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Analysis of Long-Term Seasonal Rainfall Trends in Sri Lanka after Eliminating the Serial Correlation Effect

A.D.S. Iresh, B.C.L. Athapattu, W.C.D.K. Fernando and Jayantha Obeysekera

Abstract: This research analyzed the annual and seasonal rainfall trends in Sri Lanka. It used daily rainfall data from 266 rain gauge stations across the island, covering 60 years from 1960 to 2020. A trend-free pre-whitening method utilizing Mann-Kendall's nonparametric trend test and Sen's slope estimator was employed for the analysis. This technique helped remove the data's correlation effects and estimate clear trends. The results showed that rainfall trends vary by region and season. The Kalu, Kelani, Nilwala, Attanagalu, Deduru Oya, and Upper Mahaweli basins in the central hills experienced a mild decrease in rainfall over the past 60 years. In contrast, the Maha Oya and Deduru Oya basins showed an increase in average annual and seasonal rainfall. Other basins did not show significant trends. Additionally, stations like Nuwara-Eliya, Nakkala, and Padiyathalawa have experienced consistently declining extreme rainfall trends for six hours over the last decades.

Keywords: TFPW, Trend analysis, Mann-Kendal, Seasonal rainfall

1. Introduction

The global climate is changing due to the rapid increase in the atmospheric concentration of greenhouse gases through human activities, which is expected to increase rapidly [1]. Man-made activities add a high carbon percentage to the atmosphere, causing an increase in air temperature [2]. A rise in atmospheric temperature causes changes in the water cycle, resulting in climate change [3]. The regional moisture content of the air is the most sensible factor for rainfall in a region. As the air warms, water carrying capacity increases by 7% of moisture for every 1^0C rise in temperature [4]. Research on global meteorology indicates that rainfall from tropical cyclones is increasing at an average rate of about 1.3% per year [1]. Similarly, research on rainfall patterns in Southeast Asia revealed a significant increase in rainfall across most regions, while some areas experienced a slight decrease [5]. Rainfall is the imperative hydro meteorological variable that influences the climatic condition of a tropical region. The presence of water bodies, direct radiation on the surface, central mountains, and seasonal winds causes excessive moisture in Sri Lanka's atmosphere [6]. Subsequently, it produces rainfall with spatial, temporal, and scale variations in the country. Analysis of historical and forecasted rainfall trends in an area provides a clear understanding of climate change and is especially important for a tropical region [7].

A recent study examining climate-induced disasters in Sri Lanka has revealed that the agricultural sector is the most severely impacted by heavy rainfall and drought, resulting in considerable commercial losses. Furthermore, the industrial sector suffers significant adverse effects from strong winds and landslides caused by excessive rain[8]. Therefore, a precise understanding of rainfall trends is crucial. Previous research employed various methods to examine long-term rainfall trends in Sri Lanka. The analysis from 1930 to 2020 revealed that positive and negative trends fluctuate depending on spatial and temporal factors. A review of recent studies on rainfall indicates that it has primarily been investigated at the national level [3], [4], [6], [7], [9-18] or basin/regional scale [19-23].

Basin or regional studies encompass the Kalu Ganga Basin, Central Mountain region, Uma Oya Basin, Badulu Oya Basin, Mahaweli Basin, Anuradhapura, and the Northwestern and Eastern coastal lines.

***Eng. A.D.S. Iresh**, MIE(SL), IESL Part I, II, III, C. Eng., M.Tech. (India), Dip.Irrig.Eng (ITIG), Chief Engineer (Hydrology & Disaster Management Division), Irrigation Department, Sri Lanka. Email:shahikairesh@gmail.com*
ORCID ID: http://orcid.org/0000-0003-2345-3769
***Eng.(Prof.)B.C.L. Athapattu**, MIE(SL), B. Sc. Eng. (Moratuwa), M.Eng.(Osaka), PhD (Osaka), Professor, Open University of Sri Lanka.*
Email:bcliy@ou.ac.lk
ORCID ID: http://orcid.org/0000-0002-4811-8572
***Eng.(Prof.)W.C.D.K. Fernando**, AMIE(SL), B. Sc. Eng. (Moratuwa), M.Eng. (Moratuwa), PhD (Moratuwa), Professor, General Sir John Kotelawala Defence University, Sri Lanka. Email:kumari@kdu.ac.lk*
ORCID ID: http://orcid.org/0000-0003-3066-8389
***Prof. Jayantha Obeysekera**, B. Sc. Eng. (Peradeniya), M. Eng (India), PhD (Colorado), Director and Research Professor, Sea Level Solution Center, Institute of Environment, Florida International University, FIU, Miami, USA. Email:jobeysek@fiu.edu*
ORCID ID: https://orcid.org/0000-0002-7038-1668

Additionally, the methodologies employed for trend analysis include linear regression (LR), Mann-Kendall (MK) test, Sen's slope (SS), and the sequential MK test. In the context of national-level trend analysis, LR, SS, least squares regression analysis, and MK test were utilized. Most of these studies have used the MK test to detect the monotonic trend in the observed rainfall time series data. The MK test was a popular method used in different research studies. One of the main glitches in time series data analysis using the MK test is autocorrelation or serial dependence. When non-parametric trend tests such as MK are used on autocorrelated time series data, they tend to be misleading or show extremely high rejection rates [24]. The research community has undergone numerous modifications and additions to the MK test. Popular MK methods used by hydrologists include the Modified MK (MMK) test, the Pre-whitened (PW) MK test, and the Trend-free Pre-whitening (TFPW) MK test [24-30].

Originally, Von Storch (1995) introduced the PW approach to diminish the impact of serial correlation on the MK test. The PW MK test removes serial correlation by the lag-one auto-regressive (AR (1)) model. Subsequently, the MK test was applied to the residual, which was independent of serial correlation. Similarly, Hamed and Rao (1998) introduced a modified MK test to address the influence of serial correlation dependence. The MMK test adjusts the variance of the MK statistic to compensate for the impact of serial correlation. Although the PW MK and MMK test methods reduce the rejection of the null hypothesis, they still exceed the prescribed significance threshold level [24]. However, these approaches do not fully eliminate the influence when both serial correlation and trend are present within the time series. Yue et al. (2002) then presented the TFPW approach as a practical solution for addressing the influence of serial correlation within the time series. TFPW can accommodate stations with weak temporal signals [31]. The TFPW approach involves estimating the trend slope (*β*) of the sample data using the approach proposed by Theil (1950) and Sen (1968), detrending the sample data assuming a linear trend. Hence, the lag-one serial correlation coefficient of the detrended series was estimated. Subsequently, pre-whitening was used to remove the AR(1) process from the detrended series. Consequently, the residual series becomes independent. The removed original series trend (slope, *β*)was added back to the residual series, resulting in a trend series that is free from serial dependence. This new series comprises trends and noise that are not influenced by serial correlation.

Numerous studies investigated rainfall trends in Sri Lanka. These studies, often conducted at basin, regional, or national scales, have typically relied on a limited number of rainfall monitoring stations. This restriction is significant, as it may not adequately represent the meteorological trends across the entire country or region, particularly on a national scale. The MK test is a widely recognized statistical technique for identifying trends in time series data. However, when applying this test, it is crucial to consider the impact of serial correlation in the data. Ignoring this factor can lead to erroneous conclusions, creating false alarms regarding trends in rainfall patterns in Sri Lanka. This study aims to address this research gap by comprehensively evaluating the performance of the MK test, eliminating the serial correlation, and utilizing the modified TFPW (Theil-Sen-based Fixed-Points Weighting) method. This adjustment is crucial as it enables a more precise assessment of rainfall trends. Moreover, unlike previous research efforts that often utilized a limited number of stations, this study incorporates a significantly larger dataset. By incorporating more monitoring stations, the analysis will yield a more robust and reliable understanding of the rainfall trends across Sri Lanka. This approach aims to provide more precise insights into the country's rainfall trend, offering valuable information for future meteorological research and practical applications in water resource management and climate adaptation strategies.

2. Study Area

Sri Lanka is situated in the Indian Ocean between the Equator and the Tropic of Cancer. Geographically, the country lies between latitude 6^{o} and 10^{o} N and longitude 79.5^{o} and 82^{o} E, as shown in Figure 1 [32], [33]. The total land extent of Sri Lanka is about 62,710 km^2. The climate of Sri Lanka is classified as a tropical monsoon. Based on spatial variation of the mean annual rainfall, the country is classified into three main climatic zones: wet zone (>2500 mm), intermediate zone (1750 - 2500 mm), and dry zone (< 1750 mm). Four monsoons with spatial variation receive rainfall for the country: the First Inter-monsoon (FIM) season (March-April), the Southwest Monsoon (SWM) season (May-Sep), the Second Inter-monsoon (SIM) (Oct-Nov), and the Northeast Monsoon (NEM) (Dec-Feb) [34], [35].

The central mountains of Sri Lanka are the source of over a hundred rivers (103) that flow in a radial direction to the sea[29]. The land elevation in Sri Lanka is classified into coastal (0 - 30 m above sea level), lowland (30 - 300 m) and central highlands (above 300 m) (Figure 1). The wet zone of Sri Lanka is susceptible to heavy rainfalls, leading to frequent flooding in river basins such as Kalu, Kelani, Gin, Nilwala, and Attanagalu during the Second Inter-monsoon [34], [36-38].

3. Material and Method

This section provides a detailed discussion of the data collection process and the methods used. The method used to estimate the trend, excluding serial correlation, is illustrated in Figure 2.

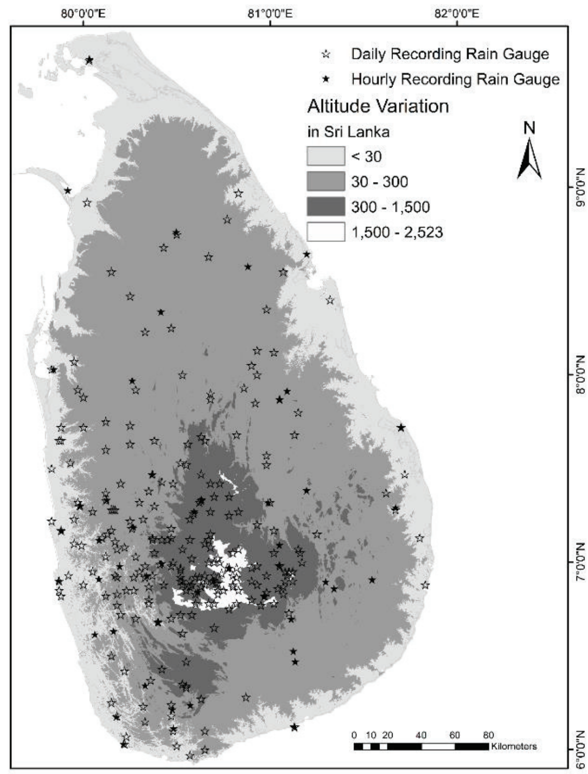

Figure 1 - The Locations of Rainfall Gauge Stations and Topographic Variations of Sri Lanka

3.1 Description of Meteorological Stations and Data Used

The monsoon wind brings moisture-laden air across the Arabian Sea, leading to heavy rainfall in the central highlands of Sri Lanka due to the orographic effect. Additionally, the northeast monsoon wind carries moist air through the Bay of Bengal, causing rainfall in the eastern parts of the country. The rainfall from the northeast monsoon is less than that from the southwest monsoon rain, as the Bay of Bengal is smaller than the Arabian Sea. This rainfall has been measured by conventional rain gauges, which are the primary sources of rainfall data in Sri Lanka. Most of the rain gauges were placed considering flood and landslide impacts. Hence, the meteorological station distribution is uneven and concentrated in the wet zone area. The study utilized data from 266 rain gauges installed by the Department of Meteorology and Irrigation Department of Sri Lanka. The daily time series spans around 60 years, from 1960 to 2020. The rainfall data was corrected for errors using the meteorological data error correction methods [39], [40]. Figure 1 shows the location map of the study area and rain gauge stations. The daily time series was utilized to create annual, FIM, SWM, SIM, and NEM time series. Rainfall intensities over one, three, and six hours were estimated using data from 50 hourly recorded rain gauges for trend analysis to illustrate extreme rainfall. Moreover, trends in consecutive wet and dry days were also evaluated annually and seasonally.

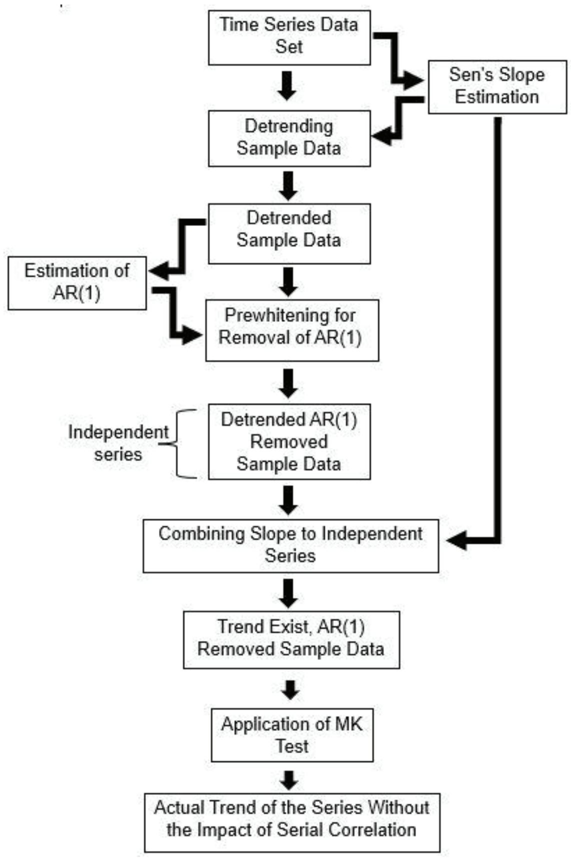

Figure 2 - Schematic Diagram of the TFPW Method

3.2 TFPW MK Test

Yue et al. (2002) introduced the TFPW MK test procedure, beginning with an initial estimation of the trend slope (β) of the original data by applying Sen's slope estimator [41-42]. For a given time, series $X_i = x_1, x_2, \ldots, x_n$, with n pairs of data, the slope is calculated as

$$\beta_i = \frac{x_j - x_k}{j-k}, \forall\, k < j \quad ...(1)$$

where k = 1, 2, … ,n, and j = 2, 3, …, n-1. The median of n values of β_i gives the Sen's estimator of slope β.

$$\beta_i = \begin{cases} \frac{\beta_{n+1}}{2} & if\ n\ is\ odd \\ \frac{\beta_{\frac{n}{2}} + \beta_{\frac{n+2}{2}}}{2} & if\ n\ is\ even \end{cases} \quad ...(2)$$

After calculating the slope (β) of the original data set, which signifies the trend over time, this slope is subsequently subtracted from the observed values. For the sake of brevity, the details regarding the trend subtraction process have not been included in this paper; readers are encouraged to refer to Yue et al. (2002) [24] for more comprehensive information. This procedure effectively removes the trend component, resulting in a trend-free series that highlights the underlying fluctuations in the data, free from the influence of the overall directional trend. Hence, the PW procedure is applied to the detrend series. The detrended series $Y_i = y_1, y_2, \ldots, y_n$, with lag-1 serial correlation coefficient r_1 is calculated as

$$r_1 = \frac{\frac{1}{n-1}\sum_{i=1}^{n-1}(x_i - E(x_i)).(x_{i+1} - E(x_i))}{\sum_{i=1}^{n-1}(x_i - E(x_i))^2} \quad ...(3)$$

where $E(x_i)$ is the mean of the sample, and n is the sample size

$$E(x_i) = \frac{1}{n}\sum_{i=1}^{n-1} x_i \quad ...(4)$$

The probability limits for r_1 on the correlogram of an independent series are estimated as

$$r_1 = \begin{cases} \frac{-1+1.645\sqrt{n-2}}{n-1}, for\ the\ one - tailed\ test \\ \frac{-1\mp1.96\sqrt{n-2}}{2n-1}, for\ the\ two - tailed\ test \end{cases} \quad ...(5)$$

Hence, the PW series X'_t is given by Von Storch (1995) as

$$X'_t = Y_t - r_1 Y_{t-1} \quad ...(6)$$

In the final stage of TFPW, the monotonic trend component is added back to the residual series X'_t to generate the trend-free pre-whitening series X^*_t

$$X^*_t = X'_t + \beta t \quad ...(7)$$

Then, the MK test [26], [27] is applied to the TFPW series X^*_t. MK test statistic S is calculated as

$$S = \sum_{i=1}^{n-1}\sum_{j=1+1}^{n} sgn(x_j - x_i) \quad ...(8)$$

where x_i and x_j are the data values in time series i and j (j >i), respectively, and $sgn(x_j - x_i)$ is the sgn function as

$$sgn(x_j - x_i) = \begin{cases} -1 & , if\ (x_j - x_i) < 0 \\ 0 & , if\ (x_j - x_i) = 0 \\ +1 & , if\ (x_j - x_i) > 0 \end{cases} \quad ...(9)$$

Statistic S is usually distributed with parameters $E(S)$ and variance $V(S)$ as

$$E(S) = 0 \quad ...(10)$$

$$V(S) = \frac{n(n-1)(2n+5) - \sum_{k=1}^{m} t_k(k)(k-1)(2k+5)}{18} \quad ...(11)$$

where m is the number of tied groups, and t_k denotes the number of data values in the k[th] tied group. Standardized test statistic Z is estimated using the formula below.

$$Z = \begin{cases} \frac{S-1}{\sqrt{V(S)}} & , if\ S > 0 \\ 0\ , & if\ S = 0 \\ \frac{S+1}{\sqrt{V(S)}} & , if\ S < 0 \end{cases} \quad ...(12)$$

To test for a monotonic trend at an α significance level (α = 5%), the alternative trend hypothesis is accepted if the absolute value of standardized test statistic Z is greater than the $Z1- \alpha/2$ value obtained from the standard normal cumulative distribution table. A positive sign of the test statistic indicates an increasing trend and a negative sign indicates a decreasing trend. Finally, the slope (β) of the trend in the residual series is also estimated by applying Sen's slope estimator [41-42] to identify the magnitude of the trend in the residual series. The open-source library package,"zyp,"developed in R-language [43], was used to perform the TFPW MK test mentioned in this study. This package is freely available via the CRAN repository and the GitHub version control platform.

4. Results and Discussion

The analysis evaluated annual and seasonal rainfall trends and wet and dry day patterns based on data from 266 rain gauge stations and extreme rainfall series measured over one, three, and six-hour intervals from 50 rain gauge stations. Only the gauges showing significant trends at the 5% significance level were considered for the results and discussion due to conciseness. The TFPW-MK test was used for rainfall trend analysis.

Table 1 - Summary of the Trend Impact for the Basins and Stations in Which the Trend Exists

Basin/Station	Annual			FIM			SWM			SIM			NEM			Extreme RF	
	Total	Wet days	Dry days	Total	Wet days	Dry days	Total	Wet days	Dry days	Total	Wet days	Dry days	Total	Wet days	Dry days	1hr	6hr
Kelani	Mixed	Normal Decrease	Mixed	Mild Decrease	Normal Decrease	Mild Increase	Mild Decrease	Normal Decrease	Normal Increase	No trend	Normal Decrease	Normal Increase	No trend	No trend	Mixed	No trend	No trend
Kalu	No trend	Normal Decrease	Normal Increase	No trend	Normal Decrease	No trend	No trend	Normal Decrease	Normal Increase	No trend	Normal Decrease	Normal Increase	No trend	No trend	No trend	No trend	No trend
Nilwala	Mild Decrease	Normal Decrease	Normal Increase	No trend	Mixed	Mixed	Normal Decrease	Mixed	Normal Increase	No trend	Normal Decrease	No trend	No trend	No trend	No trend	No trend	No trend
Upper Mahweli	Mixed	Normal Decrease	Normal Increase	Mixed	Mixed	Mixed	Mild Decrease	Normal Decrease	Normal Increase	Mixed	Normal Decrease	Mild Increase	Normal Decrease	Normal Decrease	Normal Increase	No trend	No trend
Maha Oya	Mixed	Mixed	Normal Decrease	Normal Decrease	Mild Increase	Normal Decrease	Mild Increase	Mixed	Normal Decrease	No trend	Normal Decrease	Normal Decrease	No trend	No trend	Normal Decrease	No trend	No trend
Attanagalu oya	No trend	No trend	Normal Decrease	No trend	No trend	Normal Decrease	No trend	Normal Increase	Normal Decrease	No trend	Normal Decrease	Mixed	No trend	No trend	No trend	No trend	No trend
Deduru Oya	No trend	Mixed	No trend	No trend	No trend	No trend	Mixed	Normal Increase	Normal Decrease	No trend	Normal Decrease	No trend	No trend	No trend	Normal Decrease	No trend	No trend
Malwathu Oya	No trend	No trend	Normal Decrease	No trend	No trend	No trend	No trend	Mixed	Normal Decrease	No trend	Normal Decrease	No trend	No trend	No trend	No trend	No trend	No trend
Gin Ganga	No trend	No trend	Normal Decrease	No trend	No trend	No trend	No trend	No trend	No trend	No trend	Normal Decrease	No trend	No trend	No trend	No trend	No trend	No trend
Kala Oya	No trend	No trend	No trend	No trend	No trend	No trend	No trend	No trend	No trend	No trend	Normal Decrease	No trend	No trend	No trend	No trend	No trend	No trend
Mi Oya	No trend	Normal Increase	No trend	No trend	No trend	No trend	No trend	No trend	No trend	No trend	Normal Decrease	No trend	No trend	No trend	No trend	No trend	No trend
Upper Kirindi Oya	Normal Increase	No trend	No trend	No trend	No trend	No trend	No trend	No trend	No trend	No trend	Normal Decrease	No trend	No trend	No trend	No trend	No trend	No trend
Colombo	No trend	No trend	No trend	No trend	No trend	No trend	No trend	No trend	No trend	No trend	No trend	No trend	No trend	No trend	No trend	Normal Decrease	No trend
Nuwara-Eliya	No trend	No trend	No trend	No trend	No trend	No trend	No trend	No trend	No trend	No trend	No trend	No trend	No trend	No trend	No trend	No trend	Normal Decrease
Nakkala	No trend	No trend	No trend	No trend	No trend	No trend	No trend	No trend	No trend	No trend	No trend	No trend	No trend	No trend	No trend	No trend	Normal Decrease
Padiyatha-lawa	No trend	No trend	No trend	No trend	No trend	No trend	No trend	No trend	No trend	No trend	No trend	No trend	No trend	No trend	No trend	No trend	Normal Decrease

Normal Decrease -
Mild Decrease -
High Decrease -
Normal Increase -
Mild Increase -
High Increase -
No trend -
Mixed -

The magnitude of the trend was classified based on Sen's slope (β) severity, denoting 'Normal' for slope(β) < 10, 'Mild' for 10 ≤ β< 20, 'Moderate' for 20 ≤ β<30, 'High' for 30 ≤ β< 40 and 'Extreme' for β ≤ 40. Additionally, the spatial variation of the trend was considered at the river basin scale. The results revealed that among the 103 river basins in Sri Lanka, only 10 exhibited significant susceptibility to rainfall trends. These basins were identified as Mahaweli, Kelani, Kalu, Gin, Nilwala, Maha Oya, Deduru Oya, Mi Oya, Attanagalu Oya, and Kirindi Oya river basins as depicted in Figure 3. Furthermore, Table 1 summarizes the severity of observed trends within these affected river basins. Figures 4, 5, 6, 7, and 8 visually represent the rainfall trends for annual, FIM, SWM, SIM, and NEM, respectively, as well as the trends of consecutive wet and dry days across various basins in Sri Lanka. Subsequently, the trends within the river basins were discussed from the most to the least affected by rainfall trends. The magnitude of trends in specific river basins was assessed by analyzing individual trends from scattered gauges across the basin using the Thiessen polygon method, which averages the trends from the stations.

Upper Mahaweli Basin (MB) is the largest basin in the country, covering almost 60% of the central mountains with altitudes of more than 1500 m above mean sea level (MSL). The Mahaweli River originates from Adam's Peak and flows towards the eastern part of the country before reaching the Bay of Bengal on the southwestern side of Trincomalee. There has been a mild to high decreasing trend in annual rainfall over the MB, particularly for stations located in hilly terrain. Additionally, there is a normal decrease in consecutive wet days and an increase in dry days. Based on the Thiessen polygon, which averages the station trends, the estimated average basin-wide rainfall trend is decreasing by 6.10 mm per year. The rainfall trends in the upper MB during the FIM season show a mix of decreasing and increasing trends. However, most of the rain gauges in the central mountains of MB show a normal to mild increase trend. FIM rainfall is decreasing on wet days, while on dry days, there are mixed results with both increasing and decreasing trends. Overall, there is a basin-wide average decreasing rainfall trend of 1.42 mm/season for FIM rainfall.

In the SWM season, the rainfall trend in upper MB shows a normal to moderate decreasing trend. Specifically, the wet day trend in the upper MB during SWM shows a normal decreasing trend, while dry days show a normal increasing trend. The basin has an average decreasing trend for SWM rainfall of 11.63 mm/season. The SIM rainfall trend in upper MB showed mixed results, which increased and decreased. The SIM wet days trend results of the MB show a normal decreasing trend all over the basin. However, the SIM dry day results show a decreasing trend for upper MB, while the central part of the basin shows an increasing trend. On average, the upper MB area has experienced a growing trend of 2.48 mm/season in SIM rainfall.The NEM rainfall trend of the Mahaweli basin shows a normalto moderate decreasing trend. Only two upper MB stations show a normal increasing trend in wet-day rainfall. The dry-day rainfall trend indicated a normal increase in the upper MB (central hills). Over the last 60 years, the trend for the Mahaweli basin has indicated that the upper part is most vulnerable and is experiencing a decreasing trend with increasing dry days. These trends will significantly impact the Mahaweli Multi-Purpose Project, which provides hydroelectric power generation upstream and irrigation water supply downstream for agriculture. Water scarcity will negatively affect Sri Lanka's economy and food security.

Malwathu Oya (MOB) is the second-longest river in Sri Lanka. Analysis of rainfall trends from 1960 to 2020 shows that annual dry days and SWM dry days are decreasing in the MOB. The study also revealed a decreasing trend in the magnitude of wet days during the annual and SIM seasons. Since the basin is mainly used for agriculture, using the existing reservoirs efficiently is essential.

Kelani River, the fourth longest river in Sri Lanka, shows contrasting trends in its upper and lower basins. The lower Kelani basin has experienced an increasing trend in annual rainfall, while the upper Kelani basin showed a decreasing trend. The basin's annual series and wet day trend display both increasing and decreasing trends. However, the average annual rainfall trend for the Kelani River basin indicates an overall increase of 4.25 mm/year. Correspondingly, average hourly rainfall for the Kelani River Basin shows a rising trend of 3 mm/year. It is not significant in the short run but becomes substantial in the long run.

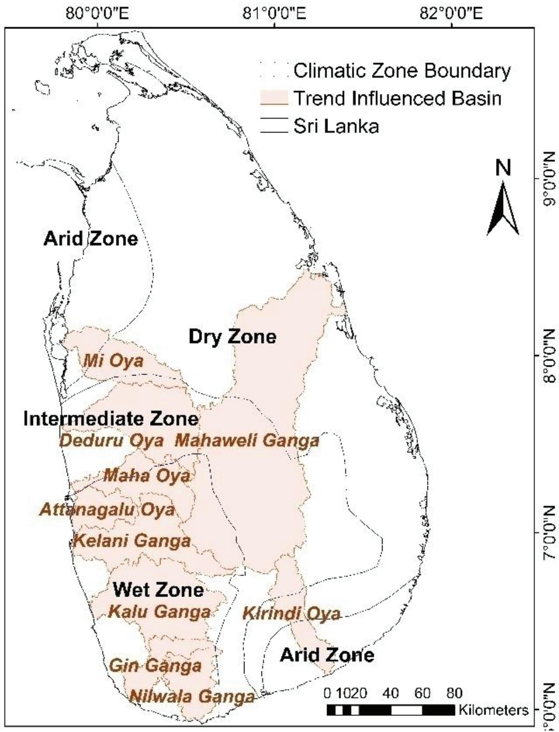

Figure 3 - River Basins Subjected to Rainfall Trends

The Deduru Oya is the sixth-longest river in Sri Lanka. The annual trend results for the Deduru Oya Basin (DOB) indicate no significant trend. Specifically, the upper DOB annual wet day trend shows a normal decrease, while the central part of the basin shows a normal increasing trend. According to the FIM rainfall trend analysis, there is no significant trend in DOB at the 5% level. However, the SWM rainfall trend analysis results show a normal decreasing trend in the upper DOB. SWM wet days have a normal increasing trend in the central part of DOB, while the upper DOB hilly areas show a normal decreasing trend. Similarly, SWM dry days have a normal increasing trend in the upper DOB hilly areas, and the central part of the BOD shows a normal decreasing trend.

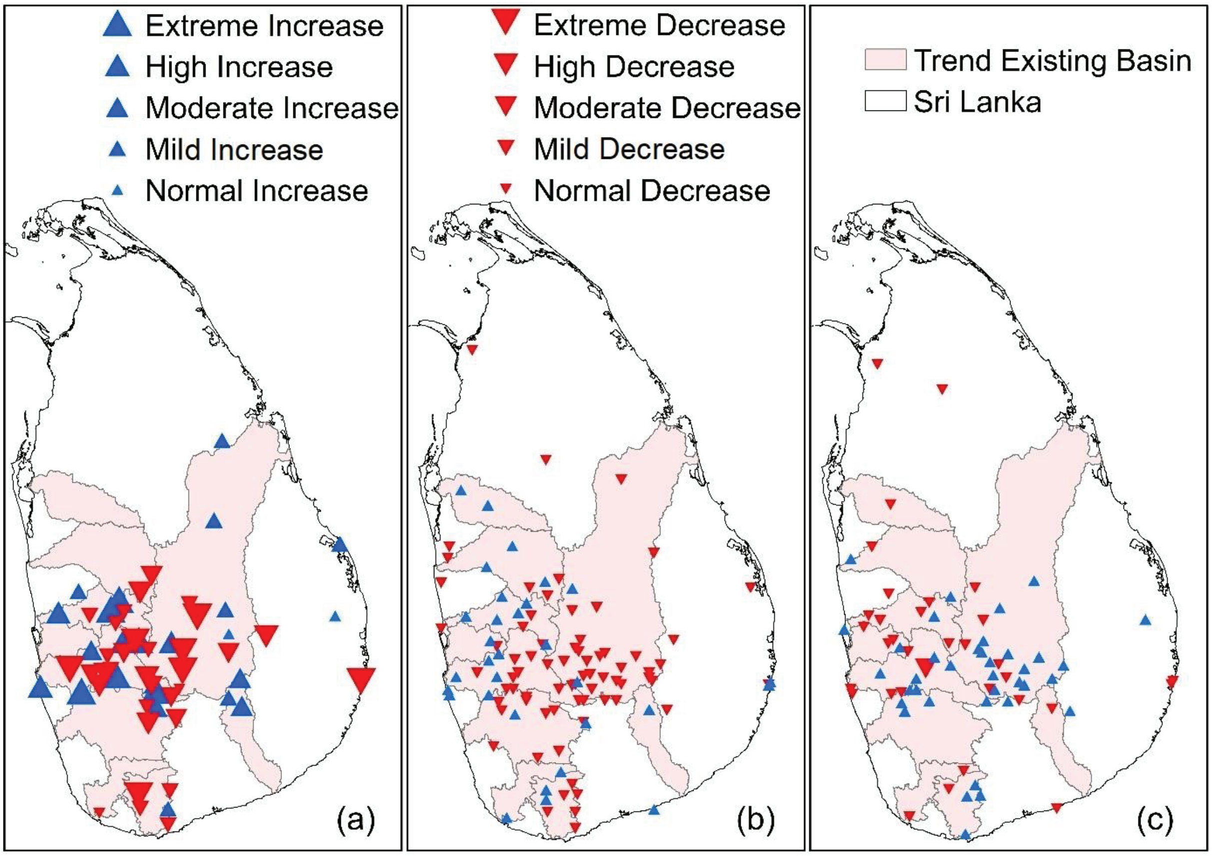

Figure 4 - The Annual Rainfall Trend: (a) Annual Rainfall Trend Variation, (b) Annual Wet Day Trend Variation, (c) Annual Dry Day Trend Variation

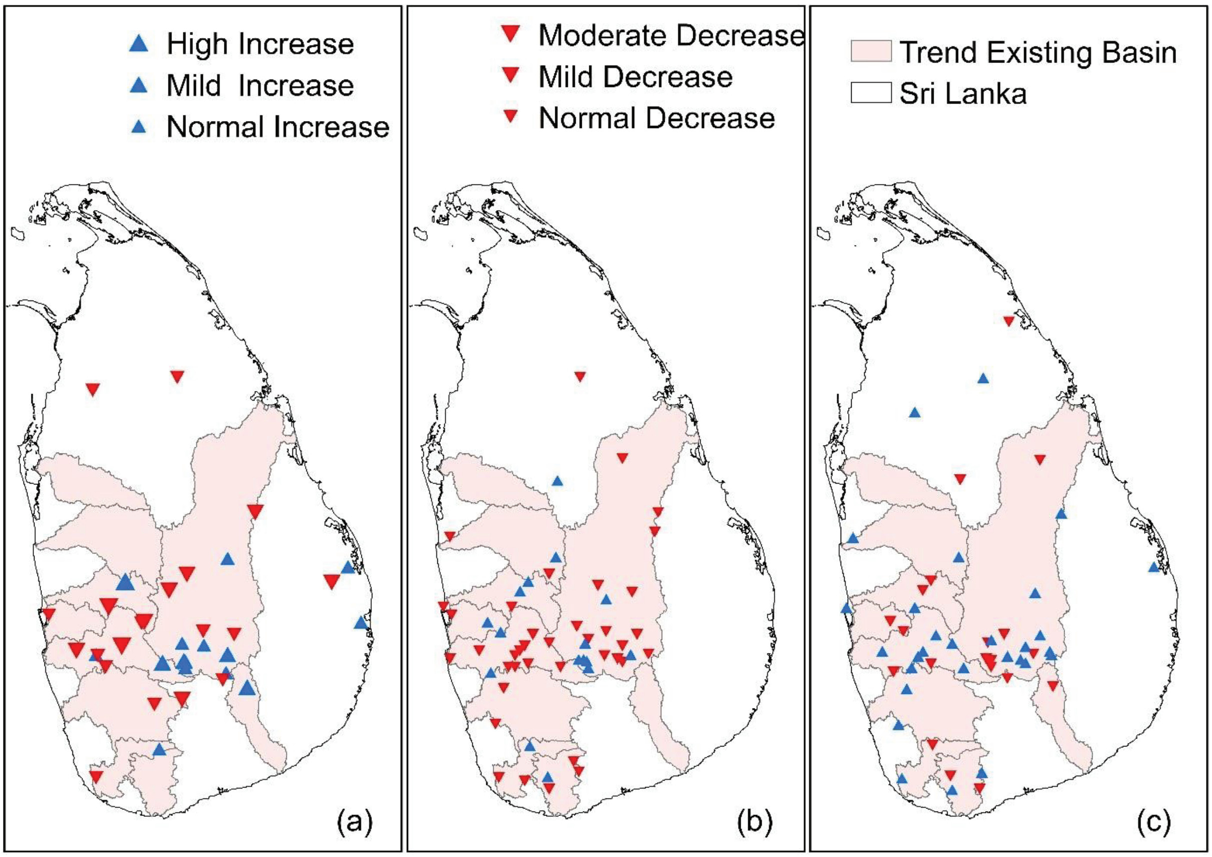

Figure 5 - The FIM Rainfall Trend: (a) FIM Rainfall Trend Variation, (b) FIM Wet Day Trend Variation, (c) FIM Dry Day Trend Variation

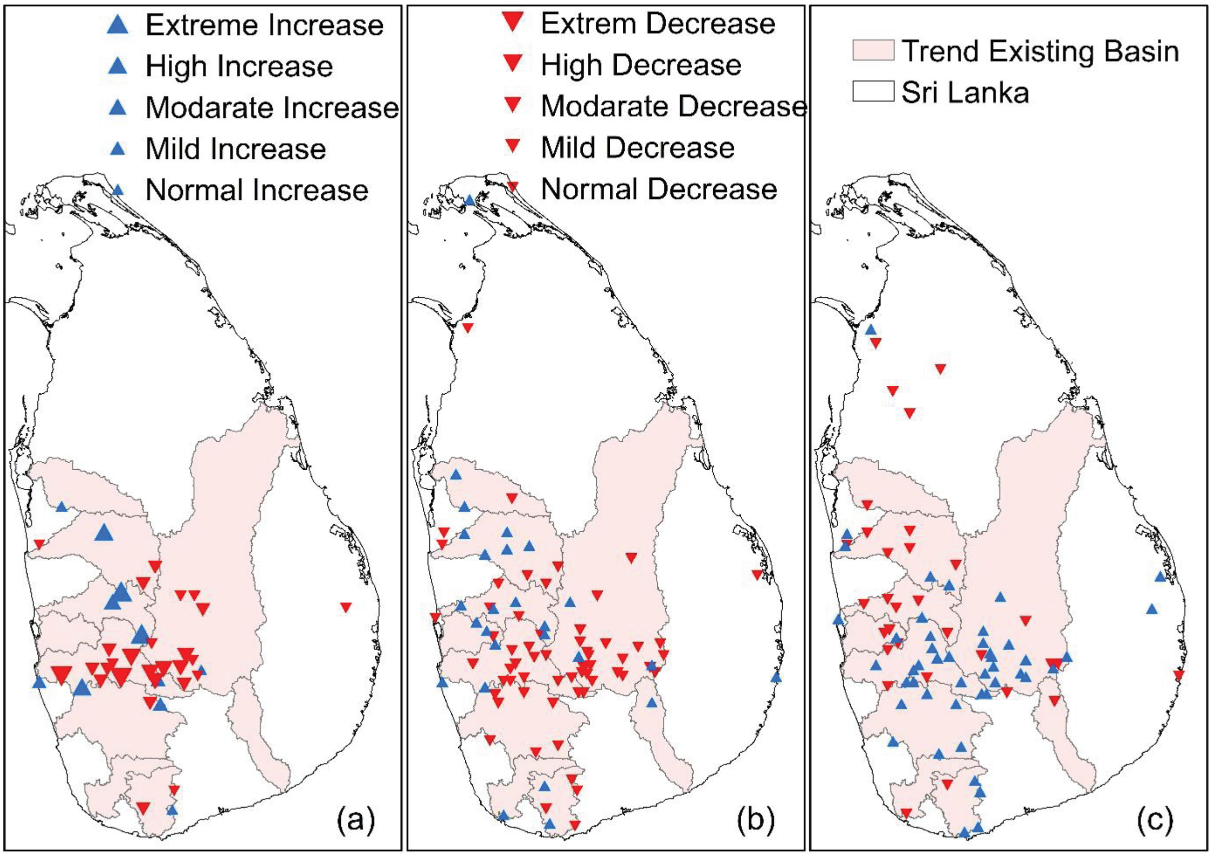

Figure 6 - The SWM Rainfall Trend: (a) SWM Rainfall Trend Variation, (b) SWM Wet Day Trend Variation, (c) SWM Dry Day Trend Variation

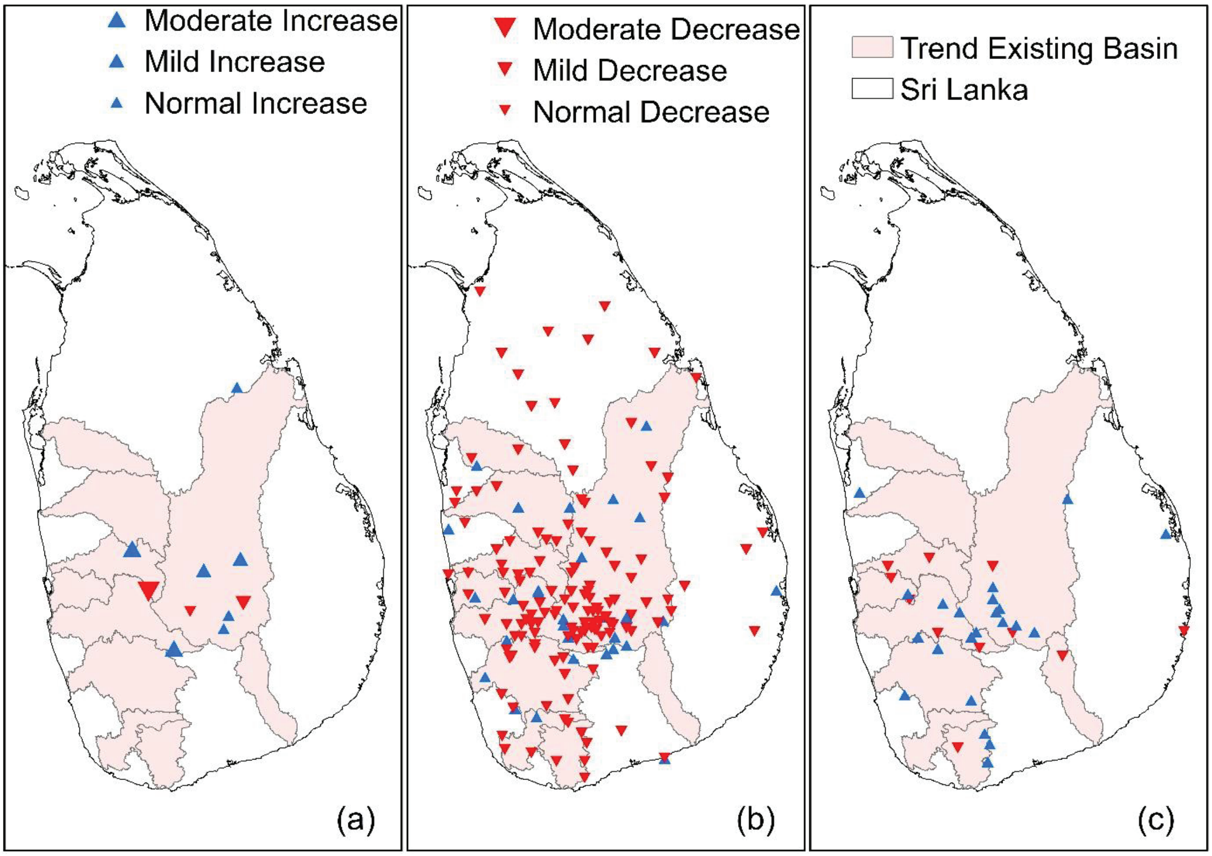

Figure 7 - The SIM Rainfall Trend: (a) SIM Rainfall Trend Variation, (b) SIM Wet Day Trend Variation, (c) SIM Dry Day Trend Variation

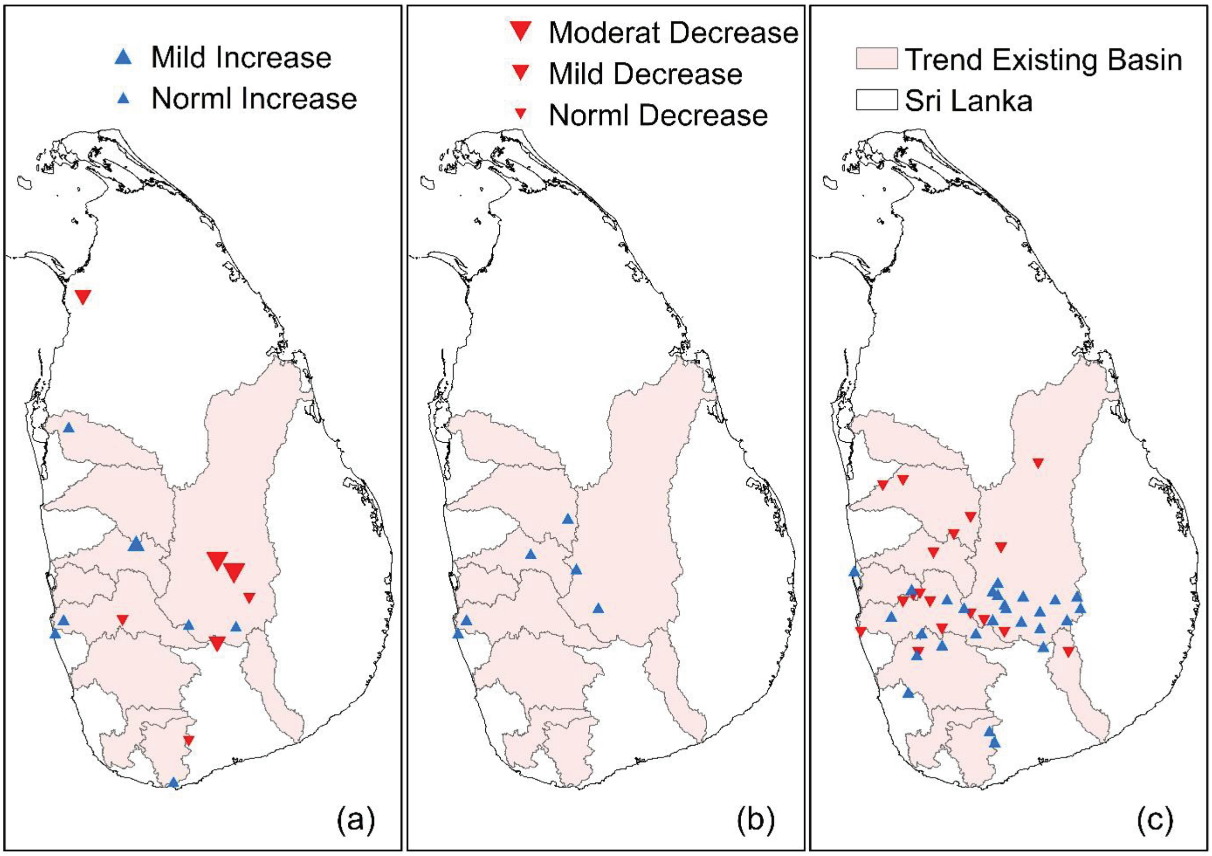

Figure 8 - The NEM Rainfall Trend: (a) NEM Rainfall Trend Variation, (b) NEM Wet Day Trend Variation, (c) NEM Dry Day Trend Variation

No trend was observed for SIM rainfall; however, SIM wet days show a normal decreasing trend in the upper DOB hilly mountain area and downstream of DOB. The central part of the DOB shows a normal increasing trend in wet days. No trend was observed for SIM dry days in DOB. Similarly, the DOB shows no trend for NEM rainfall or NEM wet days. However, the NEM dry day series shows a normal decreasing trend at the upper and lower DOB. The upper DOB hilly mountain area shows a high decreasing annual rainfall trend, which could lead to a reduction in the availability of water resources in DOB, similar to the MB.

The Maha Oya Basin (MHOB) exhibits a varied trend in annual rainfall, with differing results across its various regions. In the upper MHOB, the number of annual wet days is declining, whereas in the lower MHOB, there is an increase in wet days. Conversely, the annual dry days in the MHOB are decreasing. In terms of FIM rainfall, FIM wet days, and FIM dry days, no significant trends are observed in the MHOB. SWM rainfall is significantly increasing in three rain gauges of the basin. SWM wet days show mixed results with both increases and decreases in MHOB, while SWM dry days generally decrease. SIM rainfall does not show a significant trend in the MHOB. However, the number of SIM wet days exhibits a normal decreasing trend, while SIM dry days do not show any considerable trend, except for two rain gauges. However, there is no significant trend in the extreme series of the MHOB. The analysis of rainfall patterns indicates that the MHOB has become wetter, and this excess moisture during the monsoon season could lead to devastating floods in the basin.

The Kalu-Ganga River is Sri Lanka's tenth-longest river, and the Kalu-Ganga Basin (KGB) is a region susceptible to changes in rainfall patterns. In the KGB, there is no significant trend in annual and seasonal rainfall. However, there is a normal decreasing trend in annual wet days, FIM wet days, and SIM wet days. On the other hand, only the dry days of SIM and SWM show a normal increase. Although there is a trend in SIM seasonal rainfall for both dry and wet days, it is not significant, as there is no trend in extreme rainfall (measured over one hour, three hours, and six hours).

The analysis of the Gin River basin indicates that only FIM wet days are decreasing. As such, the basin has no annual or seasonal rainfall trend. In contrast, the Nilwala River basin (NB) is susceptible to rainfall trends. The central region of the Nilwala Basin shows rainfall trends from two rain gauges in an annual series. While there are mixed trends in annual rainfall wet days in the NB, the trend for annual dry days is increasing normally. Although seasonal rainfall in NB does not show a significant trend, the SIM wet day series shows a slight decreasing trend. Meanwhile, the SWM and SIM show a consistently increasing trend in the dry-day series. Consequently, a continuous rise in dry days may result in drier conditions during the SWM and SIM periods. The Kirindi Oya basin (KOB) exhibits a relatively low vulnerability to fluctuations in rainfall patterns over time. However, observations indicate that the upper regions of KOB are experiencing a mild increase in rainfall. This trend mirrors the conditions observed in the NEM rainfall patterns, where a gentle upward trend has also been noted in the upper KOB area. As a result, the water deficit currently observed in the KOB is anticipated to diminish as these rainfall trends continue to develop gradually.

The research findings further highlight that the Mi Oya Basin (MIOB), KOB, and Attanagalu Oya Basin (AOB) are recognized as the least vulnerable to changes in rainfall trends compared to other basins. In particular, the MIOB and AOB show no significant trends in annual or seasonal rainfall patterns, indicating stability in these regions. However, upon closer examination of MIOB, it is noted that there is a normal increasing trend in annual wet days. This suggests that while wet conditions may become more frequent, the basin could also experience shorter dry spells as the annual dry days are trending downwards. Conversely, the AOB reveals a normal decreasing trend in dry days during the SWM season, signaling that this basin may encounter more periods of wet weather. These insights suggest that both basins are experiencing complex changes that could affect water availability and management strategies in the future.

The analysis of extreme rainfall measured over one hour, three hours, and six hours from 46 rain gauges across the country showed no significant trends after removing serial correlation. In contrast, four stations, Colombo, Nakkala, Padiyathalawa, and Nuwara Eliya, did exhibit significant trends.The Colombo rain gauge, which records one-hour extreme rainfall, demonstrated a steady increase of 3 mm annually. This finding aligns with the results reported by Karunathilaka et al. [14]. In contrast, rain gauges in Nakkala, Padiyathalawa, and Nuwara Eliya consistently decreased in one-hour and six-hour extreme rainfall. This observation is also supported by a previous study conducted by Naveendrakumar et al. (2018) [38]. The analysis did not show extreme rainfall anomalies at the basin scale, as these trends were only observed in the three rain gauges of Kelani, Kubukkan Oya, Maduru Oya, and the Upper Mahaweli basin.

Among the rain gauges analyzed, 6.5% demonstrate a significant upward trend, highlighting the importance of monitoring changes in precipitation patterns. In similar studies, Karunathilaka et al. (2017), Nisansala et al. (2020), Amarasinhe (2020), and Alahakoon and Edirisinghe (2021) also found a significant upward trend in annual rainfall [4]. However, these studies utilized fewer rain gauges than this study, and the percentage increase they reported was higher. In contrast, the rainfall data from the FIM indicates a decreasing trend of 13.6% across all stations.

In this study, the Southwest Monsoon (SWM) exhibits a 5.17% decrease in rainfall trends across all stations. Similarly, Karunathilaka et al. (2017), Nisansala et al. (2020), and Naveendrakumar et al. (2018) reported significant decreasing trends of 84%, 78%, and 68%, respectively. In contrast, Alahakoon and Edirisinghe (2021) observed a non-significant increasing trend in SWM rainfall. Conversely, the Southeast Monsoon (SIM) rainfall showed a 2.6% increase across all stations. Similarly, Karunathilaka et al. (2017), Nisansala et al. (2020), Naveendrakumar et al. (2018), and Alahakoon and Edirisinghe (2021) identified an upward trend in SIM rainfall as well. Furthermore, previous research findings align closely with these results, except for the FIM period, which displayed a significantly higher percentage magnitude. This discrepancy may be attributed to the serial correlation in the original data series, as the TFPW approach was not employed to address this effect.

Notably, 32% of the stations display serial correlation. Furthermore, the proportion of stations exhibiting a TFPW trend is 10% higher than in the original series. This trend is consistent across all annual and seasonal series. This suggests that auto-correlated time series data may be misleading or produce disproportionately high rejection rates when assessing trends without utilizing the TFPW approach.

The TFPW method operates on a set of specific assumptions that are crucial for its successful application in time series analysis. Firstly, the residuals obtained after conducting the pre-whitening process must demonstrate stationarity. This means that the statistical properties of the residuals, such as mean and variance, should remain constant over time, which is essential for drawing valid inferences from the data. Moreover, the TFPW method assumes that the time series data has either a deterministic or linear trend. A deterministic trend implies a predictable and consistent pattern in the data over time, while a linear trend suggests a consistent increase or decrease. The method posits that applying an Autoregressive model of order one (AR(1)) is adequate for effectively removing any ingrained linear trends in the dataset. Following applying the TFPW method, it is anticipated that the residuals will conform to the properties of white noise. White noise signifies that the residuals exhibit randomness, with no discernible patterns, and are uncorrelated across time. This characteristic is pivotal for confirming that the original data has been adequately de-trended and that any remaining variation is not systematic. However, it is essential to note that the TFPW method is primarily designed to identify linear or monotonic trends within the data. The approach may not yield reliable results if the time series displays persistent autocorrelation, where observations correlate over time. Furthermore, in scenarios characterized by high noise levels or when trends are weak, the efficacy of the TFPW method may be significantly limited, potentially leading to ambiguous or misleading conclusions.

5. Recommendation

The findings of this comprehensive study indicate a notable decreasing trend in annual rainfall within the central hills of Sri Lanka, which is particularly concerning for the region's ecological and socio-economic stability. The research further highlights that most river basins surveyed, including crucial watersheds, are experiencing similar declines in annual rainfall and consecutive wet days. This reduction in precipitation could result in significantly diminished river flows, especially in vital river systems such as the Mahaweli River, which is crucial for irrigation and hydroelectric power generation. In contrast, the Kelani River basin has shown an increasing trend in rainfall, which may pose challenges related to flooding.

The implications of these varying rainfall patterns could be profound for the agricultural sector, especially in the MB area, which heavily relies on consistent water supply for crop production. Such fluctuations in rainfall and river flow could jeopardize food security and local economies, underscoring the urgent need to develop and implement robust strategies to mitigate the risks of high floods, especially in the Kelani River basin, as it shows an upward trend in precipitation.

Moreover, the observed variability in rainfall trends across different river basins in Sri Lanka suggests potential connections to broader climatic phenomena. Factors such as large-scale atmospheric circulation patterns, changes in land use, and increasing urbanization likely play significant roles in these trends, indicating an urgent requirement for additional research to explore these relationships in greater depth.

Conducting detailed trend analyses of climatic variables is essential to understand their monotonic trends and localized impacts, particularly in the face of ongoing climate change. While global climate models provide valuable insights, they often lack the specificity needed for effective local planning; therefore, a regional perspective is critical for gaining a nuanced understanding of these shifts.

Identifying and analyzing rainfall trends is paramount for effectively managing water resources allocated for essential use such as drinking, agricultural irrigation, hydroelectric power generation, and recreational activities. Access to accurate and up-to-date data informs water management strategies and equips policymakers with the necessary tools to protect communities and natural resources from potential climate-related disasters. Ultimately, the findings from this study can serve as an essential foundation for future water resource development and management initiatives, facilitating better preparedness and resilience in the face of climatic uncertainties.

6. Conclusions

This study comprehensively investigated temporal trend variation in rainfall patterns using records from 266 daily and 50 hourly recording stations spread across Sri Lanka. It examined different temporal scales, such as annual, seasonal, and extreme rainfall series. It aimed to detect monotonic rainfall trends in Sri

Lanka while eliminating the impact of serial correlation.

The 60 years of meteorological data analysis revealed trends in the ten river basins of Sri Lanka, indicating a possible influence of climate change. The study thoroughly examined the spatial and temporal variations in the occurrence of the identified trends. It provided a detailed analysis of annual fluctuations, breaking down the data to reveal seasonal patterns and the distribution of consecutive wet and dry days. This analysis encompassed annual and seasonal temporal scales, allowing for a comprehensive understanding of how these trends vary over different time frames and geographic locations. The study utilized more rain gauge stations than previous research, and the findings are valuable for scholars and scientists who want to understand rainfall trends as a proxy for studying climate change. The study highlights the dynamic nature of rainfall patterns, which are influenced by a mix of local, regional, and global factors. Monitoring these trends is essential for effective climate adaptation and long-term environmental planning.

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References

1. Guzman, O., and Jiang, H. "Global Increase in Tropical Cyclone Rain Rate," *Nat Commun*, Vol. 12, No. 1, Dec. 2021, pp. 1–8.

2. Nunes, L. J. R., "The Rising Threat of Atmospheric CO2: A Review on the Causes, Impacts, and Mitigation Strategies", *MDPI,* Apr. 01, 2023.

3. Dissanayaka, K. D. C. R., and Rajapakse, R. L. H. L., "Long-Term Precipitation Trends and Climate Extremes in the Kelani River Basin, Sri Lanka, and Their Impact on Streamflow Variability Under Climate Change", *Paddy and Water Environment*, Vol. 17, 2019, pp. 281–289.

4. Abeysingha, N. S., "A Review of Recent Changes in Rainfall Trend in Sri Lanka," *Tropical Agricultural Research and Extension,* Vol. 25, No. 1, Apr. 2022, pp. 1-13.

5. Singh, V., and Qin, X., "Study of Rainfall Variabilities in Southeast Asia Using Long-term Gridded Rainfall and Its Substantiation Through Global Climate Indices", *J Hydrol (Amst)*, Vol. 585, Jun. 2020.

6. Burt, T. P., and Weerasinghe, K. D. N., "Rainfall Distributions in Sri Lanka in Time and Space: An Analysis Based on Daily Rainfall Data",*Climate*, Vol. 2, No. 4, Dec. 2014, pp. 242–263.

7. Ampitiyawatta, A. D., and Wijeratne, A. W., "Impact of Temporal Changes of Rainfall on Major Climatic Zones of Sri Lanka", *Tropical Agricultural Research & Extention*, Vol. 18, No. 4, 2015, pp. 148–152.

8. Weerasekara, S. C., Lee, Wilson, B., Hoang, V. N., Managi, S., and Rajapaksa, D., "The Impacts of Climate-induced Disasters on the Economy: Winners and Losers in Sri Lanka Central Bank of Sri Lanka, Sri Lanka," 2021.

9. Alahacoon, N., Matheswaran, K., Pani, P., and Amarnath, G., "A Decadal Historical Satellite Data and Rainfall Trend Analysis (2001-2016) for Flood Hazard Mapping in Sri Lanka," *Remote Sens (Basel)*, Vol. 10, No. 3, Mar. 2018.

10. Alahacoon, N., and Edirisinghe, M., "Spatial Variability of Rainfall Trends in Sri Lanka From 1989 to 2019 as an Indication of Climate Change," *ISPRS Int J Geoinf*, Vol. 10, No. 2, Feb. 2021.

11. Amarasinghe, A. G., "Analysis of Long-Term Rainfall Trends in Sri Lanka Using CHRIPS Estimates", 2020.

12. Jayawardene, H. K. W. I., Jayewardene, D. R., and Sonnadara, D. U. J., "Interannual Variability of Precipitation in Sri Lanka", 2015.

13. Jayawardene, H. K. W. I., Sonnadara, D. U. J., and Jayewardene, D. R., "Trends of Rainfall in Sri Lanka Over the Last Century", 2005.

14. Karunathilaka, K. L. A. A., Dabare, H. K. V., and Nandalal, K. D. W., "Changes in Rainfall in Sri Lanka During 1966-2015", *Engineer*, Vol. L, No. 02, 2017, pp. 39–48.

15. Naveendrakumar, G., Vithanage, M., Kwon, H. H., Iqbal, M. C. M., Pathmarajah, S., and Obeysekera, J., "Five Decadal Trends in Averages and Extremes of Rainfall and Temperature in Sri Lanka", *Advances in Meteorology*, Vol. 225, 2018, pp. 110–120.

16. Nisansala, W. D. S., Abeysingha, N. S., Islam, A., and Bandara, A. M. K. R., "Recent Rainfall Trend Over Sri Lanka (1987–2017)", *International Journal of Climatology*, Vol. 40, No. 7, Jun. 2020, pp. 3417–3435.

17. Nissanka, S. P., Punyawardena, B. V. R., Premalal, K. H. M. S., and Thattil, R. O., "Recent Trends in Annual and Growing Seasons Rainfall of Sri Lanka," in *Proceedings of the International Conference on the Impact of Climate Change in Agriculture. Faculty of Agriculture, University of Ruhuna, Mapalana, Sri Lanka*, 2011, pp. 249–263.

18. Wickramagamage, P., "Spatial and Temporal Variation of Rainfall Trends of Sri Lanka", *Theor Appl Climatol*, Vol. 125, No. 3–4, Aug. 2016, pp. 427–438.

19. Khaniya, B., Jayanayaka, I., Jayasanka, P., and Rathnayake, U., "Rainfall Trend Analysis in Uma Oya Basin, Sri Lanka, and Future Water Scarcity Problems in Perspective of Climate Variability", *Advances in Meteorology*, Vol. 2019, No. 1, 2019.

20. Pawar, U., and Rathnayake, U., "Spatiotemporal Rainfall Variability and Trend Analysis Over Mahaweli Basin, Sri Lanka", *Arabian Journal of Geosciences*, Vol. 15, No. 4, Feb. 2022.

21. Perera, A., Ranasinghe, T., Gunathilake, M., and Rathnayake, U., "Comparison of Different Analyzing Techniques in Identifying Rainfall Trends for Colombo, Sri Lanka", *Advances in Meteorology*, Vol. 2020, No. 1, 2020.

22. Perera, H., Gunathilake, M. B., Panditharathne, R., Al-Mahbashi, N., and Rathnayake, U., "Statistical Evaluation and Trend Analysis of ANN Based Satellite Products (PERSIAN) for the Kelani River Basin, Sri Lanka", *Applied Computational Intelligence and Soft Computing*, Vol. 2022, No. 1, 2022.

23. Ruwangika, A. M., Perera, A., and Rathnayake, U., "Comparison of Statistical, Graphical, and Wavelet Transform Analyses for Rainfall Trends and Patterns in Badulu Oya Catchment, Sri Lanka", 2020, *Complexity*, Vol. 2020, No. 1, 2020.

24. Yue, S., Pilon, P., Phinney, B., and Cavadias, G., "The Influence of Autocorrelation on the Ability to Detect Trend in Hydrological Series", *Hydrol Process*, Vol. 16, No. 9, Jun. 2002, pp. 1807–1829.

25. Hamed, K. H., and Rao, A. R., "A Modified Mann-Kendall Trend Test for Autocorrelated Data," *J Hydrol*, Vol. 204, 1998, pp. 182–196.

26. Kendall, M. G., "Rank Correlation Methods", 1948.

27. Mann, H. B., "Nonparametric Tests Against Trend," *Econometrica: Journal of Econometric Society*, 1945, pp. 245–259.

28. Storch, H. V., "Misuses of Statistical Analysis in Climate Research", *Analysis of Climate Variability: Applications of Statistical Techniques Proceedings of an Autumn School Organized by the Commission of the European Community on Elba from October 30 to November 6,* 1993, pp. 11-26.

29. Yue, S., Pilon, P., Phinney, B., and Cavadias, G., "Patterns of Trend in Canadian Streamflow", *in 58th Eastern Snow Conference,* 2001, pp. 1–12.

30. Yue, S., Pilon, P., and Phinney, B., "Canadian Streamflow Trend Detection: Impacts of Serial and Cross-Correlation," *Hydrological Sciences Journal*, Vol. 48, No. February, 2003, pp. 51-63.

31. Blain, G. C., "The Influence of Nonlinear Trends on the Power of the Trend-free Pre-whitening Approach," *Acta Sci Agron*, Vol. 37, No. 1, 2015, pp. 21–28.

32. Iresh, A. D. S., Dilthara, G. W. A. S., and Sugeeshwara, S. P. C., "Estimation of Catchment Parameters of Snyder's Synthetic Method for Water Resources Planning and Flood Management in Sri Lanka", *Engineer: Journal of the Institution of Engineers, Sri Lanka*, Vol. 57, No. 2, May, 2024, pp. 81–86.

33. Iresh, A. D. S., Obeysekera, J., Athapattu, B. C. L., and Fernando, W. C. D. K., "Rainfall Intensity Duration Frequency Curves Using Cluster and Regional Frequency Analyses", *J Hydrol Eng*, Vol. 29, No. 5, Oct. 2024.

34. Iresh, A. D. S., Marasinghe, A. G. N. S., Wedanda, A. M. T. S. H., Wickramasekara, G. P., Wickramasooriya, M. D. J. P., and Premathilake, M. T. C., "Development of a Hydrological Model for Kala Oya Basin Using SWAT Model", *Journal of the Institution of Engineers, Sri Lanka*, Vol. 54, No. 01, 2021, pp. 57–65.

35. Iresh, A. D. S., "Drought Studies in Kalaoya Basin, Sri Lanka", *Water Productivity*, Vol. 3, No. 1, 2023, pp. 19-34.

36. Iresh, A. D. S., "Flood Frequency Analysis for Kelani River Basin: Case Study in Sri Lanka," *Annual Sessions of IESL2019*, pp. 571–578.

37. Weerabangsa, M. Z., Himanujahn, S., Iresh, A. D. S., and Athapattu, B. C. L., "Flood Frequency Analysis for Upper Kalu River Basin at Ratnapura, Sri Lanka," *in 2023 Moratuwa Engineering Research Conference (MERCon)*, IEEE, 2023, pp. 403–408.

38. Iresh, A. D. S., Athapattu, B. C. L., Obeysekera, J., and Fernando, W. C. D. K., "Floodplain Zoning and Mapping for Lower Kelani River, Sri Lanka," *Engineer*, Vol. 57, No. 3, Aug, 2024, pp. 23–33.

39. Sevruk, B., "World Meteorological Organization Methods of Correction for Systematic Error in Point Precipitation Measurement for Operational Use," 1982.

40. Iresh, A. D. S., "Screening of Annual Rainfall Time-Series Data in Kala Oya Basin: Case Study in Sri Lanka," *Engineer*, Vol. 53, No. 2, 2020, pp. 69–75.

41. Sen, K. P., "Estimates of the Regression Coefficient Based on Kendall's Tau," 1968.

42. Theil, H., "A Rank-Invariant Method of Linear and Polynomial Regression Analysis", *Indagationes Mathematicae*, Vol. 12, No. 85, 1950.

43. Bronaug, D., and Werner, A., "zyp: Zhang + Yue-Pilon Trends Package," 2019, CRAN: R package version 0.10-1.1. Accessed: Aug. 07, 2024.