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Research Article

Long-Term Rainfall Variability and Trends for Climate Risk Management in the Summer Monsoon Region of Southeast Asia

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This study presents an analysis of long-term rainfall variability and trends in the summer monsoon region of Southeast Asia, encompassing Lao People's Democratic Republic (Lao PDR), Thailand, Vietnam, Cambodia, and Myanmar, as well as their respective river basins. Utilizing Climate Hazards Group InfraRed Precipitation with Station Data (CHIRPS) having a spatial resolution of 5 km spanning from 1981 to 2021, rainfall variability and trends were examined. Data preprocessing and geospatial analysis were conducted using R-Studio and ArcGIS software. The Mann–Kendall (MK) test and Sen's slope estimator were employed for annual and seasonal rainfall trend analysis. Myanmar exhibited the highest average annual rainfall of 2137 mm during the study period, while Thailand had the lowest (1641 mm). Over the past four decades, the Peninsula Malaysian Basin experienced the highest average annual rainfall (2691 mm), whereas the Chao Praya Basin recorded the lowest (1311 mm). Increasing trends in rainfall were observed across all five countries and nine major river basins. Vietnam displayed the highest annual rainfall trend of 5.63 mm/year, while Lao PDR exhibited the lowest trend (3.16 mm/year). Among the river basins, the Chao Phraya Basin demonstrated the maximum annual rainfall trend (11.21 mm/year), while the Peninsula Malaysia Basin had the minimum trend (1.21 mm/year). These findings could significantly contribute to climate change monitoring in the region and can aid policymakers in sectors such as agriculture, urban planning, and disaster management.

1. Introduction

The Earth's climate has experienced remarkable transformations in recent decades, primarily attributed to global warming [1]. These changes have led to a substantial escalation in the destructive impacts of floods, droughts, and other natural calamities across numerous nations [2]. Consequently, climate change poses a severe threat to agricultural productivity and poses a significant challenge to food security at both local and global scales [3].

Rainfall plays a pivotal role as a fundamental environmental factor when examining the meteorological characteristics of a specific area, enabling the monitoring of climate and weather pattern shifts [4]. It serves as a crucial indicator for studying the impacts of climate change, as the spatial distribution of rainfall directly influences global temperature fluctuations. Variations in rainfall intensity and magnitude are key indicators of changes in flood occurrences, drought events, and exceptionally dry or wet seasons, which can result in significant harm to ecosystems, plant and animal life, property, and food security through declines in agricultural output [5–7]. Moreover, investigating macro-level variables and trends in rainfall is essential for researchers examining extensive geographic areas such as river

basins, countries, or regions, enabling the exploration of sustainable solutions for flood control and drought mitigation [8–12].

In addition, rainfall trend studies provide a solid foundation for micro- and macro-level resource management assessments based on the geographical context used for the analysis [13]. Furthermore, studies related to rainfall trends have been conducted through several statistical models to provide a proper concept of agricultural activity, floods, droughts, and water systems. However, a significant number of studies using the spatial variability of rainfall are lacking [14–19].

However, studies have shown that worldwide rainfall has increased by 2% over the past ten decades [20], while other studies [21] have emphasized that the study of seasonal and annual precipitation, based on conventional climate center data, is a high priority. However, rainfall variations in river basins and climatic zones have not received significant attention in previously reported studies [22, 23]. It is expected that a significant increase in rainfall in Asia by 2099 will mainly be due to the summer monsoon [24]. On the other hand, a substantial portion of the world's population is in the Asian monsoon region. Henceforth, drastic changes in rainfall may affect the socioeconomic activities in the region [24, 25]. On the other hand, the island kingdoms of Malaysia, Singapore, Indonesia, and Papua New Guinea, however, receive boreal winter monsoon rainfall, which extends from November to March [26–30]. Moreover, Southeast Asian (SEA) countries such as Myanmar, Vietnam, Thailand, Lao People's Democratic Republic (Lao PDR), and Cambodia are largely affected by the South Asian summer monsoon system, bringing significant rainfall to those regions from May to September (list of abbreviations and acronyms are stated in Table 1) [31].

However, global climate projections show that floods will increase in many parts of the world over the next century due to increasing trends in precipitation [32]. In order to manage climate risk in an area, it is most important to study historical weather conditions and how they have changed in the present. Also, the study of rainfall variability and trends at a particular place under consideration is very helpful in climate risk management, as regional climate behavior varies more or less compared to global climate change [33]. On the other hand, precipitation variability and trend analyses are very important in formulating and implementing action plans to reduce exposure to extreme climatic conditions [34].

However, a few studies have been conducted to study the rainfall patterns and trends covering the summer monsoon region of SEA [35, 36]. These studies have shown changes in the SEA's monsoon system due to changes in temperature and monsoon rainfall in the late 21st century [37, 38]. Various studies have also found significant variations in summer monsoon rainfall in Southeast Asia [39, 40]. However, the SEA region has reported no proper climate change forecasting due to the lack of information on rainfall trends.

Henceforth, the objective of this study is to explore the rainfall variability and trends of summer monsoon countries of SEA using long-term rainfall data. The study also focuses on the trends in rainfall over the year and monsoon, covering countries and major river basins in the study area. A long-term (1981–2021) grid-based (5 km × 5 km) precipitation dataset [41–44] has been used for rainfall variability and trend analysis in other parts of the world. We strongly believe that this study's findings will help policymakers decide on sectors such as agriculture, urban planning, and disaster management.

Table 1: List of abbreviations and acronyms.

Abbreviations/ acronyms	Definition
CHIRPS	Climate Hazards Group InfraRed Precipitation with Station Data
CV	Coefficient of variation
DIM	Dry intermonsoon
DRM	Disaster risk management
FAO	Food and Agriculture Organization of the United Nations
Lao PDR	Lao People's Democratic Republic
Max	Maximum
Min	Minimum
MK	Mann–Kendall
NEM	Northeast monsoon
SEA	Southeast Asia
STD	Standard deviation
SWM	Southwest monsoon

2. Materials and Methods

2.1. Study Area. The Southeast Asian (SEA) region includes major land and oceanic islands and is characterized by tropical climatic conditions. However, the climatic setting of the SEA region is majorly controlled by the changes in the seasonal wind pattern. The SEA region exhibits extremely complex climatic conditions and strong spatial rainfall patterns. The root cause of these complex climatic conditions is the geographical changes caused by the proliferation of multiple islands near the sea. Figure 1 shows the summer monsoon region of SEA used as the study area covering Lao PDR, Thailand, Vietnam, Cambodia, and Myanmar, except for Malaysia in Southeast Asia. Although Malaysia belongs to the summer monsoon region of Southeast Asia, Malaysia is not used for this study because it has two land parcels separated by a wider ocean (more than 650 km). The selected region receives rainfall mainly from the Summer Monsoon of South Asia [36].

2.2. Data. Climate Hazards Group InfraRed Precipitation with Station Data (CHIRPS) used a spatial resolution of 5 km to generate the rainfall data, combined with satellite-estimated rainfall data with station-based rainfall measurements to provide reasonably accurate rainfall products. The primary input data for this study is CHIRPS which is available in various time scales: daily, monthly, and annually. Monthly and annual CHIRPS data from 1981 to 2021 used for this study were downloaded from the Climate Hazard Center [45].

Boundaries of country, region, and major river basins were freely downloaded from the World Bank's official boundary data catalog (https://datacatalog.worldbank.org/dataset/world-bank-official-boundaries), and the FAO data

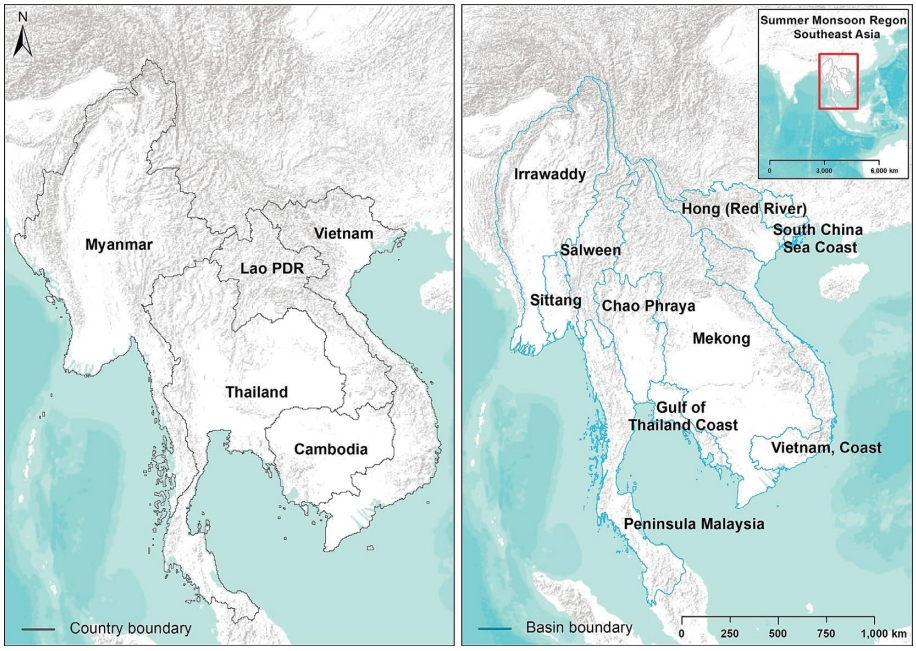

Figure 1: Study region (summer monsoon of Southeast Asia).

catalog (https://data.apps.fao.org/map/catalog/), respectively, considering their high accuracy [46]. A high degree of accuracy in major river basin boundaries is provided by the fact that the river basins are derived using hydrologically corrected elevation data (WWF HydroSHEDS and Hydro1K).

2.3. Methodology. Annual data were used directly to study annual rainfall trends, and the cumulative sum of available monthly data for the relevant monsoon seasons (May to September) was used to compile data. The CHIRPS data downloaded as NetCDF (Network Common Data Format) was converted to GeoTIFF through R-Studio software for easy reading and handling by the GIS system. Since the converted CHIRPS data are in raster format, the cumulative sum of monthly data to calculate monsoon rainfall was conducted using a geospatial data analysis technique called cell statistics. The zonal statistical calculation of the spatial statistics tool kit of ArcGIS was then used to calculate the average values of monsoon and annual rainfall covering the geographical areas of each country and river basins. The Mann–Kendall test and Sen's slope calculations were conducted by using the R-Studio statistical software package.

2.3.1. Mann–Kendall Test. The nonparametric Mann–Kendall (MK) test is mainly used in this study because it does not depend on the geographical settings of the particular region and is widely used to determine trends in precipitation, temperature, and river discharge [19, 41, 47–49]. Positive and negative values of the MK trend test indicate the increasing or decreasing trend of the considered parameters [50, 51]. Rainfall trend analysis is conducted using two approaches, i.e., the MK test and Sen's slope estimator. Whether there is a uniform linear increase or decrease trend in the considered parameter is analyzed through the MK test, and a quantitative value of that linear trend is given through Sen's slope.

MK's trend test has been performed in a series of sequential data values x_j and x_i, where $i = 1, 2, \ldots, n-1$, and $j = 1, 2, \ldots, n$. MK statistics "S" can be calculated by using the following equations:

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

$$\operatorname{sgn}\left(x_j - x_i\right) = \left\{ \begin{array}{c} +1, >\left(x_j - x_i\right), \\ 0, =\left(x_j - x_i\right), \\ -1, <\left(x_j - x_i\right) \end{array} \right\}. \tag{2}$$

The MK test requires more than ten records to analyze linear trends. Furthermore, the records used for the MK test are not considered that data are normally distributed or linear, but it needs to have autocorrelation. The null hypothesis of the MK test is that there is no trend, and the alternative hypothesis is that there is a trend. If the number of records used for the MK test is 10 or greater than 10, the variance of S is calculated using the following equation:

$$\operatorname{Var}(s) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(i)(i-1)(2i+5)}{18}, \tag{3}$$

where t_i is denoted by the number of ties of extent i.

The Z value calculated through the MK test assesses whether or not there is a significant trend of increase or decrease. If the Z value is positive, it indicates an increase in the trend of the considered parameter, and the period for which the negative Z values are considered is a decreasing/negative trend of the relevant parameter. Because the MK test is a two-tailed test, $|Z| > Z\alpha/2$ rejects the null hypotheses and is the level of

significance for the test. The MK trend test was performed to detect trends with a 5% significance level and a 95% confidence level.

$$Z = \left\{ \begin{array}{c} \dfrac{S-1}{\sqrt{\mathrm{Var}(S)}}, S > 0, \\ 0, S = 0, \\ \dfrac{S+1}{\sqrt{\mathrm{Var}(S)}}, S < 0 \end{array} \right\}. \quad (4)$$

2.3.2. Sen's Slope Estimator. Whether or not the considered parameter has a significant increasing (positive) or decreasing (negative) trend is indicated through the MK test, and Sen's slope estimator is used in conjunction with the MK test to quantitatively determine the magnitude of the decrease or increase. Sen's slope estimation method uses a simple nonparametric and systematic procedure [52] to estimate the true slope without being limited to the calibration of a linear trend estimator. Using equations (5) and (6), Sen's slope can be estimated for a particular parameter.

$$Qi = \frac{x_j - x_k}{j-k} \text{ for } i = 1, 2, 3, \ldots\ldots N, j > k, \quad (5)$$

$$\mathrm{Qmed} = \left\{ \begin{array}{c} \left(T_{(N+1/2)}\right), N \text{ is odd}, \\ \frac{1}{2}\left(T_{(N/2)} + T_{(N+2)/2}\right), N \text{ is even} \end{array} \right\}, \quad (6)$$

where Qi is the slope at the ith time and x_j and x_k are the data values at time j and k ($j > k$), and $N = n\,(n-1)/2$. The median of the N values of Qi is determined as Sen's slope estimator (Qmed).

3. Results and Discussion

This section focuses on representing descriptive statistics of the country and the basin scale, followed by half-decadal rainfall variability analysis.

3.1. Descriptive Statistics Generated Using CHIRPS Data for Country and Basins. Figure 2 represents annual rainfall variability over the entire study region and in the respective five countries (Cambodia, Lao PDR, Myanmar, Thailand, and Vietnam) for 32 years (from 1989 to 2021). Although an apparent deviation in the annual rainfall can be observed in the region in 2015 and 2019 compared to other years, the overall rainfall represents an increasing trend in all countries and the entire study region. It is important to note that there was an apparent decrease in rainfall in 2015 and 2019 compared to other years.

As Figure 2 indicates, among the countries in the region, the highest annual rainfall is in Myanmar, while the lowest rainfall is in Thailand. It is important to point out that there is no other country in the region that has received less rainfall than Thailand during the last 32 years. However, in 1986, 2000, 2009, 2014, 2016, and 2021 Cambodia received the highest annual rainfall in the region.

The study of changes in annual rainfall at the river basin level is more practical and effective than at the country level because decision-making bodies such as the Basin Management Authority can easily manage their task. When considering the change in annual rainfall from the river basin level, Peninsula Malaysia receives the highest rainfall, and the Chao Phraya River basin (Figure 3) receives the lowest rainfall.

Table 2 shows the statistical parameters such as maximum, minimum, mean, standard deviation, and coefficient of variation of annual rainfall at the level of countries in SEA, while Table 3 shows the relevant annual rainfall statistics for the major river basins of the study area. The highest average annual rainfall of 2137 mm was recorded in Myanmar, while the lowest average rainfall of 1641 mm was recorded in Thailand during the study period (between 1989 and 2021). Moreover, Myanmar and Thailand recorded their highest rainfall at 2444 mm and 2005 mm, respectively. It is important to note that the lowest rainfall between 1981 and 2021 was recorded in Thailand (1378 mm).

Considering the detailed rainfall statistics in the major river basins shown in Table 3, it is possible to identify essential differences relative to the countries where they fall. Even though Thailand recorded the lowest average rainfall, the second-highest rainfall of 2318 mm was recorded in the "Gulf of Thailand Coast" river basin. On the other hand, it is important to detect significant deviations in rainfall when considering the river basins relative to the country level. In countries, the standard deviation is between 139 mm and 187 mm, but in the river basins, it is between 113 mm and 278 mm.

The coefficient of variation (CV) is widely used to understand the interannual variability of the considered parameters. The CV of country rainfall ranges between 7.34 and 9.56, while in the river basin, the range is between 7.30 and 12.55. Accordingly, it can be stated that a significant variability of annual rainfall is not identified at the country and river basin levels. The depiction of the 1st and 3rd quartiles for each country and river basin can be found in Figure 4.

3.2. Half-Decadal Average Rainfall Variation. An important point to address in this study was the study of the differences in the spatial and temporal distribution of the average five-year rainfall. The spatial and temporal variability of the five-year average rainfall was studied for the target period (1981 to 2020) using eight intervals: 1981–1985, 1986–1990, 1991–1995, 1996–2000, 2001–2005, 2006–2010, 2011–2015, and 2016–2020. Figure 5 represents the spatial distribution of the five-year average rainfall of the study region in five different rainfall classes classified based on the natural break statistical classification.

In addition to the spatial representation of that five-year average rainfall, the change in the areas, where that rainfall was received over time was also investigated according to the rainfall classes considered. The most significant finding was

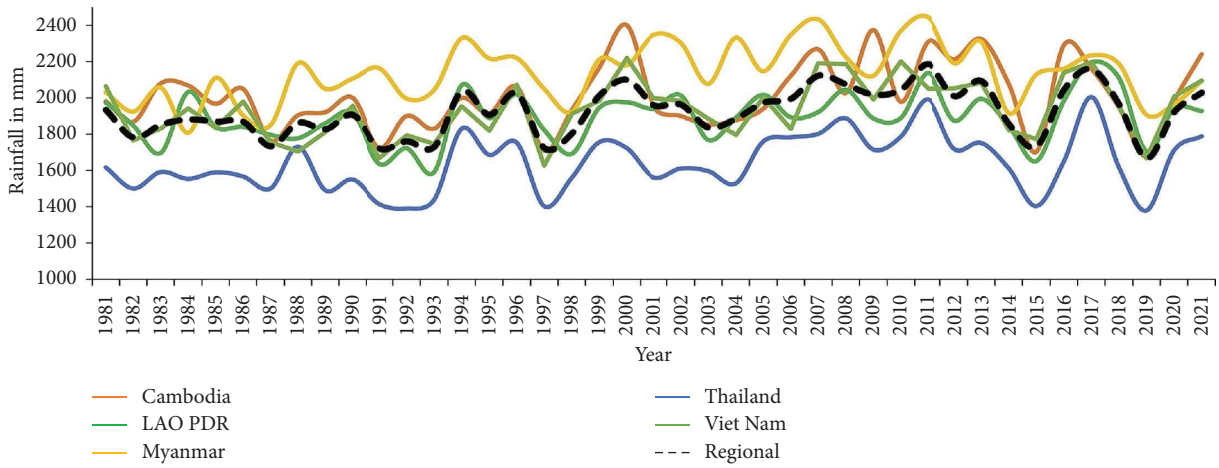

Figure 2: Annual average rainfall distribution in five countries and the entire study region.

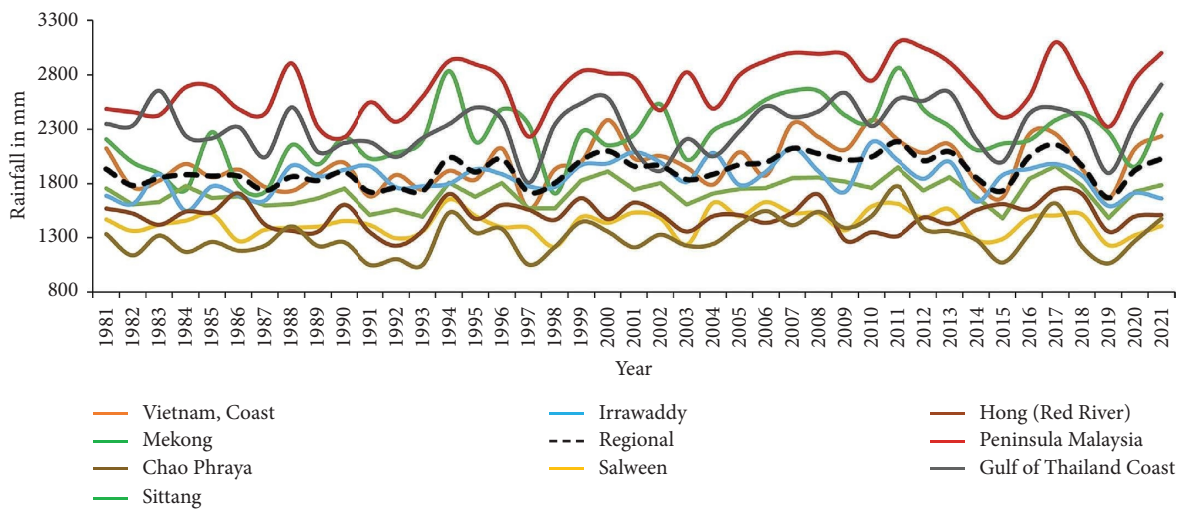

Figure 3: Annual average rainfall distribution in nine river basins and the entire region.

Table 2: Country-wise descriptive annual rainfall (in mm) statistics.

Country	Average	Max	Min	STD	%CV	Median	Recorded years (max/min)
Cambodia	2012	2400	1678	187	9.27	1982	2000/2019
Lao PDR	1892	2195	1591	139	7.34	1889	2017/1993
Myanmar	2137	2444	1808	161	7.55	2147	2011/1984
Thailand	1641	2005	1378	157	9.56	1616	2017/2019
Vietnam	1935	2220	1628	162	8.39	1955	2000/1997

Table 3: Descriptive annual rainfall (in mm) statistics in river basins.

Basin	Average	Max	Min	STD	%CV	Median	Recorded years (max/min)
Vietnam, Coast	1980	2386	1567	210	10.63	1948	2010/1997
Sittang	2246	2863	1710	278	12.37	2249	2011/1998
Salween	1437	1653	1217	113	7.88	1453	1994/1998
*Malaysia	2691	3100	2226	247	9.19	2735	2011/1990
Mekong	1717	1962	1478	125	7.30	1742	2017/2015
Irrawaddy	1852	2179	1549	152	8.23	1875	2010/1984
Hong (Red River)	1500	1743	1227	127	8.44	1508	2017/1992
**Thailand	2318	2710	1809	224	9.67	2344	2021/1997
Chao Phraya	1311	1773	1051	165	12.55	1321	2011/1993

*Peninsula of Malaysia; **Gulf of Thailand Coast.

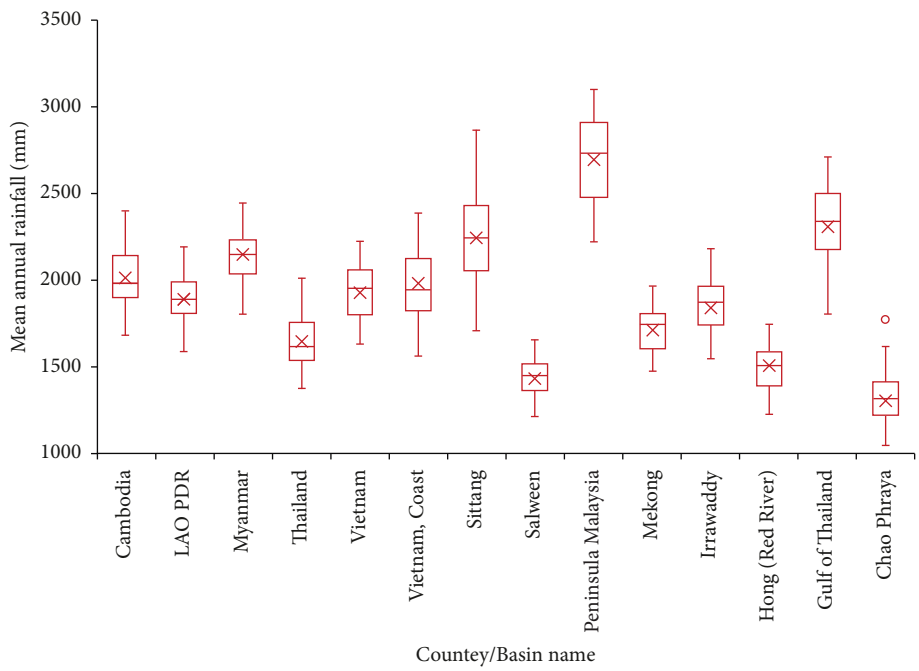

Figure 4: Box plot of rainfall distribution of each country and river basin.

that a significant increase in the average rainfall above 3500 mm in the area was found from 1989 to 2020, and that value increased from 1.8% to 6.3% of the total land area studied.

The rainfall of 2600–3500 mm also shows an increase in the areas receiving that rainfall, but the 2000–2600 mm and 1500–2000 mm classes do not observe a clear increasing or decreasing trend like other classes. However, the areas receiving less than 1500 mm of rainfall also saw a clear declining trend from 1981 to 2010, but a slight increase in the area over 2011–2015 and 2016–2020 can be observed. The spatial distribution of the abovementioned changes can be better understood using Figure 6. The coastal areas of Myanmar, Thailand, and parts of South Vietnam are identified as the increased areas receiving more than 3500 mm of rainfall.

3.3. Annual Rainfall Trends in the Country. The annual rainfall trends were calculated through the Mann–Kendall (MK) trend test for five countries, i.e., Cambodia, Lao PDR, Myanmar, Thailand, and Vietnam, including the entire region which is represented in Figure 7. However, the MK trend results show an increasing trend of rainfall in the entire study area and in all countries. However, Myanmar, Thailand, and Vietnam have significant rainfall trends. Conferring to Sen's slope estimator, the maximum annual rainfall increase recorded in Vietnam is about 5.63 mm/year, the highest among those five countries.

Although it does not represent a statistically significant increase in rainfall, the minimum annual rainfall increase recorded in Lao PDR is 3.16 mm/year; furthermore, in countries that represent a statistically significant increase, an increase in annual rainfall of more than 5 mm/year is the key finding of this analysis.

3.4. Annual Rainfall Trends in the River Basins. Annual rainfall trends in the river basins also show an increasing trend while providing a positive Kendall's tau (calculated through the MK test using R-Studio statistical software) value for all the basins. However, except for the Mekong Peninsula of Malaysia, the Gulf of Thailand Coast, and the Salween, all the other river basins show a statistically significant rainfall trend (Figure 8).

In terms of river basins, the maximum annual rainfall trend of 11.21 mm/year has been recorded in the Chao Phraya river basin, followed by the Sittan with 9.12 mm/year. However, the lowest annual rainfall increase of 1.21 mm/year was recorded in Peninsula Malaysia. Although a clear increase in annual rainfall can be detected in all countries and river basins, as described earlier, a detailed investigation of seasonal rainfall trends can provide important information needed to activate food security, such as crops and water management.

Tables 4 and 5 show the distribution of Kendall's tau, Z value, P value, and Sen's slope values at country and river basin levels for the monsoon seasons of dry intermonsoon (DIM-February to April), Southwest monsoon (SWM-May to October), and Northeast monsoon (NEM-November to January). An important finding in this analysis is the presence of negative trends in both DIM and NEM monsoon rainfalls in Thailand and Myanmar, respectively. There is no statistically significant rainfall trend in the dry intermonsoon and Northeast monsoon in any of the countries except Vietnam, but positive rainfall trends (increasing) can be identified for all

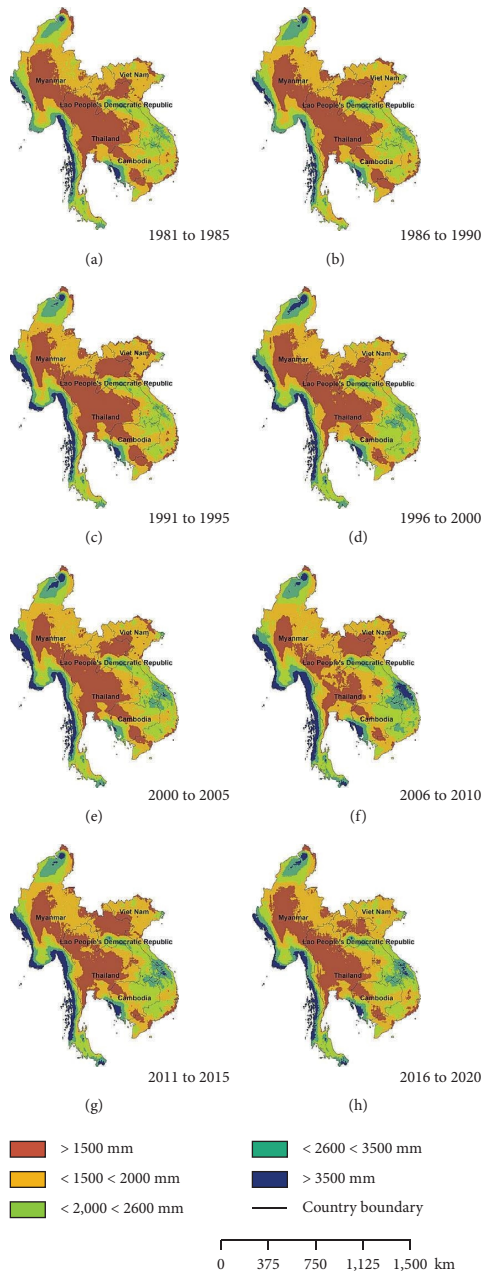

Figure 5: Spatial distribution of half-decadal average rainfall in five different rainfall classes.

monsoon rainfall seasons except for Myanmar's Northeast monsoon and Thailand in dry intermonsoon.

Although there is a statistically significant increase in annual rainfall trends in Myanmar, Thailand, and Vietnam in the Southwest monsoon, the Southwest monsoon is limited to Myanmar and Thailand. The main reason for this could be that Vietnam also receives significant rainfall during the Northeast monsoon.

Notably, no statistically significant increase or decrease was observed in any of the basins during the dry intermonsoon rainfall (Table 5). The major river basins of the Hong (Red River), Irrawaddy, and Salween present a negative rainfall trend, while the other six basins represent a positive trend. In contrast, the Southwest monsoon shows a positive seasonal rainfall trend in all the basins, but only in the Bay of Bengal-Northeast Coast, Chao Phraya, Mekong, and Sittang basins showing a statistically significant increase in rainfall. The Sittang basin indicates the highest trend (10.63 mm/year), and the minimum increase is in the Red River basin, which is 0.84 mm/year.

In the Northeast monsoon, only the Peninsula Malaysia and Vietnam-Coast river basins show statistically significant increases, with 5.05 mm/year and 3.37 mm/year, respectively. However, Chao Phraya, Irrawaddy, Salween, and Sittang indicate negative rainfall trends (decreasing) in the Northeast monsoon.

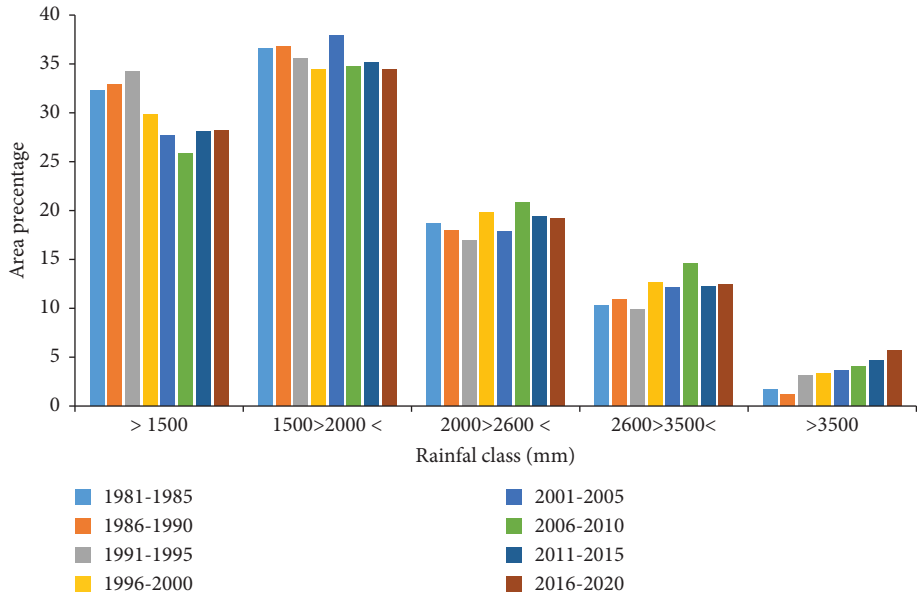

Figure 6: Area distribution (in percentage) for the study region that receives rainfall in five different classes.

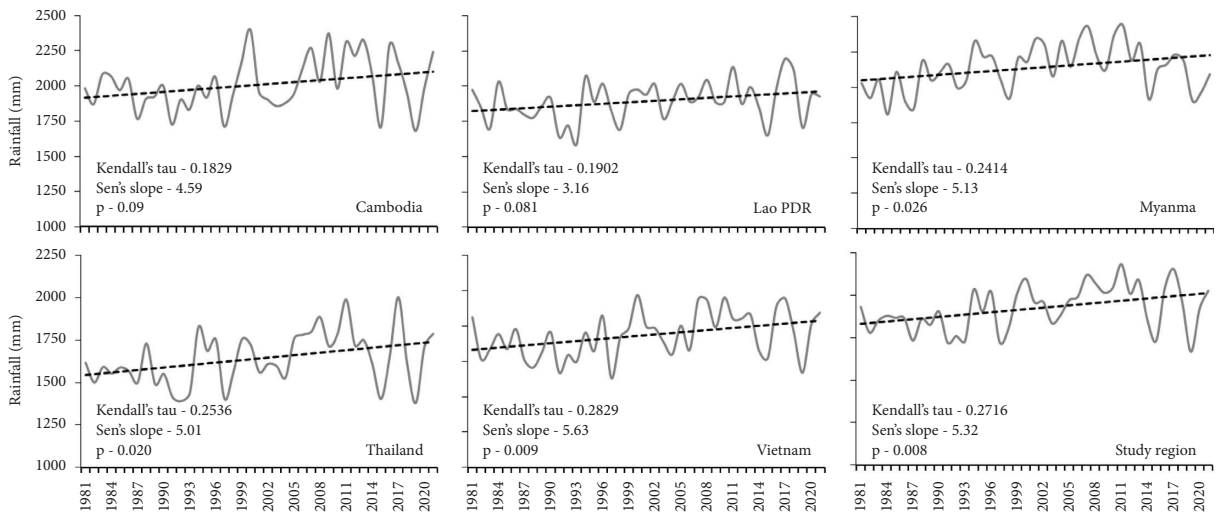

Figure 7: Annual rainfall trends in countries.

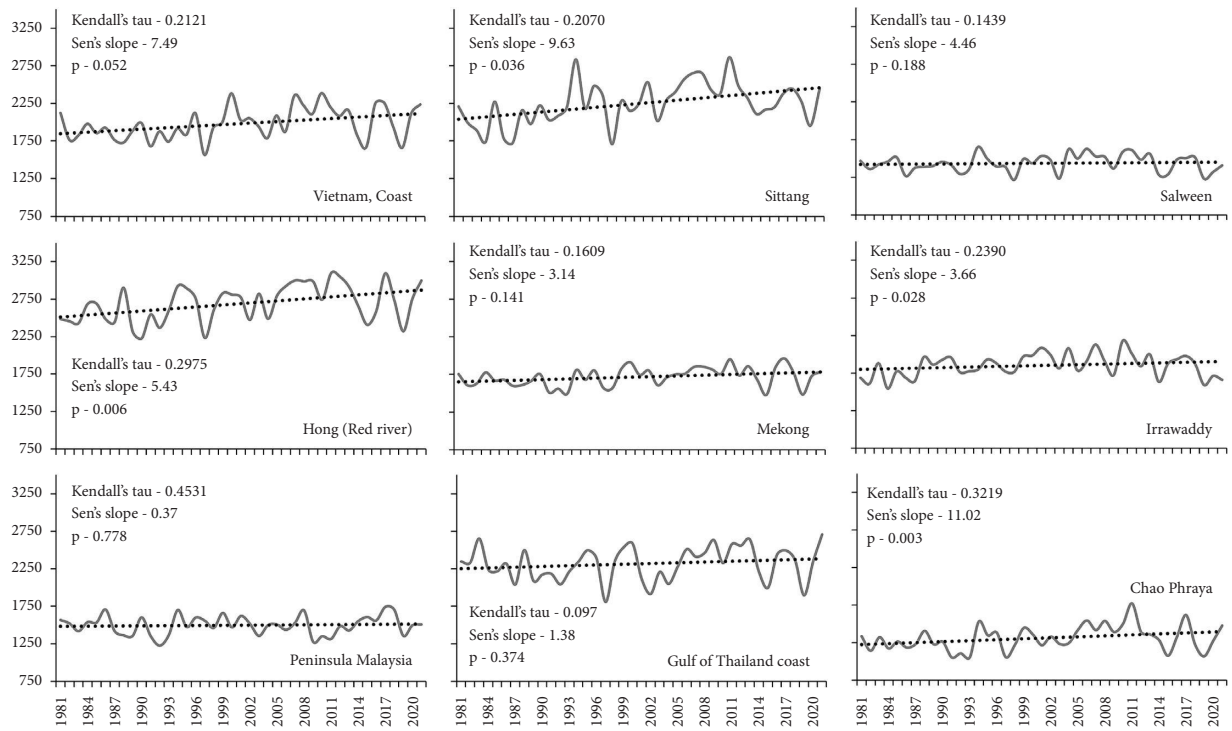

Figure 8: Annual rainfall trends in river basins.

Table 4: Rainfall trend at the country level in three monsoons.

Country	Kendall's tau	Z value	*P* value	Sen's slope	Kendall's tau	Z value	*P* value	Sen's slope	Kendall's tau	Z value	*P* value	Sen's slope
	Dry intermonsoon (Feb–Apr)				Southwest monsoon (May–Oct)				Northeast monsoon (Nov–Jan)			
Cambodia	0.1780	1.6286	0.1034	2.28	0.1098	0.9996	0.3175	2.05	0.1000	0.9097	0.3629	0.60
Lao PDR	0.0000	0.0000	1.0000	0.00	0.2024	1.8533	0.0638	2.96	0.2024	1.8533	0.0638	0.40
Myanmar	0.0171	0.1460	0.8839	0.23	0.3195	2.9315	0.0034	4.44	−0.1122	−1.0221	0.3067	−0.29
Thailand	−0.0488	−0.4380	0.6614	0.77	0.2390	2.1902	0.0285	2.99	0.1659	1.5163	0.1294	0.83
Vietnam	0.0512	0.4605	0.6452	0.37	0.2098	1.9207	0.0548	2.25	0.2951	2.7069	0.0068	2.40

Table 5: Rainfall trend at the river basin level in three monsoons.

Basin	Kendall's tau	Z value	*P* value	Sen's slope	Kendall's tau	Z value	*P* value	Sen's slope	Kendall's tau	Z value	*P* value	Sen's slope
	Dry intermonsoon (Feb–Apr)				Southwest monsoon (May–Oct)				Northeast monsoon (Nov–Jan)			
Chao Phraya	0.0951	0.8648	0.3871	1.12	0.2390	2.1902	0.0285	3.58	−0.0488	−0.4380	0.6614	−0.11
Gulf of Thailand Coast	0.1000	0.9097	0.3629	1.78	0.0537	0.4829	0.6291	1.49	0.0902	0.8199	0.4123	0.59
Hong (Red River)	−0.0171	−0.1460	0.8839	−0.13	0.0659	0.5952	0.5516	0.84	0.0732	0.6626	0.5075	0.22
Irrawaddy	−0.0073	−0.0561	0.9552	−0.04	0.1732	1.5837	0.1133	2.83	−0.1805	−1.6611	0.0987	−0.38
Mekong	0.1171	1.0670	0.2860	1.07	0.2317	2.1218	0.0338	2.61	0.1073	0.9771	0.3285	0.34
Peninsula Malaysia	0.0146	0.1235	0.9017	0.44	0.2244	2.0554	0.0398	3.10	0.3537	3.2460	0.0012	5.05
Salween	−0.0122	−0.1010	0.9195	−0.08	0.1024	0.9322	0.3512	1.20	−0.0293	−0.2583	0.7961	−0.10
Sittang	0.0317	0.2808	0.7789	0.40	0.3927	3.6055	0.0003	10.63	−0.0659	−0.5952	0.5516	−0.21
Vietnam, Coast	0.1171	1.0670	0.2860	0.84	0.1561	1.4265	0.1537	2.67	0.3171	2.9091	0.0036	3.37

4. Conclusion

This study reports a long-term (1981–2021) rainfall variability and trend analysis carried out in Lao PDR, Thailand, Vietnam, Cambodia, and Myanmar, which are in the summer monsoon region of Southeast Asia together with its major river basins, using CHIRPS rainfall data. Accordingly, it was observed that for the study period (1981–2021), there is an increasing trend in rainfall for all five countries; hence, the entire study region also shows a rising trend. The average annual rainfall of these five countries varies from 1641.38 mm to 2136.87 mm, whilst showing an increasing trend varying from 3.16 mm/year to 5.63 mm/year. This study also found that, for the study period, the average rainfall received above 3500 mm in the summer monsoon region of Southeast Asia has significantly increased from 1.8% to 6.3% of the total land area studied. This increase is mainly in the coastal areas of Myanmar, Thailand, and parts of South Vietnam. Thus, a significant increase in rainfall and the geographic area in which it occurs will increase the frequency of future flood events. However, rainfall variability and trends provide valuable forecast information for formulating disaster risk management (DRM) policies and procedures to reduce severity and exposure to future floods. On the other hand, a clear declining trend of the areas receiving less than 1500 mm of rainfall has been observed from 1981 till 2010, and since 2010, it has slightly increased. The observed seasonal rainfall trends during three monsoon seasons, dry intermonsoon (February-April), Southwest monsoon (May-October), and Northeast monsoon (November-January), also provide important information for effectively managing food security, such as crops and water management. These observations clearly show a climate change in the region that will affect the global climate in the future. Henceforth, it is recommended to consider the findings of this study by the policymakers and other relevant stakeholders dealing with the sectors such as agriculture, urban planning, and disaster management, in the summer monsoon region of Southeast Asia. The main problem associated, especially in developing countries, is the scarcity of weather stations; thus, it is also recommended that for similar-like study areas around the globe, researchers should investigate respective rainfall trends to better understand regional climate change by adopting the methodology followed in this study or with any other suitable approach.

Data Availability

Daily gridded rainfall data (CHIRPS data) are available at Climate Hazards Group InfraRed Precipitation corrected with stations data (https://data.chc.ucsb.edu/products/CHIRPS-2.0/global_daily/netcdf/p05/ (accessed on July 05, 2023). Summer monsoon region boundaries of Southeast Asia were downloaded from the World Bank official boundary data catalog (https://datacatalog.worldbank.org/dataset/world-bank-official-boundaries, accessed on July 05, 2023). The major river basin boundaries were downloaded from the FAO data catalog to cover the summer monsoon region of Southeast Asia (https://data.apps.fao.org/catalog//iso/7707086d-af3c-41cc-8aa5-323d8609b2d1, accessed on July 05, 2023).

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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