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ORIGINAL PAPER

Spatiotemporal rainfall variability and trend analysis over Mahaweli Basin, Sri Lanka

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Abstract

The hydrometeorological characteristics of the Mahaweli Basin are influenced by rainfall distribution. For that reason, it is significant to identify spatiotemporal rainfall fluctuations and trends over the Mahaweli Basin. Accordingly, rainfall data from 1990 to 2019 available for the 15 raingauge stations were analyzed for rainfall variability and trends. Serial autocorrelation was checked before applying rainfall time series data to Mann–Kendall (MK) test. The result exhibited no serial autocorrelation in the data. The MK test, Sen's slope estimator (SSE), and innovative trend analysis (ITA) were applied to recognize rainfall trends. The inverse distance weighting (IDW) interpolation method was applied to show the spatial pattern of rainfall characteristics with the support of ArcGIS 10.1. Some fluctuations were observed in the rainfall over the 30 years with decreasing and increasing trends. Nevertheless, significant trends in the annual rainfall were noted for Bandarawela (+15.7 mm), Ledgerwatta (+40.3 mm), Duckwari (−36.3 mm), and Bakamuna (24.3 mm). At the basin scale, no significant trends were noted in rainfall of the Mahaweli Basin. The rainfall trend analysis results obtained by ITA have validated the results of the nonparametric test. Therefore, the analysis showed that despite the seasonal variations in rainfall over the Mahaweli Basin, rainfall is regular, and results acquired by MK test, SSE, and ITA methods are reliable.

Keywords Mahaweli Basin · Mann–Kendall test · Sen's slope estimator · Innovative trend analysis · Inverse distance weighting

Abbreviations

AFIMSR	Average first inter-monsoon season rainfall
ASWMSR	Average south-west monsoon season rainfall
ASIMSR	Average second inter-monsoon season rainfall
ANEMSR	Average north-east monsoon season rainfall

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Introduction

Spatiotemporal variations in hydrometeorological variables are associated with climatic variability (Nobre et al. 2017). Moreover, climate change hastens rainfall variability that results in floods and droughts on a regional or global scale (Zhang et al. 2011; Meshram et al. 2017). Globally, rainfall variability, as well as trends, is a pivotal aspect in the research of climate change (Patra et al. 2012). Nevertheless, precise and trustworthy information about rainfall has great significance for water resource planning and management, which is directly associated with agriculture and disaster management (Supit et al. 2012; Prakash et al. 2015). Therefore, examination of rainfall unevenness at spatial (local or regional) and temporal (seasonal and annual) scales is essential in a climate change scenario. Moreover, an analysis of the precipitation tendencies and changeability at national, regional, and river basin scales has great significance in hydrologic assessments, water resources planning and management, for disaster preparedness, and to identify climate change effects on water resources (Goswami et al. 2006; Rahmat et al. 2015; Soro et al. 2016). Moreover, floods

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and droughts are highly associated with rainfall variability (Wang et al. 2017; Pawar 2019). In order to minimize the rainfall-associated problems, accurate and precise estimation of rainfall trends and variability has received greater attention worldwide (Praveen et al. 2020;Wang et al 2020.

Frequent attempts were made by scholars to understand the rainfall variability and trends throughout the world (Kumar and Jain 2011; Pawar 2019; Patil and Hire 2020). Onyutha et al. (2016) have used the MK test to investigate the rainfall tendencies in the Nile Basin based on 39 raingauge stations data. They mentioned that the length of the rainfall data can be influenced results of rainfall trends. Statistical analysis usually has a very good correlation with the number of data points, and therefore, Onyutha et al. (2016) findings are very acceptable. Shrestha et al. (2019) noted a mixed (positive and negative) trend of rainfall over the two mountainous river basins in southern slopes of the central Himalayas (Kali Gandaki and Koshi river basins). On the other hand, Singh et al. (2008) proposed that most of the river basins in northwest and central India have denoted an increasing trend in annual rainfall and relative humidity. Also, Bisht et al. (2017) have looked for the rainfall trends in 85 river basins in India, and upward trends were concluded for most of the river basins in India from this study. However, downward rainfall trends were noted while observing the increasing frequency of rainfall extremes also presented by many researchers to Indian River basins (Rajeevan et al. 2008; Ghosh et al. 2016; Shah and Mishra 2016; Deshpande et al. 2016; Sharma et al. 2017).

It is very essential to understand the rainfall tendencies over the various river basins of nearby Sri Lanka. Sri Lanka is a blessed country, which has a significant amount of water resources, while the whole country is covered by rivers. However, in the recent past, the country has experienced some adverse effects on the water resources caused by climate change (Droogers 2004; Esham and Garforth 2013; Khaniya et al. 2018). Increased temperatures, more extreme rainfall events, and increased drier periods are now common to the country. Muthuwatta et al. (2017) have searched for the rainfall trends over Malwathu Oya and Kalu River in Sri Lanka from the perspective of farmers. They have detected upward rainfall trends in both river basins using the Mann–Kendall test; however, when interviewed, farmers pointed out their experience on downward rainfall trends. Therefore, solid conclusions are not drawn straightforward from this research for any adaptation measures. Nisansala et al. (2019) and Khaniya et al. (2019) have found upward trends in rainfall of the Uma Oya Basin in Sri Lanka.

In Sri Lanka, several studies were conducted to identify rainfall trends over different river basins such as Kelani Basin, Kirindi Oya Basin, Mee Oya Basin, and Kala Oya Basin (Abeysingha et al. 2017; Dissanayaka and Rajapakse 2019; Karunarathne and Rajapakse 2019; Iresh 2020). Shelton and Lin (2019) observed the streamflow variability and seasonal rainfall of the Mahaweli River; however, it was not an extensive study for the rainfall trends in the whole river basin. Mahaweli River is a significant source of water in the dry zone area of the basin. The Mahaweli River irrigates about 55% of the dry zone of Sri Lanka (Withanachchi et al. 2014). Besides, seven major hydropower projects in the Mahaweli Basin supply about 17% electrical energy to the national grid annually with a capacity of 775 MWs (40% of the island-wide hydropower potential) (Hewawasam 2010). Therefore, it is very crucial to study the spatiotemporal rainfall variability and seasonal as well as the annual trend of rainfall over the Mahaweli Basin. However, there is no comprehensive rainfall trend analysis of the Mahaweli Basin. The present study focuses on the rainfall characteristics of the Mahaweli Basin especially variability and trends in a comprehensive manner.

Study area

Mahaweli River originates from the Ambewela reservoir as the Agra Oya in Nuwara Eliya district of Sri Lanka at an elevation of 2500 m and drains into the Trincomalee Bay. It flows for a length of 335 km from wet to dry climatic regions of Sri Lanka. The Kothmala, Puna, Hulu, Maha, Badulu, Uma, Kurundu, and Beliul are the main tributaries of the Mahaweli. The Mahaweli River has 10,420 km^2 basin areas which cover about 16% of the area of Sri Lanka (Elakanda 2010) (Fig. 1), and about 15% (2.8 million people) population of Sri Lanka resides in the basin (Lin and Shelton 2020). The Mahaweli Basin extends from 6° 48′ N to 8° 37′ N latitude and from 80° 29′ E to 81° 17′ E longitude. The Mahaweli Basin receives 1875 mm rainfall annually on average, whereas utmost rainfall is concentrated during the northeast monsoon season (NEMS) than other seasons.

Materials and methods

Data requirement

To examine rainfall characteristics (variability and trends) of the Mahaweli Basin, 15 raingauge sites were carefully chosen based on the availability of rainfall data. These stations are well presented in the Zoomed section of Fig. 1. Monthly rainfall data (1990 to 2019) were acquired from the Department of Meteorology, Sri Lanka. The rainfall data were classified into four seasons of Sri Lanka. These are (i) first inter-monsoon season (FIMS) between March and April, (ii) southwest monsoon season (SWMS) between May and September, (iii) second inter-monsoon season (SIMS) between October and November, and (iv) northeast monsoon season (NEMS) between December and February

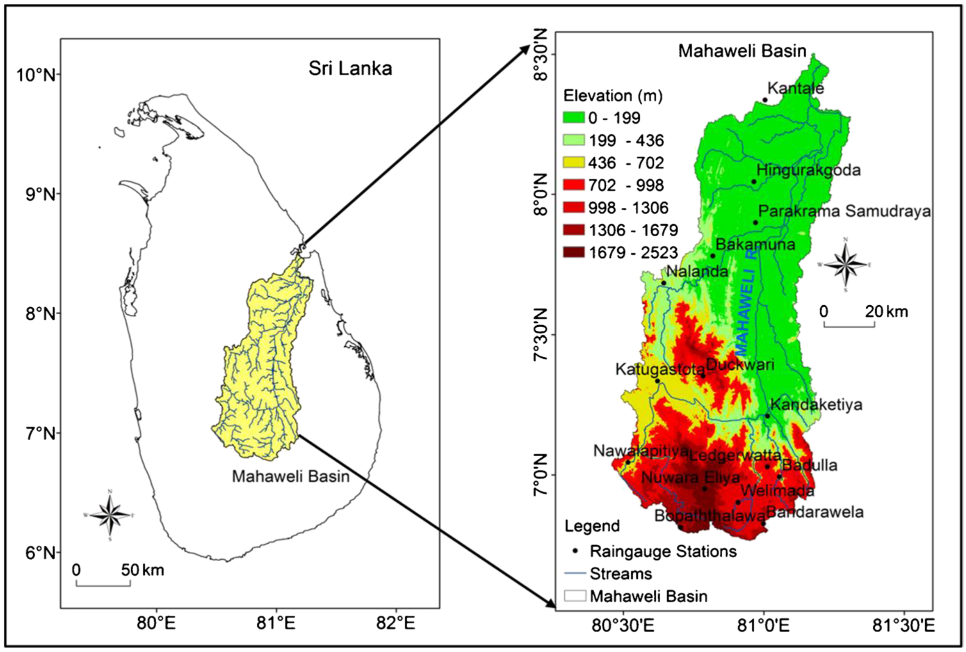

Fig. 1 Location of the Mahaweli Basin and raingauge stations under review

Table 1 Geographical information of rain gauge stations

Stations	Latitude	Longitude	Elevation (m)
Nuwara Eliya	6° 58′ N	80° 46′ E	1868
Bopaththalawa	6° 50′ N	80° 43′ E	1534
Bandarawela	6° 49′ N	80° 59′ E	1226
Ledgerwatta	7° 01′ N	81° 01′ E	1449
Welimada	6° 54′ N	80° 55′ E	1017
Duckwari	7° 22′ N	80° 46′ E	1001
Badulla	6° 59′ N	81° 03′ E	652
Nawalapitiya	7° 03′ N	80° 32′ E	588
Katugastota	7° 18′ N	80° 37′ E	468
Nalanda	7° 40′ N	80° 38′ E	400
Bakamuna	7° 46′ N	80° 49′ E	143
Kandaketiya	7° 12′ N	81° 00′ E	123
Hingurakgoda	8° 02′ N	80° 58′ E	65
Parakrama Samudraya	7° 54′ N	80° 58′ E	58
Kantale	8° 21′ N	81° 00′ E	46

(Wickramagamage 2016). Accordingly, rainfall data of the Mahaweli Basin were analyzed to study characteristics of rainfall over the Mahaweli Basin. Table 1 exhibits geographical information of raingauge stations under review.

Methods

Rainfall distribution characteristics of the Mahaweli Basin were studied by elementary statistical methods (mean, standard deviation (SD) and coefficient of variance (CV)). In addition, inter-seasonal and inter-annual rainfall changeability and percent rainfall deviation from mean rainfall of the Mahaweli Basin was represented by plots of rainfall variability and percent departure from mean rainfall. The MK-test, SSE, and ITA methods were applied to recognize rainfall trends and the magnitude of change. A serial autocorrelation in rainfall data was checked before applying rainfall data to the MK test. The results of the MK test and SSE were tested at a 95% confidence level of significance. Moreover, spatial rainfall changeability and trends over the Mahaweli Basin were depicted with the inverse distance weighting (IDW) method using ArcGIS 10.1 software. A detailed methodology has been explained as follows:

Serial autocorrelation analysis

Positive and negative correlated data are common in time-series analyses. However, when it exists in the hydrometeorological time series data; there is a probability of detecting positive and negative trends from the nonparametric tests, where there are no real trends in the data (Hamed and Ramachandra 1998; Serinaldi and Kilsby 2015). Pre-whitening is a technique to sort the correlated data and then check for the trends using nonparametric tests. Therefore, the climatic time series are usually checked for serial autocorrelation before they apply for the trend analysis. Thus, the serial autocorrelation was verified using the PAST 4.03 version of the software, and then, the correlogram plots were obtained for rainfall of the Mahaweli Basin at varying times lags.

Coefficient of variation (CV)

The coefficient of variation (CV) was computed to understand spatial and temporal rainfall variations over the study area. The CV was calculated by the following equation:

$$CV = \frac{\sigma}{\overline{x}} \times 100 \quad (1)$$

where σ = standard deviation and $\overline{x}$ = mean rainfall for the selected time scales (monthly, seasonal, and annual). According to Hare (2003) and Asfaw et al. (2018), CV specifies a degree of variability and is categorized as high ($CV > 30$), moderate ($20 < CV < 30$), and low ($CV < 20$) variability.

Mann–Kendall (MK) test

Spatiotemporal rainfall trends over the Mahaweli Basin were noted by using MK test (Mann 1945; Kendall 1975). The following equations were applied to observe rainfall trends:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mathrm{sgn}\left(X_j - X_i\right) \quad (2)$$

where n = the number of data points; X_i and X_j = data values in the time series; i and j ($j > i$), respectively, and sgn ($X_j - X_i$) = sign function as follows:

$$\mathrm{sgn}\left(X_j - X_i\right) = \begin{cases} +1 \ if \left(X_j - X_i\right) > 0 \\ 0 \ if \left(X_J - X_i\right) = 0 \\ -1 \ if \left(X_j - X_i\right) < 0 \end{cases} \quad (3)$$

when $n \geq 10$, S becomes approximately normal distribution with mean = 0 and variance as follows:

$$\sigma_s^{\ 2} = \frac{1}{18}\left[n(n-1)(2n+5) - \Sigma_t t(t-1)(2t+5)\right] \quad (4)$$

where t = extent of any given tie and Σ_t = summation of all ties. The value of Z_c is computed as follows:

$$Z_c = \begin{cases} \frac{S-1}{\sigma_s}, S > 0 \\ 0, S = 0 \\ \frac{(S+1)}{\sigma_s}, S < 0 \end{cases} \quad (5)$$

where Z_c = standard normal variate and positive (negative) values of Z indicate increasing (decreasing) trends. When $|Z| > Z_1 - \alpha_{/2}$, a null hypothesis is rejected, and a noteworthy trend occurs in the time series. All the results are verified at $\alpha = 0.05$ ($Z = 2.042$) significance level.

Sen's slope estimation (SSE) test

The SSE was used to identify the magnitude of the rainfall trend, and it is a widely applied method in the climatic trend analysis (Sen 1968; Masroor et al. 2020; Abungba et al. 2020).

$$Q_i = \frac{X_j - X_k}{j - k}, i = 1, 2, \ldots \ldots .N \quad (6)$$

where X_j and X_i are values in series at time j and k ($j > k$), respectively.

The median of these N values of Q_i is Sen's estimator of the slope. If there is a single datum in each period, then N = n (n – 1)/2 where n is the number of periods. However, if the number of values in every year is many, then $N <$ n (n – 1)/2 where n is a total number of observations. First N values were ranked from smallest to biggest. Then, the median of slope (β) is computed as follows:

$$\beta = \begin{cases} \frac{Q_n+1}{2} if \ N \ is \ odd \\ \frac{1}{2}\left(\frac{Q_n}{2} + \frac{Q_n+2}{2}\right) if \ N \ is \ even \end{cases} \quad (7)$$

The $\pm \beta$ shows the positive or negative trend of the data series.

Rainfall magnitude change (%)

Rainfall magnitude change (%) was computed by the following equation (Yue and Hashino 2003):

$$\mathrm{Parentagechange}(\%) = \frac{\beta \times \text{length of year}}{\text{mean}} \times 100 \quad (8)$$

Inverse distance weighting (IDW) interpolation

The IDW interpolation is the estimation of the value z at location x which is a weighted mean of nearby observations. The common formula of IDW is as follows (Bartier and Keller 1996):

$$\boldsymbol{x} = \frac{\sum_{i=1}^{n} \boldsymbol{ziwi}}{\sum_{i=1}^{n} \boldsymbol{wi}} \quad (9)$$

where x = point to be estimated; Zi = control value for the i^{th} sample point; Wi = weight that describes the relative significance of the single control point Zi in the interpolation technique; and $Wi = 1$ for the n control points contiguous to the interpolated points and/or for the set of control points within a certain radius r of the point to be interpolated; otherwise, $Wi = 0$.

Innovative trend analysis (ITA)

The ITA method was introduced by Sen (2012) to identify the trends in climatic time series data. It is a qualitative method, which can be effectively used in the initial stages of the trend detections. This method was used by many researchers (Gedefaw et al. 2018; Alifujiang et al. 2020; Perera et al. 2020; Ruwangika et al. 2020; Yang et al. 2020). The first stage in the ITA is to categorize hydrometeorological time series into two identical sub-series, and then all the data points in both sub-series are ranked independently in ascending order. These two series positioned on a Cartesian coordinate system (Xi: $i=1, 2, 3 \ldots n/2$) on an ordinate (*X*-axis) and (Yi: $i=n/2+1, n/2+2 \ldots n$) on an abscissa (*Y*-axis). Moreover, the 1:1 (45°) line of no trend divides the diagram (Fig. 2) into two equal triangles, where an area above (below) the 1:1 line shows the increasing (decreasing) trend of the time series data. Besides, if the observations in the scatter plot fall on or near to this line of no trend (1:1 line), then it specifies no significant trend in the time series.

Results and discussion

Descriptive statistics and rainfall distribution

The results of the descriptive statistics for the raingauge stations under review were summarized in Table 2. The stations were presented in the descending order of their elevation from source to the mouth of the river (Fig. 1). The mean seasonal rainfall over the Mahaweli Basin ranged between 249 (FIMS) and 577 mm (NEMS), while the annual average rainfall (AAR) of the Mahaweli Basin is 1875 mm (Table 2). Table 2 showed that seasonal values of SD for the whole basin were varied from 71 (SIMS) to 374 mm (SWMS). The station-wise descriptive statistics

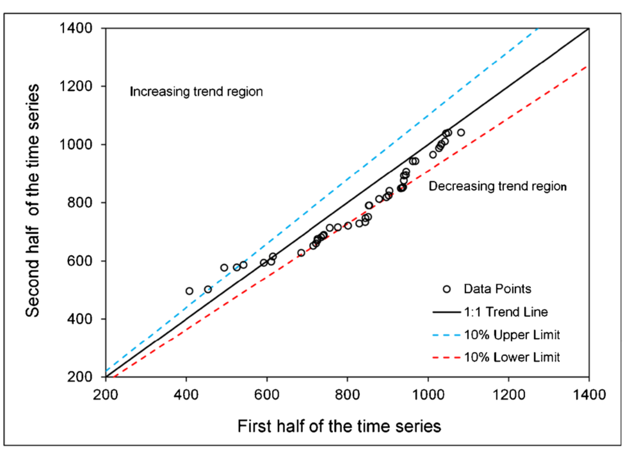

Fig. 2 Illustration of the innovative trend analysis

indicate that the lowest rainfall (142 mm) was observed for the Kantale, and the Nawalapitiya receives the highest (1632 mm) seasonal average rainfall in the Mahaweli Basin during FIMS and SWMS, respectively (Table 2; Fig. 3a, b). The Bakamuna station located in the Lower Mahaweli Basin (LMB) received maximum seasonal average rainfall during NEMS (Fig. 3d). Furthermore, seasonal analysis of rainfall also indicates that Upper Mahaweli Basin (UMB) received maximum rainfall during SWMS, and LMB receives the highest rainfall in NEMS (Fig. 3b and d). The annual rainfall analysis suggested that Nawalapitiya station receives the highest (2910 mm) annual average rainfall (AAR) in the basin (Fig. 3e). The UMB received maximum rainfall from March to September, and it decreases from October to February. Therefore, the seasonal and annual variations in the rainfalls over the Mahaweli Basin can be well-identified.

The seasonal rainfall variability in the Mahaweli Basin ranged between 27% (Katugastota) during SWMS and 63% (Nalanda and Nawalapitiya) in SWMS and NEMS, respectively (Table 2; Fig. 4b and d). Nevertheless, annual rainfall varied between 16 (Nuwara Eliya and Katugastota) and 32% (Nawalapitiya) during 1990–2019 (Table.2; Fig. 4e). Although station-wise rainfall variability seems to be high, whole basin annual rainfall variability (22%) in the Mahaweli Basin is not so high (Table 2). Furthermore, Table 2 showed that seasonal rainfall variability in the basin varied between 37 (SIMS) and 51% (FIMS).

Rainfall departure from mean

The analysis of rainfall departure from the mean rainfall of the Mahaweli Basin showed that during FIMS, rainfall departure varied between + 130 and – 69% (Fig. 5a). There were 13 years when FIMS rainfall was below the mean FIMS rainfall (249 mm) of the basin. As concerns SWMS, the rainfall was below the average rainfall of the basin (496 mm) during SWMS from 2001 to 2012 except 2010 and ranged between + 70 and – 55% (Fig. 5b). During SIMS, rainfall departure was observed between + 49 and – 54% from the mean rainfall of the SIMS (553 mm) over the Mahaweli Basin. The rainfall was 50% (15–15 years) of time and was above and below the average SIMS rainfall of the basin (Fig. 5c). Figure 5d showed 16 years of low rainfall during NEMS compared to the average NEMS rainfall (577 mm) of the basin. The NEMS indicates that inter-seasonal rainfall departure ranged between + 98 (2011) and – 54% (2016) (Fig. 5d). Although annual rainfall of the Mahaweli Basin was frequently (17 years) below the annual average rainfall (1875 mm) of the basin, negative rainfall departure was not very high during 1990–2019 except 2017 (– 38%). Nevertheless,

Table 2 Station-wise descriptive statistical analyses for seasonal and annual rainfall in the Mahaweli Basin

Station	FIMS			SWMS			SIMS			NEMS			Annual		
	Mean (mm)	SD (mm)	CV (%)	Mean (mm)	SD (mm)	CV (%)	Mean (mm)	SD (mm)	CV (%)	Mean (mm)	SD (mm)	CV (%)	Mean (mm)	SD (mm)	CV (%)
Nuwara Eliya	208	96	46	788	245	31	474	151	32	379	128	34	1849	303	16
Bopaththalawa	357	144	40	798	228	29	459	186	40	254	131	52	1869	342	18
Bandarawela	289	127	44	429	122	28	507	191	38	361	140	39	1585	328	21
Ledgerwatta	339	189	56	315	122	39	656	286	44	1064	459	43	2374	626	26
Welimada	200	104	52	334	193	58	402	128	32	361	148	41	1298	301	23
Duckwari	280	109	39	681	248	36	625	204	33	571	215	38	2158	501	23
Badulla	278	138	50	398	133	33	528	171	32	574	217	38	1777	349	20
Nawalapitiya	372	217	58	1632	637	39	641	289	45	264	166	63	2910	974	32
Katugastota	290	123	43	583	156	27	584	196	34	397	181	46	1854	287	16
Nalanda	263	156	59	233	147	63	550	202	37	635	277	44	1680	439	26
Bakamuna	188	110	59	230	142	62	614	245	40	771	277	36	1803	452	25
Kandaketiya	182	110	60	199	95	48	551	198	36	959	322	34	1890	420	22
Hingurakgoda	156	87	56	246	98	40	549	198	36	660	250	38	1611	335	21
Parakrama Samudraya	195	94	48	242	138	57	588	263	45	764	316	41	1789	473	26
Kantale	142	77	54	337	94	28	562	173	31	634	260	41	1675	332	20
Mahaweli Basin	249	73	51	496	374	41	553	71	37	577	244	42	1875	377	22

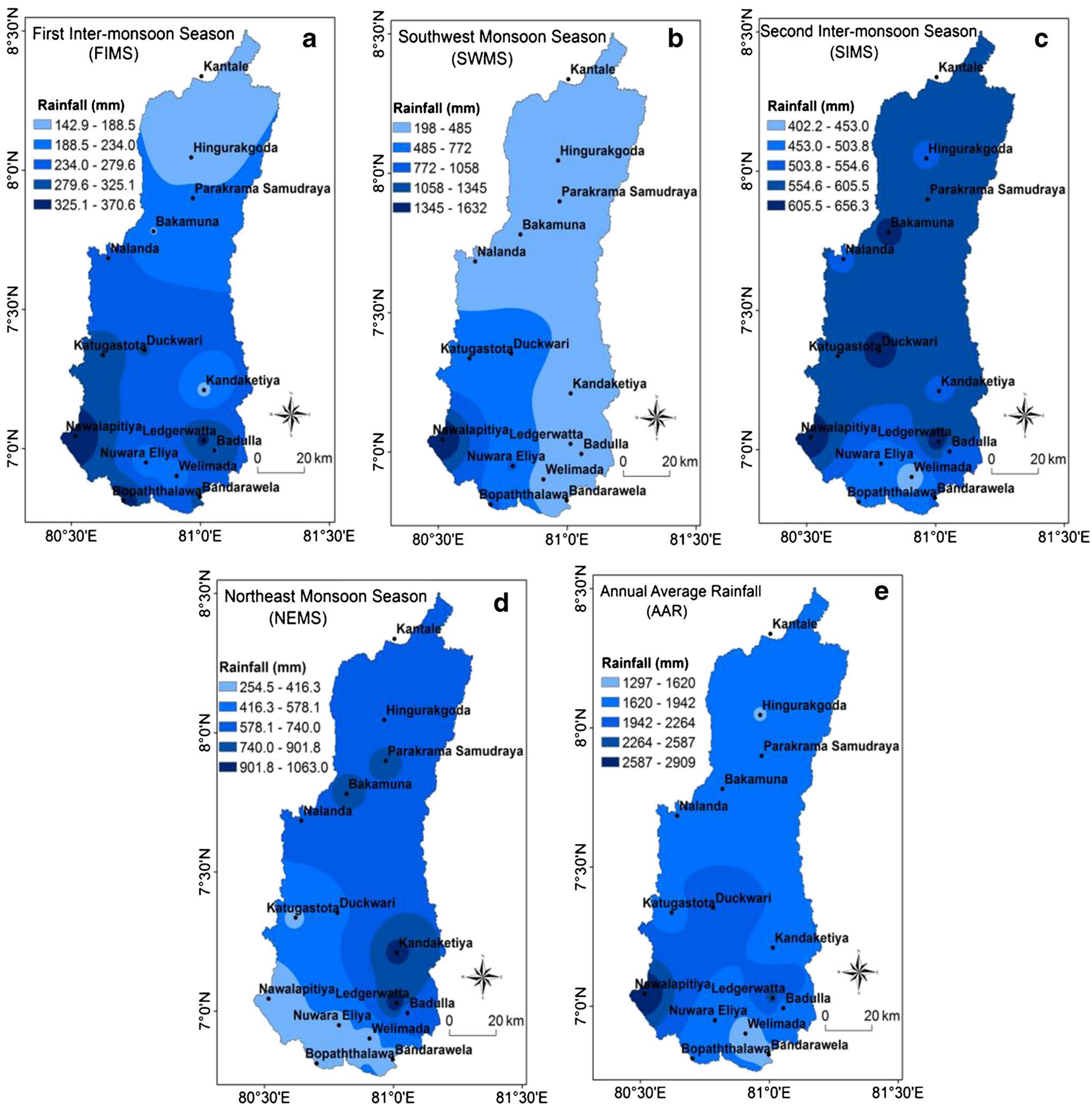

Fig. 3 Seasonal and annual rainfall distribution over Mahaweli Basin

annual rainfall departure ranged between + 25 and − 38% (Fig. 5e). Therefore, the analyses suggest significant fluctuations in rainfall over the Mahaweli Basin.

Serial autocorrelation analysis

The correlograms were developed for the seasonal and annual rainfall data of the Mahaweli Basin. The correlograms indicate that rainfall values were between the limit of the 95% confidence level for different time lags. This denotes that there is no serial autocorrelation in the rainfall data (Fig. 6a–e). Therefore, original time series data directly apply for the rainfall trend analysis over the Mahaweli Basin.

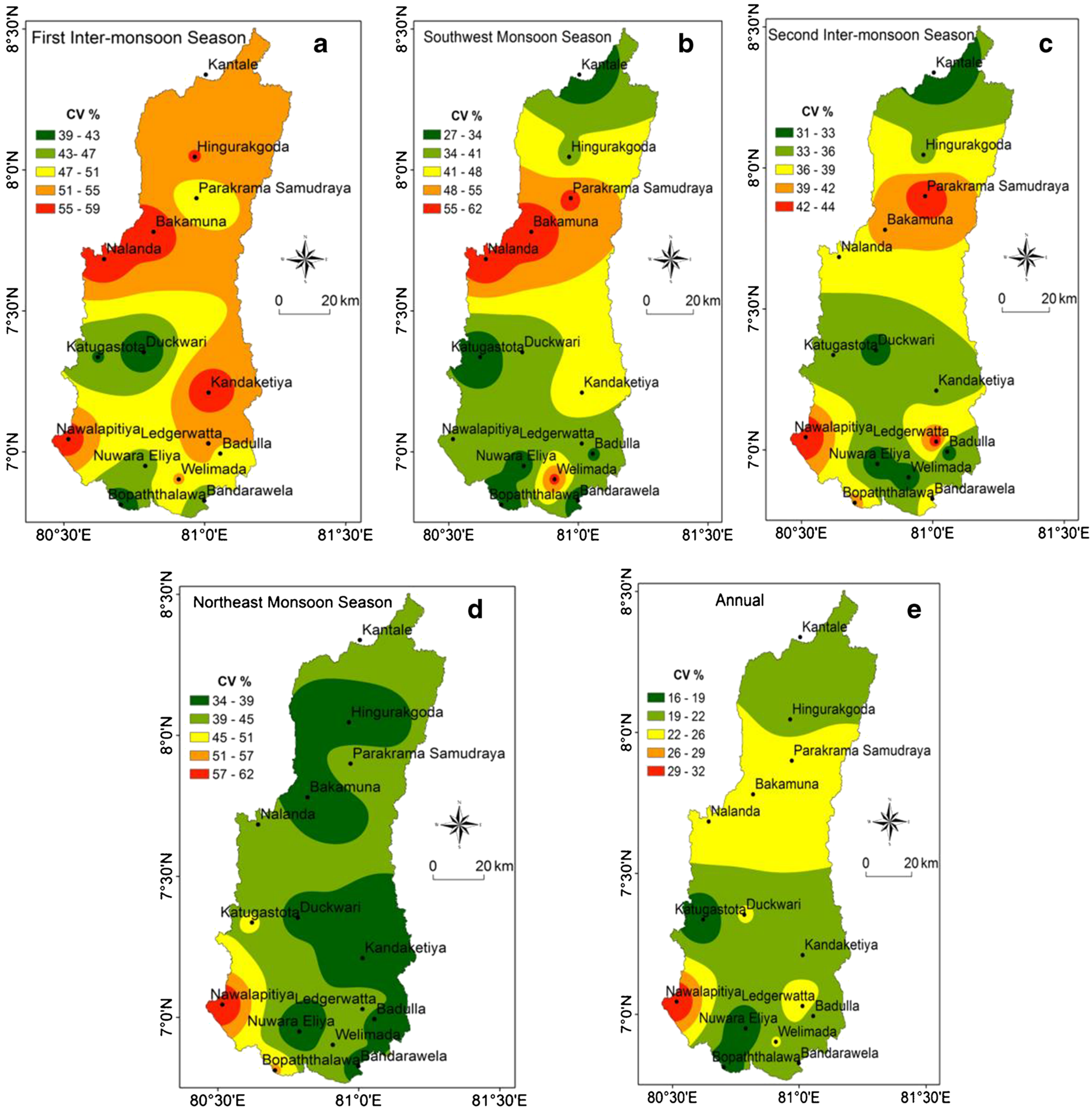

Fig. 4 Seasonal and annual rainfall variability over Mahaweli Basin

Mann–Kendall test and seasonal and annual rainfall trend

The results of the rainfall trends over the Mahaweli Basin are summarized in Table 3, and spatial representation was depicted in Fig. 7a–e. The FIMS rainfall showed an insignificant increase in rainfall over the Mahaweli Basin except for Duckwari, Hingurakgoda, and Nalanda, whereas the Kandaketiya denoted no trend ($Z_{MK}=0.00$) (Table 3; Fig. 7a). During SWMS, Kandaketiya ($Z_{MK}=2.1$) and Nawalapitiya ($Z_{MK}=2.00$) showed a statistically significant increasing trend, and Bopaththalawa ($Z_{MK}=-2.2$), Duckwari ($Z_{MK}=2.2$), and Hingurakgoda ($Z_{MK}=-2.8$) showed a significantly decreasing rainfall trend (Table 3; Fig. 7b). During SWMS, statistically significant decreasing trend in rainfall at Hingurakgoda was reported by Nisansala et al.

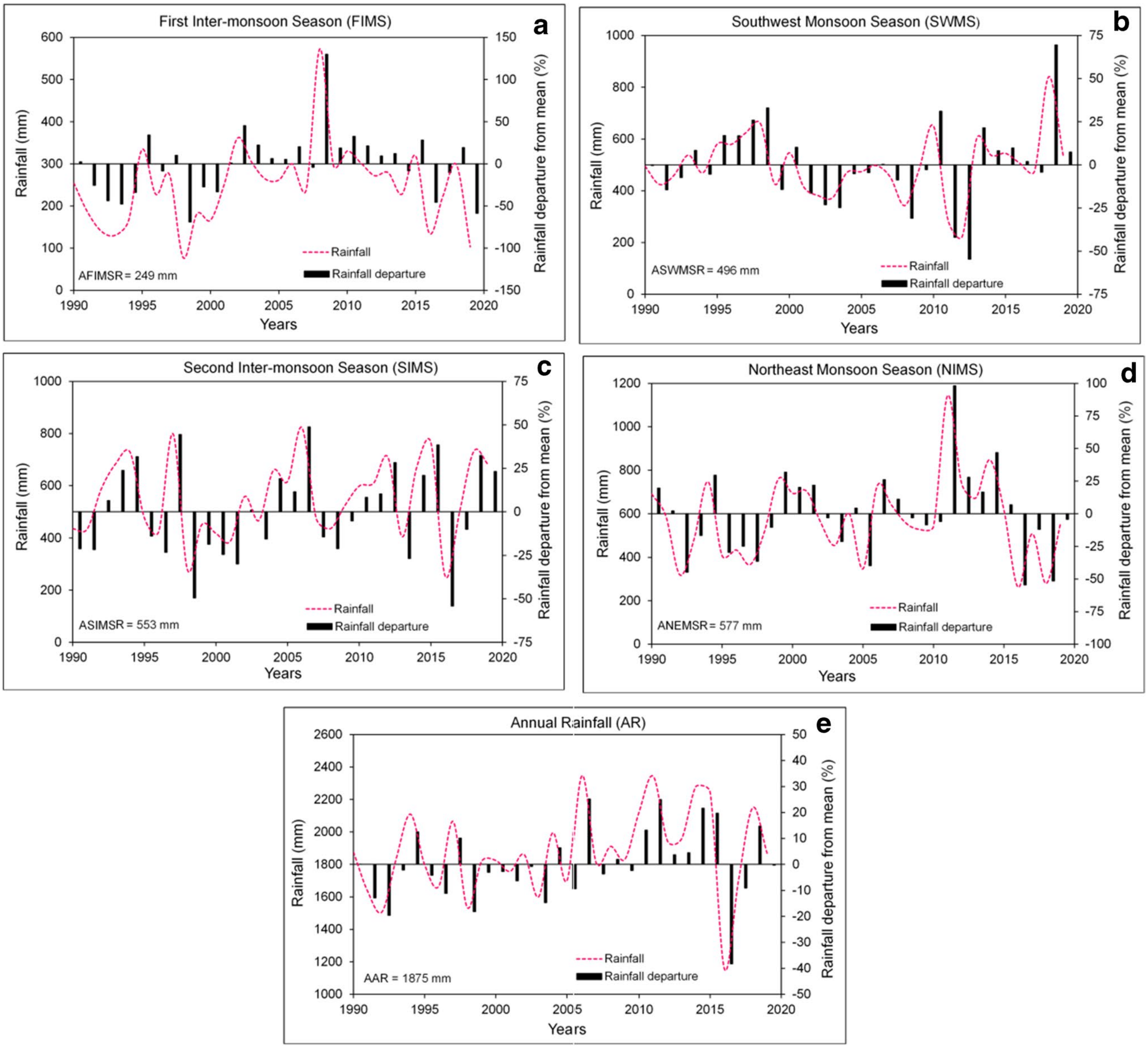

Fig. 5 Plots of rainfall variability and departure from mean rainfall

(2019). Nevertheless, SIMS rainfall mostly showed a significant increase in rainfall only for the Ledgerwatta station (Table 3; Fig. 7c). Furthermore, Duckwari (Nawalapitiya) has indicated significant decreasing (increasing) rainfall trends during NEMS (Table 3; Fig. 7d). The annual rainfall trend analysis exhibited a noteworthy increasing trend for Bakamuna, Bandarawela, and Ledgerwatta stations, whereas a significant fall in annual rainfall was observed for Duckwari station (Table 3; Fig. 7e). The previous studies conducted by Karunathilaka et al. (2017) and Naveendrakumar et al. (2018) showed a significant increasing trend in annual rainfall for Bandarawela which is similar to the present finding. Domroes and Schaefer (2000) observed a statistically significant decrease in annual rainfall for Nuwara Eliya station over the period 1895–1996. Nevertheless, the present study also denoted an insignificant declining trend in annual rainfall for the same station which is the opposite of the present study. Moreover, an increasing trend of rainfall (SIMS and annual) at Ledgerwatta was also reported by Ruwangika et al. (2020) which is similar to the results of the present study. In the same study, Ruwangika et al. (2020) reported no trend in seasonal rainfall for Kandaketiya station which is the opposite (significant increase) of the present research. Overall, the annual rainfall of the Mahaweli Basin did not display a significant increasing or decreasing trend as a whole basin (Table 3).

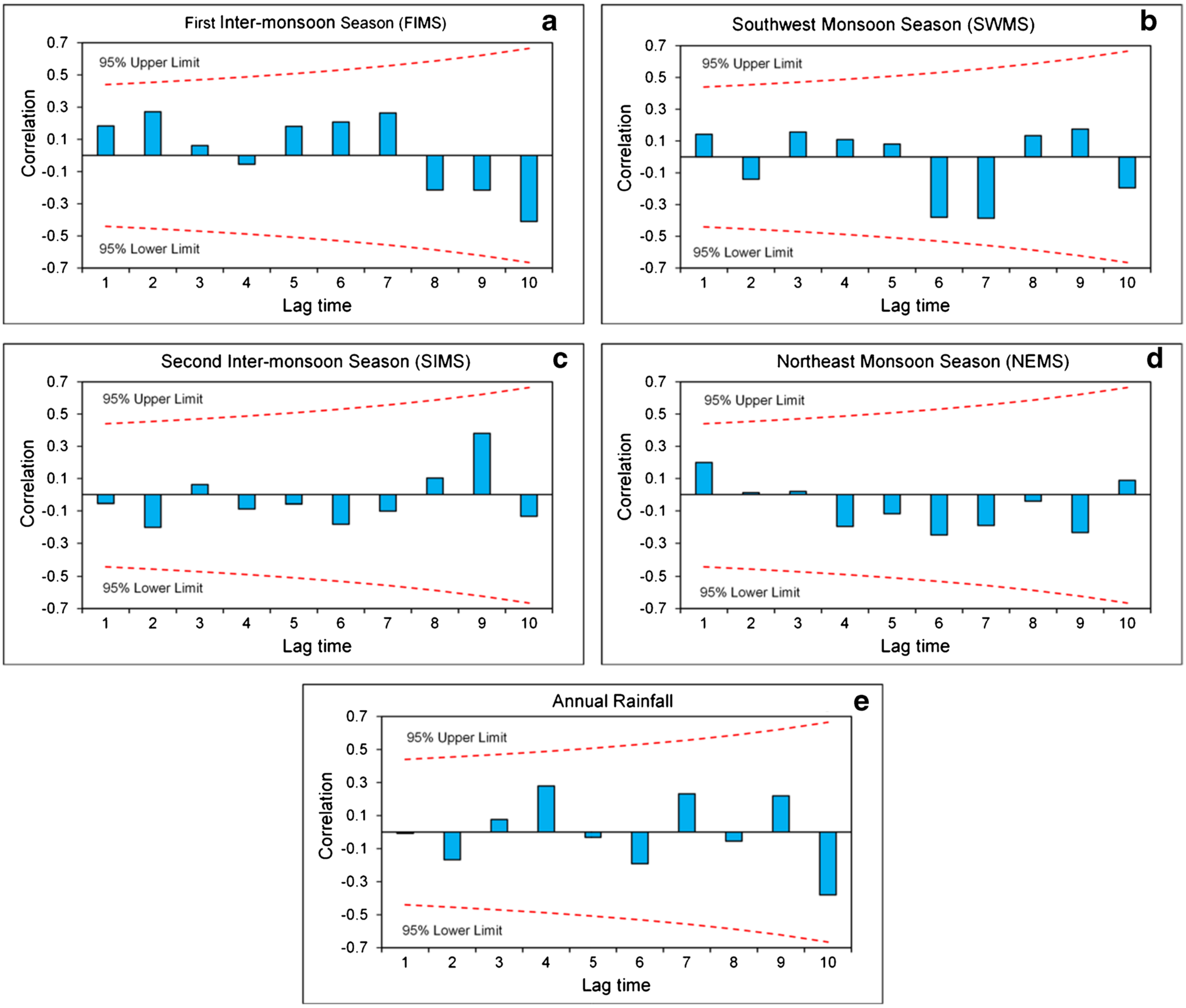

Fig. 6 Plots of correlograms for seasonal and annual rainfall of the Mahaweli Basin

Sens's slope estimator (SSE) and rainfall change (%)

Rainfall change analysis exhibited that Ledgerwatta showed an insignificant increase of 65.6% rainfall, and Hingurakgoda denoted an insignificant decrease of – 61.2% in the rainfall during FIMS in the last 30 years (Table 3; Fig. 8a). The Bopaththalawa (– 36.1%), Duckwari (– 64.4%), and Hingurakgoda (– 71.9%) have displayed a significant decrease in rainfall, whereas Kandaketiya (4.3%) and Nawalapitiya (32.5%) denoted a significant increase in rainfall during SWMS over 30 years (Table 3; Fig. 8b). The SIMS rainfall analysis revealed that only the Ledgerwatta station displayed a noteworthy increase (63.3%) in the rainfall over the Mahaweli Basin (Table 3; Fig. 8c). During NEMS, Nawalapitiya station displayed a substantial increase of 92.2% in rainfall, and Bakamuna station showed a decrease in rainfall of 59.6%, which is the major rainfall change in the Mahaweli Basin from 1990 to 2019 (Table 3; Fig. 8d). Moreover, annual rainfall showed a significant increase of rainfall between 29.8 (Bandarawela) and 51.0% (Ledgerwatta). However, annual rainfall did not show a specific change in rainfall over the whole Mahaweli Basin (Table 3; Fig. 8e).

Innovative trend analysis (ITA) and rainfall trend

In addition, the rainfall trends over the Mahaweli Basin were observed using the ITA method, and results are represented by ITA plots (Fig. 9a–e). Although seasonal rainfall shows an increasing and/or decreasing rainfall over the Mahaweli

Table 3 Results of MK, SSE, and percent change in rainfall during 1990–2019

Station	FIMS			SWMS			SIMS			NEMS			Annual		
	Z_{MK}	SSE (β)	% change	Z_{MK}	SSE (β)	% change	Z_{MK}	SSE (β)	% change	Z_{MK}	SSE (β)	% change	Z_{MK}	SSE (β)	% change
Badulla	1.6	5.0	54.5	1.3	3.1	23.0	1.5	6.6	37.6	0.0	0.2	1.3	1.4	12 0	20.2
Bakamuna	1.3	3.3	53.2	0.5	1.5	18.9	1.5	8.7	42.7	1.3	8.5	33.2	**2.4**	24.3	40.4
Bandarawela	1.0	2.4	24.7	1.1	3.0	21.0	1.6	7.1	41.8	0.7	3.2	26.4	**2.9**	15.7	29.8
Bopaththalawa	1.3	4.7	39.3	**−2.2**	−9.6	−36.1	0.5	2.8	18.1	1.2	3.3	38.5	0.3	1.7	2.8
Duckwari	−1.6	−3.9	−41.3	**−2.2**	−14.6	−64.4	−1.6	−6.5	−31.1	**−2.2**	−11.3	−59.6	**−3.3**	−36.3	−50.5
Hingurakgoda	−1.7	−3.2	−61.2	**−2.8**	−5.9	−71.9	0.9	3.7	20.0	0.4	2.3	10.5	−0.7	−6.5	−12.1
Kandaketiya	0.0	0.1	1.4	**2.1**	4.3	64.2	1.0	4.2	22.6	−0.3	−1.9	−5.8	1.0	8.6	13.6
Kantale	1.3	2.5	51.6	0.5	0.9	7.7	1.2	3.8	20.2	0.7	2.2	10.4	1.5	9.1	16.4
Katugastota	0.7	1.1	10.9	−0.7	−2.1	−10.7	0.3	1.9	9.6	0.6	−2.4	−18.4	0.7	3.6	5.8
Ledgerwatta	1.7	7.4	65.6	1.2	4.2	39.5	**2.0**	13.9	63.3	1.5	11.5	32.4	**3.4**	40.3	51.0
Nalanda	−0.3	−1.1	−12.4	0.7	1.6	20.8	0.4	1.4	7.6	0.3	2.7	12.9	1.0	9.2	16.5
Nawalapitiya	1.9	7.2	58.5	**2.0**	32.5	59.7	1.7	10.3	48.3	**2.1**	8.1	92.2	1.6	41.1	42.4
Nuwara Eliya	1.9	4.3	61.5	−1.7	−11.1	−42.2	0.4	1.6	10.1	0.0	0.0	−0.3	−0.9	−5.9	−9.6
Parakrama Samudraya	0.6	1.2	19.0	0.0	0.0	0.4	−0.3	−2.2	−11.0	0.1	1.2	4.6	0.1	1.0	1.7
Welimada	1.5	3.5	51.9	−1.1	−2.4	−21.9	0.6	1.9	14.1	−1.4	−4.6	−38.0	−0.4	−2.1	−4.9
Mahaweli Basin	1.1	2.6	31.0	0.3	0.6	3.7	1.3	4.1	22.5	0.3	1.2	6.1	1.9	9.7	15.5

Figures in bold are statistically significant at 0.05% (α = 2.042) significance level; *FIMS*, first inter-monsoon season; *SWMS*, southwest monsoon season; *SIMS*, second inter-monsoon season; *NEMS*, northeast monsoon season

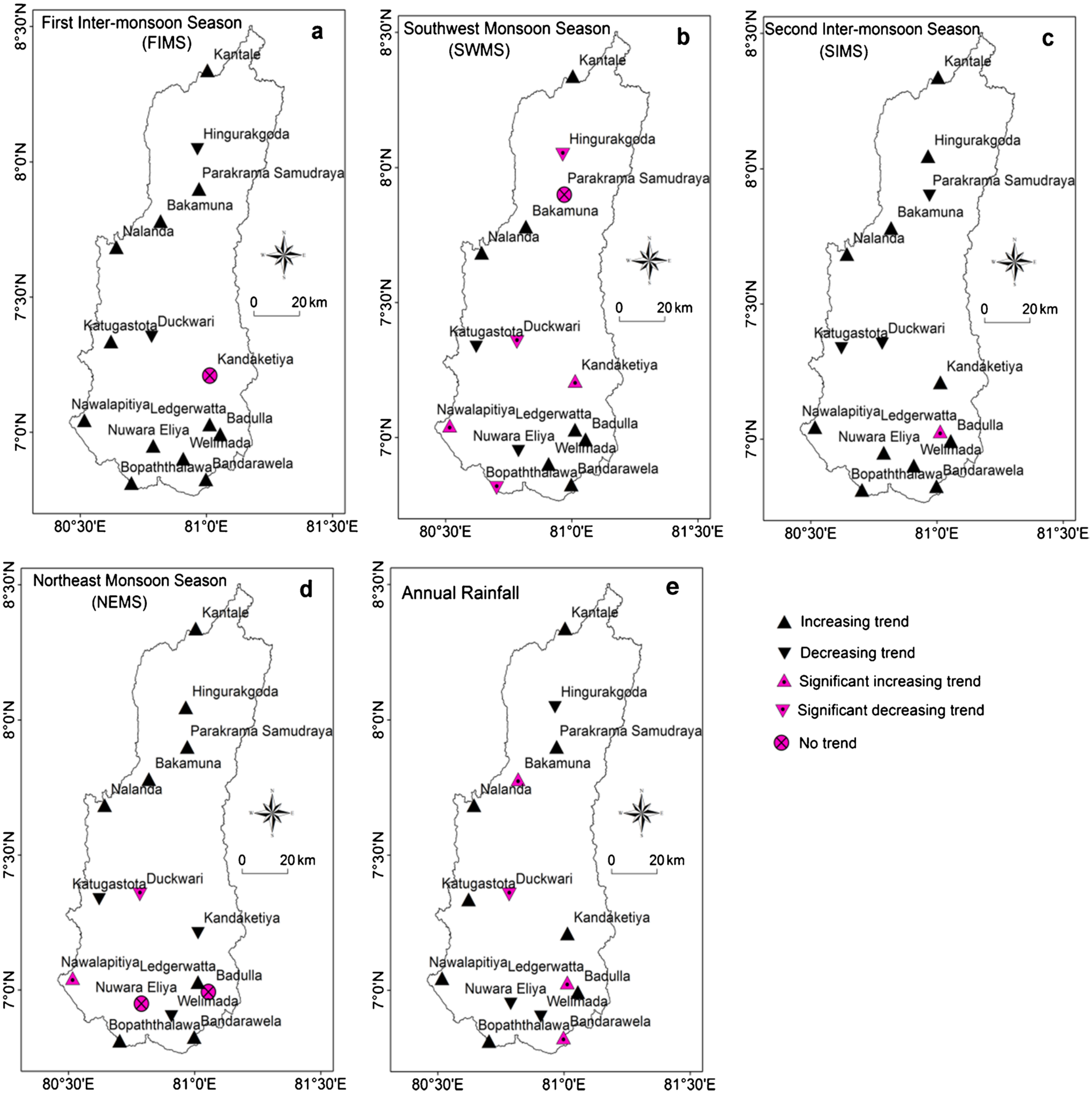

Fig. 7 Rainfall trends over Mahaweli Basin by Mann–Kendall

Basin, these are not significant trends at the basin scale in the last 30 years (Fig. 9a–d). Although Fig. 9e represents that all the rainfall values are above the no trend line or close to it, it doesn't show a significant increasing trend as some of the points are below the line of 10% upper limits. This suggested that results obtained by quantitative (MK test) and qualitative (ITA) methods for rainfall trend analysis of the Mahaweli Basin are reliable and use for the water resource planning in the basin. Therefore, it shows that despite the seasonal variations in rainfall over the Mahaweli Basin, rainfall is regular and reliable.

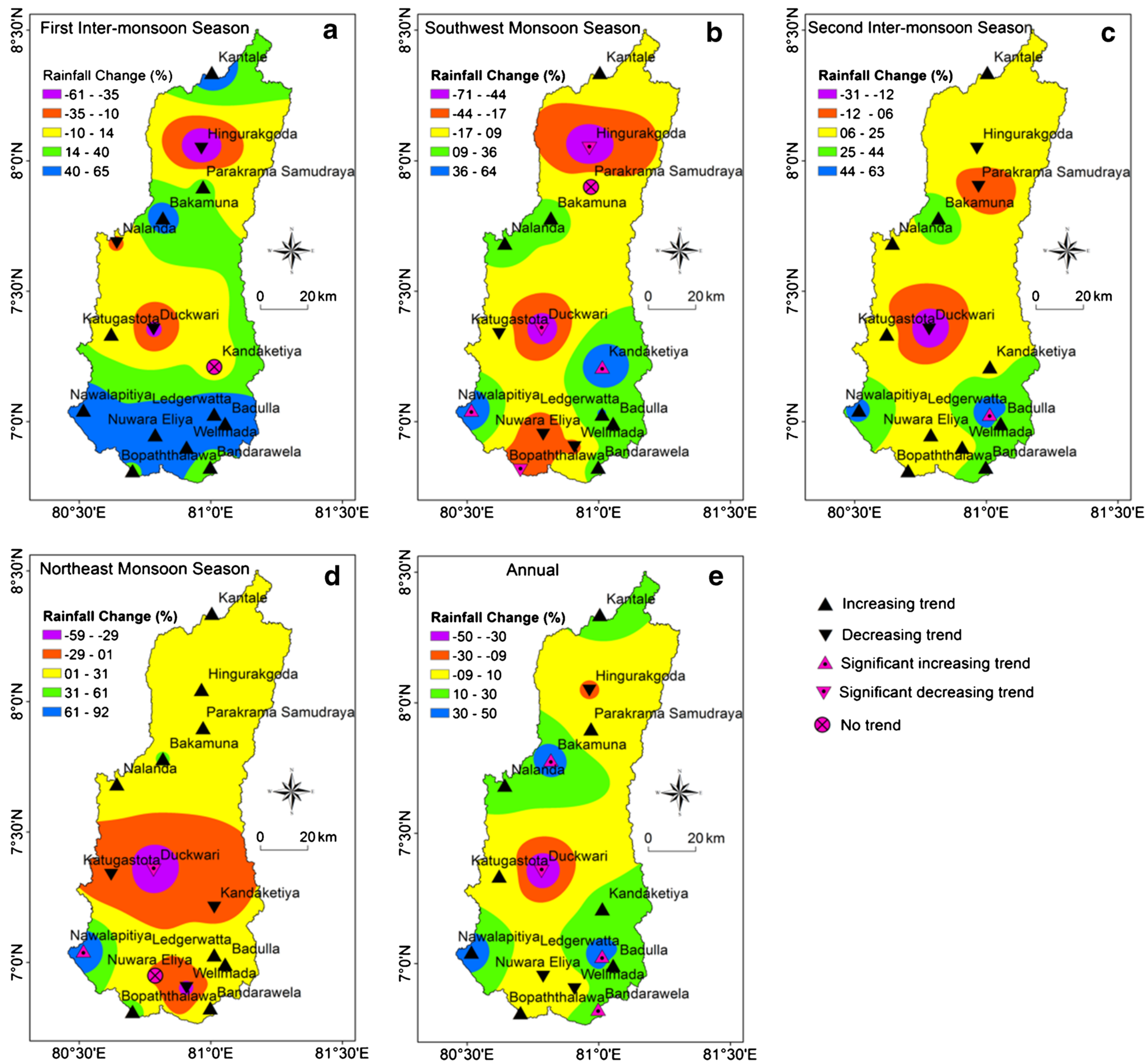

Fig. 8 Rainfall change over the Mahaweli Basin

Conclusions

The spatial, as well as temporal, rainfall variability and trends (seasonal and annual) over the Mahaweli Basin is the fundamental aspect of the research. Therefore, rainfall data of 15 raingauge stations located in the Mahaweli Basin were analyzed using the coefficient of variability (CV), Mann–Kendall (MK), Sen's slope estimator (SSE), and innovative trend analysis (ITA) methods to derive average rainfall characteristics. The CV analysis reveals that there is not high rainfall variability in the Mahaweli Basin as the value of the CV is below 30. Rainfall departure from mean denoted seasonal and annual fluctuations in rainfall over the Mahaweli Basin during 1990–2019. The seasonal rainfall (SWMS) analysis showed a significant increase in rainfall at Nawalapitiya and Kandaketiya, while at Bopaththalawa, Duckwari, and Hingurakgoda station, significant decreasing trend was noted. In the case of the SIMS, only the Badulla station revealed an increase in rainfall. During NEMS, significant trends were noted for Nawalapitiya (increasing) and Duckwari (decreasing). A significantly increasing rainfall trend in annual rainfall was detected for the Bandarawela, Badulla, and Bakamuna stations, whereas Duckwari is the only station that displayed

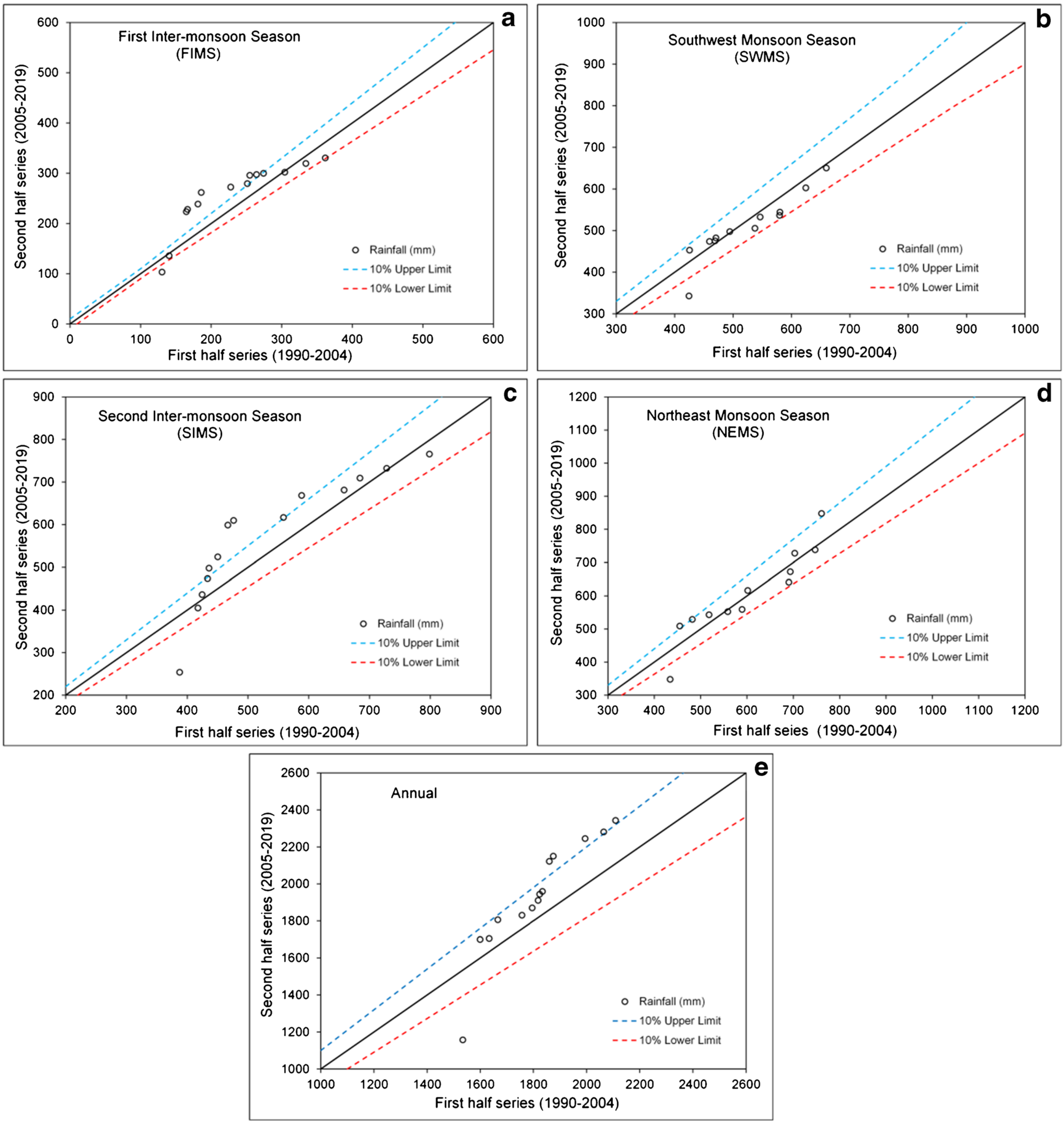

Fig. 9 Plots of innovative trend analysis for the Mahaweli Basin

a significant decrease in annual rainfall. During the last 30 years, the Ledgerwatta reveals the greatest increase (51%) in annual rainfall, while the utmost decrease in rainfall (−50.5%) was observed for the Duckwari. At the basin scale, comparable results of rainfall trends (seasonal and annual) noted by the MK test and ITA specify that rainfall trends are reliable and can be used for the water resource planning, irrigation strategies for dryland zone farming, and flood and drought management in the Mahaweli Basin. Nevertheless, short record-length of the rainfall data and limited previous works on Mahaweli Basin for discussion on the past and present situation results of the analysis are the limitations of this research.

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Data Availability The datasets are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare that they have no competing interests.

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