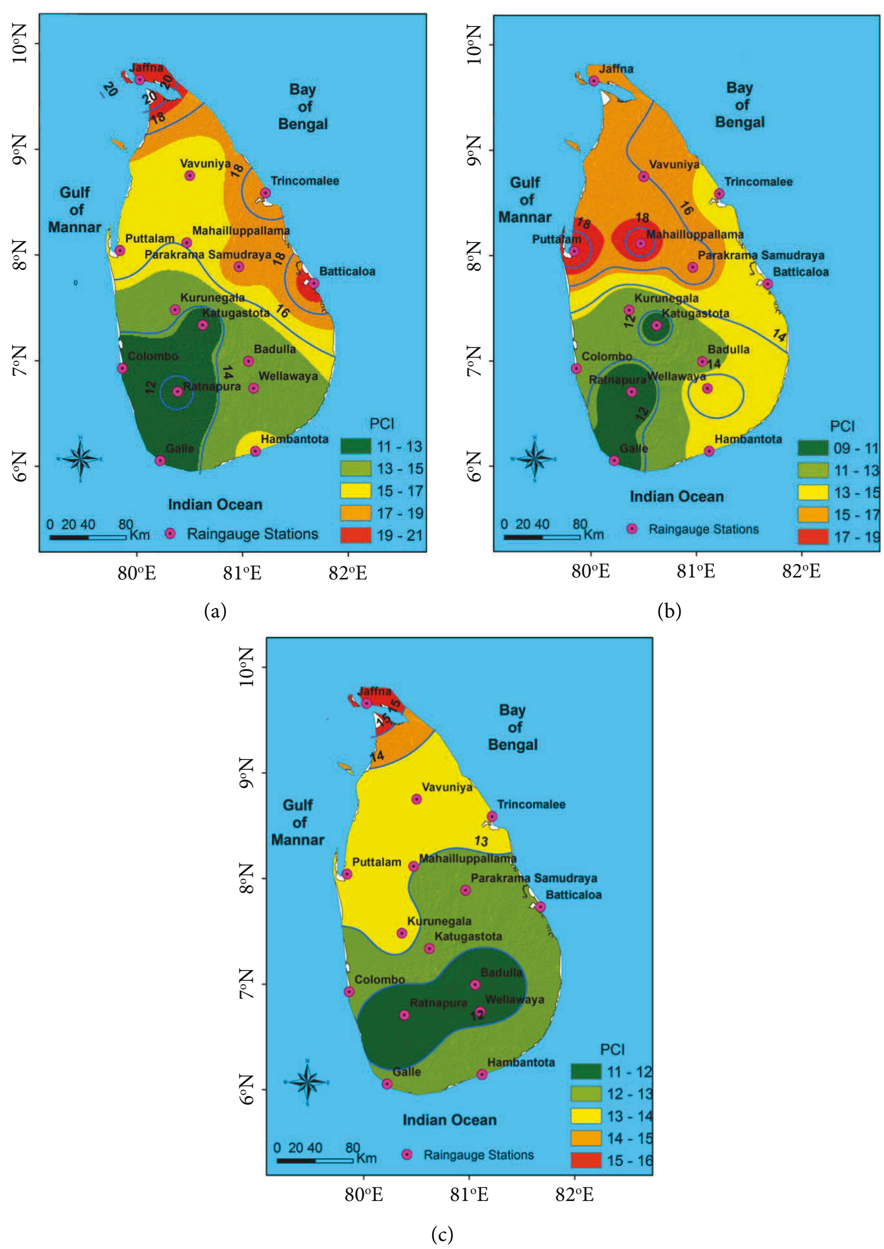

Figure 5: Spatial distribution of mean annual and seasonal PCI in Sri Lanka. (a) For annual PCI. (b) For SWM PCI. (c) For NEM PCI.

Table 5: PCI distribution.

PCI distribution	PCI range	Annual	SWM	NEM
Uniform precipitation	<10	*NA*	Ratnapura	*NA*
Moderate precipitation	11 to 15	Kurunegala, Katugastota, Badulla, Colombo, Ratnapura, Wellawaya, Galle	Trincomalee, Batticaloa, Kurunegala, Katugastota, Badulla, Colombo, Wellawaya, Galle, Hambantota	Vavuniya, Trincomalee, Puttalam, Mahailluppallama, Parakrama Samudraya, Batticaloa, Kurunegala, Katugastota, Badulla, Colombo, Ratnapura, Wellawaya, Galle, Hambantota
Irregular	16 to 20	Vavuniya, Trincomalee, Puttalam, Mahailluppallama, Parakrama Samudraya, Batticaloa, Hambantota	Jaffna, Vavuniya, Puttalam, Mahailluppallama, Parakrama Samudraya,	Jaffna
Strong irregularity	>20	Jaffna	*NA*	*NA*

Table 6: Result of trends and percent change in PCI during 1990–2019

Stations	Annual			SWMS			NEMS		
	MK Z	SS β	Change %	MK Z	SS β	Change %	MK Z	SS β	Change %
Jaffna	0.32	0.02	2.16	0.63	0.04	7.04	0.72	0.12	23.09
Vavuniya	0.65	0.05	9.41	**2.21**	0.18	33.64	0.45	0.04	8.81
Trincomalee	0.93	0.01	1.56	**2.20**	0.16	31.26	−0.59	−0.07	−15.02
Puttalam	0.50	0.05	8.60	0.64	0.09	14.56	0.50	0.05	10.90
Mahailluppallama	−0.09	0.00	0.00	0.00	0.00	0.00	0.54	0.04	9.39
Parakrama Samudraya	−0.04	0.02	3.39	0.52	0.04	6.96	0.00	0.02	4.92
Batticaloa	0.00	0.00	0.00	***1.69***	0.09	18.79	0.16	0.01	2.41
Kurunegala	0.42	0.02	4.25	−0.84	−0.05	−12.36	0.52	0.03	6.54
Katugastota	**2.17**	0.09	21.39	−0.35	0.00	0.00	***1.81***	0.12	29.70
Badulla	0.64	0.04	8.76	0.51	0.02	4.58	0.00	0.00	0.00
Colombo	0.02	0.00	0.00	0.22	0.01	2.51	−0.65	−0.02	−4.94
Ratnapura	−0.03	0.01	2.77	0.57	0.01	3.06	1.40	0.05	13.69
Wellawaya	***1.76***	0.09	17.60	1.55	0.07	13.63	0.50	0.04	10.02
Galle	−1.50	−0.05	−11.91	−1.30	−0.04	−10.95	0.56	0.04	9.87
Hambantota	−0.23	−0.02	−3.84	1.48	0.10	21.27	1.43	0.08	18.27

Values in **bold** (*Italic*) are statistically significant at **0.05** (*0.10*) significance level.

In addition, the rate of change in precipitation concentration based on PCI was calculated for all stations at annual and seasonal scales from 1990 to 2019 (refer to Figure 7). The significant positive changes on an annual scale were noted for Katugastota (21.39%) and Wellawaya (17.60%), respectively (refer to Figure 7(a)). Figure 7(b) showcases significant positive changes in precipitation concentration for Vavuniya (33.64%), Trincomalee (31.26%), and Batticaloa (18.79%) rainfall stations in SWMS. In addition, a significant positive change in precipitation concentration was reported for the Katugastota (29.70%) in the last 30 years (refer to Figure 6(c)). However, as per the holistic view, rainfall distribution and concentration change do not show a positive and negative change in the rainfall pattern of Sri Lanka in spite of a few stations experiencing significant positive changes.

4.6. Comparison of Research Findings to Literature. Wickramagamage [59] discussed the spatial and temporal variation of rainfall over Sri Lanka using 48 rain gauges for 30 years (1981–2010). Linear regression techniques were used to analyze the trends even though rainfall is a nonlinear variable. The analysis was carried out to resolve seasonal rainfall. Mixed negative and positive rainfall trends were found in this study. In contrast, the authors of this research paper have used nonparametric tests to identify the spatio-temporal rainfall trends and concentration over Sri Lanka. Therefore, the nonlinearity of the rainfall has been taken into account. In addition, Wickramagamage [59] has used the Mann–Kendall test and Sen's slope estimator test to showcase the spatial and temporal rainfall trends over Sri Lanka for the period 1989 to 2019. However, they have not used the coefficient of variation, standardized rainfall anomaly index, and precipitation concentration index to identify the rainfall variation and concentration. Nevertheless, Alahacoon and Edirisinghe [60] found that annual rainfall increases across Sri Lanka. In addition, there are several studies to discuss the rainfall trends in localized catchments using non-parametric tests in Sri Lanka [37, 38, 55, 61, 62]. However, they have not developed graphical explanations of the spatial and temporal distribution

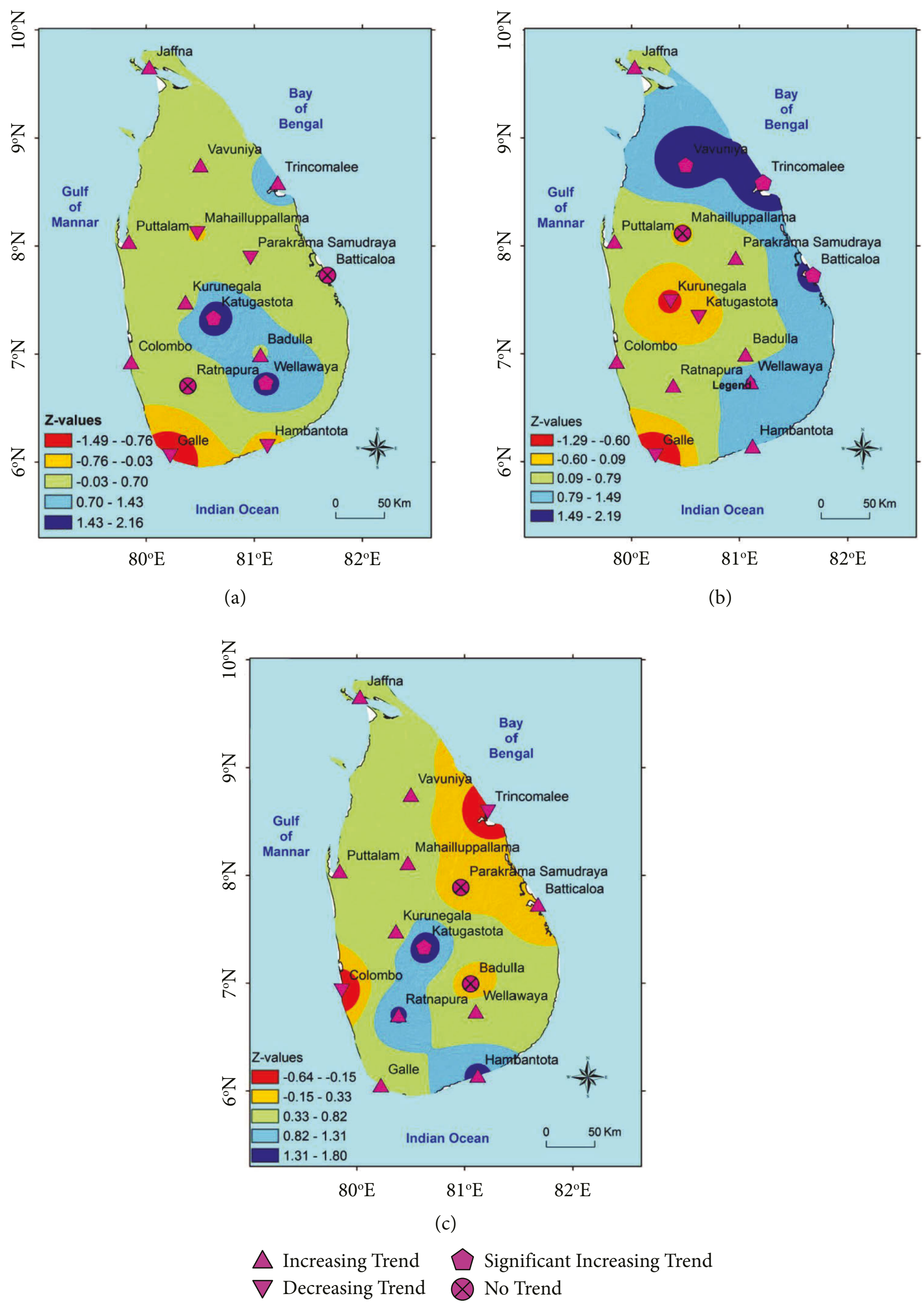

FIGURE 6: Spatial trend of mean annual and seasonal PCI in Sri Lanka. (a) For annual PCI trends. (b) For SWM PCI trends. (c) For NEM PCI trends.

of rainfall variation and concentration across Sri Lanka. Therefore, the presented research study herein adds a novel contribution to the literature. In addition, the findings can be effectively used to manage the water resources in Sri Lanka, which is a threat at the moment. Sri Lanka is an agricultural country, and it has an engineered but ancient irrigation system. In addition, cash crops like tea still bring significant income to the country. However, recent changes in rainfall intensity have severely impacted agricultural lands [63]. Therefore, the harvest in some of the areas is washed away. Not only the floods but also the unexpected droughts have created a loss of harvest of the staple food of Sri Lanka. Furthermore, the harvest of cash crops has been reduced due to the seasonal changes in rainfall. The rainfall patterns have impacted the weather in central hills and created issues for tea estates, ultimately leading to a reduced harvest. Therefore, the findings of this research can be effectively used to manage the water resources in Sri Lanka, which are under threat at the moment.

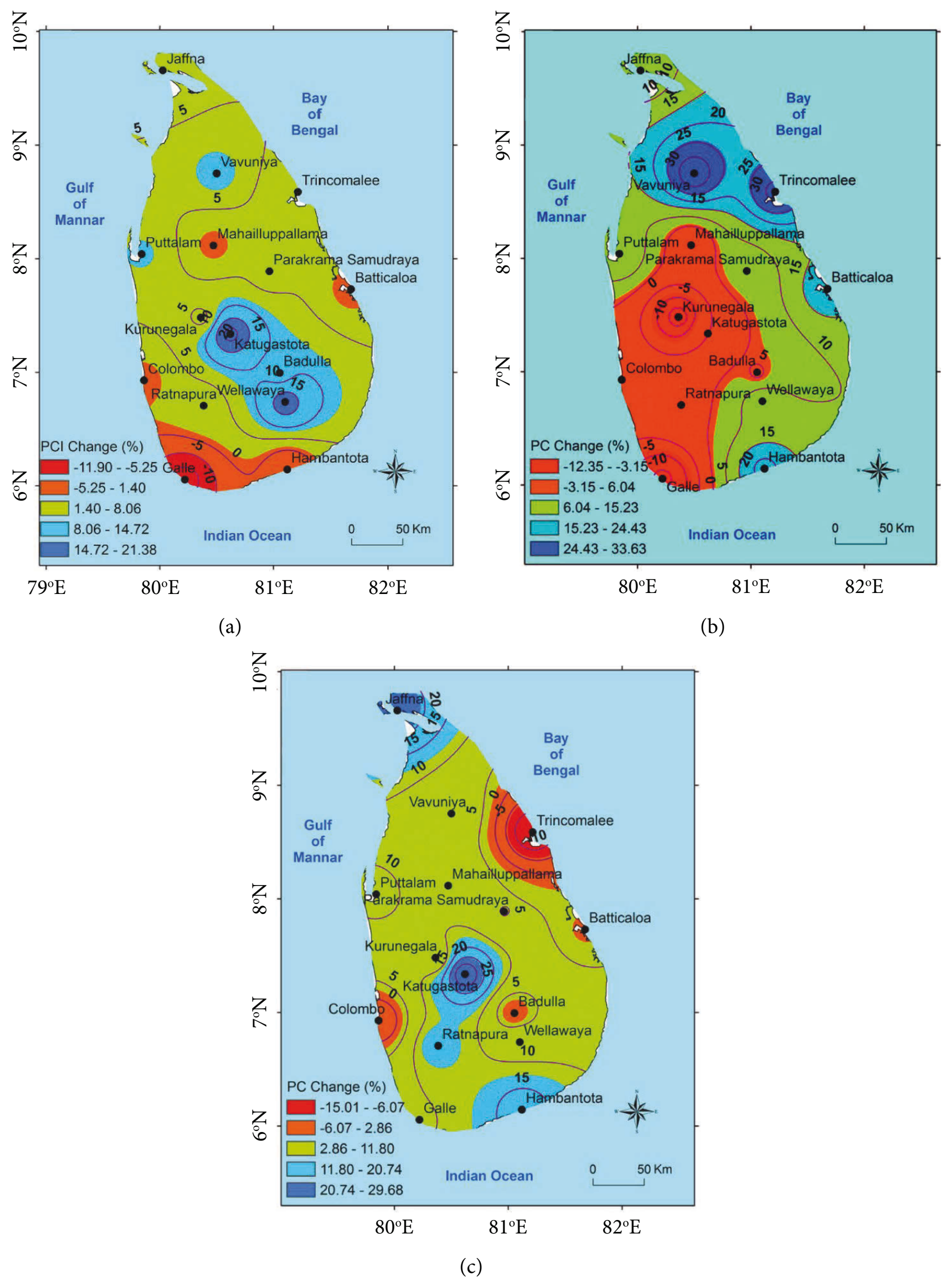

Figure 7: Spatial distribution of annual and seasonal change in PCI in Sri Lanka. (a) For annual PCI change. (b) For SWM PCI change. (c) For NEM PCI change.

Studies of similar nature, investigating rainfall variability, have been conducted previously in India [64, 65]. Sahany et al. [64] analyzed rainfall variability over 113 years throughout the entirety of India and concluded that significant decreasing trends in seasonality along with decreasing rainfall were discovered over sections of central India, the Indo-Gangetic Plains, and parts of the Western Ghats. However, no significant trends were observed for the southern region of India, which is near Sri Lanka. Nair et al. [65] investigated rainfall trends in the state of Kerala in South India over the last 100 years and found that the annual and seasonal trends of rainfall in most regions had decreased significantly. In contrast, the results obtained for Sri Lanka indicated that rainfall distribution and concentration change do not show a positive and negative change in the rainfall pattern of Sri Lanka despite a few stations experiencing significant positive changes.

5. Summary and Conclusions

This study focuses on the spatio-temporal precipitation distribution and concentration characteristics of Sri Lanka.

SRAI and PCI were utilized to analyze the monthly rainfall to obtain the distribution and concentration of precipitation both annually and seasonally (SWM and NEM). Additionally, the percentage variation in PCI alongside the Mann–Kendall trend test and the Sen's slope method were studied, and the key outcomes of the study are highlighted below:

(1) The seasonal analysis of the coefficient of variation showed that NEM rainfall is more variable as compared to SWM. The NEM has higher rainfall variability which is above 30% compared to those of 20% to 30% in SWM. However, annual rainfall variability is less than seasonal variability. The variability in annual scale shows less than 20%.

(2) The SRAI revealed that the 2011 and 2014 years were the extremely wet years of Sri Lanka during NEM. During the NEM season, rainfall was 62% more than that of an average northeast monsoon rainfall (ANEMR) and the SRAI value was 2.27, which caused 2014 years to be considered the extremely wet years of Sri Lanka from 1990 to 2019.

(3) The SRAI denoted that despite spatial precipitation variations in the wet and dry periods, Sri Lanka received normal rainfall most frequently and less frequently wet and dry years between 1990 and 2019.

(4) The analysis of PCI showed moderate to irregular rainfall distribution at annual and seasonal (SWM and NEM) timescales for most of the stations, except Jaffna and Ratnapura. Jaffna indicated a significant variability in precipitation distribution (high precipitation concentration of PCI 19–21) at the annual scale whereas Ratnapura exhibited a uniform precipitation distribution (low concentration; PCI 9–11) during SWM.

(5) The MK test analysis showed that PCI does not show a positive or negative change in the rainfall pattern of Sri Lanka in spite of a few stations experiencing significant positive changes. On an annual scale, only Katugastota and Wellawaya stations showed a significant positive change in the precipitation concentration whereas the seasonal trend of PCI specified a positive increasing trend for Vavuniya, Trincomalee, Batticaloa, and Katugastota. No station under review revealed a significant decreasing trend in the PCI from 1990 to 2019. Therefore, it is concluded that the rainfall in Sri Lanka is regular and reliable in spite of spatial seasonal variations.

Data Availability

The meteorological data and data of analysis are available upon request from the corresponding author for research purposes.

Conflicts of Interest

All authors declare that they have no conflicts of interest.

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